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Investigating secondary school students’ understanding of climate change

Lorna Elaine Jarrett

University of Wollongong

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Investigating Secondary School Students’ Understanding of Climate Change

Lorna Elaine Jarrett

A thesis submitted in fulfillment of the requirements for the award of the degree

Doctor of Philosophy

Faculty of Engineering and Information Sciences

University of Wollongong

Australia

2013

Supervisors: Doctor George J Takaes and Professor Brian Ferry
CERTIFICATION

I, Lorna Elaine Jarrett, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Physics, Faculty of Engineering and Information Sciences, University of Wollongong, is wholly my own work unless otherwise acknowledged. No part of this research or document has previously been submitted for any qualification at the University of Wollongong or any other institution.

Lorna Elaine Jarrett 29th March 2013
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ABSTRACT

A large body of international research confirms that misconceptions about the science of climate change remain common, despite the topic having been part of many science syllabi for more than a decade. This study explored students’ ideas about the key scientific concepts underlying the topic.

To do this, I developed the Climate Change Concept Inventory (CCCI), a 27 item multiple-choice diagnostic instrument. The concepts addressed by the CCCI were determined through a Delphi study of experts in secondary science teaching and climate science, and a review of research literature on students’ understanding of the topic. I applied a rigorous methodology for development and validation of the CCCI. This included writing distractors based on known student misconceptions identified in literature and student focus group interviews; application of item-writing guidelines; and statistical evaluation of item and test performance.

The CCCI addressed seven conceptual areas: the carbon cycle and fossil fuels; the electromagnetic spectrum; interactions between greenhouse gases and electromagnetic radiation; proportions of greenhouse and non-greenhouse gases in the atmosphere; feedback; equilibrium of energy; and conservation of energy. The first draft version of the CCCI was trialed with 229 students in Years 9 and 10. Sixty-eight undergraduate students also completed the CCCI; their responses were used for further statistical evaluation of the instrument. I conducted post-trial focus group interviews with 32 high school students to triangulate responses to the CCCI and to explore reasons behind their responses in depth.

I derived forty-five findings from the school students’ CCCI responses, and obtained corresponding post-trial focus group interview data for thirty-three of these. Twenty-seven of these thirty-three findings were corroborated by the focus group data. These included: overestimation of human contributions to atmospheric carbon inputs; overestimation of the proportion
of ultra violet radiation in sunlight; lack of awareness of the water solubility of carbon dioxide and the role of oceans in the global carbon cycle; overestimation of the proportion of greenhouse gases in the atmosphere; misidentification of greenhouse gases; lack of understanding of Earth’s energy balance and black body radiation; misconceptions about the nature of interactions between electromagnetic radiation and atmospheric gases; and limited understanding of carbon chemistry and the process of fossil fuel formation. Most participants were able to reason correctly about climate feedback scenarios but reported that they had not encountered these in school.

The study’s findings suggest that students in NSW Stage 5 (ages thirteen to sixteen) do not have the necessary accurate knowledge about the underlying concepts in order to comprehend the science of climate change. A number of recommendations are made for possible learning and teaching approaches to address misconceptions and lack of knowledge of these concepts.
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CHAPTER 1 - INTRODUCTION

1.1 Context of the study

Climate change is likely to be one of the most significant environmental issues that students, as future citizens, will face (IPCC 2007; Schreiner et al. 2005). While reducing greenhouse gas emissions is the aim of recently passed Federal legislation in Australia (Australian Federal Government 2012), it has already been the driving force behind government policy worldwide for almost a decade (Schreiner et al. 2005).

Climate change is now explicitly an issue about which students, as future citizens and voters, will be asked to make important decisions. To make informed decisions, these students require an accurate understanding of the basic science underlying the phenomenon. However, researchers into students’ understanding of the science of climate change report that despite different teaching methods and curricula, and the passage of nearly 20 years, the frequency and nature of misconceptions remain remarkably constant (Boyes & Stanisstreet 2001; Shepardson et al. 2011). This suggests that the various educational strategies designed to improve students’ understanding of the topic have had limited success.

Some environmental education pedagogies employed over the past 30 years were often based upon a model developed out of the original work of Stapp and Cox (1974). Their spaceship earth model made use of a curriculum based upon environmental sensitivity, factual knowledge, problem solving skills and spaceship earth philosophy. Others were based upon the concept of experiential education as proposed by Kolb (1984). However, the success of these pedagogies on a large scale is not strongly supported by empirical research (Kischner et al. 2006).

Several authors have argued that accurate knowledge of the science is required to guide positive behaviour with respect to climate change (Bord et al. 2000; Francis et al. 1993; McNeill & Vaughn 2010; Mason & Santi 1998; Schreiner et al. 2005; Shepardson et al. 2011). For example, accurate
knowledge about climate change was found to be the strongest single predictor of behavioural intentions by Bord et al. (2000), who pointed out that positive attitudes, on their own, are not sufficient to guide decision-making. These authors asserted that positive attitudes alone might lead to well-intentioned actions that are ineffective or counter-productive, and claimed that “Effective public education on global warming, and other environmental threats, is essential.” (p.216). Francis et al. (1993) gave a specific example of this when they reported that 86% of their participants thought that leaded petrol caused the greenhouse effect, suggesting that those participants believed that using unleaded petrol would prevent climate change.

Schreiner et al. (2005) explained that “empowerment is a prerequisite for action and includes content-specific knowledge and cognitive skills, motivational patterns and personal value orientations” (p.8); and specified that sufficient knowledge about the science of climate change is a necessary prerequisite for such empowerment.

Mason and Santi (1998) also stressed the importance of accurate knowledge as a first step in changing attitudes and hence behaviour: “such change in attitudes can rely on the construction of new, more advanced knowledge about ecological topics” (p.69). These authors saw accurate knowledge as “a fundamental component” (p.68) in individual and societal response to environmental threats.

McNeill and Vaughn (2010) concluded that beliefs alone are not sufficient to motivate students to take action. Participation in a learning unit increased both conceptual understanding and engagement in environmental action among high school students, although their participants’ belief in the reality of climate change did not alter. The authors suggested that stronger conceptual understanding of the problem increased students’ desire to take action, and recommended that learning activities should address common misconceptions about the topic.
Shepardson et al. (2011) pointed to “the importance of students learning about the greenhouse effect in order to understand the arguments and debates about the science of global warming and climate change” (p.1). According to these authors, it is essential to understand how students conceptualise the topic in order to design appropriate learning experiences. They argued that “if earth and environmental science education is to improve citizens’ understandings about global warming and climate change, students must develop mental models that are more closely aligned with scientific models” (p.2).

Various syllabi in Australian states have reflected a similar emphasis on fundamental knowledge about climate change. For example, concepts related to climate change have been part of the NSW Stage 4 Science syllabus since at least 1998 (NSW Board of Studies 1998) and the NSW Stages 4 and 5 Design and Technology and Geography syllabi since at least 2003 (NSW Board of Studies 2003). The greenhouse effect has been included in the NSW Science syllabus since 1989 (Skamp 2000). Students are also likely to encounter the issue in other high school subjects and in primary school. Despite this, high school students frequently hold misconceptions about the mechanism of climate change, for example conflating it with the topic of ozone depletion (Fisher 1998). The National Curriculum for Science (Australian Curriculum, Assessment and Reporting Authority 2012) contains similar content to the current NSW Science syllabus, so is unlikely by itself to result in any improvements in students’ understanding of the topic: it needs to be supported with further comprehension of students’ prior knowledge so more effective teaching methods can be developed. Hansen et al. (2010) support this view and stated that topics prescribed in a curriculum cannot be enacted without adequate teacher knowledge and availability of learning materials.

Various explanations have been suggested for the high rate of misconceptions about the mechanism of climate change. For example, Rye et al. (1997) offered a number of possible reasons for conflating with ozone depletion: interaction between new information and students’ intuitive
knowledge that ultra-violet radiation is “hot”; higher awareness of the issue of ozone depletion through media coverage; and the fact that both issues are human-induced and related to the atmosphere, which often leads to them being taught together. From interviews with students, Koulaidis & Christidou (1999) inferred that misconceptions about the nature of solar radiation, e.g. conflation of solar radiation, ultra-violet radiation and heat, might contribute to conflation of climate change and ozone depletion. They recommended that learning address the properties of the electromagnetic spectrum.


Osterlind (2005) described the difficulties that Year 9 students encountered when applying knowledge learned in other contexts to understand the mechanism of climate change, raising the possibility that students are struggling to apply their knowledge of underlying scientific concepts appropriately when thinking about climate change.

However, none of these hypothesised explanations was tested directly. This thesis addresses this gap in the research literature by exploring the above issues in more depth. My research consisted of determining which scientific concepts are needed for a basic understanding of climate change, and assessing students’ knowledge of these concepts.

Lambert et al.’s (2012) assessment instrument for pre-service primary teachers, in development at the same time as my research, addresses some of the same broad issues as my research in that the aim was to assess understanding of key concepts underlying climate change. However that study differs from my research in a number of ways: it involves pre-service primary teachers rather than high-school students; the authors did not
specify how they derived their list of underlying concepts; the assessment instrument contains both multiple-choice and extended-response items; and it addresses a wider range of concepts, including the effects of climate change. However the parallels between the two studies emphasise the importance of the topic as well as the lack of prior research in this area.

1.2 Research problem and significance of the study

Explaining the mechanism of climate change at the level of complexity taught as part of the NSW Stage 5 syllabus involves the application of a number of scientific concepts including the carbon cycle, the nature of energy emitted by the Sun and Earth, and some properties of the electromagnetic spectrum. Research to date on students’ understanding of climate change has focused on understanding of the topic as a whole, but misconceptions or gaps in knowledge of the underlying scientific concepts will inevitably confound understanding of the topic.

Many of the researchers who have investigated students’ understanding of climate change have listed concepts which they consider to underlie the topic (Andersson & Wallin 2000; Boon 2009; Boyes & Stanisstreet 1993; Boylan 2008; Browne & Laws 2003; Dove 1996; Fisher 1998; Hansen 2010; Hobson 2003; Keller 2006; Koulaidis & Christidou 1999; Rebich & Gautier 2005; Rye et al. 1997; Schultz 2009; Shepardson et al. 2009; Österlind 2005). Some of these researchers have suggested possible ways in which problems with understanding of underlying topics could lead to misconceptions about climate change (Andersson & Wallin 2000; Hansen 2010; Koulaidis & Christidou 1999; Mason & Santi 1998; Österlind 2005; Rye et al. 1997). However to date, little research has been conducted that: (i) explicitly and systematically determines which scientific concepts are fundamental to a basic understanding of the science of climate change; and (ii) examines high school students’ understanding of these key concepts.

Further, students currently learn about these concepts in a number of different contexts. For example students usually encounter the electromagnetic spectrum in the context of communication (NSW Board of
Studies 2003). In order to make sense of learning materials used in teaching climate change, students have to recall and apply this knowledge in the new context. Students’ ability to apply knowledge learned in one context to another context may therefore also be a factor in the development of misconceptions.

This thesis contributes to the literature on high school students’ understanding of a number of scientific concepts. These findings can give insight into students’ understanding of other topics underpinned by one or more of these concepts. As Mestre (2001) explained, “Physics is perhaps the only science in which a handful of concepts can be applied to solve problems across a wide range of contexts” (p.49).

Another outcome of the study is the development and validation of a concept inventory for these concepts. This concept inventory has potential applications for undergraduate students studying the topic, as well as school students. As Treagust (1988) pointed out, “The development of multiple choice tests on students’ misconceptions has the potential to make a valuable contribution, not only to the body of work in the area of misconceptions, but also to assist in the process of helping science teachers use the findings of research in this area” (p.160).

Lambert et al. (2012) asserted that “the continued development of better tools to assess students’ knowledge of climate change is crucial to reveal and identify alternative conceptions … This requires research and development of reliable and valid instruments” (pp.1184-1185).

1.3 Statement of purpose

As outlined in the previous two sections, students require accurate knowledge about the science of climate change in order to make informed decisions about issues related to the topic. Moreover, it is known that misconceptions about the science of climate change are common, and that these may be caused or exacerbated by a lack of adequate understanding of the underlying scientific concepts. Therefore, this study focuses on students’ conceptual understanding of the science of climate change.
The purpose of the study was to investigate NSW Stage 5 students’ understanding of the key scientific concepts required to make sense of the topic at a basic level.

This involved deriving a descriptive list of the key concepts underlying a basic but scientifically acceptable explanation of the mechanism of climate change, validating the importance of these concepts, and developing a concept inventory for data collection.

This study employed a constructivist theoretical framework, which states that rather than being transmitted unaltered from teacher to learner, knowledge is actively constructed by the learner when new information interacts with the learner’s pre-existing knowledge.

Most research on this topic to date has taken a relatively broad view of students’ understanding of the causes, effects and possible actions to reduce climate change. Often the focus is on effects and possible actions, however, as Bord (2000) and Mason and Santi (1998) emphasised, accurate understanding of the cause of the problem is integral to understanding of solutions and must not be neglected. Therefore this study focused on the mechanism of climate change, in order to allow a deeper examination of the issues. It is anticipated that findings will be used in future work to inform the development of learning strategies for the topic.

1.4 Research questions

The following research questions are derived from the statement of purpose and served to guide the development of the research plan.

1. What underlying scientific conceptual knowledge is required for students to make sense of a basic explanation of the mechanism of climate change?

2. What do NSW Stage 5 students understand about these underlying scientific concepts?

Before investigating students’ understanding of the key concepts underlying
the science of climate change, it is first necessary to identify these key concepts and describe the depth to which they must be understood. Researchers have suggested a number of such concepts, for example, the electromagnetic spectrum (Koulaidis & Christidou 1999) or carbon cycle (Shepardson et al. 2009). However these may not be the only concepts underlying the topic, or the most important. Research question 1 therefore forms the basis of the study as it addresses the need for a validated descriptive list of key concepts.

Research question 2 sets out to address some possible reasons for misconceptions suggested by researchers (Andersson & Wallin 2000; Hansen 2010; Koulaidis & Christidou 1999; Mason & Santi 1998; Rye et al. 1997) by exploring students’ ideas about the key concepts.

1.5 Theoretical framework of the study

1.5.1 Constructivist learning theory

Constructivist learning theory forms the basis of the theoretical framework for this study. Five principles of this theory are important to this study.

1. Rather than being transmitted unaltered from teacher to student, learning involves knowledge being actively constructed by students. Bodner (1986) asserted that: "This constructivist model can be summarised in a single statement: Knowledge is constructed in the mind of the learner" (p.1).

2. This knowledge is constructed when new information interacts with the students’ pre-existing ideas. This implies that each individual’s understanding of a concept is unique. It also implies that learners’ existing ideas play a crucial role in determining how new knowledge is constructed. Ausubel (1963) asserted that the most important principle in education psychology is “what the learner already knows”.

Driver (1989) stated that learning happens when learners actively construct knowledge by building "mental representations of the world around them" (p.481), and that these representations are themselves used in the interpretation of new information. Driver (1983) pointed out that learners
cannot be expected to perceive the same connections between concepts as experts, so they cannot be expected to make and interpret observations as experts do. To illustrate this, Driver (1983) referred to novices focusing on irrelevant aspects of a phenomenon when making observations. A similar example was given by Allain (2010) who described the difficulties faced by teachers who were not content experts in setting up experiments: “When you are not a content expert, you have no idea what aspects are important and which are not”. Driver (1983) saw prior knowledge as the “lenses” through which students make and interpret their observations and which give rise to conceptualisations.

3. Constructed knowledge is tested for “fit” with learners’ experience. von Glasersfeld (1984) asserted that knowledge is seen in constructivism not as a "copy" of reality but as a "key": it has to “fit” with the learners’ experiences of reality rather than being expected to match reality. “The constructivist model is an instrumentalist view of knowledge. Knowledge is good if and when it works, if and when it allows us to achieve our goals” (Bodner 1986; p.5). According to Bodner (1986), construction of knowledge involves both building knowledge and testing it for “fit”.

4. Such learning, actively constructed by the learner and linked to their existing knowledge, is considered meaningful, rather than rote-learning. Dykstra et al. (1992) stressed that the process of construction is essential for conceptual understanding. Ausubel (1963) explained that meaningful verbal learning takes place when new knowledge is integrated appropriately with existing ideas.

5. A hallmark of successful meaningful learning is that it can be applied to new contexts. In contrast, when information is rote-learned, students are unable to use it in novel contexts and instead revert to their pre-existing ideas. White and Gunstone (1992) point out that understanding is a higher-order form of learning than rote learning, and that understanding involves using knowledge to solve novel problems. Driver (1983) and Resnick (1983) observed how learners may be able to apply a new principle in the learned concept but revert to their old explanation when thinking about a
new context: “in making predictions he trusts his intuition” (Driver, 1983, p.39). Conversely, in Driver’s (1989) opinion, the extent is debatable to which childrens' intuitive ideas about science are used consistently across different contexts or have coherent internal structure, suggesting that intuitive ideas do not function in the same way as learned conceptual knowledge.

1.5.2 Constructivist perspectives on learning in science
Driver (1989) saw learning science as more than just meaning making undertaken by an individual. She saw it also as being inducted into the scientific communities' tried and tested "ways of seeing". Driver saw this as a process that learners cannot undertake independently, because they would not be able to distinguish between a scientifically incorrect interpretation that happened to fit the appearance for a particular context, and a scientifically accepted interpretation.

Bruning et al. (2004) asserted that students need to learn to “organise their knowledge into schemata that are … related to fundamental scientific concepts” (p.350). Driver (1983) made the same point: “Many substantive concepts in the sciences take their meanings not simply through the network of other substantive concepts to which they relate, but through the nature or structure of the relationship between them” (p.58).

1.6 Outline of research design

1.6.1 Pilot study
I carried out a pilot study in 2008 and 2009 to investigate the structure of students’ knowledge of climate change using concept mapping and semi-structured individual interviews. The pilot study is summarised in Appendix 1. Findings from the pilot study informed the design and choice of data-collection methods for this study, following the principles of an action-learning model (Kemmis & McTaggart 2000). This helped to ensure that suitable methods were used for this study, and that assumptions about participants’ knowledge, based on literature, were reasonable.
1.6.2 Outline of design for this study

Figure 1.1 summarises the main stages of the research design. The study employed multiple data-collection methods: text analysis, online survey, semi-structured focus groups and multiple-choice questions. This use of multiple methods yielded multiple perspectives and a rich dataset, enabling the triangulation of findings, thereby enhancing credibility (Mertens 2005).

Research Question 1 underpinned Research Question 2 because it determined the nature, scope and depth of the concepts investigated in Research Question 2. Therefore, to take account of a broad a range of perspectives, I employed multiple methods to address Research Question 1. These were (i) a review of literature on students’ understanding of climate change; and (ii) a Delphi study (an iterative online survey) involving 18 people with expertise in climate change education.

![Figure 1.1 Summary of research design showing sequence of main events]
A key advantage of Delphi studies is that they allow a group of people to collaborate in decision-making without having to attend meetings (Linstone & Turoff 1975). The findings from the literature review and Delphi study were synthesised to produce a list of conceptual statements setting out the key concepts (Jarrett et al. 2011).

Research Question 2 investigated students’ understanding of the key concepts underlying the science of climate change. To address Research Question 2, I used the conceptual statements from Research Question 1 in two data-collection activities to investigate students’ understanding of the key concepts. First, the conceptual statements prescribed the content for a multiple-choice survey (a concept inventory, or CI) administered to 229 students in Years 9 and 10; and second, they formed the basis of questions and activities for semi-structured focus group interviews.

The climate change concept inventory (CCCI), developed as part of this study, provided the main body of data to address Research Question 2. To enhance its quality and validity, I used findings from a review of literature on CI development and validation methods. One such finding was that incorrect CI item response options, i.e., distractors, should reflect known student misconceptions (Richardson 2004). In order to achieve this, I reviewed literature on misconceptions about the key underlying concepts, used open-ended questions in focus groups, and wrote item distractors to reflect the misconceptions reported in literature or voiced by participants.

To assess the quality of CI items and the test as a whole, I calculated statistical measures recommended in CI validation literature including item difficulty, item discrimination and point biserial coefficient, and compared these with recommended values. As an additional source of information on CI quality, I administered the CI to 68 undergraduate students studying introductory-level climate change and again calculated statistical measures. The CI development, trial and validation process was reported in Jarrett, Ferry and Takacs (2012).
The second data collection activity for Research Question 2 involved focus groups, using open-ended questions and activities derived from the conceptual statements. The focus groups involved a subset of the high school students who had completed the CI, and served to elaborate on the CI data.

1.7 Outline of literature related to the study

Table 1.1 summarises the areas of literature reviewed for this study, the purpose of each section of the literature review, and the chapter in which each section is discussed.

Sections 2 and 3 of Chapter 2 set the context for the study. They include literature explaining the importance of students understanding the science of climate change, and a review of studies that assessed the state of students’ knowledge of the topic. This review focused on studies that explored conceptual understanding rather than, for example, attitudes or behaviours; and on studies that investigated ideas about the mechanism of climate change in detail, rather than focusing on its effects or possible solutions.

Section 4 of Chapter 2 involved identifying conceptual knowledge cited by researchers as underlying the science of climate change. This served as a second source of data for Research Question 1, enhancing validity by incorporating multiple perspectives (Mertens 2005).

In Section 5 of in Chapter 2, I reviewed literature on students’ understanding of the essential underlying concepts synthesised from the Delphi study and Section 2.4. A key guideline in CI development is that distractors should reflect known misconceptions. The purpose of Section 2.5 was to identify such misconceptions so that distractors for CI items could be written to reflect them.

Section 3.4.3 of Chapter 3 describes the background and method for focus group interviews.
Table 1.1: Summary of literature reviewed

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 2</td>
<td>2.2 Why do students need to understand the science of climate change?</td>
<td>Context: summary of the issues</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>2.3 Students’ knowledge about the science of climate change: summary of research to date</td>
<td>Context: summary of the issues and illustration of gap in literature</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>2.4 What are the essential scientific concepts underlying the science of climate change?</td>
<td>Identification of concepts considered necessary for understanding of the topic. Used to synthesise the list of statements of essential conceptual knowledge</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>2.5 Students’ ideas about the essential underlying concepts</td>
<td>Summary of research findings: used to develop CI item distractors that reflected known misconceptions</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>3.4.3 Focus group interviews</td>
<td>Rationale for use of focus group interviews: practicalities</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>4.2 Delphi method: origin; advantages and limitations; use of Delphi method in science, mathematics engineering and computing; and study design</td>
<td>Rationale for use of Delphi method: determination of method for this study</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.2 Concept inventories in science, mathematics and engineering: methods for CI development and validation</td>
<td>Determination of method for development and validation of the CCCI</td>
</tr>
</tbody>
</table>

In Section 2 of Chapter 4, I reviewed literature on the origin, advantages, disadvantages, design and administration of Delphi studies. The creation of a valid set of key concepts played a central role in the study. It not only answered Research Question 1 but also underpinned Research Question 2 by forming the basis of the CCCI and focus group questions used to address this research question. Therefore, to enhance the validity of the key concepts and their conceptual statements, I conducted a Delphi study in order to consult with as large a group of discipline experts as possible. Delphi studies are often used in the development of CIs (Danielson 2005; Goldman et al. 2008; Gray et al. 2005; Herman 2011; Rowe & Smaill 2007;
Stone et al. 2004; Streveler et al. 2003) to determine which concepts should be covered, because choosing concepts based on expert opinion contributes to the CI’s validity (Richardson 2004; Treagust 1988).

Section 2 of Chapter 5 comprised a review of literature on the development and validation of concept inventories. This review was carried out so that the CI development and validation process would be as rigorous as possible: Libarkin (2008) pointed out that CI validity derives in large part from a rigorous development procedure.

1.8 Outline of the remainder of the thesis

Chapter 2 presents literature on students’ ideas about the science of climate change and underlying concepts. It discusses studies that demonstrate the importance of accurate scientific knowledge in guiding attitudes and behaviour, and summarises research investigating students’ ideas about the topic. It also summarises the findings of research into students’ ideas about scientific concepts underlying the science of climate change.

Chapter 3 describes the methods for collection and analysis of data. These included: design and administration of a Delphi study; development, administration and validation of a concept inventory; and administration of semi-structured focus group interviews.

Chapter 4 describes the development of a validated list of conceptual statements setting out the key knowledge required to understand a basic explanation of the mechanism of climate change. This list was synthesised from two data-sources: the results of a Delphi study involving 18 discipline experts, and a review of research literature on students’ ideas about climate change which cited conceptual knowledge considered by the authors to underlie the topic. This chapter includes: a review of literature of Delphi study methodology; the method for, and findings of, my Delphi study; the process of synthesis of findings from the Delphi study and literature review, and the resulting synthesised list of conceptual statements. This list forms the findings for research question 1.
Chapter 5 reports on the CCCI development and validation process. It includes a review of literature on CIs in science, mathematics and engineering, focusing on development and validation procedures. It then describes the development and validation method employed in this study, including field trial procedures and a discussion of the statistical measures used for evaluation.

Chapter 6 presents the statistical measures of CCCI performance for individual items and the test as a whole. Data are compared for high school students and undergraduates, and the quality of the CCCI, as deduced from statistical measures, is discussed.

Chapter 7 presents high school students’ responses to the CCCI items and discusses what these suggest about participants’ knowledge of the key underlying concepts.

Chapter 8 presents data from the post CI focus group interviews. It describes how these data were collected, analysed and used to validate CI findings, and summarises the results of the validation process.

Chapter 9 comprises the general discussion and conclusions of the study. It includes a discussion of the study’s findings, recommendations for teaching practice, and outlines possible future research directions.

1.9 Summary of key terms

The following terms are used extensively in this thesis. To minimise ambiguity, they are defined below.

Climate change

This term was chosen in preference to the “enhanced greenhouse effect” or “global warming” but covers the same conceptual areas of the natural greenhouse effect plus causes of enhancement both direct (e.g. burning of fossil fuels) and indirect (e.g. feedback mechanisms). This study focuses on the physical mechanism of the greenhouse effect: increased absorption and re-radiation of infra-red radiation by excess greenhouse gases such as
carbon dioxide and methane released into the atmosphere by human activity. This study did not examine students’ ideas about possible effects such as rising sea levels or possible actions to reduce climate change, such as reducing fossil-fuel use.

**Concept inventory (CI)**

A validated, multiple-choice assessment instrument designed to test conceptual understanding of several related concepts, and to identify the occurrence of known misconceptions. CIs have been developed for a wide range of topics and disciplines in science, computing, mathematics and engineering (Anderson et al. 2002; G. L. Herman 2011; Pavelich et al. 2004; Smith et al. 2008; Stone 2006). The Force Concept Inventory (Hestenes et al. 1992) was the first such test to be called a concept inventory, however the principle of using multiple-choice tests with distractors based on known misconceptions as tools to investigate learners’ conceptual understanding was in use in the 1970s (Tamir 1971).

**Conceptual area**

An area of knowledge containing a number of closely related concepts. In this study, I organised the key concepts underlying the science of climate change into a set of ten conceptual areas. Seven of these formed the basis of the climate change concept inventory (CCCI).

**Conceptual statement**

This term refers to a statement describing scope and depth of knowledge of a key concept underlying the science of climate change (see below). In this study, conceptual statements served to set the boundaries of what learners need to know in order to understand the topic of climate change. They defined the content to be covered by the CCCI and the ideas to be discussed in focus groups. In CI development, conceptual statements therefore serve the same purpose as do Propositional Knowledge Statements (PKS) in the development of diagnostic tests (Treagust 1988).
Delphi study

While variable in format, the key features of a Delphi study are: multiple versions of a survey; summaries of the group’s responses to the previous version fed back to participants along with the next version; and participant anonymity. Delphi studies are carried out where collaborative consultation is required to aid decision-making.

Distractor

An incorrect item response choice in a multiple-choice test. In a concept inventory, distractors are written to reflect known misconceptions.

Item

A question in a concept inventory.

Key concept

One of the concepts underlying the science of climate change, considered necessary in order for a learner to comprehend a basic explanation of the topic. Key concepts in this thesis are expressed as single words or short phrases, and each is elaborated in a corresponding conceptual statement. Therefore the key concepts act as “titles” for the conceptual statements.

Misconception

An idea held by a learner that is not in agreement with the scientifically accepted concept. A number of terms have been used to refer to such ideas including “alternative framework” (Driver 1981), “alternative conception” (Harrison et al. 1999), “childrens’ science” (Gilbert et al. 1982), “preconception” (Novak 1977) and misconception” (Helm 1980). I chose “misconception” for brevity and to emphasise the difference between students’ ideas that align with scientific ideas and those which do not.

Underlying concept

One of the key concepts considered necessary in order to understand the science of climate change. Also referred to as a key concept in this thesis.
CHAPTER 2 – REVIEW OF LITERATURE

2.1 Chapter overview and structure

This chapter discusses literature on learners’ conceptual understanding of climate change and related scientific concepts. The literature is divided into four sections.

Figure 2.1 and Table 2.1 show how these sections relate to the purpose and structure of the study.

Figure 2.1: Relationships between the sections of the literature reviewed in Chapter 2 and the research design

Figure 2.1 shows the elements of the research design that either emerged from, or incorporated findings from, the literature review. It uses the same
symbols and layout as Figure 1.1 in Chapter 1, but focuses on the contribution made by each section of the literature review to either the framing of the research problem and significance of the study, or to one of the research questions. Table 2.1 elaborates on Figure 2.1 by explaining the purpose of each section of the literature review in more detail.

Table 2.1: Summary of literature reviewed in Chapter 2

<table>
<thead>
<tr>
<th>Section Heading</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 Why do students need to understand the science of climate change?</td>
<td>To elaborate on the research problem and significance of study by explaining the importance of students understanding the science of climate change.</td>
</tr>
<tr>
<td>2.3 Students’ knowledge about the science of climate change</td>
<td>To elaborate on the research problem and significance of study by summarising research to date on students’ ideas about the topic.</td>
</tr>
<tr>
<td>2.4 What are the essential scientific concepts underlying climate change?</td>
<td>Findings were used to develop the list of essential underlying concepts, to address Research Question 1.</td>
</tr>
<tr>
<td>2.5 What do students know about the essential underlying concepts?</td>
<td>To identify known misconceptions about the essential underlying concepts for use in development of the concept inventory to address Research Question 2.</td>
</tr>
<tr>
<td>2.6 Critique of methodologies</td>
<td>To inform the development of methods for this study.</td>
</tr>
<tr>
<td>2.7 Conclusions</td>
<td>To explain how my study contributes to the body of literature on the topic.</td>
</tr>
</tbody>
</table>

2.2 Why do students need to understand the science of climate change?

Several authors have linked accurate scientific knowledge of the topic to support for appropriate action to prevent climate change. The concern also exists that citizens who hold misconceptions about climate change may take well intentioned but ineffective measures. Other researchers consider the importance of climate change as sufficient justification for its inclusion in curricula, and for accurate knowledge of the topic to be important.
Bord et al. (2000) surveyed 1218 American adults about a number of social and environmental issues. This research is significant because the authors investigated correlation between understanding of the causes of climate change and support for appropriate action to prevent it, thus explicitly investigating the relationship between knowledge and action. The authors investigated correlation between understanding, belief and willingness to act. They found that accurate knowledge of the causes of climate change was the strongest predictor of willingness to take voluntary action and support appropriate government policies. In concluding, the authors strongly stated their belief that accurate scientific knowledge is an essential prerequisite for appropriate decision-making: “Training for environmental citizenship must go beyond merely sensitising people to environmental problems. More in-depth knowledge is required. A basic understanding of cause and probable effects is necessary, with all the uncertainty and complexity included” (p.216).

By contrast, Francis et al (1993) acknowledge that accurate knowledge does not always lead to action, however they stressed that “some environmental issues are of such potential importance that every contribution to their solutions should be explored and exploited” (p.391). Taber and Taylor (2009) also highlighted the importance of the topic, stating that “The issue of global warming is one of great concern for Australian children. This points to the need for effective teaching about this issue” (p.97). Similarly Boon (2009) concluded that, as a scientific literacy issue of importance to students as future citizens, there needs to be greater emphasis on climate change in classrooms and syllabus documents, so that “voters enter the polling booth with adequate knowledge” (p.46). Further, Shepardson et al. (2009) raised the issue of learners’ prior knowledge of the topic. They asserted that if science education is to result in students becoming informed citizens on the topic of climate change, “it is essential to determine what students’ conceptions are” (p.550) so that learning experiences can be designed accordingly. This highlights the importance of research examining students’ misconceptions about the topic.
Some authors suggested specific ways in which these misconceptions may prevent learners, as future citizens, from making appropriate decisions. For example, Francis et al. (1993) reported that 86% of their participants thought that leaded petrol causes the greenhouse effect, and warned that if this misconception is not addressed, it might lead to motorists believing that by using unleaded petrol they are avoiding contributing to climate change. Boyes and Stanistreet (1993), who found even higher rates of this misconception among under-13s, expressed the same concern. Rye et al. (1997) made the same point regarding the use of aerosol cans, which Rye et al.’s (1997) participants believed to cause climate change by destroying the ozone layer. The U.S.A banned CFCs as aerosol propellants in 1978 (United States Environmental Protection Agency 2012), however this misconception centres on conflation of ozone depletion and climate change.

Gowda et al. (1997) said of confusion between ozone depletion and climate change: “This mistake is significant because peoples’ perceptions regarding causes help dictate their responses to the problem … they may have the false impression that they are doing a significant amount to prevent global warming, while actually having no effect” (p.2234), while Bord et al. (2000) asserted “Those believing that aerosols and insecticides cause global warming are not likely to make wise choices on referenda questions for government policies.” (p.216).

2.3 Students’ knowledge about the science of climate change

2.3.1 Introduction

Several studies were carried out in the 1990s to determine students’ conceptions of climate change, coinciding with intense political and media interest in the lead-up to the Kyoto Conference (Leggett 2000; Vongalis-Macrow 2007). These studies consistently reported widespread and significant misconceptions. Given the emerging nature of the science and associated political and social changes of the last twelve years, it might be expected that student knowledge has improved. However, more recent research has refuted this, with some studies suggesting that awareness of the
issue is at levels lower than before. For example, Boon (2009) hypothesised that 16 years of advances in scientific knowledge and evidence would be reflected in an improvement in students’ understanding of the phenomenon, when comparing an English 1991 cohort with Australian students in 2007. However she found no statistically significant difference between the two groups. Similarly, Boyes and Stanisstreet (2001) revisited their 1993 study, and found no significant change in students’ ideas.

2.3.2 Research methods and findings
Table 2.2 summarises the methods and contexts of the studies reviewed in this section.

Table 2.2: Summary of literature reviewed on learners’ ideas about climate change

<table>
<thead>
<tr>
<th>Authors</th>
<th>Location</th>
<th>Age of participants</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boyes and Stanisstreet (1993)</td>
<td>U.K.</td>
<td>11-16</td>
<td>Closed-response survey and follow-up interviews</td>
</tr>
<tr>
<td>Francis et al. (1993)</td>
<td>U.K.</td>
<td>8-11</td>
<td>One section of Boyes et al.’s (1993) survey and follow-up interviews</td>
</tr>
<tr>
<td>Dove (1996)</td>
<td>U.K.</td>
<td>Pre-service teachers</td>
<td>Closed-response survey and diagram-annotation</td>
</tr>
<tr>
<td>Rye et al. (1997)</td>
<td>U.S.A.</td>
<td>11-14</td>
<td>Semi-structured interviews</td>
</tr>
<tr>
<td>Gowda et al. (1997)</td>
<td></td>
<td>14-16</td>
<td>Open-response survey</td>
</tr>
<tr>
<td>Mason and Santi (1998)</td>
<td>Italy</td>
<td>9-10</td>
<td>Interviews and recordings of classroom interactions</td>
</tr>
<tr>
<td>Koulaidis and Christidou (1999)</td>
<td>Greece</td>
<td>11-12</td>
<td>Extended semi-structured interviews with activities including concept map construction</td>
</tr>
<tr>
<td>Andersson and Wallin (2000)</td>
<td>Sweden</td>
<td>11-19</td>
<td>Open-ended writing task on several environmental issues</td>
</tr>
<tr>
<td>Authors</td>
<td>Country</td>
<td>Age Range</td>
<td>Methodology</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------</td>
<td>--------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Boyes and Stanisstreet</td>
<td>U.K.</td>
<td>11-17</td>
<td>Mixed-response survey</td>
</tr>
<tr>
<td>Pruneau et al. (2001)</td>
<td>Canada</td>
<td>7-8, 12-14 and adults</td>
<td>Semi-structured interviews</td>
</tr>
<tr>
<td>Kurup (2003)</td>
<td>WA, Australia</td>
<td>Year 10 students</td>
<td>Closed response survey</td>
</tr>
<tr>
<td>Rebich and Gautier (2005)</td>
<td>U.S.A.</td>
<td>Undergraduates</td>
<td>Concept mapping</td>
</tr>
<tr>
<td>Keller (2006)</td>
<td>U.S.A.</td>
<td>Undergraduates</td>
<td>Concept inventory</td>
</tr>
<tr>
<td>Boon (2009)</td>
<td>Qld., Australia</td>
<td>12-16</td>
<td>Open-response survey</td>
</tr>
<tr>
<td>Shepardson et al. (2009; 2011)</td>
<td>U.S.A.</td>
<td>11-12</td>
<td>Open-response survey and draw-and-explain exercise</td>
</tr>
<tr>
<td>Taber and Taylor (2009)</td>
<td>NSW, Australia</td>
<td>11-12</td>
<td>Closed-response survey informed by Boyes et al.’s (1993) survey and semi-structured interviews</td>
</tr>
<tr>
<td>Boon (2010)</td>
<td>Qld., Australia</td>
<td>15-16 and Pre-service teachers</td>
<td>Multiple choice and open-response survey</td>
</tr>
<tr>
<td>Lambert et al. (2012)</td>
<td>U.S.A.</td>
<td>Pre-service teachers</td>
<td>Concept inventory and open-response questions including optional labeled diagrams</td>
</tr>
</tbody>
</table>

According to Hansen (2010), that author was the first researcher to publish in this field, however no English translation of the work could be obtained.

In the U.K., Boyes and Stanisstreet (1993) used closed-response questionnaires and follow-up interviews to investigate understanding of causes, consequences and actions to reduce the greenhouse effect, in 861 students aged eleven to sixteen. Sixty students participated in follow-up interviews. The questionnaire content was informed by findings from an open-response questionnaire piloted by 60 Year 9 students. Eighty-three
percent of 14-15 year-olds agreed with the statement “The Greenhouse effect is made worse by holes in the ozone layer”, with little variation in this figure for younger (86%) and older (70%) students, suggesting that the idea is formed early and persistent. Sixty percent of students also thought that the greenhouse effect was due to excessive amounts of the Sun’s rays reaching Earth. Interview responses confirmed that students thought that damage to the ozone layer led to increased amounts of the Sun’s rays reaching, and warming, the Earth. The authors used factor analysis to look for evidence of “general underlying conceptual frameworks” (p.544). They found an association between agreement with increased penetration of Sun’s rays as a cause, skin-cancer as a consequence and CFCs as a cause. All these ideas are linked to the phenomenon of ozone depletion.

Francis et al. (1993) used the subsection of Boyes and Stanisstreet’s (1993) instrument that asked about possible actions to reduce the greenhouse effect, with 563 participants aged between 8 and 11. Follow-up interviews with 15 participants revealed conflation with ozone depletion, and the idea that using unleaded petrol would reduce the greenhouse effect.

In England, Dove (1996) used a mixed questionnaire to investigate 60 pre-service teachers’ knowledge of climate change. Her survey instrument resembled that used by a number of researchers, including Boyes and Stanisstreet (1993), in that it asked students to agree, disagree or respond “I don’t know” to a number of statements. A diagram-annotation question showing two semi-circles, representing the Sun and Earth as stimulus, was also included. Analysis of diagrams revealed participants’ limited understanding interactions between greenhouse gases and solar and terrestrial radiation. Most diagrams featured a barrier, either unnamed or labelled “ozone layer” or “greenhouse gases”, and most participants thought that solar, rather than terrestrial radiation, was involved in the greenhouse effect.

Boyes and Stanisstreet (1997) developed a questionnaire based on responses in previous interviews, to investigate 501 thirteen and fourteen year-old students’ mental models of the causes of the greenhouse effect and ozone
depletion. The authors (Boyes & Stanisstreet 1993) had previously acknowledged the limitations of asking about causes without investigating mechanisms. Only 50% of Boyes and Stanisstreet’s (1997) participants thought CO₂ caused the greenhouse effect while about 50% thought that UV rays are “hotter” than heat rays. By examining students’ responses to two or more questions, the researchers built up models of the students’ reasoning. The dominant model, inferred for about 60% of participants, was that holes in the ozone layer cause the greenhouse effect by letting in either more UV or more heat rays, or both.

In the U.S.A., Rye et al. (1997) analysed and categorised students’ ideas about climate change using standardised open-ended interviews of 20-30 minutes with students in Years 6-8. These interviews covered a number of topics including the nature and cause of climate change and perceived connections between climate change and ozone depletion. The questions about ozone were placed at the end of the interview to avoid “leading” students, however over half of participants independently raised the topic of ozone depletion at the beginning of the interview, and a further 25% during the interview.

The authors identified five interwoven misconceptions related to the ozone layer: that ozone depletion causes global warming (54% of participants); that aerosol sprays contain CFCs and damage the ozone layer (54%); that CFCs cause global warming solely by damaging the ozone layer (25%); that carbon dioxide damages the ozone layer (50%); and that carbon dioxide causes global warming solely by damaging the ozone layer (33%). Three quarters of participants linked ozone depletion and/or UV radiation to global warming, with 54% appearing to consider them the only, or primary, cause. A number of participants thought of carbon dioxide both as an ozone-destroying substance and a heat-trapping substance, demonstrating that learners can have both correct and incorrect ideas about a concept: “It’s sort of like the gases that trap the Sun rays also eat the ozone layer away” (Rye et al. 1997, p.542). Few participants showed evidence of understanding the mechanism of the greenhouse effect: the students who did talk about gases
trapping heat were more likely to talk about the Sun’s heat being trapped than the Earth’s.

Gowda et al. (1997) surveyed 99 high school students, mostly in Year 9. They used open-ended questions to investigate their knowledge of basic issues related to climate change, focusing on identifying misconceptions and suggesting possible reasons for these. When asked about the causes of climate change, 8% of responses mentioned ozone depletion or the ozone layer; 5% mentioned chemicals or harmful/unnatural gases; 5% mentioned CFCs and 14% mentioned pollution in general. Of correct responses, 12% mentioned fossil fuel use and 9% mentioned deforestation.

Fisher (1998) studied 149 students aged between 11 and 18 in Victoria to investigate the development of their ability to explain global warming, following similar work by the author in England. Students were given the following questions to answer as a pen and paper exercise:

1. What is the greenhouse effect?
2. What causes the greenhouse effect?
3. Is the greenhouse effect good or bad for us? – explain.
4. How could we make the greenhouse effect smaller?

These questions were taken from Boyes and Stanisstreet’s (1993) survey, however Boyes and Stanisstreet supplied a range of possible answers to each question. Fisher (1998) classified responses as either “lifeworld” or “scientific”, following the work of Solomon (1993, cited in Fisher 1998), which focuses on progression in models of thinking as students mature. The greenhouse effect and ozone depletion were widely conflated. However, the reliance on students’ written responses means that students who possessed a sophisticated conceptual framework might not have been able satisfactorily to express it in writing, and it did not allow the researcher to clarify responses, probe for more information or rectify misunderstandings. Further, the analysis was carried out according to a set of specific pre-
determined categories, namely those of Solomon (1993), which raises the possibility that other themes may have been overlooked.

Mason and Santi’s (1998) research with Italian Year 5 students focused on social cognitive interactions in the classroom and the correlation between conceptual change and metaconceptual awareness. Group discussions and pre- and post-instruction individual interviews were audio-recorded. This research is related to my methodology in that both studies involved groups of students working together to construct knowledge and debate misconceptions. The authors ranked conceptual understanding of the cause of climate change on a five-point scale from “no response” to “complete understanding”. Suggested causes of climate change included fumes from cars, hotter Sun, a change to Earth’s rotational axis, volcanism, ozone holes and a barrier caused by sprays.

In Greece, Koulaidis and Christidou (1999) analysed and categorised 40 eleven- and twelve-year-old students’ ideas about the mechanism of the greenhouse effect. This work was similar to that of Rye et al. (1997), however Koulaidis and Christidou (1999) employed an in-depth approach involving semi-structured interviews during which participants completed a number of tasks. This study was prompted by Koulaidis and Christidou’s (1993) study of childrens’ conceptions of ozone depletion, which concluded that teaching climate change and ozone depletion together resulted in students conflating the two phenomena. These findings led the authors to study students’ conceptualisations of the greenhouse effect in more detail.

For their 1999 study, Koulaidis and Christidou conducted introductory interviews in which students discussed images and mass-media material. These were followed by semi-structured, 60-70 minute interviews using 19 cards with terms related to the greenhouse effect. Questions were designed to “focus discussions on the mechanisms, processes and interactions involved in the greenhouse effect” (p.562). Students grouped the cards into related sets, then into pairs to show cause-and-effect relationships. Finally, students answered a set of structured questions while manipulating the cards to produce a concept map (White & Gunstone 1992).
As did Rye et al. (1997), Koulaidis and Christidou categorised students’ concepts into a number of models and proposed teaching strategies to overcome misconceptions. However, the models described by Koulaidis and Christidou were conceptually much more complex than those of Rye et al. (1997), despite their participants being in the same age group. An example of a model from each paper is given below for comparison.

“Model A (Based on 27.5% of students' views). Carbon dioxide and/or methane are released in the atmosphere from man-made as well as natural sources. Those gases are described by students as forming a layer at a certain altitude around the earth. This layer acts like the glass or plastic covering the greenhouses: it lets the solar and thermal rays reach the earth and warm the ground and lower parts of the atmosphere, but prevents heat from escaping back to space. As a result the earth warms up, a phenomenon known as 'the greenhouse effect'.” (Koulaidis and Christidou 1999 p.564)

“Carbon dioxide causes global warming exclusively by destroying the ozone layer”. (Rye et al. 1997 p.536)

This difference in complexity between Rye et al.’s and Koulaidis and Christidou’s models is likely to be due to the greater time Koulaidis and Christidou (1999) spent discussing the topic and provision of material for students’ perusal. It is also clear that their participants were not unduly influenced by this extra interaction because they did not describe more scientifically correct ideas, just more detailed and complex ones. This demonstrates that students hold complex ideas about the topic and highlights the value of in-depth data-collection methods for exploring conceptual understanding in detail.

Andersson and Wallin’s (2000) research sought to explore students’ ideas about a number of environmental issues including the greenhouse effect. Over 1000 Swedish students aged 11-12, 15-16 and 18-19 were given an open-ended written task. The component relating to the greenhouse effect had one question: “describe in your own words what the greenhouse effect is!” (p.5). Responses were categorised into five inductively derived models
of increasing detail and complexity. “The categorisation … is based on the assumption that an explanation of the greenhouse effect requires the integration of various elements of knowledge. These are incoming radiation, outgoing radiation, and a barrier (the greenhouse gases) … To explain this you need to introduce different properties for incoming and outgoing radiation.” (p.13). The researchers generated pictorial models of categories, in a way similar to those of Koulaidis and Christidou (1999).

Andersson and Wallin (2000) found explanations involving a “barrier” more common than ozone conflation. The authors suggest the following possible explanation for ozone conflation: it is simpler than the scientific explanation and it “fits in well with everyday experience – less resistance makes it easier to get through” (p. 14). A criticism of this approach is that my research shows that “barrier” explanations and “ozone” explanations are often the same thing, in that the “barrier” is often identified as being the ozone layer. Another limitation is that an open-ended writing task such as that used by Andersson and Wallin (2000) does not allow researchers to confirm that they have understood the students’ input, or probe for clarification and detail. The authors used only this form of data-collection so there was no corroboration. However, despite the limitations of the methodology, this study is useful in that it points to some possible explanations for misconceptions: the authors discussed students’ difficulties in terms of the underlying physical concepts required to explain the greenhouse effect, for example the different properties of radiation entering Earth’s atmosphere and radiation leaving it.

In the U.K., Boyes and Stanisstreet (2001) surveyed nearly 1500 high school students from Years 7 to 11, using an extended version of their 1993 questionnaire which included open-ended questions on students’ level of concern, perceptions of their own knowledge, and knowledge sources. Responses were analysed to investigate differences between grades as well as between the 1993 and 2001 cohorts. The authors found that students had less familiarity with the topic than did their 1993 counterparts, but also that they held fewer misconceptions: in other words, they had fewer ideas of any
kind about the topic. The authors speculated that this was due to decreased media attention to the issue, particularly television coverage, as other environmental issues such as ozone depletion and genetically modified organisms came to the fore.

In Canada, Pruneau et al. (2001) conducted semi-structured interviews with seven- to eight-year-olds, twelve- to fourteen-year-olds and adults to investigate participants’ constructions of climate change. Of the twelve- to fourteen-year-olds, over 12% blamed climate change on ozone depletion, fewer than 2% identified CO₂ as the cause, nearly 80% could not formulate an explanation and over 70% claimed not to think about the issue.

In the U.S.A. Khalid (2003) adapted Dove’s (1996) survey instrument to probe 27 pre-service high school science teachers’ understanding of the greenhouse effect, ozone depletion and acid rain. Almost 56% of participants thought that holes in the ozone layer would increase the greenhouse effect and eight students said that these holes would allow more radiation to reach the Earth, suggesting that the participants thought the greenhouse effect was due to incoming solar radiation rather than terrestrial radiation. Eight students linked the greenhouse effect, through ozone depletion, to skin cancer, and some thought that CO₂ from cars destroys ozone molecules.

Kurup’s (2003) research resembled mine in that he developed a set of propositional knowledge statements (PKS) (Treagust 1988) to “identify the concepts and propositions necessary to understand the greenhouse effect ...” (p.32), and created a survey to address this knowledge. According to the author, his research was “unique in that no previous research has taken such a comprehensive approach” (p.33). The author identified five levels of understanding of the topic and reported that only 1.4% of Year 10 students in Western Australia had a “high” level of understanding. However, a number of limitations mean that this study is unable to answer my research questions. These limitations are described in Section 2.8, and include the limited consultation process used to develop the PKS, the limited number of
survey items addressing the concepts and the use of the true/false/don’t know” format in the survey.

Rebich and Gautier (2005) used concept mapping to investigate prior understanding and conceptual change following an enquiry-based course on climate change for upper-level undergraduates. This study is relevant because of the strong constructivist pedagogy and the focus on conceptual knowledge about the mechanism of climate change. Several scientifically inaccurate mental models were deduced from the concept maps. These included the idea that ozone depletion allows more solar radiation to reach Earth; that solar energy was being trapped by greenhouse gases; and that the gases themselves were being trapped. Few participants introduced the concept of terrestrial radiation. Some participants conflated greenhouse gases, pollution and aerosols, while others appeared to have a “generalised” view of a number of environmental issues. From the post-instruction concept maps, Rebich and Gautier (2005) deduced that some misconceptions were tenacious. These included misconceptions related to aerosols, the electromagnetic spectrum and its interactions with greenhouse gases.

Keller (2006) developed a concept inventory to investigate undergraduate students’ knowledge of the natural greenhouse effect. His concept inventory development is discussed in Chapters 4 and 5. The most common mental models inferred involved either an increase in incoming energy, often blamed on ozone depletion, or a decrease in outgoing energy, often blamed on trapping of either energy or gases. Few participants appeared to understand absorption and re-emission of infrared radiation by greenhouse gases.

Boon (2009) surveyed 389 Years 8 and 10 students in a regional city in Queensland, Australia, using an instrument originally developed and used in the U.K. in 1991. When asked “what is the greenhouse effect?”, 30% of the Australian students did not know, 13% gave responses that involved the ozone layer and 14% gave responses that were classified as correct. Australian participants’ comments about the ozone layer suggested that
although they knew the ozone layer was important, they were unsure of the details of its function. The author described her Australian participants’ explanations as “qualitatively similar” (p.55) to those of the 1991 English cohort, as well as those described by earlier researchers such as Boyes and Stanisstreet (1993) and Lee et al. (2007).

Schultz (2009) used pre- and post-tests to measure the effect of a 20 minute computer simulation task on 150 Years 7 and 8 students in the U.S.A. These consisted of five multiple choice questions, a concept mapping exercise and one open response question: “explain in words how the Earth’s greenhouse effect works” (p.90). Four students were also interviewed. The multiple choice questions were taken from Keller’s (2006) Greenhouse Effect Concept Inventory, however the use of subsets of questions from concept inventories is not generally advised because they are assessed and validated as complete tests: this issue is discussed in Chapter 5. Additionally, Keller’s (2006) concept inventory was developed for undergraduates and had not been validated with high school students. According to Schultz (2009), gains in knowledge were modest following the computer activity and misconceptions remained. Conflation with ozone depletion was the most common misconception detected.

The purpose of Shepardson et al.’s (2009) qualitative research with American Year 7 students was to investigate students’ conceptions about global warming and climate change. Ninety-one students in three classes completed a survey with four open response questions including graph interpretation, possible effects of climate change, and a draw-and-explain exercise. Data analysis was inductive. Only 13% of participants gave a scientific explanation: “These students identified carbon dioxide as a greenhouse gas and explained its role as a greenhouse gas” (pp.558-559). Further, half of these students drew CO₂ as a distinct atmospheric layer. A limitation of this study is the difficulty of interpreting participants’ drawings. White and Gunstone (1992) described the use of the draw-and-explain method in interviews in which learners could be asked about their drawings directly. Because Shepardson et al.’s (2009) study involved no
interviews, interpretation of drawings depended entirely on the researchers. However this was mitigated by: (i) the fact that participants were asked for a written explanation of their drawing which would have provided corroboration of the researchers’ interpretation; and (ii) comparison of analyses by multiple researchers.

Taber and Taylor (2009) studied Year 6 students in regional NSW, Australia to determine what misconceptions they held and how effective a constructivist teaching program would be at addressing them. The mixed methods design combined pre- and post-testing with semi-structured post-interviews using purposeful sampling for the interviews, and a specially prepared teaching unit. For the pre- and post-tests, a 25-item true/false instrument was developed. The largest improvement in knowledge was associated with hands-on activities. An increase in knowledge was associated with increase in concern in some cases, as well as an increase in the belief that positive action could be taken by the students. Confusion with ozone depletion was observed in interviews and pre- and post-tests: there was little improvement on this misconception.

Boon (2010) compared the knowledge of pre-service teachers with that of secondary students using a mixed multiple choice and open ended survey, to determine whether the pre-service teachers had acquired additional knowledge during their training. The author found a lower rate of ozone confusion among secondary students than among pre-service teachers. She summarised misconceptions reported in other studies and suggested they are “probably due to, among other things, the complexity of the science” (p.106). A weakness with Boon’s (2010) study was that the mechanism of the greenhouse effect was linked in the survey questions to the reason for an actual greenhouse being hotter than outside. In fact, the greenhouse effect is not the sole mechanism for the temperature increase inside a glass building: this is mostly due to the trapping of warm air, which would otherwise be dispersed by wind and convection currents (Abdel-Ghany & Kozai 2006). Another problem with corroboration of findings was the fact that no other
data, for example interviews, was collected to corroborate the findings of the survey.

In Norway, Hansen (2010) surveyed 15-year-old students to track the development of learning from 1989 to 2005 through four curricula, the last two of which explicitly mention climate change. The survey comprised seven true/false questions but did not ask for reasons behind choices, so provides limited information about participants’ conceptual understanding. The author found more conflation with ozone among the 2005 cohort than among previous cohorts, with 27% agreeing that “the greenhouse effect is caused by ozone gas in the ozone layer” (p.410), but also more knowledge of the greenhouse effect as a natural phenomenon, with 75% agreeing that “the greenhouse effect is necessary for life on Earth” (p.407).

Shepardson et al. (2011) derived five qualitatively different mental models of the greenhouse effect from inductive analysis of annotated drawings by 225 Year 7 students in the U.S.A. The authors claim that research on students’ conceptual understanding of the greenhouse effect “is rather sparse” (p.3) and reviewed 18 international studies. The mental models described by the authors are as follows:

- Rays reflected between Earth’s surface and greenhouse gases (13%)
- Greenhouse gases “trap” Sun’s rays (35%)
- Greenhouse gases mentioned but no mechanism (17%)
- Specific conflation with ozone (6%)
- A greenhouse for growing plants (29%)

The prevalence of the idea of a greenhouse for growing plants has not been widely reported elsewhere. It may be due to the presence of greenhouses in rural Midwest America, where the research took place. However, greenhouses are also common in the U.K. and other cool temperate countries and this idea was not reported in research from those countries.

A significant element of Shepardson et al.’s (2011) study for my research is that those authors listed core concepts or elements of each mental model. These include both correct scientific concepts and alternative conceptions.
- Carbon dioxide/greenhouse gas
- Other greenhouse gases: methane, water vapour
- Sun’s rays or heat
- A layer of greenhouse gases/carbon dioxide
- Energy reflected from Earth’s surface
- Energy reflected by greenhouse gases
- Sun’s energy trapped by greenhouse gases
- Air pollutants as greenhouse gases
- Ozone layer reflecting or trapping energy
- Fossil fuels as a source of greenhouse gases.

Lambert et al. (2012) developed a mixed multiple choice and open-response assessment instrument to measure learning gains among pre-service primary teachers. The participants “still held many of the same alternative or naive conceptions as those of middle- and high-school students and practicing and pre-service elementary teachers described over a decade ago” (p.1182).

In summary, a significant body of literature on young peoples’ ideas about the science of climate change confirms that misconceptions are common, and that few students are able to explain the science correctly. Common misconceptions include conflation with ozone depletion and the idea that heat from the Sun, rather than the Earth, is responsible for the greenhouse effect. The methods employed included open and closed response surveys, semi-structured interviews, analysis of drawings, multiple choice and true/false tests, qualitative analysis of concept maps and qualitative analysis of recordings of student discussions. The findings of my pilot study were similar to those reported in the literature, suggesting that these misconceptions are also common among New South Wales students. The fact that studies using a wide variety of methods came to similar conclusions lends credibility to the findings.

2.3.3 Explanations for misconceptions suggested by researchers
The research reported in Section 2.3.2 demonstrates that misconceptions about the science of climate change are common, consistent and persistent.
In most cases, the research was concerned with helping students to overcome these misconceptions and in order to do this it is necessary to determine what causes them.

A number of the studies described above suggest cognitive issues such as: the abstract nature of the topic and underlying concepts; misconceptions about concepts underlying the topic; similarities with the topic of ozone depletion; difficulties with synthesising ideas about a large number of concepts; problems applying scientific knowledge which had been learned in a different context; or a combination of these. These may explain the high rate of misconceptions, although none of the studies investigated these inferences.

Francis et al. (1993) suggested the complexity and abstract nature of the topic as possible explanations for the high rate of misconceptions, and speculated that if information sources other than school were important, the lack of interaction with teachers and other students could lead to misconceptions becoming strongly held. The authors also thought misconceptions might be related to the fact that greenhouse effect and ozone depletion share some common concepts, for example, some greenhouse gases also contribute to ozone depletion, or that students distinguish between the two issues in a general way but fail to differentiate between the mechanisms involved.

Gowda et al. (1997) posited four possible factors that could contribute to misconceptions: insufficient information availability, with limited teaching time and a lack of interdisciplinary approach in schools; reliance on the mass media, which was seen as presenting skewed and sensationalised information; psychological factors such as difficulty believing that small temperature changes could have significant effects; and “fuzzy environmentalism” (p.2237): failure to separate causes and effects of different environmental issues sufficiently. Similarly to Gowda et al.’s (1997) idea of “fuzzy environmentalism”, Boyes and Stanisstreet (1993) suggested that some students might believe that “all environmentally ‘friendly’ actions will ‘help’ all environmental problems” (p.551).
Rye et al. (1997) “speculate that concepts such as ozone hole, UV rays, CFCs, and greenhouse effect may be 'loose' in many students' cognitive structures and connected inappropriately to make sense of formal instruction on global warming” (p.547). The authors also raised the idea that confusion might be due to climate change and ozone depletion sharing a number of concepts. The authors suggest five conceptual areas that may require clarification:

- differences between incoming and outgoing radiation
- absorption by greenhouse gases of outgoing, but not incoming radiation as the mechanism of the greenhouse effect
- enhancement of the greenhouse effect due to increased concentrations of greenhouse gases, as the cause of global warming
- that there are two distinct undesirable atmospheric effects of CFCs (but not CO₂): ozone depletion and as a greenhouse gas
- that aerosol cans in the U.S.A. do not contain CFCs

The authors also suggested several factors that may lead to students’ post-instruction misconceptions including tenacious pre-existing misconceptions, misconceptions that develop during instruction, the instructional model used, integrating the study of climate change with that of ozone depletion, and the learners’ age-dependent capacity for abstract reasoning.

Meadows and Weisenmeyer (1999) critiqued explanations posited by Francis et al. (1993) and Rye et al. (1997). The authors suggested that the commonly reported conflation with ozone depletion is a “logical” construct based on students’ experience that the Sun’s rays are hot, and that a hole in a protective layer would allow more heat through.

Koulaidis & Christidou (1999) suggested that their participants’ misconceptions about climate change may be due to misconceptions with one or more of the underlying physical concepts: they “might be attributed to … lack [of] a consistent conceptual distinction between ultraviolet radiation and other forms of sunlight” (p.571) or “seem to be due to … lack [of] a conceptual distinction between solar and terrestrial radiation” (p.572).
The authors also concluded that “children do not seem to understand the energy exchanges that take place between the Earth and the atmosphere” (p.571). Koulaidis and Christidou’s use of “might be” and “seem to be” underlines the fact that these inferences were not directly tested.

According to Andersson and Wallin (2000), “an explanation of the greenhouse effect requires the integration of various elements of knowledge. These are incoming radiation, outgoing radiation, and a barrier (the greenhouse gases), which form a sub-system of the atmosphere. Incoming and outgoing radiation pass the same barrier, although in different directions. The former comes through quite easily, the latter with difficulty. To explain this you need to introduce different properties for incoming and outgoing radiation” (p.13). In other words, both studies suggest that two cognitive processes are necessary in order to understand the topic: conceptual understanding of the different properties of the radiation emitted by the Sun and Earth, and the ability to integrate ideas.

Österlind (2005) concluded that “the most interesting result of this study is … that the learner can have difficulty in deciding what aspect of the same phenomenon is relevant in different contexts … the subject of radiation is common to [ozone depletion and climate change] but the aspects that are relevant to each of the two issues are quite different” (p.904). “The results make clear that concepts do not have given meanings but get their meanings from a given context” (p.905). This is significant because NSW high school students encounter the key concepts underlying climate change in a number of diverse contexts, often completely unrelated to the topic of climate change.

Boon (2009) suggested that TV and the Internet, which were information sources for 68% and 49% of participants respectively, might report possible effects of climate change without explaining the science, or might overemphasise uncertainty about the phenomenon, thereby causing students to discount it. She also speculated that transmissive teaching methods employed in schools were not designed to take account of, and challenge,
students’ existing misconceptions, and that the long-term nature of climate change makes it more difficult for learners to engage with it.

Schultz (2009) suggested that her participants’ gains in propositional knowledge about infrared radiation “may be due to students starting with little or no knowledge about what infrared radiation is” (p.70). The author also reported significant gains in participants’ understanding that sunlight incident on Earth’s surface would cause its temperature to increase therefore it is possible that her participants also had little initial awareness of this concept.

Boon (2010) suggested that misconceptions are “probably due to, among other things, the complexity of the science” (p.106). The author suggested that “although some participants may understand the physics of radiation absorption they have difficulty assimilating the complex physical processes and chemical reactions in the atmosphere” (p.114).

In summary, Rye et al. (1997); Koulaidis and Christidou (1999); Andersson and Wallin (2000); Österlind (2005); Schultz (2009); and Boon (2010) suggested that students’ problems with underlying concepts may contribute to misconceptions about the topic as a whole. These authors identified a number of concepts they thought might require clarification, however this cannot be assumed to be an exhaustive list of essential concepts underlying the science of climate change. Section 2.4 therefore presents a review of literature on students’ ideas about climate change, carried out in order to determine what concepts a larger number of authors considered important.

2.4 What are the essential scientific concepts underlying climate change?

My research focuses on students’ understanding of the essential underlying scientific concepts that are required in order to understand climate change. Researchers who studied students’ understanding of the science of climate change often mentioned scientific concepts that, in their opinion, were required in order to understand climate change. Koulaidis and Christidou
(1999) used 19 cards “labeled with the main terms relative to the greenhouse effect” (p.562) so their research explicitly involved a set of underlying concepts, however they did not list the concepts named on the cards. Browne and Laws (2003) asked their students to make a list of concepts they considered they would need to understand in order to understand climate change. Therefore, as part of the process of creating a descriptive list of essential underlying concepts, I reviewed 16 studies to determine which concepts were mentioned and how often. Most of these studies are a subset of the research literature I reviewed on students’ ideas about climate change, in Section 2.3.2. As far as possible, I chose studies which involved students close in age to the participants in my study, and which focused on conceptual understanding of the science of climate change in detail rather than simply asking students about possible effects. However, given the relatively small number of such studies, as was also noted by Shepardson et al. (2011), I also included studies involving pre-service teachers and undergraduates. I chose these studies because they focused on conceptual understanding of the science, and involved participants who were studying the topic at introductory level.

The studies reviewed for this purpose are: Andersson & Wallin (2000); Boon (2009); Boyes & Stanisstreet (1993); Boylan (2008); Browne & Laws (2003); Dove (1996); Fisher (1998); Hansen (2010); Hobson (2003); Keller (2006); Koulaidis & Christidou (1999); Rebich & Gautier (2005); Rye et al. (1997); Schultz (2009); Shepardson et al. (2009) and Österlind (2005).

Table 2.3 summarises concepts mentioned in research on learners’ ideas about climate change that were investigated as part of my study. The process used to derive this list is reported in detail in Section 4.4 of Chapter 4.
Table 2.3: Preliminary list of essential scientific concepts underlying the mechanism of climate change, summarised from a review of 16 studies of learners’ ideas about climate change.

<table>
<thead>
<tr>
<th>Concept</th>
<th>No. of studies</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which gases are greenhouse gases (GHGs)</td>
<td>11</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Dove (1996); Fisher (1998); Hansen (2010); Keller (2006); Koulaidis and Christidou (1999); Österlind (2005); Rebich and Gautier (2005); Schultz (2009) Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Interactions between GHGs and (e.m.r.)</td>
<td>10</td>
<td>Andersson and Wallin (2000); Boyes et al. (1993); Browne and Laws (2003); Dove (1996); Hansen (2010); Keller (2006); Koulaidis and Christidou (1999); Österlind (2005); Rye et al. (1997); Schultz (2009)</td>
</tr>
<tr>
<td>Burning fossil fuels adds CO₂ to the atmosphere</td>
<td>9</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Dove (1996); Fisher (1998); Keller (2006); Österlind (2005); Rebich and Gautier (2005); Schultz (2009); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>The natural greenhouse effect</td>
<td>8</td>
<td>Andersson and Wallin (2000); Dove (1996); Hansen (2010); Keller (2006); Koulaidis and Christidou (1999); Österlind (2005); Rebich and Gautier (2005); Schultz (2009)</td>
</tr>
<tr>
<td>Absorption and/or emission of e.m.r.</td>
<td>8</td>
<td>Boon (2009); Boyes et al. (1993); Browne and Laws (2003); Dove (1996); Fisher (1998); Österlind (2005); Rye et al. (1997); Schultz (2009)</td>
</tr>
<tr>
<td>The electromagnetic spectrum (e.m.s.)</td>
<td>7</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Hobson (2003); Koulaidis and Christidou (1999); Österlind (2005); Rye et al. (1997); Rebich and Gautier (2005)</td>
</tr>
<tr>
<td>Radiation from the Sun</td>
<td>7</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Dove (1996); Keller (2006); Koulaidis and Christidou (1999); Österlind (2005); Rye et al. (1997)</td>
</tr>
<tr>
<td>Radiation from Earth.</td>
<td>7</td>
<td>Dove (1996); Keller (2006); Koulaidis and Christidou (1999); Österlind (2005); Rye et al. (1997); Rebich and Gautier (2005); Schultz (2009)</td>
</tr>
<tr>
<td>Feedback mechanisms</td>
<td>7</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Fisher (1998); Hansen (2010); Rebich and Gautier (2005); Rye et al. (1997); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>7</td>
<td>Andersson and Wallin (2000); Boyes et al. (1993); Dove (1996); Keller (2006); Koulaidis and Christidou (1999); Rebich and Gautier (2005); Rye et al. (1997)</td>
</tr>
<tr>
<td>Equilibrium of energy into and out of Earth/</td>
<td>6</td>
<td>Andersson and Wallin (2000); Boyes et al. (1993); Browne and Laws (2003); Fisher (1998); Keller (2006); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Concept</td>
<td>Frequency</td>
<td>References</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-----------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Atmosphere system</td>
<td></td>
<td>Dove (1996); Koulaidis and Christidou (1999); Österlind (2005); Rye et al. (1997); Schultz (2009)</td>
</tr>
<tr>
<td>Enhanced greenhouse effect</td>
<td>5</td>
<td>Boyes et al. (1993); Dove (1996); Fisher (1998); Rebich and Gautier (2005); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Deforestation</td>
<td>5</td>
<td>Boyes et al. (1993); Dove (1996); Fisher (1998); Rebich and Gautier (2005); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>GHG sinks</td>
<td>4</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Keller (2006); Österlind (2005)</td>
</tr>
<tr>
<td>Temperature</td>
<td>4</td>
<td>Browne and Laws (2003); Keller (2006); Shepardson et al. (2009); Schultz (2009)</td>
</tr>
<tr>
<td>Black body radiation: wavelengths emitted linked to temperature</td>
<td>3</td>
<td>Boyes et al. (1993); Browne and Laws (2003); Koulaidis and Christidou (1999)</td>
</tr>
<tr>
<td>Location of GHG in the atmosphere</td>
<td>3</td>
<td>Fisher (1998); Koulaidis and Christidou (1999); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Radiative forcing (explicitly mentioned)</td>
<td>2</td>
<td>Fisher (1998); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Rate</td>
<td>2</td>
<td>Browne and Laws (2003); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Difference between weather and climate</td>
<td>2</td>
<td>Boylan (2008), Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Conservation of energy</td>
<td>2</td>
<td>Andersson and Wallin (2000); Boylan (2008)</td>
</tr>
<tr>
<td>Climate variability</td>
<td>2</td>
<td>Rebich and Gautier (2005); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Albedo</td>
<td>2</td>
<td>Rebich and Gautier (2005); Shepardson et al. (2009)</td>
</tr>
<tr>
<td>Heat</td>
<td>1</td>
<td>Rye et al. (1997)</td>
</tr>
</tbody>
</table>

The concepts in Table 2.3 are a preliminary list, with some overlap between concepts. The final list of key underlying concepts, which answered Research Question 1, was produced by synthesising this preliminary list with findings from the Delphi study to produce a list of conceptual statements setting out the essential knowledge. The synthesis process is described in Chapter 4, Section 4.5 and was reported in Jarrett et al. (2011).

Four other publications directly address the issue of concepts underlying climate change: Lambert et al. (2012); McCaffery and Buhr (2008); Climate Literacy Network (2009); and Gautier et al. (2006).
Lambert et al.’s (2012) research was not published until after the completion of my research, including the above review of literature, but provides support for my findings. The authors developed a curriculum and learning materials for pre-service primary teachers, including a study guide on “science underlying weather and climate change … concepts such as the carbon cycle, photosynthesis and respiration, the greenhouse effect, heat transfer and ocean currents, the cause of the seasons, fossil fuels and the rock cycle, and the water cycle … content that a typical middle-school Earth science teacher would need to understand climate change” (p.1170). The greenhouse effect was defined as: “the natural process of green-house gases (i.e. water vapor, carbon dioxide, methane, nitrous oxide, and ozone) absorbing the infrared radiation emitted from Earth’s surface” (p.1168). Because the curriculum included weather as well as climate change, the corresponding list of concepts would be expected to include concepts such as the water cycle, the cause of the seasons and ocean currents, that did not appear in the findings of my literature review. However, all the other concepts in Lambert et al.’s (2012) list correspond to high-ranked concepts in Table 2.3.

McCaffrey and Buhr (2008) reviewed research on misconceptions about essential climate science concepts and described ten conceptual areas, along with known misconceptions. The authors also described the development of a climate literacy framework (Climate Literacy Network 2009) comprising seven essential principles, each containing several fundamental concepts. This research pertains to a broader area of learning than my study, so my study’s essential concepts could be viewed as a subset of those of the Climate Literacy Network. In addition, McCaffrey and Buhr (2008) asserted that the development of descriptions of required conceptual knowledge for climate science has long been a neglected area of research, and my study aims to contribute to this area of research.

The third publication to address the issue of required conceptual knowledge is that of Gautier et al. (2006). The misconceptions reported by these
authors were described in McCaffery and Buhr (2008) and are relevant to the development of CI item distractors. Gautier et al. (2006) also proposed a set of required conceptual knowledge for undergraduate earth science students. Their required knowledge may be too advanced to be applicable to Stage 5 school students, however the authors’ work was with non-science majors, so it is possible that their “essential knowledge” may be a useful upper limit on what a Stage 5 student would be expected to understand.

2.5 What do students know about the essential underlying concepts?

The purpose of this section of the literature review was to collate information on known student misconceptions about the conceptual areas to be addressed by this study: i.e., the final list of conceptual statements shown in Figure 2.2. This information was used when writing item distractors for the Climate Change Concept Inventory (CCCI), described in Chapter 5. The conceptual areas were determined by synthesising the preliminary list of concepts presented in Table 2.3 with findings from the Delphi study described in Chapter 4. Therefore the conceptual areas listed in this section are not identical to those shown in Table 2.3. The rest of this section of the literature review refers to this final, synthesised list of essential concepts. Figure 2.2 illustrates the relationship between the preliminary list derived from literature, the Delphi study findings and the final list of conceptual statements.

The review of literature on students’ ideas about the essential underlying concepts showed that some conceptual areas have been studied more than others. For example, database searches yielded a far greater number of results for student ideas about heat than for electromagnetic radiation or thermodynamics. In addition, the majority of research was carried out with undergraduate participants rather than high school students. For some of the conceptual areas in the list, I identified no appropriate studies on students’ ideas. For these conceptual areas, the creation of plausible distractors for CI
items depended on misconceptions identified from focus group data reported in Chapter 5.

Figure 2.2 Relationships between preliminary list of essential concepts, Delphi study findings and final list of conceptual statements

2.5.1 Summary of research reviewed: context and purpose of studies

Table 2.4 summarises the context and purpose of each study reviewed on students’ ideas about the underlying concepts. The findings are discussed in Section 2.5.2.

Table 2.4: Research reviewed on students’ ideas about the essential underlying concepts

<table>
<thead>
<tr>
<th>Authors</th>
<th>Conceptual knowledge / purpose</th>
<th>Participants</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodzin (2011)</td>
<td>Conceptual understanding of energy resources and use</td>
<td>Year 8</td>
<td>Concept inventory</td>
</tr>
<tr>
<td>Comins (2003)</td>
<td>Compilation of a list of misconceptions about the universe</td>
<td>Undergraduates</td>
<td>10 years of observations of students’ ideas</td>
</tr>
<tr>
<td>Daniel et al.</td>
<td>Beliefs about the relative</td>
<td>High school</td>
<td>Closed</td>
</tr>
<tr>
<td>Year</td>
<td>Description</td>
<td>Methodology</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------------------------------</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>Importance of actions to reduce global warming</td>
<td>Questionnaire</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>Dove (1996) Conceptual understanding of greenhouse effect, ozone depletion and acid rain</td>
<td>Pre-service teachers, Mixed survey and diagram-completion</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Ebert-May et al. (2003) Misconceptions about the carbon cycle related to plants taking in CO$_2$ from the air during photosynthesis, and decomposers respiring CO$_2$ into the atmosphere.</td>
<td>Biology undergraduates, Assessment problems integrated into coursework</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Gautier et al. (2006) Misconceptions about climate change</td>
<td>Undergraduates, Set of questions administered several times during unit of study</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>Henriques et al. (2002) Misconceptions about the atmosphere, weather and climate</td>
<td>K-12, Review of literature</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Lambert et al. (2012) Learning gains on concepts underlying weather and climate change</td>
<td>Pre-service primary teachers, Mixed-response assessment instrument</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Madsen et al. (2007) Ideas about the carbon cycle</td>
<td>Pre-service teachers, Online assessment</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>McCaffery and Buhr (2008) Misconceptions about concepts related to climate science</td>
<td>Students and the public, Literature review</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Mohan et al. (2009) Charting development of students’ ideas about carbon cycling</td>
<td>Upper elementary to high school, Assessments and interviews</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Österlind (2005) How scientific knowledge is conceptualised to explain the greenhouse effect and ozone depletion.</td>
<td>Three Year 9 students, In-depth case studies</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Pompea et al. (2007) To address known misconceptions about light</td>
<td>All ages, Development of a hands-on optics course</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Rule (2005) Ideas about fossil fuel energy</td>
<td>Years 1-6, Interviews</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shepardson et al. Conceptual understanding of global warming and climate</td>
<td>Year 7, Open-ended survey and draw-</td>
<td></td>
</tr>
</tbody>
</table>
2.5.2 Misconceptions about the essential underlying concepts

The ten concepts listed below correspond to the final essential conceptual areas: shown in full in Chapter 4. I reviewed the literature summarised in Table 2.4 for descriptions of students’ misconceptions and conceptual difficulties. These are described under the relevant conceptual area, numbered 1-10.

1. The carbon cycle and fossil fuels

The following studies suggest that students are likely to think that plants get their carbon from the soil rather than from CO$_2$ in the atmosphere. This is significant because these learners would not understand the role of plants as a sink for atmospheric CO$_2$, nor the fact that carbon in fossil fuels was once in the atmosphere. The literature also suggests that high school students are likely to struggle with concepts relating to the movement of chemical elements through nutrient cycles. Further, they may lack an understanding of the origin and chemical composition of fossil fuels as well as the chemical products of their combustion.
Wandersee (1986) reported that students in grades 5 and 11, and second year undergraduates, did not see atmospheric CO\textsubscript{2} as the major raw ingredient for photosynthesis. According to Ebert-May et al. (2003), 28\% of participants initially thought that biomass gained by plants came from dissolved substances taken up by roots and 15\% thought that the mass came from particles in soil. Only 4\% identified air as the source of material for biomass increase. Even after instruction, 20\% still thought that plant roots absorb CO\textsubscript{2}. The authors report that many students believe that the process of decomposition destroys matter, and that photosynthesis provides only energy for plants, which then take up carbon and nutrients through their roots.

Smith et al. (1986) concluded that students might think of photosynthesis as plants turning carbon dioxide into oxygen. Stavy et al.’s (1987) Years 8 and 9 participants had difficulty in understanding that CO\textsubscript{2} gas is the major source of biomass in plants. While most Year 8 students knew that plants absorb CO\textsubscript{2}, only 40\% of Year 9 students did so, suggesting that this knowledge was not retained (assuming that their learning experiences at the time were similar). The authors concluded that photosynthesis was a very difficult topic for junior high school students, but too important not to teach.

Smith et al. (1986) reported the misconception that matter is created and destroyed in ecosystem cycling, rather than moving through ecosystems in food chains. Often, their participants viewed organisms’ eating food, producing waste and growing as separate events rather than as the transformation of matter from one form into another. The physical matter making up animals, plants and the non-living environment was seen as fundamentally different from each other and not able to be transformed: “In the naive view animals are made of bone, muscle, skins, etc., plants are made of leaves, stems, and roots and the non-living environment is made of water, soil, and air. Students holding the naive view see these substances as fundamentally different and not in general transformable into each other” (pp.11-12). Most students were aware that cycles exist in ecosystems but tend to view these as a series of events involving the creation and
destruction of matter, or recognise recycling through soil minerals but without understanding the involvement of water, carbon and carbon dioxide in this recycling.

Sibley et al.’s (2007) undergraduate participants also had difficulty recognising parts of a system that are not visible or readily apparent. By this the authors meant either parts of a system that are difficult to see, such as groundwater, or abstract concepts such as chemical species: “Students who lack this ability are not able to construct diagrams with appropriate ions, molecules and/or chemical reactions.” (p.138). Sibley et al. (2007) concluded that “students must have some understanding of chemistry in order to understand the global carbon cycle” (p.145), and that their undergraduate students’ errors were consistent with a lack of functional mental models of atoms, ions and molecules. Nearly all errors were related to chemical reactions that occur as carbon moves between reservoirs. This finding suggests that Stage 5 students are very likely to have trouble visualising greenhouse gas molecules and making sense of how they are linked to fossil fuel molecules, and other greenhouse gas sources and sinks. Sibley et al. (2007) stressed the difficulty of these chemistry concepts as follows: “The fact that students in a general education earth systems course have difficulty using concepts of ions, molecules, chemical reactions and phase change is not surprising. Students in college chemistry classes have trouble with these concepts” (p.145).

Stavy et al. (1987) found serious gaps in their participants’ knowledge of chemistry, with confusion about the concepts “element” and “compound” and “carbon” and “carbon dioxide”. Participants were able to recite the formula for glucose but could not say which chemical elements it contained, suggesting that chemical formulae were rote-memorised rather than understood.

Mohan et al. (2009) cited a number of studies that showed that students do not use scientific principles such as conservation of matter when explaining processes through which carbon is transformed from one form to another (e.g. photosynthesis). The authors pointed out that processes such as
combustion, or the link between burning fossil fuels and climate change, occur on small or large scales that cannot be observed directly. According to the authors, students may also struggle with the chemical composition of living organisms and see oxygen as being converted directly to carbon dioxide. They devised a four-level qualitative learning progression. Students equivalent in age to NSW Stage 5 are most likely to have ideas corresponding to levels 2 or 3.

Some characteristics of Mohan et al.’s (2009) level 2 are:

- failure to conserve mass (for example, petrol was seen as turning into energy)
- gases seen as not having mass
- the use of names for some chemical species but without understanding of the chemical processes by which matter is transformed “they did not have a systematic way to explain how reactants could become products” (p.687).

At level 3 students had more appreciation that matter is transformed through chemical processes (for example by naming photosynthesis), but their understanding of chemical substances was still limited. Gases were still unlikely to be seen as having mass and students still saw matter as being converted into energy. The authors considered level 4 reasoning essential for students to become informed citizens but found this level of reasoning rare, even among college students and science teachers.

Mohan et al. (2009) reported that for questions relating to large-scale processes, including the link between burning petrol and global warming, about 40% of students were not able to identify atomic/molecular processes. According to the authors “A notable limitation for level 3 students is that they cannot follow carbon through key processes, nor can they … explain large-scale change using atomic-molecular accounts, both of which are essential for making sense of environmental issues involving global carbon cycling” (p.694).
Bodzin (2011) identified a paucity of literature on middle school students’ ideas about energy resources and use. Almost two thirds of Bodzin’s (2011) participants were unaware that natural gas is a non-renewable resource. Fewer than 13% identified oil and gas as coming from the remains of marine organisms that lived millions of years ago. Only 17% knew that coal originates from swamp plants that grew millions of years ago.

Rule (2005) observed misconceptions among primary students including that: fossil fuels have existed since the origin of the Earth; that they can form in a short time; that oil is made from soil; that coal comes from rock; and that oil forms from molten metal.

Lambert et al. (2012) observed the misconception that the Sun’s energy turns into carbon dioxide that becomes trapped in the atmosphere, and other instances of conflation of the carbon cycle and greenhouse effect. Prior to instruction, participants were unable to describe any processes related to the carbon cycle, including processes that add CO$_2$ to, or remove it from, the atmosphere. These findings suggest very limited understanding of related chemistry concepts. Lambert et al. (2012) also found little evidence of understanding of the role of fossil fuels in climate change.

Madsen et al. (2007) reported the misconception among pre-service teachers that burning fossil fuels destroys carbon and that CO$_2$ released by burning fossil fuels does not affect the climate. Participants lacked understanding of some basic elements of the cycle, in particular movement between reservoirs. The authors reported a common misconception that carbon is involved with evaporation, is associated with clouds and falls as precipitation into oceans or onto land. Although the participants linked pollution caused by human activities with changes to the carbon cycle, they rarely specified the type of pollution or the changes to the carbon cycle.

Ebert-May et al. (2003) reported two misconceptions related to the carbon cycle:

- the largest pools of carbon are on land and in living organisms
- carbon moves through different pools at the same rate.
2. The electromagnetic spectrum

A number of studies explored undergraduates’ understanding of aspects of electromagnetic radiation, but I identified fewer studies on younger students’ ideas about the basic concept of the electromagnetic spectrum. The studies suggest that students are likely to have difficulty understanding the nature of the relationships between different bands of the electromagnetic spectrum. They are also likely to struggle with concepts related to absorption and emission of electromagnetic radiation.

Few of Lambert et al.’s (2012) pre-service teacher participants differentiated between different types of radiation from the Sun, and only a minority introduced the idea of radiation emitted by the Earth.

Pompea et al. (2007) reported that many children and adults believe “all radiation is harmful” (p.7). This implies that students might associate the term with ionizing radiation rather than any band of the electromagnetic spectrum. Lambert’s (2005) participants also had difficulty understanding the term “radiation”.

The American Institute of Physics Operation Physics project (1998) reported that elementary and middle school students think of bands of the electromagnetic spectrum as completely different entities. Browne and Laws’ (2003) undergraduate participants struggled with the concept of the electromagnetic spectrum, in particular similarities and differences between visible light and infrared radiation. Fewer than 30% of Lambert’s (2005) participants chose the correct order for bands of the electromagnetic spectrum. Gautier et al. (2006) reported that their undergraduate participants’ conceptual models of shortwave radiative processes were inappropriate and that students had trouble differentiating between shortwave and longwave radiation. Österlind’s (2005) 14-year-old participants had difficulty in distinguishing different interpretations of a phenomenon from different sources, as when a phenomenon is given different names, e.g., thermal radiation and IR rays.
Two thirds of Lambert’s (2005) participants thought that the Sun’s energy provides a source of heat for the Earth’s interior. Gautier et al. (2006) noted that of their undergraduate participants: “In most instances, longwave radiative processes did not appear to play any part in students’ models of the greenhouse effect. This indicates that students have difficulties viewing the Earth (let alone greenhouse gases) as radiating bodies” (p.387). After instruction, students’ understanding of the role of longwave radiation improved, however many believed that rather than absorbing and re-emitting radiation, greenhouse gases reflected it back towards Earth. Henriques et al. (2002) found the misconception among children that “Infrared is the only type of light that, when absorbed, causes objects to heat” (p.214): i.e., they did not appear to understand the phenomenon of visible light causing heating when absorbed. This phenomenon has a central role in understanding the greenhouse effect. Sheppardson et al.’s (2009) literature review showed that many high school students do not distinguish between the different kinds of radiation involved in the greenhouse effect.

3. Interactions between electromagnetic radiation and greenhouse gases

Comins (2003) reported the misconception that all electromagnetic radiation is able to pass through the Earth’s atmosphere. Gautier et al.’s (2006) undergraduate participants thought that the greenhouse effect is caused by trapping of reflected solar energy by greenhouse gases or clouds, or greenhouse gases themselves being trapped. Similarly, in a closed-response question, 45% of Dove’s (1996) pre-service teacher participants thought that greenhouse gases absorb solar radiation. Most of Lambert et al.’s (2012) pre-service teachers, prior to instruction, did not express any understanding of the greenhouse effect. The authors’ definition of the greenhouse effect includes absorption of infrared radiation emitted by the Earth.

4. Natural climate variability in the past and relationship to CO₂ levels

No literature was identified on students’ understanding of this concept. Therefore all CI item distractors for this concept had to be generated from
misconceptions described by focus group participants in the next stage of research.

5. Difference between weather and climate

Students confuse weather and climate, even immediately following instruction, according to Spiropoulou et al. (1999; cited in Henriques (2002). Gowda et al. (1997) reported the misconceptions that changing climate can be personally perceived, due to memorable weather events or preconceived ideas about “normal” weather, e.g.: an expectation of snow at Christmas; confusion between weather and climate; and lack of awareness of the long-term nature of climate change.

6 and 7. Greenhouse gases and their radiative forcing capacity

The literature reviewed suggests that students may have difficulty correctly identifying all the main greenhouse gases, or understanding how small percentages of added gas can cause significant change. The concept that some greenhouse gases have more radiative forcing capacity than others appears to be poorly understood.

Most of Lambert et al.’s (2012) pre-service teachers did not express any understanding of the greenhouse effect prior to instruction. The authors’ definition of the greenhouse effect includes the names of the most abundant greenhouse gases: water vapor, carbon dioxide, methane, nitrous oxide, and ozone. None of Shepardson et al.’s (2009) participants identified methane as a greenhouse gas or discussed agriculture or landfills as greenhouse gas sources.

Thirty-nine percent of Dove’s (1996) participants thought that carbon dioxide is the “most powerful” (p.93) greenhouse gas and 12% thought that growing more rice paddies would reduce the greenhouse effect, suggesting they either did not understand that rice paddies emit methane, or did not know that methane is a greenhouse gas. Twenty-seven percent thought that carbon monoxide was a greenhouse gas. Few mentioned methane and none mentioned nitrous oxide or water vapour.
According to Daniel et al. (2004), most children are unaware of the variety of greenhouse gases, their sources, or of the concept of relative radiative forcing capacity.

8. Feedback and 9. Equilibrium of energy

No studies were identified which described students’ misconceptions about feedback or energy equilibrium.

10. Conservation of energy

Goldring and Osborne (1994) reported that half of their early Year 6 students lacked an understanding of basic energy concepts. Some students were able to recite the law of conservation of energy but could not apply it. The authors assert that the concept of energy is so closely tied to that of conservation of energy that the two cannot be discussed separately.

2.6 Critique of methodologies

Boyes and Stanisstreet (1993) acknowledged their questionnaire format as a limitation in that it did not uncover students’ reasoning. This is significant because participants may have chosen an “incorrect” response for a scientifically appropriate reason, using a sophisticated line of reasoning. Over 70% of Rye et al.’s (1997) participants correctly named carbon dioxide as a cause of climate change, however, many of these erroneously thought the mechanism for this was carbon dioxide damaging the ozone layer. This underlines the importance of collecting information about the students’ understanding of mechanisms in order to determine whether superficially correct knowledge is really accurate. Boyes and Stanisstreet’s (1997) technique of examining students’ responses to two or more survey questions is similar to the one I used for inferring students’ conceptual models by analysing responses to multiple CI items. It is powerful because it allows inferences to be made about relatively complex conceptual models from relatively simple closed response questions.
Some of Kurup’s (2003) research aims resembled mine in that they involved creation of a list of statements setting out the knowledge required for students to understand the greenhouse effect, and an instrument based on the knowledge described in the statements. However, a number of aspects of the study design mean that it cannot answer the questions that my research sets out to address. The author developed the draft of a 15-item propositional knowledge statement (PKS) based on discussions with a chemistry professor and an education professor. A chemist and an atmospheric scientist reviewed the draft document: this very limited consultation process compromises its validity. Second, the scope of the PKS is limited in that it describes knowledge strictly only in the context of the greenhouse effect. This is significant because students typically learn about the concepts underlying climate change in a number of other contexts. For example, if students hold misconceptions about the age, nature and origin of fossil fuels, this may affect their understanding of how fossil fuel burning is linked to climate change.

The other aspects concern the survey and interview design. Only six survey items addressed the mechanism of climate change: these were true/false/don’t know responses with a space for students to provide a reason. This format allows very little information about students’ understanding of the underlying concepts to be gleaned, because, as Boyes and Stanisstreet (1993) acknowledged, agreement with a statement provides little or no information about conceptual understanding. Only one interview question addressed the mechanism of climate change. Students were given a diagram to complete, and were asked “Would you explain your diagram, which shows what happens to solar radiation from the Sun?” Because it frames responses in terms of solar radiation, this question may cause other ideas to be overlooked. The diagram shows the Earth and Sun, with the atmosphere drawn as a dotted line between the two. Participants were asked to “draw arrows” (p.172) to show what they thought happened to radiation from the Sun. By prescribing what participants should draw, this research neglected other ways of thinking. White and Gunstone (1992) point out that
because drawings are the most open-ended form of data-collection, they can reveal understandings that the researchers could not predict.

**2.7 Conclusions**

Thirty years of research into learners’ conceptual understanding of climate change has shown that misconceptions are widespread, consistent and persistent. Many researchers have pointed to poor understanding of the underlying concepts as a possible factor, and shown broad agreement of the essential concepts that they consider to underlie the topic. However, to date there has been little explicit investigation of students’ ideas about these underlying concepts.

Research into students’ ideas about the essential underlying concepts shows that misconceptions are common: this gives credibility to the idea that poor understanding of underlying concepts is a factor in students’ misconceptions about climate change.

Several researchers asked about their participants’ sources of knowledge and suggested how these might be a factor in the development of misconceptions, but the mechanisms of these relationships were not investigated further. However, these studies did show that sources of information have changed over time, and that different sources are important for learners of different ages. This means that in order to understand how learners’ sources of information contribute to the construction of their knowledge, it is necessary to have reliable information about what these sources are.

My research contributes to the literature in the following ways:

1) Through the development of a set of conceptual statements setting out the essential knowledge underlying the science of climate change

2) By investigating Australian high school students’ ideas about these essential underlying concepts.
CHAPTER 3 – METHODOLOGY

3.1 Introduction

This chapter describes the data collection methods used in the study. It explains how the choice of methods was informed by findings from the pilot study reported in Appendix 1, and by the critique of methods employed by previous researchers, described in Chapter 2. It describes each method used, explains how the data-collection activities relate to research questions and discusses the choice of participants for each data-collection activity.

3.2 Use of pilot study findings to inform methods for this study

The research design for this study drew on three key findings from the pilot study described in Appendix 1. These were:

- Similarity of participants’ ideas to those reported in the literature;
- Limitations of concept mapping as a large-scale data-collection instrument for middle school students; and
- Limitations of individual interviews with middle school students.

3.2.1 Similarity of participants’ ideas to those reported in the literature

Misconceptions such as conflation of climate change and ozone depletion, described in previous research as mentioned in Chapter 2, were observed among participants in the pilot study. This is significant for the research reported here because it suggests that participants’ knowledge structures about the topic are similar to those reported in the literature, rather than being idiosyncratic or atypical. This is important as it supports the view that the findings from this study might be applicable to the wider NSW, Australian and international school populations.

3.2.2 Limitations of concept mapping with middle school students

My pilot study revealed a number of deficiencies in the use of concept mapping as a large-scale data-collection instrument for junior high school
students. The time taken to learn to produce concept maps meant that at least half of the data-collection time available had to be devoted to teaching the skill of concept map creation. This is difficult to justify when participants are required to produce only one map each.

Pilot study participants’ maps also revealed significantly less about their ideas than semi-structured interviews. This suggests that one lesson in concept map creation was not sufficient to allow participants to fully express their ideas through concept mapping, or that some prompting was necessary in order to help them recall and express their ideas. In the case of the interviews, this prompting took the form of planned and follow-up questions, though prompts can take a variety of forms including reading material, images and individual words (Koulaidis & Christidou 1999).

The literature lends weight to the idea that more time was needed for the high school students to learn concept mapping. According to Novak (1990), students require time and practice to learn the concept mapping technique in order to be able to express their ideas fully. Schultz (2009), who used concept maps to probe students’ ideas about climate change, suggested that they might have been too difficult for her Year 7 and 8 participants. Van Zele et al. (2004) considered their concept map analysis method appropriate for use with high school students, however their research involved only undergraduates. As it was not feasible to ask participating schools to provide several preparatory lessons to teach concept mapping prior to data collection, another large-scale data-collection technique had to be used.

3.2.3 Limitations of individual interviews

The pilot study highlighted limitations of individual interviews for eliciting information from middle-school students about aspects of their science knowledge. The individual student interviews of the pilot study varied considerably in duration and depth, with some students elaborating on their ideas in detail while others were able to offer very little information.

Figure 3.1 shows interview lengths for the pilot study. Nine of the fifteen interviews took seven minutes or less, which was not considered enough
time to discuss the topic in sufficient depth. In total, the fifteen interviews took one hour and 48 minutes, while the time taken to collect the data was three hours.

![Figure 3.1: Duration of interviews with pilot study participants](image)

In contrast, a focus group conducted with first-year undergraduate students (Jarrett et al. 2010) took up all the available time: i.e., one hour. It resulted in thoughtful and lively discussion between participants, deep reflection on ideas and a very rich dataset.

Although the students in Jarrett et al.’s (2010) study were undergraduates rather than school students, observation of whole-class interactions during the pilot study suggested that focus groups were likely to be successful, with students possibly feeling less intimidated about expressing their thoughts in the company of their peers, as well as generating more ideas than individual interviews through interaction between group members. These observations are in agreement with research literature on focus group interviews (Kidd & Parshall 2000; Lederman 1990; Osborne & Collins 2001; Rabiee 2004).
3.3 Findings from critique of methods used by previous researchers

This section briefly summarises the critique of methodologies in Section 2.8 and outlines how this influenced the design for my study.

Much of the large-scale research into students’ ideas about climate change employed closed response surveys that asked participants if they agreed with a list of statements. As Boyes and Stanisstreet (1993) acknowledged, this method can give misleading results because it does not probe the reasoning behind participants’ choices. Therefore it was necessary to ensure that my chosen methods yielded sufficient data to enable inferences to be made about participants’ reasoning.

A limitation of Kurup’s (2003) research was the limited consultation process that the author used in order to derive his propositional knowledge statements. As my study also required the creation of a list of knowledge statements, I needed to use a more rigorous consultation process for this stage than did Kurup (2003).

3.4 Summary of methods

I employed multiple data collection methods because these allow for multiple perspectives on data, enable triangulation and enhance credibility in qualitative research (Bogdan & Biklen 2002; Conrad & Serlin 2006). Different modes of communication provide different perspectives and enhance mode validity (White & Gunstone 1992). Therefore I chose methods which involve different modes of communication.

Data collection methods consisted of:

1. A Delphi study
2. A review of literature to identify concepts considered important for understanding climate change
3. A concept inventory (CI)
4. Semi-structured focus group interviews.
The Delphi study, CI and focus group interviews are described briefly in Sections 3.4.1–3.4.3. The review of literature was discussed in Chapter 2. The Delphi study and CI are discussed in detail in Chapters 4 and 5.

3.4.1 Delphi study

The Delphi method is “a method of structuring a group communication process” (Clayton 1997; p.376). A Delphi study consists of multiple iterations of a survey on the topic of study, distributed to a group of identified experts. Feedback is provided to participants after each iteration, in the form of summaries of the group’s responses. The purpose of this feedback is to allow members to modify their initial responses based on the views of the group as a whole (Clayton 1997). The Delphi method allows researchers to consult a group of experts without their having to meet, thus allowing contributions from geographically dispersed group members and preventing discussion being dominated by strong personalities (Linstone & Turoff 1975; Rowe 2007). In recent years, CI developers have used Delphi studies to ascertain which concepts their CI should cover (Danielson 2005; Goldman et al. 2008; Gray et al. 2005; Herman et al. 2010; Rowe & Smaill 2007; Stone et al. 2004; Streveler et al. 2003).

I used the Delphi method in this study to determine the essential concepts underlying the science of climate change. I conducted an online Delphi study using SurveyMonkey (2010) to consult a range of people with expertise in climate science and climate change education. The final list of concepts to be included in the CCCI was a synthesis of the findings from this Delphi study with the review of literature described in Section 2.4 of Chapter 2.

Chapter 4 reviews literature on Delphi study design and administration; describes the design, administration and results of the Delphi study; explains the process used to synthesise the Delphi findings with those of the literature review; and presents the final list of conceptual statements.
3.4.2 Concept inventory

Concept inventories (CIs) are validated multiple-choice tests designed to assess conceptual understanding in a particular area of science, usually at early undergraduate level. CIs contain distractors based on known misconceptions (Bardar et al. 2006; Evans et al. 2003) so they provide insight into misconceptions. I have previously developed multiple-choice concept questions using known misconceptions in distractors (Jarrett et al. 2010).

For this study, I developed a 27-item concept inventory: the climate change concept inventory (CCCI). In Chapter 5, the literature on CIs in science, engineering and mathematics is reviewed, and the development and validation processes of the CCCI are reported. The CCCI is shown in Appendix 2.

I chose to develop a concept inventory as an alternative large-scale data-collection instrument to concept mapping for six reasons:

- Concept inventories are suitable for large-scale data-collection
- Their multiple-choice format is already familiar to students, so they do not require extensive preparation of participants. The main preparation was explaining that the CCCI was not a test: i.e., my interest was that participants should express their own ideas rather than aiming to get “the right answers”
- They are useful for probing understanding about a number of distinct concepts
- They are useful for investigating the occurrence of known misconceptions
- Information in CI item stems and options act as prompts to activate students’ knowledge about a concept and help them recall their ideas – a useful strategy when participants may not have knowledge about a topic readily available in memory or may lack confidence in expressing their ideas, as was observed during the pilot study
Treagust (1988) explained that diagnostic tests with distractors based on known misconceptions are valuable in allowing teachers to make use of educational research – the CCCI therefore has potential for future application in schools.

A disadvantage of CIs is that they cannot explore reasons behind responses. However, carefully designed questions can give more insight into conceptual understanding than the “agree/disagree” surveys widely used as large-scale data-collection instruments to investigate students’ knowledge of the topic, e.g., Boyes et al. (1993). CIs also lack the capacity of concept mapping to investigate how students perceive relationships among concepts, however this information can be gathered to some extent through face-to-face data-collection. This is discussed in Section 3.2.3.

### 3.4.3 Focus group interviews

Focus group interviews were carried out to supplement and corroborate findings from the concept inventory about students’ understanding of the key underlying concepts by:

- assessing the extent to which participants’ articulated ideas corresponded to CI response choices and
- exploring reasons behind response choices.

The method for focus group interviews was informed by the work of Gibbs (1997), Lederman (1990), Rabiee (2004), and by findings from the pilot study. Interviews offer the best opportunity to gain detailed insight into understanding (Mertens 2005), and focus group interviews have numerous advantages over individual interviews for eliciting deeper insight into participants’ ideas (Lederman 1990).

I chose focus group interviews rather than individual interviews for this study because they:

- enhanced participation through peer interaction;
- minimised interviewer talking-time and maximised student talk;
allowed topics to be covered in more depth in a given amount of time; and

minimised inconvenience to participating schools.

However, it is acknowledged that individual interviews may be just as applicable in a different context.

According to Lederman (1990), focus groups originated in group therapy and were based on the assumption that people who share a common problem will be more willing to discuss it than if they were interviewed individually, thereby eliciting ideas that would not surface in individual interviews. Participants can respond to, challenge, confront and criticise each others’ ideas, so focus groups foster honest rather than socially-acceptable responses, and result in more than the sum of what participants could contribute as individuals (Kidd & Parshall 2000; Lederman 1990; Osborne & Collins 2001):

“The data generated in [focus group interviews] are often richer and deeper than data elicited in the one-on-one interview situation” (Lederman 1990, p.119), probing not only what participants think but how they think and why they think it (Kitzinger 1994). This is significant because exploring reasons behind responses was a key objective of the focus group interviews.

Gibbs (1997) added that as well as questioning each others’ views, focus group interactions allow participants to re-evaluate and reconsider their own ideas. I considered this important in the context of students reflecting on misconceptions.

Focus groups also allow issues to be explored in more depth, and more data to be collected in a given amount of time than would occur in individual interviews, because after one member has responded to a question, the rest of the group can respond to the same question by expressing their agreement, adding comments or explaining why they disagree, rather than each responding to the question individually (Lederman 1990).
Focus groups are seen as less threatening than individual interviews because the presence of peers offers support and security, encouraging shy individuals to speak up (Lederman 1990; Osborne & Collins 2001). This is useful, as during the pilot study some high school students appeared shy and reticent when interviewed as individuals. However, Gibbs (1997) took the opposite view, suggesting that focus groups may be more intimidating for shy individuals, although the author pointed out that participation can also be beneficial and empowering. On balance, I judged that the presence of classmates would decrease anxiety for shy participants because all participants were from the same age group and similar backgrounds.

Finally, focus group interviews have the additional advantages of allowing more students to participate while minimising inconvenience to schools and being more acceptable to schools, because they do not involve students being alone with the researcher.

Lederman (1990) cautioned that group dynamics may have unwanted or unintended effects on some participants, but that this is mitigated by the ability of the researcher to intervene in unproductive interactions. There is an additional disadvantage of focus groups for my study: it is difficult to compare participants’ ideas as expressed in focus groups directly with their CI responses. This is because on audio recordings it is not always clear which participant is talking, or sometimes an idea was jointly constructed by several participants during the discussion, and therefore could not be attributed solely to any one participant. However, I considered the advantages of focus groups to outweigh this disadvantage.

According to Rabiee (2004), the recommended number of participants is between six and ten, although Osborne and Collins (2001) reported that groups of between four and twelve are practical. Rabiee (2004) cited personal experience in going against the popular view (e.g., Lederman 1990) that participants should not know each other. It was not possible in my study to have focus group participants who did not already know each other because interviews had to take place in the participants’ schools during class time. However, the participation of students from a single
school and single year-group meant that the groups were relatively homogenous in age, socio-economic background and experience, as recommended by the literature (Lederman 1990; Rabiee 2004).

Focus group interviews usually last between one and two hours (Gibbs 1997; Rabiee 2004). In my study the time available was dictated by the circumstances of the participating schools and was between 45 and 90 minutes.

A focus group interview guide provides protocol for the interview. It includes a list of questions derived from the research questions. These serve to guide the discussion but are not intended to be rigidly adhered to (Lederman 1990). Kidd and Parshall (2000) stated that the interview guide may evolve over a series of groups, for example when grounded theory (Strauss & Corbin 1994) is used.

Semi structured focus group interviews involve a variable amount of prompting. Typically, very open-ended questions are used at the start, in order to avoid undue influence on participants’ thinking (Lederman 1990). Careful use of follow-up questions can elicit more information while keeping influence to a minimum, although it should be noted that the conversation is influenced by the interviewer’s choices about which comments to follow up on, and what aspects of these to explore.

Gibbs (1997) listed the following key functions of the focus group moderator:

- To clearly explain the purpose of the interview and put participants at ease
- To ask open questions, challenge participants and probe for details
- To keep the conversation relevant
- To ensure that everyone has a chance to contribute
- To avoid showing too much approval or giving personal opinions.

Osborne and Collins (2001) used focus group interviews to investigate 16-year-old students’ views on their recently completed science education.
According to the authors, focus groups have not been extensively used in science education research. In their research, a key function of the moderator was “to attempt to sustain an open, inclusive and permissive atmosphere in which all felt free to express their views” (p.444). As my research involved participants of a similar age, this was an important consideration and I employed the suggestions of Gibbs (1997) mentioned previously.

### 3.5 Research design

This section explains how the methods described above were applied in this study. It describes:

- how the methods were used to address the research questions;
- the participant groups for each data collection activity; and
- the sequence of data collection activities.

#### 3.5.1 Addressing the research questions

Table 3.1 shows how the research questions are addressed by the data-collection methods described in Section 3.4. Using more than one method to collect data for each research question enables corroboration and provides multiple perspectives on the question (Mertens 2005).

**Table 3.1: Mapping of research questions to data-collection activities**

<table>
<thead>
<tr>
<th>Research question</th>
<th>Data-collection activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What underlying scientific conceptual knowledge is required for students to make sense of a basic explanation of the mechanism of climate change?</td>
<td>Delphi study</td>
</tr>
<tr>
<td></td>
<td>Review of literature</td>
</tr>
<tr>
<td>2. What do NSW Stage 5 students understand about these underlying scientific concepts?</td>
<td>Concept inventories (CIs)</td>
</tr>
<tr>
<td></td>
<td>Semi-structured focus groups</td>
</tr>
</tbody>
</table>

#### 3.5.2 Sampling considerations and participants

It would have been too disruptive to participating schools to select a sample selected such as to be statistically representative of the wider NSW student population. I therefore used opportunity sampling (Cohen et al. 2007), in that the decision to participate was made by schools. However, in order to
ensure that participants reflected the diversity of NSW students as much as practicable, I invited, and was able to secure participation of, schools from different socio-economic areas and classes from across the range of academic ability.

Table 3.2 shows participant groups and subgroups for each data-collection activity, and the criteria for participant selection. The data-collection activities are shown in chronological order. The groups and sub-groups are illustrated in a Venn diagram in Figure 3.2. Figure 3.3 shows the sequence of data-collection activities.

**Table 3.2: Participant groups for data collection activities, in chronological order**

<table>
<thead>
<tr>
<th>Participant numbers</th>
<th>Activity</th>
<th>Criteria for selecting participants</th>
</tr>
</thead>
</table>
| 18 adults working in research or secondary/tertiary education | Delphi study | Expertise in climate science and/or teaching climate change  
Willingness to participate |
| 42 high school students in four focus groups | Focus groups (1): development of CI item distractors | Students willing to take part in discussions and whom teachers considered would participate actively in, and benefit from, discussions |
| 25 high school students in two focus groups | Focus groups (2): validation of draft CI items | Students willing to take part in discussions and whom teachers considered would participate actively in, and benefit from, discussions |
| 229 high school students | CI | Entire class groups, to minimise disruption to participating schools; participating classes chosen by head teachers  
Schools invited to reflect diversity in socioeconomic circumstances |
| 68 undergraduates | CI | Volunteers from an introductory-level unit of study on climate change |
| 32 high school students in four focus groups | Focus groups (3): validation/corroboration of CI data | Students willing to take part in discussions and whom teachers considered would participate actively in, and benefit from, discussions. |
Figure 3.2: Venn diagram illustrating participant groups and sub-groups. Participant numbers for each activity are in bold type.

Figure 3.3: Sequence of data-collection activities
3.6 Summary

This study employed four methods to collect data and address the research questions listed in Chapter 1. These methods were:

1. a Delphi study;
2. a review of literature;
3. a Concept inventory; and
4. semi-structured focus group interviews.

The Delphi study was chosen in order to enable consultation from a geographically diverse group of participants while allowing them to consider and respond to each others’ views.

The methods used to collect data from high school students were chosen to complement each other. The concept inventory and survey of knowledge sources enabled data-collection from a large number of participants, maximising the likelihood that findings would reflect the breadth of knowledge in the wider population. The focus groups enabled detailed exploration of participants’ ideas and confirmation of understanding.

Approval was granted by the University of Wollongong Human Research Ethics committee for the Delphi study, concept inventory trials with high school students and undergraduates, and pre- and post-CI focus group interviews with high school students. Approval was also granted by NSW Department of Education and Training Student Evaluation and Program Evaluation Bureau (SERAP) for all data collection involving high school students. Letters of approval are in Appendix 3. For the CI trials and associated focus group interviews, only the letter from SERAP is shown because SERAP requires University Human Ethics Committee approval to be granted before applications are evaluated.

The following two chapters detail the design, development and administration of the Delphi study and concept inventory.
CHAPTER 4 – CREATION OF A LIST OF CONCEPTUAL STATEMENTS DESCRIBING REQUIRED KNOWLEDGE

4.1 Introduction

In order to make a valid assessment of students’ understanding of the essential concepts underlying climate, it is necessary first to determine what these concepts are. This is Research Question 1:

What underlying scientific conceptual knowledge is required for students to make sense of a basic explanation of the mechanism of climate change?

This chapter describes the methods used to address this research question, explains the rationale behind the methods and presents the findings in the form of a final list of conceptual statements. Figure 4.1 summarises the method used and identifies the sections of this chapter where each stage in the method is described.

Figure 4.1 Summary of methods used to produce final list of conceptual statements

This list of conceptual statements had a number of functions in the study: in addition to answering Research Question 1, it was used in Chapter 5 in the development of the climate change concept inventory (CCCI). Finally, it
formed the basis of the focus group interview guide. Therefore, it was important that the resulting list of concepts was valid: i.e., that the concepts could be reasonably considered necessary for understanding the topic.

Validity in concept inventory development derives in part from the methods used to determine the list of concepts to be covered, and Delphi studies have been used by a number of authors for this purpose. However, in qualitative research, credibility is derived from the use of multiple methods in order to enable triangulation and the consideration of multiple perspectives (Mertens 2005). Therefore, in addition to the Delphi study, I carried out a review of literature on students’ understanding of climate change to determine which concepts were most commonly cited as underlying the science of climate change. This was summarised in Chapter 2, Section 2.4. The method used to derive a ranked list of concepts from this review of literature is reported in Section 4.4 of this chapter.

The final list of conceptual statements used in the development of the climate change concept inventory is a synthesis of the two ranked lists resulting from the Delphi study and the literature review, as illustrated in Figure 4.1.

### 4.1.1 Rationale for use of the Delphi method in this study

As explained above, it was important to use a rigorous process to derive the list of conceptual knowledge statements in order to enhance their validity. A commonly used way of deriving a list of concepts is to consult a number of discipline experts, and the Delphi method provided a practical way of achieving this.

Further, the Delphi method has been used successfully in the development of concept inventories for topics in physics, engineering, mathematics and computing (Danielson 2005; Goldman et al. 2008; Herman et al. 2010; Rowe & Smaill 2007; Stone et al. 2004; Streveler et al. 2003). This means that: (i) there is evidence that Delphi studies are an appropriate method for deriving a list of conceptual statements; and (ii) there is a body of recent literature on the use of Delphi studies in this context.
4.1.2 Outline of the rest of Chapter 4

Section 4.2 reviews the literature on Delphi studies. Section 4.3 describes the procedure used for this Delphi study and summarises the findings as a ranked list of conceptual statements. Section 4.4 describes the method and results of the process used to produce a ranked list of concepts based on the review of literature on students’ understanding of climate change reviewed in Chapter 2, Section 2.4. Section 4.5 explains how these two ranked lists were synthesised to produce a final list of conceptual statements setting out the essential conceptual knowledge underlying the science of climate change. Section 4.6 reports a comparison of the final list with the Climate Literacy Network’s (2009) list of essential principles of climate science. This comparison was carried out as an additional form of corroboration. Section 4.7 presents the discussion and conclusions for the process as a whole.

4.2 Review of literature on the Delphi method

This section includes a review of the research literature of the Delphi method. It includes a discussion of the background of the method, its use in areas related to my research, its strengths and limitations, and advice on Delphi study design.

4.2.1 Origin and definition of the Delphi method

Lindstone and Turoff (1975) defined a Delphi study as a method of structuring communication between members of a group of people, in order to allow the group to effectively deal with a complex problem. Delphi studies involve multiple rounds of a survey with feedback supplied to participants after each round. This feedback is in the form of statistical summaries of responses, and gives participants the opportunity to revise their responses based on the responses of the other group members while preserving participant anonymity. This format also allows each panel member equal opportunity to contribute (Linstone & Turoff 1975; Rowe 2007; Whitman 1990). The method is named after the Oracle at Delphi and was developed by Dalkey and Helmer (1963) at the RAND Corporation as a method of forecasting technological developments.
Linstone and Turoff (1975) stressed that there is no single correct Delphi study design: a design that works well in one situation may not produce successful results when applied to a different situation. Thus, they warned against attempting to define the Delphi method too explicitly or restrictively. For example, the number of rounds can be chosen to suit the requirements of the study (Rowe 2007).

Delphi studies have been used in a wide number of disciplines and for a wide variety of purposes (Keeney et al. 2006; Levinson 2005; Osborne et al. 2003; Schmidt et al. 2001).

4.2.2 Advantages and limitations of the Delphi method

The Delphi method has a decades-long history as a tool to aid consultation and decision-making, so there is a large body of literature to act as a guide. Further, its ongoing popularity suggests that it is a genuinely useful tool rather than a fashion. Clayton (1997) described the Delphi method as a “systematic, rigorous and effective methodology designed to elicit potent and valid user-friendly answers” (p.374).

According to Rowe (2007) and Cochran (1983) the chief rationale for using the Delphi method is to retain the advantages of group decision-making while avoiding the negative aspects of group interaction. For example: some group members may feel intimidated by the presence of more senior or prestigious members; the most forceful or persuasive members may not have the most reliable information; members may be unwilling to change publicly-stated views; or the conversation may drift off-topic.

The key assumption behind the technique is that a group makes better decisions than an individual, because a group must possess at least as much knowledge as its most knowledgeable individual, while interactions between group members may lead to further improvements in decisions (Rowe 2007).

A Delphi study can be used to consult a much larger group of participants than a committee meeting, while allowing group members to consider each others’ ideas and viewpoints, which cannot be done with a survey. The
Delphi method also avoids face-to-face contact between participants. This has two advantages: it allows participation of people who, for geographical reasons or time constraints, would be unable to meet, making the process less burdensome for participants; and it prevents individuals from exerting undue influence on the group’s decision-making (Linstone & Turoff 1975).

Another notable advantage of the Delphi method is that it separates the processes of formulating ideas and evaluating them. This assists with the process of considering multiple ideas, while the multiple iterations help to prevent premature decision-making (Whitman 1990).

However, Linstone and Turoff (1975) warned that many Delphi studies have given disappointing results. Among the reasons cited were:

- over-specification of the problem by the researchers;
- poor quality feedback to participants; and
- failure to explore reasons for disagreement.

The problems listed above should be avoidable if care is taken in designing and implementing the study. However, as with all data-collection methods, the Delphi method has a number of intrinsic limitations. The following list was collated from Linstone and Turoff (1975); Clayton (1997); Osborne et al. (2003) and Whitman (1990):

- Lack of face-to-face contact means that non-verbal communication cannot take place, limiting the communication process
- Because the group never meets it is impossible to fully assess and utilise its expertise
- Lack of standardised methods for qualitative analysis of round 1 data
- Lack of established methodology (although Whitman (1990) saw the lack of standardised procedures as a strength because this allows the technique to be adapted to different situations)
• The background and experience of each participant cannot be controlled (although the same argument could be made for members attending a committee meeting)

• Time constraints might limit the consideration participants are able to give to the problem

• Participants might feel pressured into conforming

• Findings might not be exhaustive

• Researcher bias might occur.

Therefore, when using the Delphi technique it is important to acknowledge its limitations and to minimise these where possible, for example: by using participants’ own words in summaries (Whitman 1990); by soliciting detail, context and justifications for responses; and by allowing participants to comment on and improve summaries to better reflect their ideas (Osborne et al. 2003).

4.2.3 Delphi studies in science, mathematics, engineering and computing

The design of a Delphi study depends on its purpose (Linstone & Turoff 1975). Therefore, in addition to literature on Delphi study design, I also reviewed literature on Delphi studies conducted for purposes similar to mine: i.e., studies that focused on the importance of scientific concepts. In some cases, these studies were carried out for the same reason as mine, i.e., for the concept selection stage of CI development. Other studies were related to curriculum development in science. Table 4.1 summarises the key design features of the literature reviewed.
<table>
<thead>
<tr>
<th>Authors</th>
<th>Purpose</th>
<th>Participants</th>
<th>Number and format of rounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Danielson (2005)</td>
<td>Engineering (statics) CI</td>
<td>18</td>
<td>2 rounds</td>
</tr>
<tr>
<td></td>
<td>contacted via: mechanics list serv;</td>
<td></td>
<td>R1 qual: describe difficult</td>
</tr>
<tr>
<td></td>
<td>personal recommendation</td>
<td></td>
<td>concepts; important or</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>troublesome skills</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R2 quant: rate importance of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>concepts/skills;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>% of students achieving</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>concept/skill.</td>
</tr>
<tr>
<td>Goldman et al. (2008); Herman (2011)</td>
<td>Introductory computing (3 CIs)</td>
<td>21 instructors</td>
<td>4 rounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(discrete maths)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R1 qual: list 10-15 important and difficult concepts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R 2 quant: rate difficulty;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>importance; expected mastery</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R3: statistics provided; re-rate difficulty; importance; justify ratings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R4: statistics and justifications provided; re-rate difficulty; importance</td>
</tr>
<tr>
<td>Gray et al. (2003; 2005)</td>
<td>Physics (dynamics) CI “Modified Delphi”</td>
<td>25 “seasoned” instructors from diverse institution types</td>
<td>2 rounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R1 qual: difficult concepts; common misunderstandings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R2 quant: list of concepts mentioned more than once supplied: % of students who understand; importance of understanding; optional comments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chosen according to “attitude” — wide range of people in science education and physics-related fields</td>
<td>R1 qual: describe context for studying physics; associated content; associated activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R2 quant: ½- 1-page summaries supplied; rate importance</td>
</tr>
<tr>
<td>Osborne et al (2003)</td>
<td>To determine extent of agreement about curriculum content</td>
<td>25  23</td>
<td>3 rounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Criteria: fellowship of royal society; publications or textbooks; holding of eminent post; awards for teaching</td>
<td>R1 qual: 3 open-ended questions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R2 mixed: 30 themes supplied (20-40 words + 3-5 supporting statements). Rate importance; justify rating; comment on accuracy of summary; respond to supporting statements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R3: supplied themes merged/split /revised in response to comments. Re-rate.</td>
</tr>
<tr>
<td>Rowe and Engineering</td>
<td>Electromagnetics</td>
<td>Number of rounds not specified</td>
<td></td>
</tr>
</tbody>
</table>
4.2.4 Number and selection of participants

As Table 4.1 shows, most CI developers consulted around 20 participants in their Delphi studies. However, other authors on the topic of Delphi study design have offered advice on participant numbers. Table 4.2 lists some recommendations for participant numbers.

Table 4.2: Recommended participant numbers for Delphi studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>Number of participants</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haussler and Hoffman (2000)</td>
<td>20-50</td>
<td></td>
</tr>
<tr>
<td>Clayton (1997)</td>
<td>15-30 (homogeneous)</td>
<td>Few new ideas are generated by groups over 30 if well chosen and homogeneous.</td>
</tr>
<tr>
<td>Delbecq et al. (1975)</td>
<td>5-10 (heterogeneous)</td>
<td></td>
</tr>
<tr>
<td>Osborne (2003)</td>
<td>10-30</td>
<td>Attrition may occur during the course of the study.</td>
</tr>
<tr>
<td>Jones and Twiss (1978)</td>
<td>10-50</td>
<td></td>
</tr>
<tr>
<td>Martino (1983)</td>
<td>Minimum 15</td>
<td>If carefully chosen</td>
</tr>
</tbody>
</table>
Rowe (2007) suggested that it is better to collect rich data from a smaller number of participants, e.g., 12, than to collect only numerical responses from a larger group. Clayton (1997) defined a heterogeneous group as one involving people from different social or professional stratifications such as schoolteachers and academics. This means that my participant group was heterogeneous.

Based on the above advice the fact that my study involved a heterogeneous group, the minimum acceptable number of participants would be between five and ten.

The next consideration in the recruitment of participants is the set of criteria for participant selection.

This is important because, as Clayton (1997) emphasised, the Delphi’s authority and validity derive from participant selection. He defined an expert as “someone who possesses the knowledge and experience necessary to participate in a Delphi … Expertise exists in various forms and although it may be difficult to measure exactly, there are general characteristics of individuals who, in a given context, demonstrate a level of wisdom, insight, theory, practice, expertise and analysis not found common to all individuals. It is these individuals to whom the term “expert” is assigned” (pp.377-380). Similarly, Martino (1983) defined an expert as “anyone with knowledge about a specific subject” (p.32). This implies that the selection criteria depend on the topic of the study.

Haussler and Hoffman’s (2000) criteria were personal attributes: ability to engage in the required professional reflection; willingness to engage with people from outside their professional field; and commitment to achieving educational goals. Although it is almost impossible to use these criteria when choosing invitees, such people are more likely to choose to participate, having received an invitation. Whitman (1990) stressed the importance of briefing participants on the format of the questionnaires and the use to which the data will be put.
I aimed to recruit high school teachers because Delphi studies carried out for CI development usually involve consultation of teaching staff for the subject. Osborne et al. (2003) asserted that there is no commonly agreed-upon definition of an expert teacher.

4.2.5 Number of rounds
According to Whitman (1990) the classical Delphi study had four rounds and some studies have used as many as 25. Whitman (1990) recommended three or four rounds as sufficient to allow participants to respond to group feedback while avoiding fatigue and the associated tendency to conform in order to complete the process. Linstone and Turoff (1975) stated that participants are usually given at least one opportunity to revise their original ratings, based on feedback. Rowe (2007) warned that as most experts are busy they are unlikely to want to participate in a protracted Delphi study.

4.2.6 Method for first round
It is generally agreed that the first round of a Delphi study should consist of one or more open-ended questions (Haussler & Hoffmann 2000; Whitman 1990; Linstone & Turoff 1975; Pritchard et al. 2009; Osborne et al. 2003). The purpose of this is to minimise the likelihood of researcher influence through inadvertent limiting of the scope of the study (Osborne et al. 2003). Osborne et al. (2003) stated that in order to avoid their views impinging on participants’ responses, they gave little guidance on the expected content of responses to the first round of the study.

According to Osborne et al (2003) and Haussler and Hoffman (2000), participants should be asked to justify their response, giving context and detail. Clayton (1997) recommended supplying stimulus material to help participants understand the context and scope of the task; specifying that material should be as concrete as possible, to prevent participants from responding to their own, possibly inaccurate, interpretation of the problem. This contradicts Osborne et al.’s (2003) approach described above, however Whitman (1990) agreed with Clayton (1997), pointing out that validity and reliability can be threatened if questions are not well phrased and
unambiguous. Haussler and Hoffman (2000) asked participants for an associated context and activity for each physics topic they thought was important. This meant that participants had to justify each topic and outline the depth of knowledge required.

Responses from open-ended questions should be content-analysed and categorised (Haussler & Hoffmann 2000; Osborne et al. 2003). These categories or themes form the basis for the second round. Categories or themes may be in the form of a short paragraph (Osborne et al. 2003) or a page of text (Haussler & Hoffmann 2000), and may include supporting statements or quotations (Osborne et al. 2003).

Streveler et al. (2003), whose Delphi study was for CI development, adopted the criterion that only concepts that had been suggested by two or more participants would be included in the second round. This reduced their initial list of concepts from 60 to 28. Haussler and Hoffman (2000) content-analysed 500 statements to develop a half to one page summary for each category, using original words wherever possible. The authors gave an example summary.

4.2.7 Method for second round
The second round of the study involves generating a closed-response questionnaire using the categories generated in the first round. Participants’ own language should be used wherever possible (Osborne et. al 2003), however Clayton (1997) advised translating responses into generic statements. Participants indicate their level of agreement with each category on a Likert scale (Clayton 1997). Osborne et al. (2003) also asked participants to justify their ratings, to comment on appropriateness of the wording of the categories and to respond to the supporting statements. Rowe (2007) also recommended asking participants to give reasons for their ratings, but pointed out that the more rich the data, the smaller the panel of experts must be, to avoid overload. Streveler et al. (2003) advised participants not to rate any concept for which they felt they had insufficient expertise. However they did not ask participants to justify their responses.
There is some variation in the amount of written response requested in rounds two and three, with some authors asking for detailed explanations for ratings and others for none. There is a balance to be struck, although no one discusses it, between rich feedback on ratings and participant fatigue. Clayton (1997) and Whitman (1990) only specified written comments for re-ratings outside the interquartile range or central tendency. However, Linstone and Turoff (1975) acknowledged tensions between different goals of a Delphi study, such as efficiency of communication, and allowing the widest possible range of ideas to be explored, as well as the impossibility of designing a “perfect” study.

Whitman (1990) and Haussler and Hoffman (2000) recommended a five point Likert scale from “extremely important” to “not important”. Clayton (1997) recommended a five or seven point scale from “strongly disagree” to “strongly agree”, to enable the researcher “to work within an interval or quasi-interval scale of measurement (p.379).

4.2.8 Statistical methods

One of the essential features of a Delphi study is provision of feedback to participants summarising the group’s responses to previous rounds. There are a number of ways of calculating this information.

Osborne et al. (2003) calculated means, modes and standard deviations (SD) for each Likert scale. According to the authors, SD indicates the level of group consensus.

Whitman (1990) outlined a number of appropriate statistical analyses and explained the reasons for their use. She stated that means are useful when ranking items: “Although modes provide information about the most frequent response and medians about the middle response, means are often used when priorities are being determined because they provide a measure useful in the final ranking of items” (p.34). This information is fed back to participants along with qualitative responses, so that each participant is aware of both the collective opinion and arguments in favour of, or against, particular viewpoints (Whitman 1990).
Streveler et al. (2003) provided participants with non-parametric median ratings and two-quartile ranges. These were used rather than mean and SD because the surveys used an ordinal scale.

Likert scales are ordinal, so it is more appropriate to use a non-parametric measure of central tendency, i.e., median and either range or interquartile range, depending on which is more informative.

The form of feedback was determined in consultation with the University of Wollongong statistical consultant. She advised returning bar graphs rather than medians because bar graphs better conveyed where consensus existed (Personal communication, 3rd August 2011).

4.2.9 Method for third round
Osborne et al. (2003) refined or re-organised categories based on the qualitative feedback about the categories and supporting statements; for example, two categories may be merged or one split. The authors only returned categories which had been rated as >3.6 and/or mode of 5. This reduced the number of categories from 28 to 18, lessening the possibility of participant-fatigue (Osborne et al. 2003; Whitman 1990). These data were returned to participants along with statistical data: participants were asked to re-rate the statements, again justify their ratings, provide further supporting statements and suggest further improvements to category summaries.

By contrast, Streveler et al. (2003) used the same list of concepts as for the previous round. They asked participants to justify their re-rating only if it fell outside the 2-quartile range. According to Whitman (1990), participants should be given the same list as for round two and should explain their ratings if they lie outside “specified boundaries” (p.34). This implies that reasons for ratings are not required otherwise. According to Whitman (1990), asking for explanatory comments provides information about areas of, and causes of, disagreement.
4.2.10 Consensus

When responses to round three have been received, statistical analyses are again carried out, and comparisons made with results for the previous round. For studies with four or more rounds, this process is repeated (Rowe 2007).

In some Delphi studies, rounds are repeated until consensus and stability in responses are reached. Osborne (2003) defined stability as a change of a third or less in participants’ ratings between rounds two and three of the study, and consensus as two-thirds or more of participants rating a category as four or higher.

According to Holey et al. (2007), there are no objective criteria for determining when stability and consensus have been reached.

Osborne et al.’s (2003) aim was to determine degree of consensus. They found little guidance in the literature on the minimum necessary level of agreement, and acknowledged that their definitions of consensus and stability are arbitrary; stressing that these should be applied in conjunction with qualitative consideration of the data, rather than inflexibly.

According to Rowe (2007) and Cochran (1983), little change usually occurs after the second quantitative round, so two quantitative rounds should be sufficient. Cochran (1983) added that most studies stop after round three, for practical reasons.

4.3 Delphi study to determine essential concepts underlying climate change: method and results

This section describes how my Delphi study was carried out, and summarises the results.

4.3.1 Participants

I recruited participants by contacting members of climate research groups in Australian universities and at the CSIRO, several high schools and the NSW Science Teachers’ Association. Although science teachers’ knowledge of
the science is less complete than that of the experts, they have valuable
knowledge of the scope and depth at which the topic is taught. All
invitations specified that invitees should participate only if they considered
themselves qualified to do so, and invitations to teachers specified that
participants should have taught the topic in school.

I asked potential participants to pass the invitation on to colleagues whom
they considered would be suitable to participate: this is a form of snowball
sampling (Goodman 1961), and was recommended by Clayton (1997). The
majority of participants identified themselves by return email, but this
information was kept confidential. Participants who identified themselves
included twelve academics, one other researcher and two high-school
teachers.

All three rounds of the Delphi study were delivered online using
SurveyMonkey (2010). Participants were contacted by email. In order to
clarify the context and scope of the task, I attached three examples of
learning materials currently used to teach the topic in schools. These
consisted of a book section (Whalley, Neville, Robertson, & Rickard, 2005),
a newspaper section (Lennon, Engel, Leigh, & Pearce, 2010) and a website
(Australian Government Department of climate change 2009). I also
included a paragraph explaining the purpose of the Delphi study and the
wider context of the research, and a link to the survey. I indicated that
participants should contact me if the information was not sufficiently clear,
and several did so.

4.3.2 Number and format of rounds
I limited my study to three rounds: one open-ended and two quantitative, in
order to avoid undue burden on participants. However like Osborne et al.
(2003), I asked participants in the quantitative rounds to comment on their
reason for rating and on the wording of the concept statements. In all the
cases I identified where Delphi studies were used in CI development, the
quantitative rounds involved Likert ratings of concept importance, so I
formatted my study in this way. However, a concept inventory can cover
only around 10 concepts (Libarkin, 2008). Richardson et al. (2003) state that multiple questions testing the same concept increase the validity of the CI for each concept; hence the need to limit the number of concepts covered. After the second round it became clear that I would need to prioritise the concepts. To do this I added a ranking question (Okoli & Pawlowski, 2004; Schmidt et al. 2001) in round three.

4.3.3 Method for round one

In round one of the online survey the participants were asked the following two questions:

1. Please list the scientific concepts required in order to understand the learning materials provided. For each concept, please indicate which part of the learning materials it relates to, and give a brief indication of the depth of knowledge required.

2. Please evaluate the above model: describe any additional elements of the science that you feel ought to be included, or anything that could reasonably be left out, explaining your reasoning. Alternatively, you may prefer to describe the model of climate change that you feel is as simple as is scientifically acceptable, without reference to the learning materials provided or the concepts underlying them. In this case please briefly explain why you chose this approach.

Participants were asked to justify their responses, giving context and detail (Haussler & Hoffmann, 2000; Osborne et al., 2003). Only four people participated in this round, and none of these were high school teachers. This was most likely because it took place over the New Year break. As this number was not considered sufficient and included no high school teachers, I invited potential participants for the second round who had not participated in round one. This is discussed in Section 4.3.4.

I content-analysed and categorised responses, creating 24 short summary paragraphs. These are shown in Table 4.3. According to Osborne et al.
categories or themes may be in the form of a short paragraph or a page of text, and may include supporting statements or quotations.

Table 4.3: Conceptual statements derived from Round one responses. These formed the text for Likert-response questions in Round two.

1. There is a fixed amount of carbon on Earth. It is cycled between atmosphere and biosphere: photosynthesis is a sink and respiration is a source of CO₂. Oceans dissolve CO₂: warm water absorbs less CO₂ than cold water. The formation of rocks containing carbonate is also a sink for CO₂.

2. Fossil fuels contain carbon that was part of living things hundreds of millions of years ago. The process of fossilisation took this carbon out of the atmosphere-ocean-biosphere cycle. Burning fossil fuels returns this carbon to the cycle.

3. About 99% of the atmosphere consists of N₂ and O₂: these are not greenhouse gases. The atmosphere also contains small amounts of CO₂, CH₄, O₃, N₂O, H₂O and CFCs, all of which are greenhouse gases. Water vapour is a variable component of the atmosphere and is the most abundant greenhouse gas.

4. Greenhouse gases come from natural sources (e.g., respiration, decay of vegetation), human sources (e.g., burning fossil fuels, landfills) or both.

5. All atmospheric gases are transparent to visible light. Non-greenhouse gases are also transparent to IR but greenhouse gases absorb IR: this is the cause of the greenhouse effect. Greenhouse gases don't "work" by blocking UV or IR radiation.

6. The atmosphere can transmit, reflect (clouds or dust), absorb and emit electromagnetic radiation.

7. Greenhouse gases absorb IR coming "up" from the Earth but re-emit in all directions including back down to Earth.

8. Feedback: changing one parameter can have an effect on another parameter, causing a change in the original parameter. Feedbacks can be negative: (i.e., tending to return the parameter to its original value) or positive: (i.e., tending to drive the parameter further away from its original value) e.g., increasing CO₂ raises surface temps causing more water to vaporise, which further raises temps.

9. Secondary effects of the enhanced greenhouse effect are those caused by positive feedbacks. For example, reduction in sea ice extent.

10. The wave model: a wave transmits energy through oscillations, without transmitting matter. Definitions of wavelength and frequency, and the link between wave speed, frequency and wavelength.

11. The electromagnetic spectrum: waves that consist of varying electric and magnetic fields, do not require a physical substance to travel in and travel at the same speed in a
vacuum. They differ in wavelength and frequency but are not fundamentally different phenomena in the way that sound waves and alpha particles are. Infrared (IR) radiation has lower frequency than visible light, which in turn has lower frequency than ultra-violet (UV).

12. Electromagnetic radiation transmits energy. Different frequencies of electromagnetic radiation carry different amounts of energy. Higher frequency bands carry more energy.

13. Radiative forcing occurs if the amount of energy received by an object is greater than the amount emitted - this results in temperature rise.

14. If an object is at a constant temperature then the amounts of energy it absorbs and emits must be equal. The greenhouse effect results in more energy being stored in the Earth/atmosphere but inputs and outputs are still equal.

15. Concentrations of CO₂ tend to balance between different parts of the Earth's surface. e.g., as CO₂ concentrations in the atmosphere increase, more CO₂ will become dissolved in the oceans.

16. All matter emits electromagnetic radiation. Most radiation is emitted at a band which is characteristic of the object's temperature: the hotter the matter, the higher the frequency at which its radiation emission peaks. The Earth's emission peaks at IR (it does not emit radiation at higher bands) and the Sun's peaks at visible light. The Sun also emits significant amounts of UV and IR.

17. As an object emits electromagnetic radiation, it loses energy and cools down unless it receives an equal amount of energy. The Sun does not cool down because nuclear energy is being transformed providing an input.

18. Albedo: the ratio of electromagnetic energy reflected from a surface to electromagnetic energy incident on the surface, e.g., snow has a higher albedo than water.

19. Conservation of energy: if energy in one form disappears, it must appear in another form.

20. The climate has been different in the past (e.g., carboniferous period, ice ages) due to changes in energy emitted from the Sun and the distance between Earth and Sun, or CO₂ released from volcanoes during periods of high levels of volcanism. Prehistoric climate changes correlate with changes in CO₂ levels, providing evidence for the link between CO₂ levels and global temperatures.

21. Weather is short-term, day-to-day climatic conditions, climate is longer-term trends, i.e., conditions that would be expected at a given place and time of year.

22. Seasonal changes in day length and temperature are due to the tilt of Earth's axis.

23. Ecosystems (interacting systems of living things) are adapted to their climate and changes to the climate will cause changes to ecosystems. The climate contributes to how living things have evolved, and changes to the climate in the past (e.g., ice ages) have resulted in extinction of some living things and evolution of others.

24. Direct effects of an enhanced greenhouse effect are increases in global average
temperatures, climatic variability and sea level rise: due to both thermal expansion of the oceans and melting of land-based ice.

4.3.4 Method for round two

In order to have a sufficient number of participants, I needed to recruit at least ten participants for this round (Clayton 1997; Jones & Twiss 1978; Osborne et al. 2003). This meant having participants for round two who had not completed round one.

I did not identify any literature in which additional participants were sought for subsequent stages of a Delphi study. However, the breadth of the method, and the fact that some studies have not included an open-ended round at all (Rowe & Smaill 2008; Stone et al. 2004) suggests that this could be considered acceptable practice. In total, 18 people, including two high school teachers, participated in this round.

I asked participants to rate how important each concept was to a basic understanding of the science of climate change, on a 5-point Likert scale from “Not important at all” to “extremely important” (Haussler & Hoffmann, 2000; Whitman, 1990). I also asked for comments on each statement, and at the end of the survey, invited participants to add any concepts they believed were missing from the list. This was important as most of the round two participants had not completed round one, and several responses were received for this question.

In total, participants made 54 comments either requesting specific changes, criticising wording, suggesting conceptual areas to add or commenting on the relative importance of concepts.

In a similar way to Osborne et al. (2003), I used the qualitative feedback from round 2 to refine, reword, merge or split concepts. I added several new concepts to reflect responses to the open-ended question at the end of the survey. Each conceptual statement was also given a title, which helped to clarify each concept. It became apparent that some were examples of concepts rather than actual concepts. I simplified some low-rated statements
by removing detail, on the assumption that respondents were rating the
concept low because they felt that the level of detail supplied was
unnecessary. However, I retained these concepts for round three, because
literature on students’ understanding of climate change has consistently
cited them as key concepts underlying the concept.

4.3.5 Method for round three
For each conceptual statement in round three, participants were shown:

- the original statement from round 2;
- the histogram of responses from round 2;
- all comments, de-identified but otherwise verbatim; and
- the revised conceptual statements.

The 29 revised statements are shown in full in Table 4.4. Participants were
asked to rate and comment on these revised statements. Finally, I asked
participants to rank the ten most important concepts from the list.
Participants were not asked to rank all 29 concepts for two reasons. First,
according to Dillman (2007), respondents should not be asked to rank long
lists of items. Second, my priority was to identify the 10 or so most
important concepts because as Rowe and Smaill (2007) pointed out, CIs
typically can only test about 10 concepts in the time available for students to
complete them. All respondents to round three completed this question.

Table 4.4: Revised conceptual statements used for Likert-response and ranking
questions in Round 3. Revisions were based on comments received in Round 2.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1: THE CARBON CYCLE. There is a fixed amount of carbon on Earth. It is cycled among the atmosphere, biosphere, soils, rocks and oceans.</td>
<td></td>
</tr>
<tr>
<td>2: CARBON IN FOSSIL FUELS. Fossil fuels contain carbon that was part of living things hundreds of millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle. Burning fossil fuels returns this carbon to the cycle.</td>
<td></td>
</tr>
<tr>
<td>3a: PROPORTIONS OF GREENHOUSE AND NON-GREENHOUSE GASES IN THE ATMOSPHERE. Over 96% of the atmosphere consists of non-greenhouse gases. The atmosphere also contains small amounts of CO₂, CH₄, O₃, N₂O and H₂O and CFCs - all of which are greenhouse gases. Water vapour is a variable component of the atmosphere and is the most abundant greenhouse gas.</td>
<td></td>
</tr>
<tr>
<td>3b: RADIATIVE FORCING CAPACITY. Some greenhouse gases are &quot;stronger&quot;: i.e., cause more warming per molecule than others</td>
<td></td>
</tr>
</tbody>
</table>
4: SOURCES AND SINKS OF GREENHOUSE GASES. There are both natural (e.g., respiration, decay of vegetation) and human-induced sources (e.g., burning fossil fuels, landfills) and sinks (e.g., CO₂ dissolving in seawater, formation of rocks containing carbonate).

5: INTERACTIONS BETWEEN ATMOSPHERIC GASES AND ELECTROMAGNETIC RADIATION. Most of the gases that make up the atmosphere are transparent to visible light. Non-greenhouse gases are transparent to IR but greenhouse gases absorb IR: this is the cause of the greenhouse effect.

6: RADIATIVE TRANSPORT: *Unchanged from Table 4.3*

7: ASYMMETRIC RELATIONSHIP BETWEEN ABSORPTION AND EMISSION OF IR BY GREENHOUSE GASES: *Unchanged from Table 4.3*

8: FEEDBACK. *Unchanged from Table 4.3*

10a: THE WAVE MODEL. A wave transmits energy without transmitting matter.

10b: WAVELENGTH. Visual concept - recognising wavelength on a representation of a wave, usually as represented as the distance from crest to crest or trough to trough of a transverse wave.

11: THE ELECTROMAGNETIC SPECTRUM. Visible light, IR and UV radiation are all parts of the electromagnetic spectrum. IR lies beyond the red end of the visible light rainbow and UV lies beyond the violet end. They are all waves and differ in wavelength/frequency only.

12a: FORMS OF ENERGY. Electromagnetic radiation transmits energy.

12b: FORMS OF ENERGY. Heat is a form of energy.

12c: TEMPERATURE: Temperature is not a form of energy. Temperature is a measure of how hot or cold an object is.

13: NON-EQUILIBRIUM. If the amount of electromagnetic energy received is greater than the amount emitted, the temperature rises and if the amount received is less than the amount emitted, the temperature falls.

14: THE NATURAL GREENHOUSE EFFECT IS AN EQUILIBRIUM SITUATION. The natural greenhouse effect results in energy being stored in the Earth/atmosphere but inputs and outputs are still equal.

15: EQUILIBRIUM. A situation in which opposing parameters affecting a system balance each other, resulting in the system remaining in the same configuration, over time. e.g., as CO₂ levels in the atmosphere increase, more CO₂ will become dissolved in the oceans e.g., as the temperature of the Earth's surface/lower atmosphere increase, more energy will be radiated out to space.

16: BLACK BODY RADIATION. All matter emits electromagnetic radiation. The wavelengths emitted depend on the object's temperature. The Earth emits IR and the Sun emits visible light, UV and IR.

17: RATE. The speed at which a process happens, e.g., the release of CO₂ into the atmosphere by the burning of fossil fuels is happening much faster than the removal of CO₂.

18: ALBEDO. The ratio of electromagnetic energy reflected from a surface to electromagnetic energy incident on the surface. Radiation not reflected by the surface is absorbed, e.g., snow reflects more visible light than water.

19: CONSERVATION OF ENERGY. Energy can change from one form into another but the total amount of all forms of energy remains constant.
20a: NATURAL CLIMATE VARIABILITY. The climate has been different in the past (e.g., carboniferous period, ice ages) due to changes in energy emitted from the Sun and the distance between Earth and Sun, or CO$_2$ released from volcanoes during periods of high levels of volcanism.

20b: PAST CLIMATE CHANGE RELATES TO CO2 LEVELS. Prehistoric climate changes correlate with changes in CO2 levels, providing evidence for the link between CO2 levels and global temperatures.

21: DIFFERENCE BETWEEN WEATHER AND CLIMATE. *Unchanged from Table 4.3*

22: RELATIONSHIP BETWEEN EARTH'S AXIS OF ROTATION AND ANNUAL SEASONS. Seasonal changes in climatic parameters such as day length and temperature are due to the tilt of Earth's axis.

23a: RELATIONSHIP BETWEEN CLIMATE AND ECOLOGY: Ecosystems are adapted to their climate and changes to the climate will cause changes to ecosystems.

23b: RELATIONSHIP BETWEEN CLIMATE AND EVOLUTION. The climate contributes to how living things have evolved, and changes to the climate in the past (e.g., ice ages) have resulted in the extinction of some living things and the evolution of others.

24: EFFECTS. The effects of an enhanced greenhouse effect include increases in global average temperatures, rainfall variability, reduction in sea ice extent and sea level rise.

Fifteen participants responded to this round.

I calculated median ratings and interquartile ranges. Nineteen of the 29 concepts were rated four or five (“very important” or “extremely important”), i.e., too many for a concept inventory, so the ranking question played a key part in prioritising the concepts. Participants had been asked to rank the most important concept as “1”, the second most important as “2” etc. These numbers were reversed so the most important concepts were given “10”, the second most important, “9”, the tenth most important, “1” and all other concepts, zero. These numbers were then totalled for each concept in a similar way to Schmidt et al.’s (2001) “ranking-type” Delphi method. This produced a ranked list with which to compare the list from my literature review. Table 4.5 shows these totals for each statement, along with a resulting overall rank in descending order. This table also summarises the Likert-rating responses. It should be noted that although Likert-ratings were generally in agreement with ranking scores, this was not always the case.
Statements 3a and 3b were revised in response to comments by participants in round 3. The revised wording of these statements is shown below:

3a. PROPORTIONS OF GREENHOUSE AND NON-GREENHOUSE GASES IN THE ATMOSPHERE: Over 96% of the atmosphere consists of non-greenhouse gases. The atmosphere also contains small amounts of CO₂, CH₄, O₃, N₂O and H₂O and CFCs - all of which are greenhouse gases. Water vapour is a variable component of the atmosphere and is the most abundant greenhouse gas. GH gases are uniformly distributed - not in a distinct atmospheric layer.

3b. RADIATIVE FORCING CAPACITY: Some greenhouse gases have more radiative forcing capacity than others, i.e., a given amount of a "stronger" greenhouse gas would result in more radiative forcing than the same amount of a "weaker" greenhouse gas.

4.3.6 Results
The final ranked list of 29 conceptual statements resulting from the Delphi study is summarised in Table 4.5. Only conceptual statement titles are shown in Table 4.4 as the statements themselves were shown in full in Tables 4.3 and 4.4. Conceptual statements are listed in order of ranked importance. The first two columns show total rating score and total ranking for each conceptual statement in round three. Total ranking was derived using the method described in Section 4.3.5.

In my study, the number of rounds was constrained by the need to avoid undue burden on participants, therefore it was not possible to continue the study until a pre-determined level of consensus was reached. Consensus was stronger for some conceptual statements than for others. The five columns on the right of Table 4.5 reflect consensus, as indicated by the number of participants choosing each rating, i.e., Not important/Somewhat important/ Moderately important/Very important/Extremely important. Font size reflects participant numbers (1-4 = 8 point; 5-8 = 10 point; 9-12 = 12 point)
Table 4.5: Total score and rank for each conceptual statement in Round three, and consensus, as indicated by the number of participants choosing each rating

<table>
<thead>
<tr>
<th>Total</th>
<th>Rank</th>
<th>Concept number and name</th>
<th>Not</th>
<th>Som</th>
<th>Mod</th>
<th>Ver</th>
<th>Ext</th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>1</td>
<td>1. The carbon cycle</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>2</td>
<td>2. Carbon in fossil fuels</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>3</td>
<td>4. Sources/sinks of GH gases</td>
<td>1</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>4</td>
<td>20a. Natural climate variability</td>
<td>1</td>
<td>11</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>5</td>
<td>20b. Past climate/CO₂ levels</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>6</td>
<td>21. Difference weather/climate</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>7</td>
<td>3b. Radiative forcing capacity</td>
<td>1</td>
<td>11</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>8</td>
<td>5. Interactions: gases/e.m.r.</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>9</td>
<td>3a. Proportions of GH/non-GH gases in the atmosphere</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>10</td>
<td>18. Albedo</td>
<td>1</td>
<td>1</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>10</td>
<td>8. Feedback</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>11</td>
<td>14. Natural greenhouse effect</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>12</td>
<td>12a. E.m.r. transmits energy</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>13</td>
<td>23a. Climate and ecology</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>14</td>
<td>24. Effects</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>15. Equilibrium</td>
<td>2</td>
<td></td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>23b. Climate and evolution</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>17</td>
<td>13. Non-equilibrium</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>19. Conservation of energy</td>
<td>1</td>
<td>3</td>
<td>10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>7. Asymmetry: absorption/emission of IR by GH gases</td>
<td>1</td>
<td>2</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>12b. Heat is a form of energy</td>
<td>2</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>11. The e.m.s.</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>16. Black body radiation</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>22. Earth’s axis/seasons</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>17. Rate</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>none</td>
<td>12c. Temperature: hot or cold</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>none</td>
<td>6. Radiative transport</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>none</td>
<td>10a. The wave model</td>
<td>5</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>none</td>
<td>10b. Wavelength</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3.7 Discussion and conclusions for Delphi study

A significant advantage of the Delphi method for this study was that it allowed participants to respond in their own time and without having to travel. This enabled the participation of 18 people – academics from at least four universities, other researchers and high school teachers from at least two schools – who would most likely not have been able to attend meetings. An important outcome of the Delphi study was the refinement of concept statements made possible by participants’ detailed comments. Defining the scope and boundaries of concepts determines what does, and does not need to be known about each concept: this information is vital when developing concept inventory questions.

The low Delphi ratings given to some physics concepts were unexpected. For example, according to the Delphi participants, less needs to be known about concepts related to waves, than was first thought. Literature on students’ ideas about climate change consistently shows conflation with ozone depletion. Typically, students describe how damage to the ozone layer allows more heat to enter the Earth’s atmosphere, and discussion of heat radiated by the Earth is absent. This suggests problems with students’ understanding of absorption and emission of electromagnetic radiation. However, as one participant suggests, these might have been seen not as unimportant but as only a part of the bigger picture:

“I have selected the points that would allow one to understand the basics of climate change. I have not ranked the energy-related points – while I think these are very important and really get to the basic physics underlying climate change, they are very technical and require a bit more of a leap on the student's behalf to get the relevance”.

According to Rye et al. (1997) “efforts on the part of teachers to present 'all the details' may be counterproductive in helping students to initially construct a clear understanding” (p.548). One of the stated aims of the Delphi study was to determine the simplest scientifically acceptable model of climate change and the concepts underlying this, but with each round of the Delphi study more concepts and detail were added, so arguably the
study was not successful in this particular regard. However, as the
participant’s comment above suggests, the basic science might have to be
connected to the wider context in order to be meaningful.

4.4 Concepts in literature on students’ understanding of
climate change: review and ranking

This section describes the process used to generate a preliminary list of
conceptual statements, based on a review of literature.

I qualitatively analysed reports of 16 studies (Andersson & Wallin 2000;
Boon 2009; Boyes & Stanisstreet 1993; Boylan 2008; Browne & Laws
Koulaidis & Christidou 1999; Rebich & Gautier 2005; Rye et al. 1997;
Schultz 2009; Shepardson et al. 2009; Österlind 2005) to create a
descriptive list of the concepts mentioned, and ranked these concepts
according to how many of the 16 studies they appeared in. These studies
were chosen because they focused on conceptual understanding of the
science, and as far as possible, involved participants of similar age to mine.

The studies were reviewed for instances in which scientific concepts were
mentioned. These sections were copied verbatim, and then broken down
into short phrases, each relating as much as possible to a single concept.
Unlike the extended and detailed conceptual statements resulting from the
Delphi study, these were generally in the form of one or two words. As an
example of the method, some sections from Browne and Laws (2003) are
shown below. The specific phrases describing concepts are underlined.

“… dynamic equilibrium—a concept we feel is essential for a more
comprehensive understanding of global warming” (p.115).

“The Energy, Fuels, and Environment unit was designed to help students
understand how the combustion of fossil fuels, which adds carbon dioxide to
the environment, can contribute to global warming by means of the
greenhouse effect ... Here students make several observations to understand
the key role of water vapour and carbon dioxide as absorbers of infrared
radiation ... In the third section, students do several simplified calculations. They estimate the rate of carbon dioxide released to the atmosphere due to respiration by the world’s human population” (p.116).

... investigate what happens to electromagnetic radiation incident upon the surface of the Earth ... The purpose of this activity was to show that visible light coming from the desk lamp (sun) could be absorbed by the Earth (gravel or water) and emitted later as infrared radiation. Another goal of this activity was to establish the idea that surfaces with a higher temperature emit more infrared radiation (pp.118-119).

In the next activity students investigated the selective absorption of infrared radiation by water. The purpose of this activity was to observe that some substances can efficiently absorb infrared radiation even though they are virtually transparent to visible radiation (p.119).

The phrases from all 16 studies were copied into a spreadsheet, and phrases covering related conceptual areas were grouped together. I used the broad conceptual areas of the Delphi study to guide generation of categories for analysis, however these were not applied rigidly, with themes created inductively to fit the data rather than vice versa. From all the phrases in each grouping I developed a summary conceptual statement in a similar way as in the Delphi study. In some cases the statements were very short phrases because this was all that the studies had mentioned, for example, “dynamic equilibrium” and “rate” above.

I then counted the number of studies whose content had been assigned to each statement to give a ranked list of conceptual statements corresponding to the ranked list resulting from the Delphi study. The number of studies mentioning a concept was assumed to reflect its importance.
Table 4.6: Conceptual statements derived from the review of literature

<table>
<thead>
<tr>
<th>Summary conceptual statement from literature review</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Greenhouse gases (GHGs)</td>
<td>11</td>
</tr>
<tr>
<td>2. Interactions between greenhouse gases and electromagnetic radiation: greenhouse gases allow Sun's visible light in but absorb IR emitted by Earth. This is re-emitted in all directions - down as well as up</td>
<td>10</td>
</tr>
<tr>
<td>3. Fossil fuels: burning fossil fuels adds CO₂ to the atmosphere</td>
<td>9</td>
</tr>
<tr>
<td>4. Natural greenhouse effect: is responsible for keeping the Earth at a habitable temp</td>
<td>8</td>
</tr>
<tr>
<td>5. Absorption/emission of e.m.r. (Earth absorbs radiation from the Sun and re-emits IR)</td>
<td>8</td>
</tr>
<tr>
<td>6. E.m.s.: there is IR and UV beyond the visible spectrum. Differences and similarities between visible and IR</td>
<td>7</td>
</tr>
<tr>
<td>7. Radiation from the Sun: most the Sun's energy is emitted in the visible part of the spectrum (not UV). This has a short (relatively) wavelength</td>
<td>7</td>
</tr>
<tr>
<td>8. Radiation from Earth: the Earth emits IR radiation</td>
<td>7</td>
</tr>
<tr>
<td>9. Feedback: complicated feedback mechanisms in the atmosphere</td>
<td>7</td>
</tr>
<tr>
<td>10. Wavelength: different wavelengths of e.m.r. are affected by GH gases in different ways</td>
<td>7</td>
</tr>
<tr>
<td>11. Equilibrium (of energy): balance of energy into and out of the Earth/atmosphere system</td>
<td>6</td>
</tr>
<tr>
<td>12. Enhanced greenhouse effects</td>
<td>5</td>
</tr>
<tr>
<td>13. Deforestation</td>
<td>5</td>
</tr>
<tr>
<td>14. Sinks of greenhouse gases</td>
<td>4</td>
</tr>
<tr>
<td>15. Temperature</td>
<td>4</td>
</tr>
<tr>
<td>16. Black body radiation: wavelengths emitted linked to temperature</td>
<td>3</td>
</tr>
<tr>
<td>17. Greenhouse gases – location in the atmosphere</td>
<td>3</td>
</tr>
<tr>
<td>18. Effects of climate change</td>
<td>3</td>
</tr>
<tr>
<td>19. Radiative forcing</td>
<td>2</td>
</tr>
<tr>
<td>20. Rate</td>
<td>2</td>
</tr>
<tr>
<td>21. The difference between weather and climate</td>
<td>2</td>
</tr>
<tr>
<td>22. Conservation of energy</td>
<td>2</td>
</tr>
<tr>
<td>23. Climate variability</td>
<td>2</td>
</tr>
<tr>
<td>24. Albedo</td>
<td>1</td>
</tr>
<tr>
<td>25. Heat</td>
<td>1</td>
</tr>
</tbody>
</table>
This assumption does not take account of the relative importance that an author may have assigned to the different concepts they mentioned in their papers; however, there was no reliable way of determining which concepts the authors had considered most important. This resulted in a list of 25 concepts, with the highest-ranked appearing in 11 of the 16 studies. Table 4.6 shows the ranked list of conceptual statements from the literature review. This table was presented in Chapter 2 but is repeated here to clarify the synthesis process.

4.5 Creation of the final list of conceptual statements

In order to produce a final set of conceptual statements, the conceptual statements resulting from the literature review (Table 4.6) were combined with those from the Delphi study (Table 4.5).

4.5.1 Synthesis of the ranked lists resulting from the Delphi study and literature review:

Rather than simply selecting high-ranked conceptual statements from either list, the synthesis process involved further merging and refinement of conceptual statements, i.e., further qualitative analysis. In some cases, a statement from one list corresponded to more than one statement from the other list. In addition, some statements from one list did not have a corresponding statement in the other list.

I colour-coded the statements in both lists to aid to identification of corresponding statements: this allowed closely-related concepts to be grouped together to make a single synthesised conceptual statement. For example, the following three statements from the literature review:

“e.m.s.: there is IR and UV beyond the visible spectrum ... differences and similarities between visible and IR”.

“Radiation from the Sun: most the Sun's energy is emitted in the visible part of the spectrum (not UV). This has a short (relatively) wavelength”.

101
and

“Absorption/emission of e.m.r. (Earth absorbs radiation from the Sun and re-emits IR)”.

Were combined with:

“Forms of energy: electromagnetic radiation transmits energy”

from the Delphi study to generate the synthesised conceptual statement:

“Electromagnetic spectrum: there is IR and UV beyond the visible spectrum … differences and similarities between visible and IR. Sun emits mostly visible, Earth emits mostly IR”.

Concepts near the top of both lists were retained. Those ranked low in both lists, or low in one list and missing from another, were discarded. These were:

“Temperature”; “Black body radiation”; “Heat”; “Radiative forcing (non-equilibrium)”; “The wave model”; “Wavelength”; “Cycles”; “Earth as a system”; “Effects” and “Climate and ecology/evolution”.

Some low-rated concepts on one list were retained because they were related to a high-rated concept on the same list and also high-rated on the other list. For example, the following two low-rated concepts from the literature review:

“deforestation” and
“sinks”

were combined with the higher-rated concept:

“fossil fuels: burning fossil fuels adds CO2 to the atmosphere”

and synthesised with the Delphi conceptual statement 4:

“sources and sinks of greenhouse gases”
to produce:

“Carbon cycle and fossil fuels: There is a fixed amount of carbon on Earth: it is cycled among the atmosphere, biosphere, soils, ocean and rocks. There are both natural and human-induced sources and sinks of greenhouse gases. Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle. Burning fossil fuels returns this carbon to the cycle”.

“Albedo” was combined with “feedback” because it is relevant to the science of climate change in the context of an important climate feedback scenario.

The concepts “electromagnetic spectrum” and “interactions between electromagnetic radiation and atmospheric gases” were troublesome: they were ranked high in the literature review but relatively low in the Delphi study. “Electromagnetic spectrum” was retained, however, because of its high ranking in the literature review and because the concept of interactions between the electromagnetic spectrum and atmospheric gases, which was top-ranked in literature and relatively high-ranked in Delphi, depends on understanding it.

4.5.2 Final synthesised list of conceptual statements

The final list of conceptual statements, synthesised from the findings of the Delphi study and literature review, answers Research Question one and forms the basis of methods to address Research Question two. Table 4.7 shows the final synthesised list of ten conceptual areas.
Table 4.7: Final list of statements of conceptual areas, synthesised from the Delphi study and literature review

1. Carbon cycle and fossil fuels: There is a fixed amount of carbon on Earth: it is cycled among the atmosphere, biosphere, soils, ocean and rocks. There are both natural and human-induced sources and sinks of greenhouse gases. Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle. Burning fossil fuels returns this carbon to the cycle.

2. Electromagnetic spectrum: There is infrared (IR) and ultra violet (UV) radiation beyond the visible spectrum: these are all related forms of electromagnetic energy. The Sun emits mostly visible radiation and the Earth emits mostly IR.

3. Interactions between greenhouse (GH) gases and electromagnetic radiation: Most of the gases that make up the atmosphere are transparent to visible light. Non-GH gases are transparent to IR but GH gases absorb IR: this is the cause of the greenhouse effect. GH gases allow the Sun's visible light in but absorb IR emitted by Earth. This is re-emitted in all directions – down as well as up.

4. Natural climate variability in the past and relationship to CO$_2$ levels: The climate has been different in the past (e.g., carboniferous period, ice ages) due to changes in energy emitted by the Sun, the distance between the Earth and Sun or CO$_2$ released from volcanoes during periods of high levels of volcanism. Prehistoric climate changes correlate with changes in CO$_2$ levels, providing evidence for the link between CO$_2$ levels and global temperatures.

5. Difference between weather and climate: Weather is short-term, day-to-day climatic conditions while climate is the longer-term average conditions.

6. Proportions of greenhouse and non-greenhouse gases in the atmosphere: Over 96% of the atmosphere consists of non-greenhouse gases. The atmosphere also contains small amounts of CO$_2$, CH$_4$, O$_3$, N$_2$O and H$_2$O and CFCs – all of which are greenhouse gases. Water vapour is a variable component of the atmosphere and is the most abundant greenhouse gas. GH gases are not in a distinct atmospheric layer.

7. Radiative forcing capacity: Some greenhouse gases have more radiative forcing capacity than others, i.e., a given amount of a "stronger" greenhouse gas would result in more radiative forcing than the same amount of "weaker" greenhouse gas.

8. Feedback: Changing one parameter can have an effect on another parameter, which causes a change in the original parameter. Feedbacks can be negative (i.e., tends to return the parameter to its original value) or positive (i.e., tends to drive the parameter further away from its original value) e.g., increasing CO$_2$ raises surface temperatures causing more water to vaporise, which further raises temperatures.
9. Equilibrium of energy: There is a balance of energy into and out of the Earth/atmosphere system. A net flow of energy into or out of the Earth/atmosphere system leads to temperature change over time.

10. Conservation of energy: Energy can change from one form to another but the total amount of all forms of energy remains constant.

Wording of the synthesised statements was broadly based on the Delphi study concept statements, because these had been subject to two rounds of refinement and were therefore considered more valid.

4.6 Corroboration for final list of conceptual statements

As a further measure of the validity of the final list of conceptual statements, they were compared to two existing lists of essential conceptual knowledge:

- the Climate Literacy Network’s (2009), essential principles of climate science, and
- three key principles of the greenhouse effect proposed by Gautier et al. (2006).

These lists have very contrasting foci: the first sets out essential knowledge for the broad field of climate science and is intended to apply to learners from kindergarten onwards, so is likely to cover concepts in less detail than my study. Conversely, Gautier et al.’s (2006) principles are intended as minimum required knowledge of the mechanism of the greenhouse effect, for undergraduate earth science students, so will cover fewer concepts than my study but in more detail. Therefore I expected that the Climate Literacy Network’s (2009) list would provide a lower limit of the level of detail required, while including a larger range of concepts, while Gautier et al.’s (2006) work would provide an upper limit in terms of detail, but would be a subset of my list of concepts.
4.6.1 Comparison with the list of the Climate Literacy Network (2009)

Climate change is only one part of the knowledge covered by the Climate Literacy Network’s (2009) work. Therefore the depth of understanding of climate change required by the Climate Literacy Network may be less than for NSW Stage 5 students, because the breadth is greater.

Therefore it was expected that the synthesised conceptual statements would be a subset of the Climate Literacy Network’s statements. Table 4.8 shows the results of the mapping.

Table 4.8: Mapping of synthesised conceptual statements to the Climate Literacy Network’s statements of fundamental concepts

<table>
<thead>
<tr>
<th>Final conceptual statements (number and title)</th>
<th>Corresponding text from the Climate Literacy Network’s (2009) statements of essential knowledge</th>
</tr>
</thead>
</table>
| 1. Carbon cycle and fossil fuels              | “The abundance of greenhouse gases in the atmosphere is controlled by biogeochemical cycles that continually move these components between their ocean, land, life, and atmosphere reservoirs. The abundance of carbon in the atmosphere is reduced through seafloor accumulation of marine sediments and accumulation of plant biomass and is increased through deforestation and the burning of fossil fuels as well as through other processes.”  
  “Emissions from the widespread burning of fossil fuels since the start of the Industrial Revolution have increased the concentration of greenhouse gases in the atmosphere.”  
  “Burning fossil fuels, releasing chemicals into the atmosphere, reducing the amount of forest cover, and rapid expansion of farming, development, and industrial activities are releasing carbon dioxide into the atmosphere”. |
| 2. Electromagnetic spectrum.                  | NONE                                                                                     |
| 3. Interactions between greenhouse (GH) gases and electromagnetic radiation. | “The amount of solar energy absorbed or radiated by Earth is modulated by the atmosphere and depends on its composition”.  
  “heat-trapping gases in the atmosphere, primarily water vapour, keep the Earth’s surface warm.”  
  “Greenhouse gases … absorb and release heat energy more efficiently than … nitrogen and oxygen.” |
| 4. Natural climate variability in the past and relationship to CO₂ levels. | “Gradual changes in Earth’s rotation and orbit around the Sun change the intensity of sunlight received in our planet’s polar and equatorial regions. For at least the last one million years, these changes occurred in 100,000-year cycles that produced ice ages and the shorter warm periods between them.” |
5. Difference between weather and climate.

“Climate is not the same thing as weather. Weather is the minute-by-minute variable condition of the atmosphere on a local scale. Climate is a conceptual description of an area's average weather conditions and the extent to which those conditions vary over long time intervals.”


“Greenhouse gases—such as water vapor, carbon dioxide, and methane—occur naturally in small amounts and absorb and release heat energy more efficiently than abundant atmospheric gases like nitrogen and oxygen. Small increases in carbon dioxide concentration have a large effect on the climate system.”

7. Radiative forcing capacity.

NONE


“A significant change in any one component of the climate system can influence the equilibrium of the entire Earth system. Positive feedback loops can amplify these effects and trigger abrupt changes in the climate system.”


“Sunlight reaching the Earth can heat the land, ocean, and atmosphere. Some of that sunlight is reflected back to space by the surface, clouds, or ice. Much of the sunlight that reaches Earth is absorbed and warms the planet.”

“When Earth emits the same amount of energy as it absorbs, its energy budget is in balance, and its average temperature remains stable.”

10. Conservation of energy

NONE

4.6.2 Comparison with the list of Gautier et al. (2006)

Gautier et al. (2006) studied misconceptions about the greenhouse effect among undergraduates (Rebich & Gautier 2005; Gautier et al. 2006). As a result of this work they proposed key principles of minimum knowledge about the greenhouse effect for earth science undergraduates, all three of which correspond to one of the key underlying concepts of my study. Because their work focused on the mechanism of the greenhouse effect rather than on climate change as a whole, Gautier et al.’s (2006) list was expected to be a subset of mine, and this was the case.

Gautier et al.’s (2006) key principles are shown below, along with the corresponding statement from my list of key underlying concepts:

1. “understand which constituents in the atmosphere are greenhouse gases” (p.394). This corresponds to statement 6.
2. “be able to compare their various impacts on a molecule-by-molecule basis, without necessarily understanding the intricacies of each interaction” (p.394). This corresponds to statement 7.

3. “know how gases absorb and re-emit the radiation impinging upon them in such a way that, in the atmosphere, the radiation escaping from the top of the atmosphere in the presence of greenhouse gases is smaller than that which would escape without the gases” (p.394). This corresponds to statement 3.

With regard to the third principle, the authors emphasised the importance of students understanding interactions in terms of absorption and re-emission rather than reflection. The authors pointed out that time limitations mean that it is usually impossible to teach this topic in detail, but that they are unaware of research on which teaching path is most appropriate.

4.6.3 Discussion of comparisons with the Climate Literacy Network (2009) and Gautier et al. (2006)

All of Gautier et al.’s (2006) key conceptual knowledge is included in my list of key underlying concepts. There is broad overlap between the Climate Literacy Network’s list of fundamental concepts and most of the final list of conceptual statements. In particular, statements 1, 4, 5 and 9 have closely corresponding statements in the Climate Literacy Network’s list. However, the Climate Literacy Network’s (2009) list does not include any knowledge corresponding to three of my study’s key underlying concepts. These are discussed below:

2. “Electromagnetic spectrum”

7. “Radiative forcing capacity”

10. “Conservation of energy”

While the electromagnetic spectrum was cited in seven of the 16 studies in the literature review, it was ranked relatively low by Delphi participants (20 of 29), and was not explicitly mentioned by Gautier et al. (2006). This
suggests that it is feasible to understand the mechanism of climate change without a detailed understanding of the properties of the electromagnetic spectrum. However, statement two, “electromagnetic radiation transmits energy”, was ranked 12th by Delphi participants. This suggests that, in order to understand the topic of climate change, detailed understanding of e.m.r. is not required, but an appreciation of e.m.r. as a form of energy is necessary.

Radiative forcing capacity was mentioned by only two of the 16 studies in the literature review, however it was ranked seventh out of 29 by Delphi participants. It was also seen as important by Gautier et al. (2006). Therefore it is suggested that, in order to understand climate change it is important to understand that some greenhouse gases have a greater impact than others. I therefore conclude that its absence from the Climate Literacy Network’s (2009) list suggests that this concept is relatively advanced knowledge.

Conservation of energy was mentioned in only two studies in the literature review and was not mentioned by Gautier et al. (2006), however it was given a relatively high ranking, 10 out of 29, by Delphi participants. I conclude that the absence of this concept from the research literature is because, as a very basic scientific concept not specific to climate science, it was considered assumed knowledge.

The Climate Literacy Network’s list also includes very limited detail on statement three: “Interactions between greenhouse (GH) gases and electromagnetic radiation”. It should be noted that this concept depends to some extent on an understanding of the concept in statement two: “electromagnetic spectrum”. This concept was mentioned by 10 of 16 studies in the literature review, and ranked eighth of 29 by Delphi participants. Further, Gautier et al. (2006) included it as one of their three key principles of minimum knowledge. Therefore, there is strong evidence that this concept is important.
4.7 Discussion and conclusions

Although there were several significant differences between the ranked lists resulting from the Delphi study and the literature review, it was possible to reconcile these and synthesise a final list of conceptual statements. This list of statements addressed Research Question one and formed the basis of methods to address Research Question two.

Both the literature review and the Delphi method have weaknesses. A weakness of the literature review is the impossibility of asking authors for clarification of what they have written, or checking that a statement has been understood correctly. As the literature on the Delphi method discusses, there is a fine balance to be struck between avoiding undue influence on the process and ensuring that participants have enough information to understand the issue. By combining the two methods it is hoped that the resulting list of conceptual statements has a sounder basis.

Mapping the final conceptual statements to the Climate Literacy Network’s (2009) fundamental concepts and Gautier et al.’s (2006) key principles, provided a way of validating the results of this research. Comparison with these two lists gave broad support for my list of key underlying concepts. It further suggested that:

- only basic knowledge of concept two: “emagnetic spectrum” is required in order to understand climate change;
- Concept 7: “radiative forcing capacity” is an advanced concept; and
- Concept 10 “conservation of energy” is a very basic concept and may be treated as assumed knowledge in learning situations, i.e., taken for granted when teaching about climate change.
CHAPTER 5 - DEVELOPMENT AND VALIDATION OF THE CLIMATE CHANGE CONCEPT INVENTORY (CCCI)

I developed and validated the Climate Change Concept Inventory (CCCI) as a large-scale data-collection instrument for my study. This chapter explains the reasons for using a concept inventory in this study; reviews the literature on the development and validation of concept inventories in science, engineering, mathematics and computing; and describes the method used to develop and validate the CCCI. The structure of Chapter 5 is summarised below.

- Section 5.1 explains the reasons for using a concept inventory as the large-scale data collection instrument for this study
- Section 5.2 consists of a review of the literature on concept inventories, focusing on methods used for their development and validation
- Section 5.3 describes the process used for the development and validation of the concept inventory used in this study, i.e., the Climate Change Concept Inventory (CCCI)
- Section 5.4 summarises the chapter and explains how it relates to the following chapters.

5.1 Rationale for developing and using a concept inventory in this study

Concept inventories have a number of advantages as data collection instruments. They can be used to collect data from a large number of participants; they are suitable for exploring participants’ ideas about a number of concepts; and they require little in the way of special instructions or participant preparation. Because the item distractors are based on known
misconceptions they can be used to assess the prevalence of misconceptions.

Instruments such as that developed by Boyes and Stanisstreet (1993), where students were asked to agree or disagree with a list of statements, can also be used with large numbers of participants. However, as the survey’s authors acknowledged, such instruments provide little insight into conceptual understanding because they do not distinguish between different reasons for agreeing or disagreeing with a statement. For example, students might agree with the statement “throwing away empty drink cans causes climate change” because they do not distinguish between different forms of pollution, or because they are aware that aluminum smelting uses significant amounts of electricity while aluminum recycling uses much less. Concept inventories take a “finer-grained” approach, by offering students a number of alternative responses from which to choose. While it should be acknowledged that students may choose a response for a number of different reasons, a well-designed and validated concept inventory should provide more information than a “true/false” instrument, while retaining the advantage of simple, objective analysis methods (Bardar et al. 2005).

Open-ended tasks such as concept mapping and open-ended writing tasks have also been used as large-scale data-collection methods (Andersson & Wallin 2000; Schultz 2009; Shepardson et al. 2009). I decided that a CI would have an advantage over an open-ended task because in a CI, students are prompted to choose one of a number of supplied options, rather than having to supply most or all of the information themselves. This is important because my pilot study showed that participants often volunteered very little information without prompting, but when prompted were able to express their ideas in more detail. Further, open-ended tasks require complex, subjective analysis methods. These limit the generalisations that can be made, because of the relatively small number of participants whose work can be analysed.
This study combines a closed response method such as a CI with an open-ended method, i.e., focus groups, thus benefitting from the advantages of both methods while mitigating against their limitations.

When my research took place, one concept inventory already existed that covered concepts related to climate change, i.e., the Greenhouse Effect Concept Inventory, GECI (Keller 2006). Further, five items from the GECI had been used by Schultz (2009) to investigate Years 7 and 8 school students’ ideas about climate change. However, I did not consider that adapting this existing instrument would be acceptable research methodology, for the following reasons:

• it was designed to cover a specific conceptual area, i.e., the natural greenhouse effect. Adapting it to cover all the essential concepts underlying climate change would have meant including only a small number of the GECI items while writing a much larger number;

• the GECI was developed for use with undergraduates, and has not been validated with students of similar age to those in my study; and

• the GECI was not developed using the rigorous methods recommended, e.g., by Bardar et al. (2006); Libarkin (2008); Richardson (2004); and Streveler et al. (2011), so its validity cannot be assured.

5.2 Review of literature on concept inventories

5.2.1 Concept inventories in science, mathematics and engineering
A concept inventory is a relatively short multiple-choice instrument that is designed to diagnose students’ conceptual difficulties with a topic prior to instruction or to evaluate changes in conceptual understanding following instruction (Libarkin, 2008). It is standardised and meets the demands of statistical analysis; it tests each concept several times to increase validity and reliability; it tests concepts critical to the topic; and it is applicable to many teaching programs (Herman et al. 2010). Typically, it tests about ten concepts, comprises about 20-35 questions, and is designed to be completed
in about 30 minutes (Libarkin 2008; Richardson 2004; Rowe & Smaill 2008). CIs focus on conceptual understanding rather than computational ability, so questions are usually qualitative (Hestenes et al. 1992).

CIs are often used as pre- and post-test instruments to measure learning gains following research-based learning activities (Libarkin 2008). In this study, it was administered once, and served as one source of information about students’ knowledge state, rather than attempting to measure the impact of a learning activity.

CIs originated in physics education with the Force Concept Inventory (FCI) (Hestenes et al. 1992). The impact of the FCI in physics education has been well-documented (Libarkin 2008; Richardson 2004; Rowe & Smaill 2008; Streveler et al. 2011) and in recent years CIs have been developed for other areas in physics, other sciences, engineering, mathematics, and computing (Anderson, Fisher, & Norman, 2002; Bardar, Prather, & Brecher, 2006; Ding, Chabay, Sherwood, & Beichner, 2006; Gray et al., 2005; Herman, 2011; Libarkin & Anderson, 2006; Lindell & Olsen, 2002; Martin, Mitchell, & Newell, 2004; Pavelich, Jenkins, Birk, Bauer, & Krause, 2004; Rhoads & Roedel, 1999; Richardson, Steif, Morgan, & Dantzler, 2003; Smith, Wood, & Knight, 2008; Stone, 2006; Yeo & Zadnik, 2001).

In the U.S.A., the Foundation Coalition developed thirteen CIs for topics in engineering (Foundation Coalition 2001).

Numerous efforts have been made to catalogue CIs and promote their use (Allen 2007; Evans et al. 2003; Foundation Coalition 2001; Libarkin 2008) but compiling such a catalogue is hampered by the rate of development of new CIs; irregular updating of websites; and the fact that not all CI development projects initiated may be completed.

Rather than attempting to collate an exhaustive list, Table 5.1 lists an illustrative sample of CIs developed, or under development for topics in science, mathematics, engineering and computing, i.e., STEM (Foundation Coalition 2001). Also included are instruments which their authors did not
explicitly describe as CIs, but which meet the criteria of a CI described above.

Table 5.1: Examples of CIs in science, mathematics and related disciplines

<table>
<thead>
<tr>
<th>Name and topic</th>
<th>Publications</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry (CCI)</td>
<td>Pavelich et al. (2004); Krause et al. (2004)</td>
<td>Foundation Coalition, based on work of Krause et al. (2003). Two tests, corresponding to two semesters of instruction, 20 items and 3 conceptual areas in each test. Distractors from misconceptions in literature.</td>
</tr>
<tr>
<td>Digital logic (DLCI)</td>
<td>Herman et al. (2010)</td>
<td>4 concepts; 19 items. Delphi used in concept selection. Distractors from problem-solving interviews with students. Alpha-testing had optional open-ended answers in addition to MC.</td>
</tr>
<tr>
<td>Dynamics (DCI)</td>
<td>Gray (2005)</td>
<td>11 concepts: Delphi used in concept selection. Student focus groups using item stems as open-ended questions.</td>
</tr>
<tr>
<td>Electricity and magnetism (BEMA)</td>
<td>Ding et al (2006);</td>
<td>30 items. Undergraduates. Draft CI reviewed by faculty for face and content validity.</td>
</tr>
<tr>
<td>Energy resources</td>
<td>Bodzin (2011)</td>
<td>Year 8 students. 39 items, 12 of which were modified from existing instruments. 4 distractors per item, identified from literature on misconceptions. Construct validity through expert review.</td>
</tr>
<tr>
<td>Forces (FCI)</td>
<td>Hestenes et al. (1992); Hestenes and Halloun (1995); Halloun and Hestenes (1985)</td>
<td>Six conceptual dimensions. Shares 60% of its content with an existing validated test for mechanics (MDT). High school and tertiary students. Validated through 20 post-trial interviews.</td>
</tr>
<tr>
<td>Genetics</td>
<td>Smith et al. (2008)</td>
<td>25 items with 4 or 5 options each. Undergraduates. Concepts based on misconceptions in literature and interviews with academics. Validated through 33 post-trial student interviews.</td>
</tr>
<tr>
<td>Geosciences</td>
<td>Libarkin</td>
<td>69 items covering a broad range of topics,</td>
</tr>
<tr>
<td>Subject</td>
<td>Authors/Reference</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Greenhouse effect</td>
<td>Keller (2006)</td>
<td>Concept list based on students’ responses to open-ended questions; experts consulted at final validation stage. 20 questions. Tertiary students.</td>
</tr>
<tr>
<td>Heat and energy</td>
<td>Nottis et al. (2009)</td>
<td>4 concepts, 36 items, 3-5 options. Upper-level undergraduates. Content validity through expert review.</td>
</tr>
<tr>
<td>Heat transfer</td>
<td>Jacobi et al. (2003); (Jacobi et al. 2004)</td>
<td>Student focus groups used in development. 3rd and 4th year undergraduates.</td>
</tr>
<tr>
<td>Light and Spectroscopy</td>
<td>Bardar et al. (2006)</td>
<td>Concepts “chosen to reflect the most commonly taught concepts addressed by the majority of courses” (p.2). 4 main concepts.</td>
</tr>
<tr>
<td>Natural selection</td>
<td>Anderson et al. (2002)</td>
<td>Authors intend to carry out trials with high school students, biology non-majors and biology-majors using Item Response Theory to evaluate performance (no more recent publications identified).</td>
</tr>
<tr>
<td>Materials (MCI)</td>
<td>Krause et al. (2003)</td>
<td>30 items, undergraduates. Distractors from student interviews and open-ended “intuition quizzes”.</td>
</tr>
<tr>
<td>Programming</td>
<td>Kaczmarczy et al. (2010)</td>
<td>Multi-institution project to develop three CIs for introductory computing (see Herman et al. 2010). Delphi process used by Goldman et al. (2008) in concept selection.</td>
</tr>
<tr>
<td>Statics</td>
<td>Danielson (2005)</td>
<td>Delphi method used in concept selection</td>
</tr>
<tr>
<td>Statics Tertiary students</td>
<td>Steif and Dantzler (2005)</td>
<td>8 concepts, 27 questions. Common misconceptions identified through observation of students and information sharing with other academics.</td>
</tr>
<tr>
<td>Statistics (SCI)</td>
<td>Allen (2006); Stone et al. (2004); Stone (2006)</td>
<td>32 items with 4 or 5 options, 32 topics “Modified Delphi” used in concept selection.</td>
</tr>
</tbody>
</table>
5.2.2 Concept inventory development and validation

In order to be a useful means of probing students’ understanding of a topic, a CI must demonstrate reliability and validity. As the popularity of CIs has grown, a number of researchers have focused on rigorous processes for development and validation of CIs. This section summarises this literature and describes how the findings were applied to the development and validation of the CCCI.

According to Libarkin (2008), great care must be taken at all stages of CI development to ensure the resulting instrument is effective. The author advised on concept selection, item development, and the validation process. Richardson et al. (2003) described a CI development and validation process following the development of an unsuccessful CI that had been generated using a less rigorous process. Bardar et al.’s (2006) process for development and validation of their astronomy CI was based on test development guidelines from classical test theory (Crocker and Algina 1986; cited in Bardar et al. 2006): these included guidance both in stages of test development and statistical evaluation. Libarkin and Anderson (2007) based their CI development method on a review of CI development literature, citing Hestenes et al. (1992).

According to Richardson the thermal and transport concept inventory (Miller et al. 2009; Streveler et al. 2003; Streveler et al. 2011) is “one of the
best planned and most thoroughly documented engineering concept inventories to date” (p.21). Streveler et al. (2011) described their methodology in detail.

5.2.3 Validity

The most significant difference between a concept inventory and any other multiple-choice test is the focus on validity and reliability, so that students’ responses to the CI can confidently be assumed to reflect their knowledge of the topic (Herman et al. 2010).

CI authors and test developers have defined a number of forms of validity; these are discussed below. However Allen (2006) pointed out that these are not mutually exclusive.

Some forms of validity are usually established through statistical tests: these necessarily take place after the draft CI has been developed and trialled. However most authors agree that a number of forms of validity including content validity of CIs derive from a rigorous development process (Libarkin 2008; Streveler et al. 2011). Therefore validity must be considered from the start of the CI development process.

For example, Gray et al. (2005) asserted that using the Delphi process for concept selection and focus groups for item development should, if carried out correctly, contribute to validity. Richardson et al. (2003) stated that multiple questions testing the same concept increase the validity of the CI for each concept; this must take place when the CI is being constructed. Anderson et al. (2002) established validity by having experts comment on the wording of items and check that the correct responses were actually correct. Ding et al. (2006) asserted that validity cannot be established through statistical tests but must be evaluated through expert opinion.

Steif and Danzler (2005) stated that validity is more difficult to establish than reliability and that assessing a larger number of levels of validation provides more evidence of validity. Libarkin (2008) made the same point and recommended a wide variety of approaches to determining validity. She emphasised that these must be considered early in the design phase of the
CI. According to Libarkin (2008), construct, content and communication validity are “absolutely necessary” (p.5) for a CI to be effective, however her definition of construct validity differs from that of other authors.

Because CIs are intended as measurement instruments, they should be constructed in accordance with scale development theory (Libarkin & Anderson 2006; DeVellis 2003). This theory is concerned with development, use and evaluation of instruments that quantify a trait such as conceptual understanding of a topic. According to DeVellis (2003), three types of validity are relevant to scales: content, construct and criterion-related. The author stated that content validity relates to the scale development process; criterion-related validity to the scale’s predictive ability; and construct validity to its relationship to measurements of other constructs.

Forms of validity described by CI authors are summarised in Table 5.2.

Table 5.2: Forms of validity described in CI development and validation literature.

<table>
<thead>
<tr>
<th>Form</th>
<th>Definition</th>
<th>How achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (Qualitative)</td>
<td>Coverage of content domain (DeVellis 2003; Ding et al. 2006; Gray et al. 2005; Steif &amp; Dantzler 2005; Yeo &amp; Zadnik 2001)</td>
<td>Use of known misconceptions in distractors (Steif and Dantzler 2005)</td>
</tr>
<tr>
<td></td>
<td>Test measures what it is meant to measure (Libarkin 2008)</td>
<td>Expert review of items (Bardar et al. 2006; Ding et al. 2006)</td>
</tr>
<tr>
<td></td>
<td>Coverage of content domain and scientific accuracy (Bardar et al. 2006)</td>
<td>Use of Delphi method and multiple focus groups (Gray et al. 2005)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use of established design processes including item-writing guidelines (Libarkin 2008)</td>
</tr>
<tr>
<td>Criterion-related (Quantitative)</td>
<td>Practical ability to predict outcome in a related measurement (DeVellis 2003 p.50)</td>
<td>Correlation coefficient (Ghiselli et al. 1981; cited in DeVellis p.51)</td>
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<tr>
<td>----------------------------------</td>
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<td>---------------------------------------------------------------------</td>
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<tr>
<td></td>
<td>Agreement between CI score and another measure of performance e.g., students’ grades for unit of study (Steif &amp; Dantzler 2005; Libarkin &amp; Anderson 2006)</td>
<td>Correlation between CI score and course grade (Richardson et al. 2003; Steif and Dantzler 2005)</td>
</tr>
<tr>
<td></td>
<td>Not relevant to CIs (Ding et al. 2006)</td>
<td>Correlation between sub-tests (Libarkin and Anderson 2007) Not measured (Ding et al. 2006)</td>
</tr>
<tr>
<td>Construct (Qualitative and quantitative)</td>
<td>Concepts covered are considered important (Libarkin 2008; Libarkin &amp; Anderson 2007)</td>
<td>Use of established instrument design processes including item-writing guidelines (Libarkin 2008)</td>
</tr>
<tr>
<td></td>
<td>Test measures a theoretical construct such as a personality trait – not relevant to CI development (Ding et al. 2006)</td>
<td>Confirmatory factor analysis – factors/subscales correspond to conceptual areas (Steif and Dantzler 2005)</td>
</tr>
<tr>
<td></td>
<td>Items measure the underlying theoretical construct (Steif and Dantzler 2005). Theoretical relationship between score and other variables (DeVellis 2003)</td>
<td>Multitrait-multimethod matrix (DeVellis 2003) Not measured (Ding et al. 2006)</td>
</tr>
<tr>
<td></td>
<td>Items discriminate between naïve and advanced thinkers (Yeo and Zadnik 2001)</td>
<td></td>
</tr>
<tr>
<td>Communication (Qualitative)</td>
<td>Students interpret items in the same way as test developers (Libarkin 2008)</td>
<td>Use of established instrument design processes including item-writing guidelines (Libarkin 2008)</td>
</tr>
<tr>
<td>Face (Qualitative)</td>
<td>Items assess what they appear to measure, i.e., their purpose is apparent by looking at them (DeVellis 2003)</td>
<td>DeVellis describes face validity as problematic Review of textbooks and syllabi (Bardar et al. 2006)</td>
</tr>
<tr>
<td></td>
<td>Same as content validity (Libarkin 2008)</td>
<td>Expert review of items (Ding et al. 2006; Anderson et al. 2002)</td>
</tr>
<tr>
<td></td>
<td>Items are relevant to domain (Ding et al. 2006)</td>
<td></td>
</tr>
<tr>
<td>Cultural (Qualitative)</td>
<td>Items are equally meaningful to people from different cultures (Libarkin 2008)</td>
<td></td>
</tr>
</tbody>
</table>
"Items measuring the same concept covary highly with each other and load on the same component" (Anderson et al. 2002; p.963)

Avoidance of researcher bias and use of random sampling (Libarkin and Anderson 2007)

Principal components analysis (PCA) (Anderson et al. 2002)
Expert review of items during development; researchers did not administer CI (Libarkin and Anderson 2007)

Results can be generalised to wider populations (Libarkin and Anderson 2007)
Collecting data from a wide geographical area (Libarkin and Anderson 2007)

Content validity

Content validity addresses whether the test covers appropriate content, i.e., whether the concepts addressed are important to understanding of the topic and whether they cover all important aspects of the topic (DeVellis 2003; Steif & Dantzler 2005; Ding et al. 2006). As stated above, DeVellis (2003) asserts that content validity derives from the scale development process and CI authors agree. According to Allen (2006), this is the most essential form of validity for a CI.

Criterion-related validity

As explained above, this refers to association between CI score and another measure of performance on the same concepts.

Steif and Dantzler (2005) used Spearman’s Rho coefficient to quantify criterion-related validity: they calculated the correlation between CI score and course grade. Spearman’s Rho is a measure of the association between two variables: the closer it is to +1, the more strongly the two variables are related (Steif & Dantzler 2005). Richardson et al. (2003) plotted CI score against course grade and calculate the R-squared value.

Criterion-related validity could not be used in my study because the school students are not tested specifically on their knowledge about climate change. This means there was no other score with which to compare CI scores. However, the topic is increasingly being taught at first year
undergraduate level and further research might involve comparison of CI scores to assessment results at undergraduate level.

Construct validity

To evaluate construct validity, Steif and Dantzler (2005) used confirmatory factor analysis in which their eight factors or subscales corresponded to the eight distinct conceptual areas covered by their CI. According to the UOW statistical consultant, about 500 participants are usually required for factor analysis; therefore it is unlikely that useful results would be obtained from the 229 high school participants.

Other forms of validity

Pellegrino et al. (2011) set out a model of validity for CIs consisting of three forms not mentioned by other researchers. These are cognitive validity, instructional validity and inferential validity. The authors defined cognitive validity as the extent to which a CI taps into important aspects of knowledge and understanding. This could be interpreted as content validity. Instructional validity was defined as the extent to which a CI supports teaching practice. Inferential validity was defined as the extent to which a CI contributes to the development of a model of student understanding. Evaluation of this included statistical methods, including multivariate analysis and exploratory factor analysis.

Ambiguity in definitions of validity

According to Libarkin and Anderson (2007), terms used to describe validity differ across disciplines, and this is reflected in a degree of ambiguity in how authors define the various forms of validity. For example, Bardar et al. (2006) defined face validity as items representing the appropriate content domain. However, DeVellis’ (2003) defined face validity as items measuring “what they appear to measure” (p.57), and considered face validity problematic. According to Libarkin (2008), face validity is the same as content validity, but DeVellis disagreed.
Anderson et al. (2002) cited DeVellis (1991) for their definition of internal validity, but DeVellis (2003) does not mention internal validity and Anderson et al.’s (2002) definition, “items measuring the same concept covary highly with each other and load on the same component” (p.963), appears to correspond to DeVellis’ definition of internal consistency. However, Anderson et al. (2002) differentiated between internal validity, for which they used Principal Components Analysis (PCA), and internal consistency, which they related to reliability and for which they used Kuder Richardson-20 (see Section 5.2.9).

Libarkin’s (2008) definition of construct validity corresponds to other authors’ definitions of content validity. According to Ding et al. (2006) construct validity, i.e., “the extent to which a test is demonstrated to measure … a trait such as creativity, honesty or intelligence” (pp.010105-2) and criterion-related validity, which refers to the use of test scores to “make inferences about performance in a different domain” (pp.010105-2), are not relevant to concept inventories. However Steif and Dantzler (2005) used confirmatory factor analysis in order to measure construct validity for their CI, dividing their test into eight subscales corresponding to the eight concepts it covered.

Yeo and Zadnik’s (2001) definition of construct validity (“items discriminate between naive and advanced thinkers”) does not agree with other authors’ and bears more resemblance to definitions of item discrimination.

Allen et al. (2004) referred to criterion-related validity as “concurrent validity”, which they assessed by correlating CI scores with other tests on the same topic.

Because of the ambiguity in definitions of construct, face, and internal validity, as well as the fact that criterion-related validity could not be assessed, my study focused on content and communication validity, and adopted definitions that were well agreed upon by authors.
Interviews with students and domain experts as an approach to validity

The importance of consulting domain experts was discussed in Chapter 4, however a rigorous approach to concept inventory development also involves consultation with students.

Student interview data serves a number of purposes in CI development: as a source of misconceptions for use in item distractors; to check that language is clear and unambiguous; and to confirm that students interpret items as test-developers intended by exploring the reasons for students’ choice of response to draft CI items. Many researchers used individual student interviews in CI development, however Allen et al. (2004), Gray et al. (2005), Jacobi et al. (2003) and Rhoads and Roedel (1999) used focus groups.

Gray et al. (2005) stated that “there is no better way to develop distractors than to use answers given by the students themselves” (p.3). According to Anderson et al. (2002), “the most effective way to identify misconceptions is to interview students” (p.954). As shown in Table 5.2, Libarkin (2008) advised following item writing guidelines in order to enhance communication validity. One of these guidelines is that distractors should be plausible to students in the target population. One way of achieving this is to use misconceptions observed during interviews with students from the target population.

Libarkin and Anderson (2007) stated that “careful qualitative evaluation of student conceptions” (p.149) is essential in order to develop a valid and reliable CI. They used grounded theory to interpret student interview and survey data: this meant that rather than being completely pre-determined, the content of their CI came partly from student data. Herman et al. (1997), in addition to providing distractors based on interviews, also provided space for students to write in their own answers for the alpha-version of their CI. If several students wrote in the same answer it was deemed to be a new misconception. In these cases, follow-up interviews were carried out and a distractor was written to reflect it. The authors pointed out that interviews
were needed to establish why students gave these answers. According to Yeo and Zadnik (2001), interviews with students can confirm whether students interpreted the question context and content as the test developers intended.

Hestenes et al. (1992) conducted 30-minute interviews with 20 high school students and 16 graduate students to discuss questions they had answered incorrectly. During the interviews students were asked to draw free-body diagrams to explain their reasoning for concepts they had had difficulty with in the CI. It was noted that during interviews, students were able to correct their mistakes through what was referred to as a Socratic process. As a result of these interviews, problems were highlighted with students misreading of two questions; these questions were dropped from the test.

However, care must be taken when designing protocols for interviews. For example, Anderson et al. (2002) warned that the interview tasks they used were too general and resulted in information that could not be closely associated with test items. They found think-aloud activities most useful. They also scored their interviewee responses and calculated correlation coefficients between these scores and CI scores.

5.2.4 Stages in concept inventory development

Table 5.3 lists the stages in CI development; outlines methods used for each stage; and summarises the methods used for my study.

Table 5.3: Stages in CI development

<table>
<thead>
<tr>
<th>Stage in CI development</th>
<th>Authors and methods</th>
<th>Methods used for development of CCCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identify purpose</td>
<td>Identify the primary purpose for which test scores will be used (Bardar et al. 2002)</td>
<td>PhD research questions</td>
</tr>
<tr>
<td>2. Choosing list of concepts</td>
<td>Expert opinion and review of course texts (Libarkin and Anderson 2007) Conceptually taught in majority of courses (Bardar et al. 2002) Expert opinion of concepts important for establishing validity: Delphi</td>
<td>Delphi study and review of literature</td>
</tr>
<tr>
<td>3. Initial item development</td>
<td>Items based on prior research into students’ ideas, teaching experience and student interviews. Small scale trials followed by interviews. Revision based on statistics and feedback (Bardar et al, 2002) Open-ended questionnaire and open-ended interview protocol based on list of topics. Test items based on responses (Libarkin &amp; Anderson, 2007) Two-stage process starting with open-ended stems. Options written based on student interviews, focus groups and answers to open-ended questions (Gray et al., 2005; Richardson, 2004; Streveler et al. 2011) Expert review of items (Bardar et al. 2001; Streveler et al. 2011)</td>
<td>Literature study for known misconceptions on concepts identified in stage 1. Open-ended questions written based on concepts identified in stage 1, trialled with four focus groups to determine how questions are interpreted and identify misconceptions. Development of items with distractors based on misconceptions from literature review and focus groups. Draft CI items sent to Delphi participants for review and revised as necessary. Second round of focus groups using “think-aloud” protocol with revised draft CI items.</td>
</tr>
<tr>
<td>4. Initial field trials</td>
<td>Minimum acceptable sample size is 5–10 times as many subjects as test items (Nunnally, 1967)</td>
<td>229 students in Years 9 and 10 68 undergraduates</td>
</tr>
<tr>
<td>5. Data analysis</td>
<td>See Table 5.6</td>
<td>Item difficulty, discrimination, point biserial coefficient. Assessment of reliability using Cronbach’s alpha and test-retest data.</td>
</tr>
<tr>
<td>6. Revision</td>
<td>Think aloud interviews (Libarkin and Anderson 2007) Eliminate items that do not meet pre-established criteria (Bardar et al. 2002) Improve readability, validity, reliability and fairness (Richardson 2004) Experts review items and suggested revisions. Post-tests using revised questions (Libarkin and Anderson 2007)</td>
<td>Four focus groups with high school students for validation of CI responses. Revision and development of beta version</td>
</tr>
</tbody>
</table>
5.2.5 Stage 1: Identifying the purpose of the concept inventory

Most CIs are used either for diagnosing students’ conceptual difficulties with a topic, or for evaluating the impact of research-based approaches to learning. The purpose of developing the CCCI was to investigate students’ understanding of the key scientific concepts underlying the most basic scientifically acceptable explanation of the science of climate change. This purpose derives from the research questions.

5.2.6 Stage 2: Choosing concepts

Content validity, as described in Section 5.2.3, requires adequate coverage of relevant concepts. The list of concepts to be covered can come from consultation with teaching staff and students, literature on the topic, or theory. For example, Libarkin and Anderson (2007) used student interview and survey data in their concept-selection process, while Anderson et al.’s (2002) list of concepts was pre-defined by theory of the logic of natural selection. Richardson et al. (2003) asked colleagues to send lists of important concepts. These were synthesised into one list during a face-to-face meeting, then revised and refined by the team. Richardson et al. (2003) pointed out that careful definition of the scope or boundaries of concepts assists the process of developing questions.

Danielson (2005), Gray (2005), Herman et al. (2010), Rowe and Smaill (2007), Stone (2004) and Streveler et al. (2003) used Delphi studies or elements of the Delphi technique when developing concept inventories for physics and computing; Richardson et al. (2004) also recommended the method.

How is a concept defined and stated?

Of the literature cited, only Danielson (2005) provided a theoretical basis for “concept”, citing the following definitions:

- Rules of classification (Gagne, 1977)
- Schemata (scripts or productions – Andre, 1986)
- Declarative knowledge (Tennyson and Park, 1980).
A single concept may have multiple dimensions, or sub-concepts. Hestenes et al. (2006) listed six “conceptual dimensions” (p.2) of the concept of force: these are concepts in themselves but all six are required for a complete understanding of the concept “force”.

Table 5.4 gives some examples of concept statements on which CIs were based, in order to illustrate the types of statement considered to constitute a concept statement for a CI. The statements used by Danielson (2005) are in the form of propositions, in accordance with the literature he cited.

**Table 5.4: Examples of CI developers’ ways of stating concepts**

<table>
<thead>
<tr>
<th>Authors</th>
<th>Examples of concept statements</th>
</tr>
</thead>
</table>
| Bardar et al. (2006)     | The nature of the electromagnetic spectrum, including the interrelationships of wavelength, frequency, energy, and speed  
The correlation between peak wavelength and temperature of a blackbody radiator |
| Streveler et al. (2003)  | Pressure; temperature scales; adiabatic vs isothermal processes; compressible vs incompressible flow; heat transfer modes; specific heat capacity             |
| Danielson (2005)         | For a body to be in equilibrium, the external forces and the moments acting on the body both sum to zero  
A vector has magnitude and direction  
Every contact force creates an equal and opposite reaction force  
The weight of an object is a force and is due to its gravitational attraction to another body, typically the Earth |
| Hestenes (1992)          | Velocity discriminated from position  
Acceleration discriminated from velocity  
Second law: impulsive force  
Second law: constant force implies constant acceleration |
| Steif and Dantzler (2005) | Distinctions must be drawn between a force, a moment due to a force about a point, and a couple. Two combinations of forces and couples are statically equivalent to each other if they have the same net force and moment. |
| Gray et al. (2005)        | Angular velocities and angular accelerations are properties of the body as a whole and can vary with time.  
The direction of the friction force on a rolling rigid body is not related in a fixed way to the direction of rolling. |
5.2.7 Stage 3: Developing the pool of items (questions)

Bardar et al. (2006) developed their pool of items based on three sources: literature on qualitative research into student misconceptions; teacher experience; and in-depth interviews with students. The authors advised that distractors should:

- be written in students’ natural language;
- reflect known misconceptions;
- be apparent to someone who understands the concept; and
- should not include additional “nonsensical” items.

Each of their questions addressed a single concept, and options were similar in complexity and length. These questions were distributed to other teaching staff for review and refinement.

Herman et al. (2010) based distractors on problem-solving interviews.

Klymkowsky et al. (2007) discussed how poorly designed questions can lead to “reflex responses” (p.4). These responses relied on repeating information rote-learned and failed to demonstrate conceptual understanding. In order to elicit more informative responses they devised questions in which the context was likely to be different from that in which the concepts were learned. The authors pointed out that writing questions which elicit responses based on conceptual understanding is much more difficult than writing questions to which students respond reflexively. The authors also reported that open-ended questions that required students to apply their knowledge in a new context, yielded more useful information about misconceptions.

Yeo and Zadnik’s (2001) CI was designed to include objects and experiences students are likely to encounter in everyday life, and used simple language to minimise cognitive load. This corresponds to item writing guidelines described in Table 5.5, i.e., avoiding “window-dressing” and “type K” formats.
Gray et al. (2005) used a multiple step process: focus groups provided answers to item stems; these responses were used to write distractors which were then trialed by students who were asked to explain their reasoning and flag any confusing language. Libarkin (2008) recommended careful attention to scale development rules so that questions are as valid as possible. She also recommended collecting data from the target population in order to devise plausible distractors.

*Item-writing guidelines*

The guidelines in Table 5.5 are based on: work by Haladyna et al. (2002), who synthesised a list of 31 guidelines for writing multiple choice test items, based on a review of 27 textbooks; Frey et al. (2005), who compiled a list of rules from assessment textbooks; and advice on CI item development from Libarkin (2008) and Bardar et al. (2006).

Similarly, Allen et al. (2004) cited Gibb’s (1964) seven criteria for item characteristics that may “tip-off” students with good test-taking skills, all but one of which correspond to the guidelines in Table 5.5. These are: “clang associations” (guideline 10); unconvincing distractors (guideline 4); use of “all” or “very” in distractors (guideline 9); the correct response being more clearly stated than the distractors (guideline 6); the correct response being longer than the others (guideline 6); grammatical inconsistency between distractors and stem (guideline 6); and the correct answer being “given away” by another item in the test. This last issue is discussed in Section 5.3.3.
<table>
<thead>
<tr>
<th>Rule</th>
<th>Item-writing guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Structure the stem as a question if possible (as opposed to a partial sentence which is completed by choosing an option) (Libarkin 2008; Haladyna et al. 2002)</td>
</tr>
<tr>
<td>2</td>
<td>Language should be as simple as possible and appropriate to the target population. Minimise the amount of reading in each item – avoid “window dressing” (Libarkin 2008; Bardar et al. 2006)</td>
</tr>
<tr>
<td>3</td>
<td>Stems should be unambiguous (Libarkin 2008), should clearly state the problem and directions. Include the central idea in the stem rather than in the options</td>
</tr>
<tr>
<td>4</td>
<td>Ensure that all distractors are plausible (Libarkin 2008): use known misconceptions from the target population (Bardar et al. 2006)</td>
</tr>
<tr>
<td>5</td>
<td>Avoid “type K” formats and “all of the above” as an option. Use “none of the above” sparingly (Haladyna et al. 2002) or not at all (Libarkin 2008; Frey et al. at. 2005). Avoid complexity in responses e.g., “X and Y but not Z” (Libarkin 2008)</td>
</tr>
<tr>
<td>6</td>
<td>Avoid giving hints to correct answer by keeping options homogeneous in content and grammatical structure; keep length of options about equal: the correct option should not be the longest one (Frey et al 2005)</td>
</tr>
<tr>
<td>7</td>
<td>Items should cover important concepts and objectives – avoid trivial content (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>8</td>
<td>Avoid trick and opinion-based questions (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>9</td>
<td>Avoid negatives e.g., NOT or EXCEPT (or capitalise if they must be used). Avoid absolutes such as “always, never,”etc. (Libarkin 2008) and vague frequency terms e.g., “often”, “usually” (Frey et al. 2005)</td>
</tr>
<tr>
<td>10</td>
<td>Avoid “clang associations, i.e., the same, or a very similar word appearing in stem and correct option (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>11</td>
<td>Vary the location of the right answer, place choices in logical or numerical order (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>12</td>
<td>Items should be logically independent of each other e.g., there should be no overlap in numerical ranges (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>13</td>
<td>Use novel material to test higher-level learning. Paraphrase textbook language to avoid simple recall (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>14</td>
<td>Avoid over-specific and over-general content (Haladyna et al. 2002)</td>
</tr>
<tr>
<td>15</td>
<td>Give 3-5 options (Libarkin 2008; Frey et al. 2005). Three choices are adequate (Haladyna et al. 2002; Rodriguez 2005)</td>
</tr>
<tr>
<td>16</td>
<td>Options should not have repetitive wording (Frey et al. 2005)</td>
</tr>
<tr>
<td>17</td>
<td>Questions of the same format should be together (Frey et al. 2005)</td>
</tr>
<tr>
<td>18</td>
<td>Answer options should be available more than once (Frey et al. 2005)</td>
</tr>
<tr>
<td>19</td>
<td>Each item should reflect specific content and a single specific mental behaviour (Haladyna et a. 2002)</td>
</tr>
<tr>
<td>20</td>
<td>Format options vertically (Haladyna et al. 2002)</td>
</tr>
</tbody>
</table>
Several authors investigated the effect of changing the number of distractors in multiple-choice tests.

Rodriguez (1964) conducted a meta-analysis of research, concluding that in most cases, the optimal number of options is three. A key reason for this is that students make “educated” rather than “blind” guesses, so distractors are only chosen if they are plausible. In many cases, it is not possible to write more than two plausible distractors. The meta-analysis revealed that reducing options from four to three had the following effects:

- a slight decrease in item difficulty;
- a slight increase in item discrimination;
- a slight increase in reliability;
- increased, or negligibly decreased criterion-related validity (limited evidence); and
- less time taken to complete the test.

Rodriguez (2005) noted that because three-option tests take less time to complete, more items can be included in such a test, improving content coverage. According to the author, many researchers claim that three-option tests have greater content-related and criterion-related validity, because they can comprise a larger number of items. However, this claim has not been tested directly.

Rodriguez (2005) suggested that more options can be useful if they allow information about misconceptions to be gathered. However he warned that additional plausible distractors carry a risk of supplying information to students about subsequent items.

Tversky (1964) demonstrated mathematically that three options maximises the power and discrimination capacity of a test. He also showed that if the amount of time on a test is proportional to the number of options per item, then using three options maximises the amount of information collected per unit time.
Bardar et al. (2006) pointed out that standard test construction theory has no requirement for five answer choices.

5.2.8 Stage 4: Field trials
Prior to field trials, Bardar et al. (2006) administered the first draft of their CI to 50 students from a single institution as a pre-and post-test, and conducted post-instruction interviews. This feedback was used to revise problematic items. Bardar et al.’s (2006) field trial involved 548 students in 11 institutions in a pre-test, 368 of whom also participated in a post-test. The authors cited Nunally’s (1967; cited in Bardar et al. 2006) advice that a full scale field test requires between five and ten times as many participants as test items, in order to provide sufficient data for statistical analysis.

Herman et al.’s (2010) trials involved 108 students. For their alpha version, the authors also provided space for students to write in their own answers.

Libarkin and Anderson (2007) conducted trials with 3,595 participants in institutions across the U.S.A. The purpose of this large sample was to ensure external validity and to optimise the generalisability of the CI. Streveler et al. (2011) pre-tested items on groups of about 10 students before running field trials of their draft CI.

Gray et al. (2005) administered their draft CI to 754 students at three institutions; 313 of these sat the CI as a post-test only while the rest sat it as a pre-test and post-test.

5.2.9 Stage 5: Quantitative evaluation of CI trial data
“A good test has good items. But what are good items?” (Kaplan & Saccuzzo 1997, p.160).

Quantitative analyses are carried out to determine how well the CI performs as a measure of students’ understanding, and usually include statistical determination of test reliability, item difficulty and discrimination. Measures apply either to single items or to the test as a whole. For single item measures, the average value for all items (i.e., for the test as a whole) is usually also given. Aubrecht and Aubrecht, (1983), were among the first
researchers to evaluate physics test instruments using statistical methods, namely item difficulty, item discrimination and test reliability (Ding et al. 2006).

Table 5.6 summarises statistical tests that have been used in the evaluation of concept inventories, including recommended values. However it should be noted that Smith et al. (2008) cautioned against the uncritical application of psychometric criteria developed for standardised tests, pointing out that concept inventories test understanding on a number of concepts while standardised tests tend to test only a single trait or set of skills. For example, items with discrimination values outside the recommended range on pre- and post-tests provide useful information about students’ learning. The theory underlying the most commonly used tests, and their use by researchers, are discussed in Appendix 5.

**Table 5.6: Statistical tests used to evaluate CI performance, listed in approximate order of frequency of use**

<table>
<thead>
<tr>
<th>Name of test</th>
<th>Authors and notes on use</th>
<th>Desirable values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Item difficulty</strong></td>
<td>Items should not be too easy or difficult</td>
<td>0.3-0.9 (Ding et al. 2006); optimum 0.5</td>
</tr>
<tr>
<td>(Single item)</td>
<td>There should be a range of difficulties (Bardar et al. 2006)</td>
<td>0.2-0.8 (Bardar et al. 2006)</td>
</tr>
<tr>
<td></td>
<td>Calculated by most authors</td>
<td>0.4-0.6 (Richardson 2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;=0.7 (Smith et al. 2008)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3-0.7 (Anderson et al. 2002)</td>
</tr>
<tr>
<td></td>
<td>Average 0.5 (Gronlund 1993; cited in Anderson et al. 2002)</td>
<td>Optimum ~0.63 (Anderson et al. 2002)</td>
</tr>
<tr>
<td><strong>Item discrimination</strong></td>
<td>Assesses how well items distinguish between strong and weak students (Ding et</td>
<td>Must not be negative (Ding et al. 2006)</td>
</tr>
<tr>
<td>(Single item)</td>
<td>al. 2006)</td>
<td>Reject any item with D&lt;=0.24 (Thorndyke 1999; cited in Streveler et al. 2011)</td>
</tr>
<tr>
<td></td>
<td>50%-50% and 25%-25% measures (Ding et al. 2006)</td>
<td>Good if D&gt;=0.3 (Doran 1980 cited in Ding et al. 2006; Steif and Dantzler 2005; Lindell and Olsen 2002)</td>
</tr>
<tr>
<td></td>
<td>33%-33% measure (Smith et al. 2008; Steif and Dantzler 2005)</td>
<td>D_{ave} &gt;=0.3 in Ding et al. (2006) but rationale not given</td>
</tr>
<tr>
<td></td>
<td>Calculated by most authors</td>
<td></td>
</tr>
<tr>
<td><strong>Point biserial coefficient</strong></td>
<td>Consistency of individual items with the test as a whole (Ding et al. 2006)</td>
<td>Negative value indicates defective item; average ( r_{pbs} ) &gt;=0.2; few items should have ( r_{pbs} ) &lt;0.2 (Ding et al. 2006)</td>
</tr>
<tr>
<td>(Single item)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure</td>
<td>Description</td>
<td>Typical Range</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Cronbach’s alpha</td>
<td>Measure of internal consistency used to estimate reliability</td>
<td>&gt;=0.7 (Litwin 1995 in Bardar et al.; Nunally in Gray et al.2005)</td>
</tr>
<tr>
<td>Kuder-Richardson reliability index</td>
<td>Measure of reliability</td>
<td>&gt;=0.7 for groups and &gt;=0.8 for individuals</td>
</tr>
<tr>
<td>Test-retest</td>
<td>Measure of reliability</td>
<td>Coefficient of stability (Smith et al.) &gt;0.8</td>
</tr>
<tr>
<td>Mean and SD</td>
<td>Analysis of variance to determine if gender or ethnicity affected scores</td>
<td>Not stated, although if optimum item difficulty is 0.5 then optimum test score should be 50%</td>
</tr>
<tr>
<td>Frequency response analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chi squared analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor analysis</td>
<td>Construct validity Steif and Dantzler (2005)</td>
<td>&gt;=0.9</td>
</tr>
<tr>
<td>Ferguson’s Discriminatory power of</td>
<td></td>
<td>&gt;0.9</td>
</tr>
</tbody>
</table>
### 5.2.10 Other statistical tests: Cronbach’s alpha for individual items; Factor analysis; Rasch; DIF; analysis of variance; t-tests; and Chi squared analysis

Some of the following tests have been used only by a small number of researchers in CI development, therefore there is limited evidence for appropriate methods, desirable values and application of findings in the development of CIs. Other methods such as analysis of variance, t-tests and pre- and post-tests, while well established, are not applicable to my research design.

Allen et al. (2004) used Cronbach’s alpha to estimate the reliability of each item. This was done by deleting an item from the CI and calculating Cronbach’s alpha for the remaining items. Reliable questions, when deleted, resulted in lower Cronbach’s alpha values for the remaining items.

Factor analysis is not often carried out as part of CI evaluation, possibly because of the complexity of the statistics required. The only CI identified in literature in which a rigorous approach to factor analysis was taken, was the statistics concept inventory (Stone 2006; Allen 2006). Additionally, factor analysis requires a large number of participants (Nunnally 1967). This made it unsuitable for my research design, as there were not enough participants in order for confirmatory factor analysis to produce meaningful results.

Libarkin and Anderson (2007) carried out Rasch and DIF analyses. DIF analyses determine whether or not demographic variables such as ethnicity or gender have an effect on test scores. Clauser and Mazor (1998) explained their use.
Rasch analysis is a model in Item Response Theory (IRT) (Stone 2006), which uses nonlinear equations to model item response functions (p.68). Placing all their test items on a single Rasch scale allowed Libarkin and Anderson (2007) to compare directly scores from different sub-tests generated from an item-bank. However this technique is not applicable to CIs such as the CCCI, in which the same set of items is always used. According to Allen (2006) and Stone (2006), IRT is a relatively new approach to CI development, with Libarkin and Anderson’s (2007) work being the first known example of its use.

Steif and Dantzler (2005) calculated mean score and standard deviation, and carried out an analysis of variance to determine whether scores were affected by gender or ethnicity. Gray et al. (2005) carried out t-tests and pre- and post-tests, citing Miller (1995). The authors used t-tests to establish that there were significant differences between the mean scores of two groups of participants, while the pre- and post-tests would enable evaluation of the impact of learning activities or resources.

Smith et al. (2008) used Chi squared analysis to compare the percentage of students in their two study samples who chose each response for each item. The authors state that this showed how two groups of students “differed in their preferences for particular distractors” (p.426). I have not identified any other instances of the use of this technique by CI developers.

It is possible that emerging forms of CI evaluation such as factor analysis and Item Response Theory, while beyond the scope of this study, might form future research directions.
5.3 Development and validation of the Climate Change Concept Inventory (CCCI)

This section describes the process used for development and validation of the CCCI. It includes details of focus group interviews carried out, and statistical tests used to evaluate the resulting instrument. The results of the statistical tests are presented in Chapter 6, and the post-trial focus groups are reported in Chapter 7.

5.3.1 Validity of the CCCI

Given the advice that adopting a wide range of approaches enhances validity, content and communication validity for my study derive from the following elements of the development process:

- A review of literature on students’ understanding of climate change to identify key concepts necessary to understand the topic (content validity)

- A Delphi study to consult climate science experts about the concepts they considered important for a basic understanding of the topic (content validity)

- Distractors based on misconceptions observed in the target population. These were identified during the first round of focus groups, which used open-ended questions based on the final list of conceptual statements to scope out the extent to which students were familiar with the concepts and what they understood about them. This information was used to create distractors for items. It also allowed concepts to be avoided when they appeared to be well-understood, or when all participants gave the same responses (content validity)

- Distractors also informed by misconceptions identified from a review of literature about student understanding of the concepts (content validity)
• Review of draft items by two experts who participated in the Delphi study (content validity)

• Review of draft items by a second round of focus groups to determine whether items were clearly and unambiguously written and contained plausible distractors. Students were asked to explain their choice of response and to identify any confusing language (communication validity)

• A third round of focus groups following initial CI trials to establish whether students’ choices of options were consistent with their verbally-articulated understanding. Students also discussed their interpretation of the items. Some participants identified themselves in recordings. This allowed direct comparison of ideas as voiced by individuals and their responses to corresponding CI items (content and communication validity). This analysis had a number of limitations including small sample size, but provided some direct evidence of participants’ reasons for item choices

• Application of item-writing guidelines described in Section 5.2.7 (content and communication validity).

Figure 5.1 illustrates how each of the approaches listed above correspond to one or more forms of validity.

Figure 5.1: Mapping of forms of validity considered for the CCCI, to the approaches taken in development
5.3.2 Choosing concepts for the CCCI

The list of conceptual statements that form the basis of the CCCI was derived by synthesising findings from a Delphi study involving discipline experts with findings from a review of literature on students’ understanding of the science of climate change. This process was reported in Chapter 4.

5.3.3 Developing the pool of items for the CCCI

Figure 5.2 outlines the process of development of the climate change concept inventory, showing the approximate order in which activities took place.

![Diagram of the process of development of the CCCI](image)

**Figure 5.2: Sequence of activities in development of the CCCI**

*Identifying student misconceptions for item distractors*

Data on known misconceptions came from two sources: a review of literature on students’ understanding of the concepts to be covered by the CCCI, described in Chapter 2, Section 2.5; and focus groups with students in the participant group.

This first round of student focus groups served an additional purpose: to determine whether students had any knowledge about the concepts to be covered. This was important because for some concepts, the focus group participants:
• were not aware of the concept; or

• appeared to have no misconception; or

• all gave similar responses, either incorrect or partially correct.

In the above cases, writing effective items was not possible. This is discussed in more detail below.

For the focus group interview guide, I wrote a set of open-ended questions covering the knowledge described in the final list of conceptual statements (focus group guides in Appendix 4). I carried out audio-recorded focus groups with four groups of students at four schools in the region. Participants in the first round of focus groups are summarised in Table 5.7. Focus groups took place during class time and three groups completed their discussion within one class period. The fourth group spent more time debating their ideas and took two class periods to complete their discussion. Discussions remained overwhelmingly on-topic and lively throughout the time available. They resulted in a deeper discussion of the concepts than the individual interviews in the pilot study, in which most interviews were significantly shorter than anticipated. This difference appeared to be due to interactions between students, which increased their willingness to contribute ideas, and is in agreement with literature on focus group interviews discussed in Chapter 3.

Table 5.7: Participants in the first round of focus groups

<table>
<thead>
<tr>
<th>School</th>
<th>A (suburban)</th>
<th>B (suburban)</th>
<th>E (semi-rural)</th>
<th>F (rural)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>9 (4 girls, 5 boys)</td>
<td>14 (6 girls, 8 boys)</td>
<td>9 (5 girls, 4 boys)</td>
<td>10 (7 girls, 3 boys)</td>
</tr>
<tr>
<td>Length of focus group</td>
<td>35 min (part 1)</td>
<td>37 min</td>
<td>39 min</td>
<td>47 min</td>
</tr>
<tr>
<td></td>
<td>42 min (part 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I transcribed the audio recordings in full and organised data into rows, each containing a complete utterance, then carried out data-reduction in Excel, from 2218 rows to 497 rows. This was done by:
1. removing utterances not related to conceptual knowledge;

2. grouping responses from different focus groups; and

3. coding statements with descriptive codes using a software tool described in Diment (2010), and aggregating phenomenographically (Stephanou 2007) equivalent statements to give a list of conceptual statements (correct and incorrect) for each conceptual area.

The lists of incorrect statements formed the basis of the distractors for items, along with misconceptions identified in the review of literature.

Writing and reviewing items

I wrote a total of 58 items, to allow for rejection of problematic items and selection of items considered strongest following review by researchers, students and Delphi participants. These were arranged in a table (Table 5.9) showing which conceptual statement each corresponded to. The statements in Table 5.9 are identical to those shown in Chapter 4 Table 4.7, however they are broken down into sub-concepts that can be addressed by one or more items. This allowed confirmation that all conceptual areas had been covered when choosing items from the pool to form the draft CI.

For three of the ten conceptual areas, I did not write any items. For Difference between weather and climate, no misconceptions were observed during focus groups. For Natural climate variability in the past, all participants had heard of ice ages but no other climatic periods were described, i.e., responses were homogeneous. However, it may be possible to devise items asking, e.g., whether variation was only caused by human activity. It might be advisable to address this when revising the concept inventory after analysis of field trial data, however it is also important that the test is not excessively long: most concept inventories are designed to be completed within 30 minutes (Richardson, 2004). For Radiative forcing capacity this level of understanding of the interaction between greenhouse gases and infrared radiation was not observed during any of the focus groups. Again, it might be possible to devise items addressing this concept
in subsequent versions. The remaining conceptual areas are numbered one to seven: this numbering applies to these conceptual areas for the remainder of this thesis.

Gray et al. (2005) reported not including in their CI, the concept ranked fourth most important by their Delphi study. This was because the concept, although important, was “nearly impossible to assess using a multiple choice question” (p. 821). This highlights the fact that although experts might consider concepts important, it might not be possible to include them in a CI for a number of reasons.

I followed the item writing guidelines described in Section 5.2.7. In most cases, this involved writing three options per item. However, for five items I included four options and for one item I included five. This was because it was not clear which of the possible distractors were most plausible. It is intended that distractors chosen by few students will be removed in subsequent versions of the CI.

Items were reviewed by myself and my supervisors four times, resulting in the deletion of some items, the revision of others and the creation of several more, giving a pool of 44 items.

These were sent to Delphi study participants for comments and feedback. Two replies were received: one specified minor changes, which were made, and the other said that the questions were acceptable. The 44 items were then reviewed in a second round of focus groups: a group of six students (audio recorded in two groups of three) and a whole class group of 19 students (not audio recorded). These were samples of convenience (Table 5.8). The first group of six students worked through the questions in two groups of three. They were asked to explain verbally their reasons for choice of response, to flag any words they didn't understand and to ask the researcher for explanation if any questions weren't clear. This group’s comments were reviewed and the questions adapted where required before trialing with the whole-class group.
The whole class group worked in groups of two to four students. They followed the same instructions as the first focus group but space constraints meant that audio recording was not possible because groups could not be seated in separate areas. Findings from these two focus group sessions resulted in further refinement of items and helped in rejecting problematic items.

Table 5.8: Participants in the second round of focus groups for validation of draft CI items

<table>
<thead>
<tr>
<th>School</th>
<th>B (suburban)</th>
<th>E (semi-rural)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of participants</td>
<td>6 (3 girls, 3 boys)</td>
<td>18 (whole-class group)</td>
</tr>
<tr>
<td>Length of focus-group</td>
<td>38 minutes</td>
<td>45 minutes</td>
</tr>
</tbody>
</table>

Following analysis of focus group data, my supervisors and I determined which items to retain. The aim was to retain 25-30 items (Richardson 2004; Rowe and Smaill 2008). We retained twenty-seven items. Obviously problematic items were rejected and at least one question per concept was retained. Not all the questions rejected were considered problematic: the need to keep the total number of items under 30 meant that if several items addressed a concept it was necessary to reject some, based on personal judgment.

To assist in putting the items in order, I read through them to determine what information was contained in the stem (and options, to a lesser extent) and what information was asked for. Items supplying information were put after questions asking for the same information in order to minimise the risk of questions “tipping off” students. Participants commented that during trials they sometimes found information later in the CI that helped them to answer an earlier question. I told the students that they could change their answers by crossing out the original and were asked to make a note explaining that they had changed their answer after reading another question.
Table 5.9: Statements of conceptual areas and corresponding item numbers in the first draft of the climate change concept inventory. Conceptual areas not numbered did not form part of the CCCI as it was not possible to write suitable items for them.

<table>
<thead>
<tr>
<th>Statement of conceptual area – broken down into individual concepts</th>
<th>Items</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Carbon cycle and fossil fuels:</strong> There is a fixed amount of carbon on Earth: it is cycled among the atmosphere, biosphere, soils, ocean and rocks. There are both natural and human-induced sources and sinks of greenhouse gases. Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle. Burning fossil fuels returns this carbon to the cycle.</td>
<td>3,22  1  2,8,12  13  5</td>
</tr>
<tr>
<td><strong>2. Electromagnetic spectrum:</strong> There is Infra Red (IR) and Ultra Violet (UV) radiation beyond the visible spectrum: these are all related forms of electromagnetic energy. The Sun emits mostly visible radiation and the Earth emits mostly IR.</td>
<td>6  14,24</td>
</tr>
<tr>
<td><strong>3. Interactions between greenhouse (GH) gases and electromagnetic radiation:</strong> Most of the gases that make up the atmosphere are transparent to visible light. Non-GH gases are transparent to IR, but GH gases absorb IR: this is the cause of the greenhouse effect. GH gases allow the Sun's visible light in, but absorb IR emitted by Earth. This is re-emitted in all directions - down as well as up.</td>
<td>15  16  21  11,18  23</td>
</tr>
<tr>
<td><strong>Natural climate variability in the past and relationship to CO₂ levels:</strong> The climate has been different in the past (e.g., carboniferous period, ice ages) due to changes in energy emitted by the Sun, the distance between the Earth and Sun or CO₂ released from volcanoes during periods of high levels of volcanism. Prehistoric climate changes correlate with changes in CO₂ levels, providing evidence for the link between CO₂ levels and global temperatures.</td>
<td>NONE</td>
</tr>
<tr>
<td><strong>Difference between weather and climate:</strong> Weather is short-term, day-to-day climatic conditions while climate is the longer-term average conditions.</td>
<td>NONE</td>
</tr>
<tr>
<td><strong>4. Proportions of greenhouse and non-greenhouse gases in the atmosphere:</strong> Over 96% of the atmosphere consists of non-greenhouse gases. The atmosphere also contains small amounts of CO₂, CH₄, O₃, N₂O and H₂O and CFCs- all of which are greenhouse gases. Water vapour is a variable component of the atmosphere and is the most abundant greenhouse gas. GH gases are not in a distinct atmospheric layer.</td>
<td>9  10,19  17</td>
</tr>
<tr>
<td><strong>Radiative forcing capacity:</strong> Some greenhouse gases have more radiative</td>
<td>NONE</td>
</tr>
</tbody>
</table>
forcing capacity than others, i.e., a given amount of a "stronger" greenhouse gas would result in more radiative forcing than the same amount of a "weaker" greenhouse gas.

5. Feedback: Changing one parameter can have an effect on another parameter, which causes a change in the original parameter. Feedback can be negative (i.e., tends to return the parameter to its original value) or positive (i.e., tends to drive the parameter further away from its original value) e.g., increasing CO$_2$ raises surface temperatures causing more water to vaporise, which further raises temperatures.

6. Equilibrium of energy: There is a balance of energy into and out of the Earth/atmosphere system. A net flow of energy into or out of the Earth/atmosphere system leads to temperature change over time.

7. Conservation of energy: Energy can change from one form to another, but the total amount of all forms of energy remains constant.

5.3.4 Field trials of the CCCI

Nunnally (1967) recommended that there should be 5-10 times as many participants as items. This implies that for a 30-item CI, at least 150 participants would be required for a full-scale field trial. Therefore I aimed to recruit at least 200 students in order to ensure a large enough sample for statistical analysis.

229 high school students in six schools participated in field trials: these included public and private, academically selective and non-selective schools in suburban, semi-rural and rural areas. Participants completed the CI and a short survey of knowledge sources in whole class groups, during normal class time. Students took around 25 minutes to complete the task.

I guided and supervised all data collection and emphasised the importance of students providing their own answers, whether correct or incorrect. Students were particularly asked not to guess blindly or choose answers at random, but to leave blank any such items. This served two purposes: it discouraged guessing; and it allowed the number of students who had no knowledge of each item to be determined. Table 5.10 summarises the groups of field trial participants from high schools.
Table 5.10: Participants in CI field trials

<table>
<thead>
<tr>
<th>School</th>
<th>Number of participants</th>
<th>Academic level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>27</td>
<td>Selective class</td>
</tr>
<tr>
<td>A</td>
<td>26</td>
<td>Selective class</td>
</tr>
<tr>
<td>A</td>
<td>20</td>
<td>Non-selective class</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>Non-selective class</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>Non-selective class</td>
</tr>
<tr>
<td>C</td>
<td>13</td>
<td>Accelerated students</td>
</tr>
<tr>
<td>C</td>
<td>25</td>
<td>Selective class</td>
</tr>
<tr>
<td>C</td>
<td>17</td>
<td>Selective class</td>
</tr>
<tr>
<td>D</td>
<td>19</td>
<td>Non-selective class</td>
</tr>
<tr>
<td>E</td>
<td>14</td>
<td>Non-selective class</td>
</tr>
<tr>
<td>F</td>
<td>28</td>
<td>Selective class</td>
</tr>
</tbody>
</table>

It must be acknowledged that the sample of participants was biased in favour of high academic achievement, with six of the eleven participating classes being selective classes, rather than the more typical ratios of one in three to one in six. Participating classes were selected by teaching staff, who generally selected classes likely to participate actively and benefit from taking part in the research. The inconvenience of participating in research should be balanced by direct benefit to participants, and many students particularly in focus groups, did report that they had learned something from the activities. Therefore, I consider this choice of participants to be justified.

The CI was also separately trialled by 68 undergraduates enrolled in an introductory-level unit of study on climate change. Such units of study are increasingly being offered at universities and I wished to assess the suitability of the CCCI for students at this level. Similarly, Hestenes (1992) trialled the Force Concept Inventory with both undergraduates and high school students. Trialling the CI with a group of students who were more familiar with the concepts provided the opportunity for further validation of CI. Some of the concepts in the CCCI are not explicitly covered in the Stage 5 syllabus, and therefore might be unfamiliar to school students: this was
confirmed during focus groups. Further, focus group participants’
knowledge about other concepts was contradictory and not well formed. If
CI participants had either no knowledge or tentative mental models of
concepts, this would lead to poor statistical performance of items. If this is
the case, statistical data from students more familiar with the topic should
be closer to desirable values, showing that for students with well formed
conceptual knowledge (whether correct or incorrect), the CI performs well
as a diagnostic test.

The undergraduate participants completed the climate change concept
inventory at the end of their unit of study, during normal tutorial time, and
also took around 25 minutes to complete it.

5.3.5 Statistical tests used to evaluate the CCCI
Table 5.11 shows the statistical measures calculated for the CCCI, along
with the widest recommended ranges from literature. These measures were
calculated both for the high school students’ and undergraduates’ data. The
results of these statistical tests are presented and discussed in Chapter 6.

<table>
<thead>
<tr>
<th>Statistical measure</th>
<th>Recommended values</th>
<th>Calculated for</th>
</tr>
</thead>
<tbody>
<tr>
<td>P = item difficulty = fraction of correct responses</td>
<td>0.2-0.9</td>
<td>Both groups</td>
</tr>
<tr>
<td>D_{25} = item discrimination using top 25% and bottom 25% of scores. Less likely than D_{50} to underestimate item discrimination but involves discarding half of the dataset</td>
<td>&gt;=0.24</td>
<td>Both groups</td>
</tr>
<tr>
<td>D_{50} = item discrimination using top 50% and bottom 50% of scores. More likely than D_{25} to underestimate item discrimination but includes entire dataset</td>
<td>&gt;=0.24</td>
<td>Both groups</td>
</tr>
<tr>
<td>r_{pb} = point biserial coefficient, and associated p value</td>
<td>&gt;=0.2</td>
<td>Both groups</td>
</tr>
<tr>
<td>Kuder-Richardson 20 for internal consistency</td>
<td>&gt;=0.6</td>
<td>Both groups</td>
</tr>
<tr>
<td>95% confidence interval of binomial distribution of test-retest data as an additional estimate of reliability</td>
<td>&gt; 0.4618 i.e., outside the 95% confidence interval</td>
<td>High school students only</td>
</tr>
</tbody>
</table>
D₂₅ and D₅₀ values were calculated on a spreadsheet and a subset of values from each group hand-checked. rpbs values were calculated using JMP.

**Test-retest data for reliability**

The UOW statistics consultant advised collecting retest data from a minimum of 30 students in order to provide an additional reliability measure to Cronbach’s alpha. Thirty-four students in three schools completed retests early in Term 4, 2011. As before, students participated in whole class groups but some students who were present at school during retests had not been present for first tests and vice versa, so the total number of test-retest pairs was less than the number of participating students.

As they had originally completed the concept inventory in weeks 8-10 of Term 3, this timing minimised the likelihood of their participating in any lessons on the topic in the intervening time, while still allowing some time between test and retest, to minimise remembering of responses. The concept inventory was identical for test and retest, however retest participants completed a different survey which asked: the extent to which students remembered the test from before; whether they were conscious of choosing different answers for the retest; and reasons for choosing different answers, such as having studied the topic in the intervening time.

It is not sufficient to correlate students’ total scores for test and retest. The median score for test data was 7 out of 27 and a student could score seven both times while choosing completely different answers and getting seven different items correct. Therefore, for each item I looked at whether each student chose the same response both times (whether or not their answer was correct).

First, I examined individual items. The probability that a student would choose the same option twice for an item on a three option scale if they were answering randomly (i.e., guessing) each time would be 0.33 and for a four option scale 0.25. Taking this as the probability of success (i.e., of guessing the same answer twice in two trials) the binomial distribution can be used to calculate the 95% confidence interval of the proportion using the
formula in Howell (2002). If the proportion of students who gave the same response (whether correct or incorrect) twice exceeded the upper bound of the 95% confidence interval then it can be concluded that the test-retest group were not guessing for each item where this condition is met.

To give an estimate for the whole test I used the following procedure. Using the proportions for each item described above, I calculated the average proportion of responses that were the same for test and retest. I then calculated the proportion that would be expected if participants were guessing, using the average number of options for each test and the 95% confidence interval of this proportion, and compared the average proportion to the confidence interval as before.

The results of all statistical measures for high school student and undergraduate participants are discussed in Chapter 6.

5.4 Summary

This chapter explained why I chose to develop a concept inventory for use as a large-scale data collection instrument for my study. It discussed the literature on concept inventory development and validation, and described the process I followed. It includes a description of the statistical measures I used to evaluate the CCCIs performance.

The results of the CCCI are reported in the following two chapters.

Chapter 6 contains the results of the statistical evaluation of the CCCI’s quality, i.e., how well the instrument performed as a measure of students’ understanding, and how well each item contributed to the performance of the instrument. This is important because it determines the degree to which students’ responses to the CCCI provide useful information about their conceptual understanding of the topic.

Chapter 7 presents the actual options chosen by the school students for each item, and discusses what can be inferred about their understanding of the concepts. Where two or more items addressed the same concept, I used
contingency tables to determine whether the students were consistent in their reasoning about the concept.

Chapter 8 describes the method used to analyse the post-trial focus group interviews, and discusses the results. As described in this chapter, post-trial interviews are commonly used in the validation of CIs because they provide another method of probing students’ understanding, and allow students to explain the reasoning behind their CI responses.
CHAPTER 6 – STATISTICAL MEASURES OF WHOLE-TEST AND ITEM PERFORMANCE FOR THE CCCI

In Chapter 5, Sections 5.2.9 and 5.2.10 listed a number of statistical measures used to evaluate the performance of CIs and the items that comprise them. This chapter presents the results of the statistical measures used to evaluate the performance of the Climate Change Concept Inventory (CCCI). As described in Chapter 5, I trialed the CCCI with two groups of participants: 229 high school students and 68 undergraduates.

Rationale for trialling CCCI with undergraduates

As discussed in Chapter 5, values for statistical measures are characteristic of the population being tested. Trialling the CCCI with a group of older students who had recently studied the topic provided an opportunity to carry out additional assessment of the performance of the CI. This is useful because poor values for statistical measures could be due either to the items being inherently faulty, or by a lack of firm ideas, whether correct or incorrect, among participants. If items were faulty, then values for statistical measures would also be poor for more knowledgeable students. Conversely, better CI performance with more knowledgeable students would suggest that the items were not inherently faulty but addressed concepts outside the knowledge base of the younger students.

In addition, climate change is increasingly being taught at early undergraduate level, including for non-science majors. The CCCI may be of use as a diagnostic instrument for such students; therefore collecting data with undergraduates is a useful first step towards its validation with this population.

6.1 Chapter outline

Table 6.1 summarises the structure of this chapter, including the statistical measures reported for the different groups.
Table 6.1: Structure of Chapter 6

<table>
<thead>
<tr>
<th>Section</th>
<th>Sub-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 6.2 - Brief explanation of statistical measures</td>
<td>Section 6.3.1 - Whole-test measures</td>
</tr>
<tr>
<td>Section 6.3 - Results for high school students</td>
<td>• Mean and standard deviation</td>
</tr>
<tr>
<td></td>
<td>• Cronbach’s alpha (test reliability)</td>
</tr>
<tr>
<td></td>
<td>• test-retest (test reliability)</td>
</tr>
<tr>
<td></td>
<td>• average item difficulty ($P_{average}$)</td>
</tr>
<tr>
<td></td>
<td>• average item discrimination ($D_{average}$)</td>
</tr>
<tr>
<td></td>
<td>• average point biserial coefficient ($r_{pbs,average}$)</td>
</tr>
<tr>
<td></td>
<td>• average number of informal responses (I.R. $average$)</td>
</tr>
<tr>
<td></td>
<td>Number and percentage of items which had $P$, $D$ and $r_{pbs}$ values outside the widest range recommended in literature</td>
</tr>
<tr>
<td>Section 6.3.2 - Discussion of values for whole-test measures</td>
<td></td>
</tr>
<tr>
<td>Section 6.3.3 - Individual item measures</td>
<td>• informal responses (I.R.)</td>
</tr>
<tr>
<td></td>
<td>• $P$</td>
</tr>
<tr>
<td></td>
<td>• $D_{30}$ and $D_{25}$</td>
</tr>
<tr>
<td></td>
<td>• $r_{pbs}$</td>
</tr>
<tr>
<td></td>
<td>• items with rarely chosen distractors</td>
</tr>
<tr>
<td>Section 6.3.4 - Estimation of item performance and discussion</td>
<td>• items rated according to $P$, $D$ and $r_{pbs,average}$ values</td>
</tr>
<tr>
<td></td>
<td>• Cronbach’s alpha for individual item reliability</td>
</tr>
<tr>
<td>Section 6.4 - Results for undergraduates</td>
<td>Section 6.4.1 - Whole-test measures</td>
</tr>
<tr>
<td></td>
<td>• Mean and standard deviation</td>
</tr>
<tr>
<td></td>
<td>• Cronbach’s alpha (test reliability)</td>
</tr>
<tr>
<td></td>
<td>• average item difficulty ($P_{average}$)</td>
</tr>
<tr>
<td></td>
<td>• average item discrimination ($D_{average}$)</td>
</tr>
<tr>
<td></td>
<td>• average point biserial coefficient ($r_{pbs,average}$)</td>
</tr>
<tr>
<td></td>
<td>• number of informal responses (I.R. $average$)</td>
</tr>
<tr>
<td></td>
<td>Number of items which had $P$, $D$ and $r_{pbs}$ values outside the widest range recommended in literature</td>
</tr>
<tr>
<td>Section 6.4.2 - Discussion of whole-test measures</td>
<td></td>
</tr>
<tr>
<td>Section 6.4.3 - Individual item measures for undergraduates</td>
<td>• I.R.</td>
</tr>
<tr>
<td></td>
<td>• $P$</td>
</tr>
<tr>
<td></td>
<td>• $D$</td>
</tr>
<tr>
<td></td>
<td>• $r_{pbs}$</td>
</tr>
<tr>
<td></td>
<td>• items with rarely chosen distractors</td>
</tr>
<tr>
<td>Section 6.4.4 - Estimation of item performance for undergraduates</td>
<td>• items rated according to $P$, $D$ and $r_{pbs,average}$ values</td>
</tr>
<tr>
<td></td>
<td>• Cronbach’s alpha for individual item reliability</td>
</tr>
<tr>
<td>Section 6.5 - Discussion and conclusions: comparison of performance of CCCI with school students and with undergraduates</td>
<td></td>
</tr>
</tbody>
</table>
6.2 Brief explanation of statistical measures

This section is a brief summary of statistical measures of CI performance calculated for the CCCI and reported in this chapter. They are described in detail in Appendix 5.

The whole-test measures provide an indication of the performance of the CCCI as an instrument. The individual measures assess how each item contributed to the overall performance of the CCCI. By grouping these according to the conceptual area they address, it is possible to determine whether there was any relationship between item performance and conceptual area.

As described in Appendix 5, Cronbach’s alpha is a measure of the correlation between the score for each item in a test, and the test as a whole. It is widely used to evaluate reliability for CIs. The Kuder-Richardson 20 formula (K-R 20) is equivalent to Cronbach’s alpha for items where the score is dichotomous, i.e., correct or incorrect. Both measures are considered to give conservative estimates of reliability for CIs, which typically cover a number of distinct concepts.

The method for evaluating the test-retest data was described in Section 5.3.5 and is summarised in Section 6.3.1 below.

Item difficulty (P) is the proportion of students answering an item correctly. It varies between zero and one.

Item discrimination (D) and point biserial coefficient (r_pbs) both measure the association between a student answering an item correctly and getting a high score for the entire CI. Highly discriminating items are more likely to be answered correctly by students with strong mastery of the topic, and incorrectly by students who understand the topic poorly. Low values of D or r_pbs indicate that items contribute little to discriminating between students of different ability, while negative values indicate that items are faulty. Ding et al. (2006) described advantages and limitations of different ways of calculating discrimination. According to these authors, D_{50} can...
underestimate discrimination, while \( D_{25} \) uses only data from the most consistent individuals but requires half of the dataset to be discarded. Therefore, I calculated both \( D \) measures in addition to \( r_{pbs} \).

Average values are useful in assessing the overall performance of the test (Ding et al. 2006), therefore I reported average values for \( D_{50} \), \( D_{25} \), \( r_{pbs} \) and number of informal responses.

Any item which did not have exactly one response selected was deemed “informal” (I.R.). I instructed participants to leave items blank in preference to answering randomly if they were unable to make at least an educated guess about the correct answer. The intention of this was to minimise randomly chosen, i.e., meaningless answers and also to indicate questions for which participants found it difficult to choose any answer. Therefore, some participants did not choose a response to some items, while a few participants selected more than one response for some questions. In order to calculate statistical measures for individual items, the number of formal responses was calculated for each question, e.g., the difficulty (\( P \)) for each item was the number of correct responses divided by the total number of formal responses.

**6.3 Results for high school students**

**6.3.1 Whole-test measures for high school students**

Table 6.2 presents the results for the CCCI trial with 229 high school students in Years 9 and 10. It also shows the widest range of acceptable values reported in literature for Cronbach’s alpha, \( P \), \( D \) and \( r_{pbs} \). These ranges were discussed in Section 5.2.9. The data are tabulated in Table A5.1 of Appendix 5.

The mean score on the CCCI with high school students was 7.5 (28%) and the standard deviation was 2.7. No recommended values for these quantities are cited in the literature. Note that average \( P \) in Table 6.2 is not the same as mean score, because \( P \) values were calculated based on formal responses only.
Table 6.2: Values for statistical measures of whole-test performance of CCCI with school students, and widest recommended ranges described in literature

<table>
<thead>
<tr>
<th>Measure</th>
<th>Values for school students</th>
<th>Widest recommended range/95% confidence interval for test-retest data</th>
<th>Number and percentage of items outside recommended range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cronbach’s alpha</td>
<td>0.4255</td>
<td>0.6-0.8 sufficient for classroom tests (Oosterhof 1996; cited in Allen 2006)</td>
<td>N/A</td>
</tr>
<tr>
<td>Test-retest</td>
<td>0.562</td>
<td>0.1518 to 0.4618 (see method for evaluation of test-retest data)</td>
<td>3 (11%)</td>
</tr>
<tr>
<td>$P_{\text{average}}$</td>
<td>0.28</td>
<td>0.5-0.63 (Anderson et al. 2002; Ding et al. 2006)</td>
<td>12 (44%)</td>
</tr>
<tr>
<td>$D_{50\text{average}}$</td>
<td>0.18</td>
<td>&gt;0.24 (Thorndyke 1999; cited in Streveler et al. 2011)</td>
<td>18 (67%)</td>
</tr>
<tr>
<td>$D_{25\text{average}}$</td>
<td>0.19</td>
<td>&gt;0.24 (Thorndyke 1999; cited in Streveler et al. 2011)</td>
<td>18 (67%)</td>
</tr>
<tr>
<td>$r_{\text{pbs average}}$</td>
<td>0.247</td>
<td>&gt;=0.2 (Ding et al. 2006)</td>
<td>9 (33%)</td>
</tr>
<tr>
<td>Ave. no. informal responses (I.R. average)</td>
<td>6 (2.7%)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Method for evaluation of test-retest data

Thirty-four students participated in retests early in Term 4, 2011. As they had originally completed the concept inventory in Weeks 8-10 of Term 3, this timing minimised the likelihood of their participating in any lessons on the topic in the intervening time, while still allowing some time between test and retest, to minimise remembering of responses. The concept inventory was identical for test and retest.

A paired t-test was carried out to determine whether participants had scored significantly better on the retest. There was no statistically significant difference between participants’ total scores for test and retest ($t = -1.4, p = 0.16$). This suggests that participants’ knowledge of the topic had not improved in the time between test and retest.

To assess reliability for each item I determined whether each student had chosen the same response for test and retest, whether or not their answers
were correct. The probability that a student would choose the same item each time by chance on a three item scale would be 0.33, for a four item scale 0.25 and 0.2 for five items. Taking this as the probability of success, the binomial distribution can be used to calculate the 95% confidence interval of the proportion. If the proportion of students who gave the same response both times exceeded the upper bound of the 95% confidence interval then it can be concluded that the test-retest group were not guessing. The results for this are presented in Table 6.3. For each item number of options, the corresponding 95% confidence interval for choosing the same option twice by chance, the actual proportion of students choosing the same option twice and the statistical significance of this, based on the 95% confidence interval, are shown.

Three of the items had values within the 95% confidence interval, i.e., for these items the test-retest similarity was not significantly better than if responses had been chosen randomly.

To give an estimate for the whole test I calculated the average proportion of responses that were the same for test-retest for each item, and the expected proportion if participants were guessing, using the average number of options in the CCCI. This was 3.26, so the reciprocal of 3.26, i.e., 0.307, is the proportion of identical responses expected if responses were chosen at random. Therefore the 95% confidence interval of the binomial proportion in this case is 0.1518 to 0.4618.

The observed average proportion for the CCCI is 0.562. This lies outside the 95% confidence interval of 0.1518 to 0.4618, i.e., there is less than 5% probability that the correspondence between participants’ test and retest choices is due to participants choosing answers at random. Because the observed proportion is well outside the 95% confidence interval, I calculated wider confidence intervals in order to obtain a more sensitive measure of the probability of the observed results being due to students making random choices. The observed average proportion lies outside the 99.5% confidence interval of 0.085 – 0.53, i.e., there is a less than 0.5% chance of the students having chosen answers at random.
Table 6.3: High school students’ test-retest reliability data for individual items

<table>
<thead>
<tr>
<th>Item</th>
<th>No. of options</th>
<th>95% confidence interval</th>
<th>Actual proportion of same responses</th>
<th>Significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.529</td>
<td>YES</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.706</td>
<td>YES</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.735</td>
<td>YES</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.647</td>
<td>YES</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.588</td>
<td>YES</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.588</td>
<td>YES</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.647</td>
<td>YES</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.5</td>
<td>YES</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.5</td>
<td>YES</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>0.1045-0.3955</td>
<td>0.618</td>
<td>YES</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.529</td>
<td>YES</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.529</td>
<td>YES</td>
</tr>
<tr>
<td>13</td>
<td>4</td>
<td>0.1045-0.3955</td>
<td>0.471</td>
<td>YES</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>0.1045-0.3955</td>
<td>0.618</td>
<td>YES</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.588</td>
<td>YES</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.382</td>
<td>NO</td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.647</td>
<td>YES</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>0.1045-0.3955</td>
<td>0.559</td>
<td>YES</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.559</td>
<td>YES</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.529</td>
<td>YES</td>
</tr>
<tr>
<td>21</td>
<td>5</td>
<td>0.06555-0.3345</td>
<td>0.353</td>
<td>YES</td>
</tr>
<tr>
<td>22</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.706</td>
<td>YES</td>
</tr>
<tr>
<td>23</td>
<td>4</td>
<td>0.1045-0.3955</td>
<td>0.441</td>
<td>YES</td>
</tr>
<tr>
<td>24</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.441</td>
<td>NO</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.676</td>
<td>YES</td>
</tr>
<tr>
<td>26</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.588</td>
<td>YES</td>
</tr>
<tr>
<td>27</td>
<td>3</td>
<td>0.1749-0.4918</td>
<td>0.412</td>
<td>NO</td>
</tr>
</tbody>
</table>

6.3.2 Discussion of values for whole-test measures

The value of Cronbach’s alpha for high school students was 0.4255. The minimum acceptable value cited by most CI researchers is 0.7, although Oosterhof (1996; cited in Allen 2006) considered 0.6-0.8 as an acceptable range for classroom tests. Similarly, Grolund (1993; cited in Anderson et al.
2002) gave 0.6 as a minimum acceptable value for Kuder-Richardson 20, which is equivalent to Cronbach’s alpha for dichotomous data. Therefore the CCCI did not meet the minimum acceptable value for reliability with high school students, as measured using Cronbach’s alpha.

However, Miller (1995) explained that for CIs, which tend not to be homogeneous, tests of internal consistency such as Cronbach’s alpha, can seriously underestimate reliability (as discussed in Chapter 5). Additionally, because Cronbach’s alpha characterises responses dichotomously, i.e., as either correct or incorrect, it discards information about which distractors were chosen. Because the high school participants’ scores were low, the amount of information discarded would have been high. This information is important because, as is discussed in Chapter 7, the high school students were often consistent in their choice of incorrect responses.

The test-retest data indicate a less than 0.5% chance that the participants chose the same answer twice by chance. The data also show no statistically significant difference between test and retest scores, i.e., there was no statistical evidence that the participants had learned new information about the topic between test and retest.

The test-retest results suggest that the CCCI has acceptable reliability with high school students. This is consistent with the previous suggestion that Cronbach’s alpha underestimated reliability for the CCCI. This could be due to the CCCI being heterogeneous (Miller 1995). Gray et al. (2005) described Cronbach’s alpha and Kuder-Richardson 20 as conservative estimates of test reliability. Another cause could be the high school students’ low scores resulting in loss of information, because for Cronbach’s alpha all distractor choices are assigned a value of 0, so the test does not differentiate between students’ choice of distractors. It is also possible that the high school students’ lack of firm conceptual models resulted in their reasoning inconsistently when answering items that addressed the same concepts.
Twelve items had difficulty P, below 0.2 meaning that, for school students, almost half the test items are more difficult than the literature recommends. However, the concepts covered were derived from a process (Delphi study and literature review, described in Chapter 4) designed to identify concepts important to a basic understanding of the topic. Therefore, rather than the items being poorly designed, these P values might indicate that the high school students are unfamiliar with many of the concepts identified as important. Only one item, at 0.81 is above Bardar et al.’s (2006) suggested maximum of 0.8, and none is above Ding et al.’s (2006) suggested maximum of 0.9. Therefore none of the items is excessively easy.

Although average values for discrimination, $D_{50}$ and $D_{25}$ were both below the lowest recommended value, the average point biserial coefficient, $r_{pbs}$ was above its minimum acceptable value. This suggests that the CI as a whole performed to some degree in discriminating between students with poor and good understanding of the topic. In addition, none of the D or $r_{pbs}$ values were negative, suggesting that none of the items is seriously defective.

Informal responses (I.R.) included “I don’t know”, “Not sure” and no responses selected, as well as a smaller proportion of responses indicating some measure of knowledge, e.g., “not C” or “A or B”. None of the identified literature on CI evaluation discusses informal responses; however they may give additional insight into problematic items because students were specifically asked to leave an item blank if their only alternative was guessing.

### 6.3.3 Individual item measures for school students

This section reports statistical measures for individual items, grouped according to the key concepts they address, as described and numbered in Table 5.9. This enables assessment of overall item performance through consideration of P, D and $r_{pbs}$. Also reported are the presence of rarely chosen distractors, and the number of informal responses (I.R.), an indication that students were not able to make a non-random choice.
By grouping the items according to the conceptual areas they address, it is possible to explore whether some conceptual areas had better performing items than others. This issue is important because poor item performance might be due to students not having firm ideas, whether correct or incorrect, about a concept. Rather, their conceptual understanding could be described as tentative and context dependent.

Table 6.4 summarises the ranges of individual item measures, along with the widest recommended ranges in the literature.

**Table 6.4: Individual item measures for school students – ranges of values and widest ranges recommended in literature**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Range</th>
<th>(school students)</th>
<th>Widest recommended range</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.R.</td>
<td>1-13</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.08 – 0.81</td>
<td>0.2-0.9 (Bardar et al. 2006; Ding et al. 2006)</td>
<td></td>
</tr>
<tr>
<td>$D_{50}$</td>
<td>0.04 – 0.35</td>
<td>&gt;0.24 (Thorndyke 1999)</td>
<td></td>
</tr>
<tr>
<td>$D_{25}$</td>
<td>0.02 – 0.39</td>
<td>&gt;0.24 (Thorndyke 1999; cited in Streveler et al. 2011)</td>
<td></td>
</tr>
<tr>
<td>$r_{pbs}$</td>
<td>0.0375 – 0.465</td>
<td>Few items with $r_{pbs}$&lt;0.2 (Ding et al. 2006)</td>
<td></td>
</tr>
</tbody>
</table>

Figures 6.1 to 6.5 show the values for informal responses, item difficulty, $D_{50}$, $D_{25}$ and $r_{pbs}$. The black lines on Figures 6.2 to 6.5 indicate the widest acceptable limits for these values reported in literature. Figures 6.6 to 6.10, which present the corresponding data for undergraduates, are shown at the same scales as Figures 6.1 to 6.5, for ease of comparison.
Figure 6.1: Informal responses for school students

Figure 6.2: Item difficulty values for school students

Figure 6.3: Item discrimination D50 values for schools
Figure 6.4: Item discrimination D25 values for schools

Figure 6.5: Item point biserial coefficient values for schools

*Items with rarely chosen distractors*

Smith et al. (2008) recommended rewording “rarely chosen distractors” (p.423), however they did not define “rarely chosen”. I chose <5% to define “rarely chosen”. This is because the highest acceptable value for item difficulty is 0.9; this would leave 10% of students choosing distractors. For items with three options these 10% of students would be choosing between two items, so 5% is a conservative limit for “rarely chosen”.

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Two items had distractors that were chosen by less than 5% of high school participants: 11C (4%) and 21C (4%). These items are shown below, with percentage of responses in brackets and correct responses underlined:

11. Greenhouse gases cause the Earth to warm up because:
   A  they let heat rays in but don’t let them out (36%)
   B  they allow the Sun’s rays in but they absorb rays coming from the Earth (11%)
   C  they interact with all types of electromagnetic rays (e.g., infrared, ultra-violet and visible light), creating heat (4%)
   D  they damage the ozone layer so more ultra-violet rays get in and heat up the Earth (48%)

21. What type of energy do all greenhouse gases interact with?
   A  infrared rays (12%)
   B  ultra-violet rays (19%)
   C  visible light (4%)
   D  more than one of the above (51%)
   E  none of the above (9%)

As both these items contain more than three options, it is possible in future research to remove the rarely chosen distractors. This might improve the performance of these items (described in Section 6.3.4).

6.3.4 Estimation of item performance for high school students and discussion

In order to give an overall estimate of item performance, I considered whether P, D_{25} and r_{pbs} were within the widest range recommended in literature and if not, how far short they fell. I chose D_{25} values for this estimation rather than D_{50}, because including both D values would place excess weighting on this measure of performance, and according to Ding et al. (2006), D_{50} values can underestimate discrimination. I flagged measures yellow if they were below the recommended range but greater than 0.1, and pink if they were less than 0.1. Appendix 5 presents the P, D_{25}, D_{50}, r_{pbs} (with associated p value) and number of informal responses (I.R.) in
tabulated form, with values outside recommended ranges flagged, as described in Section 6.3.4 below.

I scored the items on a scale of α - ε where:

**α** (excellent) all measures within recommended range (D>0.24, 0.2>P>0.8, $r_{pbs}>0.2$)

**β** (good) one measure flagged yellow

**γ** (acceptable) two measures flagged yellow

**δ** (borderline) three measures flagged yellow or P flagged pink

**ε** (unacceptable) any measures other than P flagged pink

The results are shown in Table 6.5. The numbers shown for each rating are the actual item numbers.

<table>
<thead>
<tr>
<th>Conceptual area</th>
<th>α</th>
<th>β</th>
<th>γ</th>
<th>δ</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Carbon cycle and fossil fuels</td>
<td>2,5,12,22</td>
<td>3</td>
<td>1,13</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2 Electromagnetic spectrum (e.m.s.)</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Interactions between GHG and electromagnetic radiation</td>
<td>16,11,21</td>
<td></td>
<td></td>
<td>15,18,23</td>
<td></td>
</tr>
<tr>
<td>4 Proportions of GHG and non-GHG</td>
<td>9</td>
<td>10,19</td>
<td></td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>5 Feedback</td>
<td>25,27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Equilibrium of energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7,20</td>
</tr>
<tr>
<td>7 Conservation of energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

I considered P values outside the required range less problematic than D or $r_{pbs}$. This is because an item might be too difficult because of a high rate of misconceptions among the population trialing the CI, rather than the
question being inherently faulty. However, an item with very low or even negative D or \( r_{pbs} \) values is more likely to be inherently faulty because a large percentage of students who otherwise demonstrated weak understanding of the topic, chose the correct response for that item. There does not appear to be any relationship between poorly performing items and large numbers of informal responses. When item performance was compared with conceptual area, some patterns emerged.

Conceptual area 1: *The carbon cycle and fossil fuels* performed well: although one of its eight items was rated “borderline, half were rated “excellent”.

Conceptual area 2: *The electromagnetic spectrum* performed poorly, with two items “unacceptable” and one “acceptable”. It contained two of the three most problematic items in the CI. The least problematic item in this area, item 24, asked about a laboratory experiment rather than the Earth or Sun. It is likely that some participants had experienced a similar activity at school and therefore had some direct experience on which to draw.

Conceptual area 3: *Interactions between greenhouse (GH) gases and electromagnetic radiation* performed poorly. Half of the six items were rated “unacceptable” and none of the items in this area performed well.

Conceptual area 4: *Proportions of greenhouse and non-greenhouse gases in the atmosphere* performed well, with one item rated “excellent”, two rated “good” and one rated “acceptable”.

Conceptual area 5: *Feedback* performed best, with only one measure outside the required range. However these questions do not require students to articulate the reason for their choice of answer. Focus group data was sought to confirm that participants chose their responses for the expected reasons. Another possible approach would be to create one or more items in which the options include reasons. Item 22 has this format:
22. The total amount of carbon on Earth, including its atmosphere, since the planet first formed has
A  remained constant for most of the time but is increasing now that fossil fuels are being burned
B  slowly decreased because when carbon dioxide absorbs heat, it rises and escapes from the atmosphere
C  stayed the same because burning fossil fuels doesn’t affect the total amount of carbon on Earth

Conceptual area 6: Equilibrium of energy. The two items, which asked about the Earth’s energy balance in abstract terms performed poorly. They also had very different difficulty values.

Conceptual area 7: Conservation of energy contained only one item, which performed excellently. It asked about a situation of which students had direct experience. This is similar to item 24 in area 2.

Poor statistical performance, as suggested above, may result from school students having tentative mental models of the concepts being tested. There was evidence for this in focus group sessions, when participants contradicted themselves; and, when asked to explain the relationship between two ideas they had articulated or to follow through a line of reasoning, stated that they were confused. This may have led to their choosing inconsistent responses to items on related concepts. I explored this further by trialling the CCCI with a group of undergraduates who had recently completed a unit of study on the topic. These results are discussed in the following sections of this chapter.

Further, the most problematic items were those addressing concepts not rated highly by Delphi participants. They were included because of their consistent appearance in literature and the incidence of misconceptions relating to them. It may be necessary to simplify the physics-related explanations for interactions between greenhouse gases and radiation. For example, one Delphi participant described the analogy of layers of blankets trapping the heat emitted by a person. This at least addresses the ozone-layer misconception. However, very simple explanations can cause confusion for more able students e.g. why most of the infrared radiation
emitted from the Sun does not interact with greenhouse gases but most of the infrared radiation emitted from the Earth does.

Quality of items with graphics was generally low: 1γ, 6ε, 8δ, 13γ. However, evidence for participants’ understanding of the graphics was sought during pre- and post-trial focus groups and there was no indication that participants found the diagrams confusing. Therefore it is likely that these items performed poorly for other reasons.

*Cronbach’s alpha for individual item reliability*

Allen et al. (2004) used Cronbach’s alpha to estimate the reliability of individual items, deleting one item at a time from the CI and calculating Cronbach’s alpha for the remainder of the test. Reliable questions, when deleted, resulted in lower Cronbach’s alpha values for the remaining items. Values of this measure for the CCCI with high school students, are shown in Table A5.2 in Appendix 5.

Comparing this estimate of item reliability with the estimate of item performance in Table 6.5 shows a general trend for items that performed well to also be reliable, while items that performed poorly or unacceptably are unreliable, according to this measure.

For example, the items that contributed most strongly to reliability were 3, 5, 9, 10, 12, 22, 25 and 27. All of these items had either “excellent” or “good” performance. All “excellent” items, when deleted, resulted in lower alpha values, indicating that they contributed positively to reliability, and of the “good” items, only item 19 resulted in a higher value. Conversely, all the items whose performance was “borderline” or “unacceptable” (6, 7, 14, 15, 18, 20, 23) resulted in higher alpha values when deleted, indicating that they contributed least to total test reliability.

Note: Calculating Cronbach’s alpha to determine the reliability of conceptual areas is not possible, because alpha increases as test length increases. As the conceptual areas contain different numbers of items, their alpha values cannot be directly compared.
6.4 Results for undergraduates

A total of 68 undergraduates, enrolled in a level one unit of study on climate change, took part in the first field trial of the concept inventory. They completed the CCCI on paper, as did the high school students, during the last half-hour of their final tutorial. Although this group was only a third as large as the high school group, it was still large enough to have statistical power (Howell 2002).

6.4.1 Whole-test measures for undergraduates

The mean score for undergraduates was 13.5 (50%) and the standard deviation was 4.714.

The results for whole-tests statistical measures are summarised in Table 6.6. Note that average P was higher than average score because informal responses were not counted in determination of P values.

Table 6.6: Values for statistical measures of whole-test performance of CCCI with undergraduates, and widest recommended ranges described in literature

<table>
<thead>
<tr>
<th>Measure</th>
<th>Values for undergraduates</th>
<th>Widest recommended range</th>
<th>Number and percentage of items outside recommended range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cronbach’s alpha</td>
<td>0.7656</td>
<td>0.6-0.8</td>
<td>N/A</td>
</tr>
<tr>
<td>P(_{\text{average}})</td>
<td>0.51</td>
<td>0.5-0.63</td>
<td>2 (7%)</td>
</tr>
<tr>
<td>D(_{\text{50average}})</td>
<td>0.21</td>
<td>&gt;0.24</td>
<td>67%</td>
</tr>
<tr>
<td>D(_{\text{25average}})</td>
<td>0.35</td>
<td>&gt;0.24</td>
<td>5 (18%)</td>
</tr>
<tr>
<td>r(_{p,k\text{average}})</td>
<td>0.37</td>
<td>&gt;=0.2</td>
<td>1 (4%)</td>
</tr>
<tr>
<td>I.R.-average</td>
<td>1.8</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

6.4.2 Discussion of whole-test measures

Cronbach’s alpha for undergraduates, at 0.7656 was well above the minimum acceptable value of 0.6, and as Cronbach’s alpha is considered a conservative estimate of reliability for CIs, this suggests that for the undergraduate group, the test was reliable. It was also considerably higher
than for the school students. This result lends credibility to the idea that the low Cronbach’s alpha result for high school participants was due to their lack of familiarity with the concepts, because the undergraduates, having just completed a unit of study on climate change, would have been more familiar with most of the concepts.

It was not possible to collect test-retest data for the undergraduates.

The number of informal responses was strongly related to item number. All items had either zero or one informal responses until item 18. After item 18 the average number of informal responses was four. This suggests that students became fatigued, or ran out of time to complete the CI. This trend was not observed with the high school students.

6.4.3 Individual item measures for undergraduates

This section reports statistical measures for individual items, set out in the same way as for the high school student data. Table 6.7 summarises the individual item statistics while Figures 6.6 to 6.10 show the values for informal responses, item difficulty, \( D_{50} \), \( D_{25} \) and \( r_{pbs} \). As before, the black lines on the figures indicate the widest acceptable limits for these values reported in literature.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Range of values for undergraduates</th>
<th>Widest recommended range</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.R.</td>
<td>0-7</td>
<td>N/A</td>
</tr>
<tr>
<td>P</td>
<td>0.11 – 0.87</td>
<td>0.2–0.9</td>
</tr>
<tr>
<td>( D_{50} )</td>
<td>0.00 – 0.53</td>
<td>&gt;0.24</td>
</tr>
<tr>
<td>( D_{25} )</td>
<td>0.06 – 0.63</td>
<td>&gt;0.24</td>
</tr>
<tr>
<td>( r_{pbs} )</td>
<td>0.0309 – 0.6293</td>
<td>Few items should have ( r_{pbs} &lt; 0.2 )</td>
</tr>
</tbody>
</table>
Figure 6.6: Informal responses for undergraduates

Figure 6.7: Item difficulty values for undergraduates

Figure 6.8: Item discrimination D50 values for undergraduates
Figure 6.9: Item discrimination D25 values for undergraduates

Figure 6.10: Item point biserial coefficient values for undergraduates
Rarely chosen distractors

With the undergraduates, a larger number of items had rarely-chosen options, i.e., <5% of responses as described in Section 6.3.3. These were:

2C (3.1%); 3B (4.7%); 10B (0%); 11C (4.7%); 13C (4.7%); 14A (4.7%); 21C (3.1%); 22B (4.7%); 25C (3.1%).

Note that 11C and 21C were also chosen by fewer than 5% of high school students. This lends credibility to the idea that these distractors are either superfluous or not plausible, and could be removed. Two possible reasons for the larger number of items with rarely-chosen distractors among undergraduates are the smaller sample size for undergraduates, and lower prevalence of certain misconceptions among this group. As described in Section 6.3.3, I did not find any recommended values for rarely-chosen distractors in the literature, and so derived a conservative value. Therefore, most of the items listed above do not necessarily require revision for use with undergraduates, and none of the items listed above performed poorly (see Section 6.4.4 below).

6.4.4 Estimation of item performance for undergraduates and discussion

I determined item quality for undergraduates in the same way as for high school students. The results are shown in Table 6.8 and the tabulated data is presented in Appendix 5. Although nearly all items performed better with undergraduates, the patterns of item performance for the seven conceptual areas with school students can still be discerned in the results for undergraduates. For example, conceptual areas one, four, five and seven performed best, while areas two and three performed less well.

In addition, differences in performance within groups persisted. For example, in area two, item 24 performed better than item six, which was the poorest-performing item with both groups. Similarly, in area three, items 15 and 23 performed more poorly than items 11, 16 and 21.
Table 6.8: Item performance ratings for undergraduates

<table>
<thead>
<tr>
<th>Conceptual area</th>
<th>α</th>
<th>β</th>
<th>γ</th>
<th>δ</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Carbon cycle and fossil fuels</td>
<td>1,2,3,5,8,12,13,22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Electromagnetic spectrum (e.m.s.)</td>
<td>24</td>
<td>14</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>3 Interactions between GHG and electromagnetic radiation</td>
<td>11,16,18,21</td>
<td>23</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Proportions of GHG and non-GHG</td>
<td>9,10,17,19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Feedback</td>
<td>25</td>
<td>26,27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Equilibrium of energy</td>
<td>7,20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Conservation of energy</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

However, items seven and 20 in area six, which had both been “unacceptable” with school students, were rated “excellent” with undergraduates.

*Cronbach’s alpha for individual item reliability*

As with the high school student data, I deleted one item at a time from the CI and calculated the alpha value for the remainder, in order to give an indication of how each item contributed to overall reliability. The data are shown in Table A5.4 of Appendix 5.

As with the results for high school students, there was a tendency for items that performed well also to be reliable, while items that performed poorly or unacceptably were unreliable, according to this measure. However, this was much less marked than with the high school students’ results. There was also less variation in the results for undergraduates.

**6.5 Discussion and conclusions: comparison of results for school students and undergraduates**

Measures of whole-test reliability were variable. Cronbach’s alpha for the undergraduate group was well above the minimum value recommended in literature, but for high school students the value was well below this value.
However, the high school students’ test-retest data indicated a less than 0.5% chance of participants having chosen responses at random. I suggest that the low vales for Cronbach’s alpha with high school students were most likely due to the low scores for these students and the resulting loss of information described in Section 6.3.2, or to tentative conceptual models among this group, resulting in inconsistent reasoning. The following chapter addresses this issue by examining how consistent the high school students were in their responses to items addressing the same concepts.

All statistical measures of item performance were better with the undergraduate group than with the high school students, with the exception on item 27, which was rated “good” for undergraduates. With the school students, eight items were rated “excellent”, four were “good”, seven were “acceptable”, one was “borderline” and seven were “unacceptable”. With the undergraduates, twenty-one items were rated “excellent”, four were “good” and one, item 15 was “acceptable”. No items were “borderline” and only item six was “unacceptable”.

Of the seven items rated “unacceptable” with school students, improvements were variable. Items seven, 18 and 20 became “excellent” with undergraduates, items 14 and 23 became “good”, 15 became “acceptable” and item six remained “unacceptable”. It can be concluded that items six and possibly 15 are intrinsically problematic and require revision. The performance of the rest of the items, and the test as a whole, with undergraduates suggests that apart from items six and possibly 15, the CCCI is of acceptable quality.

It can therefore be concluded that the poorer item and test performance among high school students was due to high rates of misconceptions and/or tentative conceptual models among this group, rather than faulty items. In the following chapter, the high school students’ item choices are used to draw inferences about their conceptual understanding. The just-acceptable performance of the CCCI with this group means that their responses require corroboration. This is achieved in two ways. First, I used contingency tables to examine how consistent the students were in reasoning about concepts.
Second, a subset of participating high school students took part in focus group interviews following the CCCI trial to discuss their understanding of the concepts in detail. The findings of these interviews are analysed in Chapter 8.
CHAPTER 7 – CCCI ITEM RESPONSE ANALYSIS FOR HIGH SCHOOL STUDENTS

This chapter, and Chapter 8 both address Research Question two:

What do NSW Stage 5 students understand about the scientific conceptual knowledge required to comprehend the mechanism of climate change?

This chapter presents the high school students’ responses to the CCCI and discusses the data. Chapter 8 discusses focus group data.

Abbreviations used in this chapter

IR = infrared
UV = ultraviolet
GHG = greenhouse gas
e.m.s. = electromagnetic spectrum
e.m.r. = electromagnetic radiation
CO$_2$ = carbon dioxide

7.1 Chapter outline

Table 7.1 summarises the structure of the rest of this chapter.

Table 7.1: Structure of Chapter 7

<table>
<thead>
<tr>
<th>Section</th>
<th>Contents</th>
</tr>
</thead>
</table>
| 7.2 - Item response analysis part 1: individual items | Items grouped by conceptual area
  • for each item, the item text is shown as it appeared in the CI, along with frequency of option choices presented in histogram format
  • discussion of models of conceptual understanding inferred from item responses
  • summary of findings for each conceptual area. |
| 7.3 - Item response analysis part 2: contingency tables for item pairs | • examination of the degree to which students responded consistently to items which address the same concepts
  • evidence for associations between related ideas
  • discussion of conceptual models inferred from contingency table findings |
| 7.4 - Conclusions | Summary of inferred conceptual models, prevalence and strength of evidence |
In Section 7.2, item response distributions are presented in histogram format along with the full item text and diagrams for ease of interpretation. Response distributions are discussed and findings summarised for each conceptual area. Section 7.3 discusses findings from contingency tables for pairs of items that address the same concepts, to determine the degree to which participants were consistent in in their reasoning. The contingency tables are shown in full in Appendix 6. Section 7.4 summarises the findings from the previous two sections, and discusses the findings with reference to the performance, as derived in Chapter 6, of the items used to derive each finding.

### 7.2 Item response analysis part 1: individual items

Item response analysis involves analysing what participants’ option choices imply about their understanding of the concepts addressed (Bodzin 2011). In this section, items are grouped in the same conceptual areas as in Chapters 5 and 6. For each item, the number and percentage of participants choosing each option is given, and illustrated, in a histogram. Correct options are in bold.

#### 7.2.1 Conceptual area 1 – carbon cycle and fossil fuels – items 1, 2, 3, 5, 8, 12, 13 and 22

*Conceptual area 1a – There is a fixed amount of carbon on Earth. Items 3 and 22*

3. Over time since the Earth first formed until now, the total amount of carbon on the planet, including its atmosphere, has:

- **A** increased 172, 75%
- **B** decreased 18, 8%
- **C** stayed the same 36, 16%
22. The total amount of carbon on Earth, including its atmosphere, since the planet first formed has

A  remained constant for most of the time but is increasing now that fossil fuels are being burned 156, 68%
B  slowly decreased because when carbon dioxide absorbs heat, it rises and escapes from the atmosphere 21, 9%
C  stayed the same because burning fossil fuels doesn’t affect the total amount of carbon on Earth 44, 19%

Discussion of conceptual area 1a

Responses to item 3 suggest that 75% of students believe the amount of carbon on Earth is not fixed, but is increasing over time. Item 22 also asks about the amount of carbon on Earth but gives reasons for choices. Slightly fewer students (68%) chose response 22A (increasing carbon) and slightly more (19% as opposed to 16%) chose 22C (constant carbon). The explanation given in 22C might have made this option more convincing.

A possible confounding factor is that the students might have misinterpreted these two items, thinking that they referred to the amount of carbon in the atmosphere and not the planet as a whole. These items were re-worded after the first round of focus groups to make this clearer, but this might not have been sufficient. Further, the results of item 1, discussed below, suggest that 40% of students thought of carbon as existing primarily in the atmosphere. Therefore the emphasis on “the planet, including its atmosphere” in items three and 22 may have further prompted them to focus on the Earth’s atmosphere rather than the Earth as a whole.
Conceptual area 1b - it is cycled among the atmosphere, biosphere, soils, ocean and rocks. Item 1.

1. Most of the Earth’s carbon is in rocks. Which of the following images BEST represents the relative amounts of carbon in the other parts of the Earth? (larger circle = more carbon)

1C is the correct response.

Discussion of conceptual area 1b

A and B were equally popular choices. Option A shows the majority of the Earth’s carbon in the atmosphere while B shows more carbon in living things than in the atmosphere. It is possible that option A appealed to students who think of carbon primarily as carbon dioxide, while option B appealed to students who have an appreciation of the carbon cycle and the existence of carbon in biomass. Therefore, choosing B would indicate a more sophisticated understanding of the carbon cycle. However, both A and B show oceans as a minor carbon reservoir. Only 17% chose the correct option, C. This suggests that most students do not appreciate the importance of the oceans as a reservoir of carbon, and may not think of oceans as containing carbon.
Conceptual area 1c - There are both natural and human-induced sources and sinks of greenhouse gases. Items 2, 8 and 12.

2. When plants make new roots, stems and leaves, where do they get the carbon from?

A  they absorb it from the air  
   89, 39%

B  they absorb it from the soil  
   88, 38%

C  they convert the Sun’s energy into new carbon atoms which didn’t exist before  
   49, 21%

8. Which of the following diagrams BEST shows movement of carbon into, and out of the atmosphere? (The WIDER the arrows, the MORE carbon is moved in or out).

8A is the correct response.
12. Carbon dioxide can be removed from the atmosphere by plants, through photosynthesis. What OTHER ways can it be removed from the atmosphere?

A when rocks such as limestone form AND escaping from the atmosphere into space 55, 24%

B by dissolving in water AND escaping from the atmosphere into space 61, 27%

C when rocks such as limestone form AND dissolving in water 106, 46%

Discussion of conceptual area 1c

Roughly equal numbers of students thought that plants get carbon from air and soil (item 2). 39% correctly identified the atmosphere as plants’ carbon source. However, 40% of students thought that most of the Earth’s carbon is in the atmosphere (item 1): these students may not think of plants as containing significant amounts of carbon. 21% of students thought that new carbon atoms are created through photosynthesis, suggesting confusion about the process.

Item 8 responses suggest that 90% of students overestimate the proportion of carbon released by fossil fuel burning compared to natural sources, and 46% underestimate the role of oceans in the carbon cycle. Roughly equal numbers of students chose option B, which shows oceans as playing a significant role in carbon flows and option C, which does not. This contrasted with item 1 where the correct option, with oceans as the largest reservoir, was chosen by only 17% of participants. These findings raise the question of how students conceptualise the oceans, and water in general, as a carbon reservoir. This issue is explored in Section 7.3 and in Chapter 8.
Almost half of students, the largest proportion, chose the correct response for item 12. However, over 50% chose options that involved the idea of carbon dioxide escaping into space.

Conceptual area 1d - Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle. Item 13

13. What effect did the process of fossil-fuel formation have on the amount of carbon dioxide in the atmosphere?

A  it decreased the amount of carbon dioxide in the atmosphere 37, 16%
B  it did not change the amount of carbon dioxide in the atmosphere 68, 30%
C  the fossil fuels were formed when the Earth formed, and it didn’t yet have an atmosphere 19, 8%
D  it increased the amount of carbon dioxide in the atmosphere 103, 45%
Discussion of conceptual area 1d

45% of students believe that fossil fuel formation increased CO$_2$ in the atmosphere. This is in spite of information provided in the item stem showing the role of plant growth in fossil fuel formation. Taken with findings that 61% of students do not appreciate that growing plants absorb CO$_2$ from the atmosphere (item 2), this might explain why, in item 13, the process of fossil fuel formation was not seen by most students as reducing atmospheric CO$_2$.

It is also possible the that students have a limited understanding of the origins of fossil fuels, or were making a “snap association” between fossil fuels and an increase in atmospheric CO$_2$, i.e., without having a conceptualised reason for this association.

Only 8% of students thought that fossil fuels formed when the Earth first formed, suggesting that either they were prompted by information in the diagram, or that most students were already aware to some degree, that fossil fuels were formed from living things. For example, they may be aware that fossil fuels formed from vegetation, but may not understand how carbon moved between reservoirs in the carbon cycle during this process.

Conceptual area 1e - Burning fossil fuels returns this carbon to the cycle.

Item 5

5. When fossil fuels are burned, carbon is added to the atmosphere. Where did this carbon originally come from?

A it was created when the fossil fuels were burned – it did not exist before 69, 30%

B it was in the Earth but had never been in the atmosphere before 112, 49%

C it was in the atmosphere a long time ago 45, 20%
Discussion of conceptual area 1e

49% of students thought that carbon released by fossil fuel burning had never been in the atmosphere before, but they did not believe the process of burning created it. These students might think of the carbon in fossil fuels as originating in soil or rocks.

Note that in item 13, 8% of participants thought that fossil fuels formed when the Earth first formed. Most students who chose 5B might believe that fossil fuels originated in soil or rocks, but were not present when the Earth was formed. As with item 13, this suggests a limited understanding about the origin of the carbon in fossil fuels, and/or the origin of the carbon in plants. Again, it should be noted that only 39% of participants responded that plants obtain their carbon from the atmosphere (item 2). Therefore, the popularity of 5B could be explained by students reasoning that the carbon in fossil fuels came from living things such as plants, but these living things obtained their carbon from the soil or rock rather than the atmosphere.

7.2.2 Conceptual area 1 – summary of findings

Evidence was found for existence of the following ideas among participants:

- Burning fossil fuels causes an increase in the amount of carbon on Earth (items 3, 75%, 5, 30% and 22, 68%). Responses suggest that students may hold tentative conceptual models about the creation of chemical elements or the location of carbon reservoirs on Earth. Alternatively, students may make a “snap association” between burning fossil fuels and increasing carbon, i.e., without reasoning about the mechanism of such an association.

- Oceans do not play a significant part in carbon stocks (item 1, 81%) and flows (item 8, 46%). Only 17% of students thought that the oceans contain a significant amount of carbon (item 1), however 52% believed that significant amounts of carbon flow into and out of oceans (item 8), suggesting inconsistent reasoning.

- Carbon is found almost exclusively in the atmosphere (item 1). Students may associate carbon primarily or exclusively with carbon.
dioxide, carbon monoxide or methane, and struggle to identify other chemical compounds containing carbon

- Overestimation of the role of fossil fuel burning in global carbon flows (item 8). These students may struggle to understand how a relatively small amount of greenhouse gas emissions can make a significant difference

- Plants do not remove carbon from the atmosphere (item 2, 59% total). Almost equal numbers of students thought that plants extract carbon from soil (38%) and from air (39%), while 21% thought that plants convert the Sun’s energy into carbon atoms (item 2)

- Carbon dioxide is able to escape into space (item 12, 51% total)

- Fossil fuel formation increased the amount of carbon in the atmosphere (item 13, 45%). However, item 5 shows that 49% of participants see the carbon in fossil fuels as originating in the ground or rock. Together, these suggest that students’ mental models link “carbon” with “atmosphere”, while fossil fuels, found in the Earth’s crust, are often linked to “rock”. This implies a lack of conceptual understanding of the carbon cycle, and in particular, flows between reservoirs. The finding that 60% of participants thought that plants either created new carbon atoms or obtained carbon from the ground, suggest that students may appreciate that fossil fuels originate from living things, but believe that those living things either obtained their carbon from the ground, or created it themselves.
7.2.3 Conceptual area 2 – e.m.s. – items 6, 14 and 24

Conceptual area 2a - The Sun emits mostly visible radiation. Item 6

6. The following graphs show different types of energy emitted (given off) by the Sun. Which graph BEST shows the amounts of each type of energy emitted by the Sun?

![Graphs A, B, and C showing energy distribution]

6A is the correct response

Discussion of conceptual area 2a

Item 6 had eight informal responses: the highest number in the first half of the CI, and the poorest statistical measures (see Chapter 6). This suggests that participants may be uncertain about this information. Possibly this topic is not usually covered in schools. Over 85% of students overestimated the proportion of the Sun’s energy that is in the form of UV radiation, with 61% believing that UV radiation makes up the majority of energy from the Sun.
14. Heat that leaves the Earth’s surface is MOSTLY:

A  heat from radioactive rocks and heat from the centre of the Earth 14, 6%
B  heat from the Sun reflected (bounced) off the Earth’s surface 115, 50%
C  heat emitted through human activity e.g., burning fossil fuels 67, 29%
D  heat emitted (given off) naturally by the Earth 26, 11%

24. Students used an infra-red radiation detector to measure radiation given off by a student and a laboratory bench. What did they find?

A  neither student nor bench emit infra-red radiation 56, 24%
B  both the student and lab bench are emitting infra-red radiation 55, 24%
C  only the student emits infra-red radiation 106, 46%

Discussion of conceptual area 2b

Responses to item 14 suggest that only 11% of students thought the Earth naturally emits radiation. The most common idea (50%) was that heat leaving Earth’s surface was simply the Sun’s heat reflected. The idea that human heat-generating activities are directly responsible for heating was also relatively common (29%). This overestimation of the impact of human activity may be linked to overestimation of the relative size of carbon flows.
into the atmosphere by fossil fuel burning (item 8). Only 6% of participants thought that radioactivity and volcanism are responsible for most of the heat emitted by the Earth. Item 14 performed very poorly on the statistical measures of item performance reported in Chapter 6.

Responses to item 24 suggest that most students are not familiar with the idea that all objects at temperatures encountered in everyday life emit infrared radiation. The largest group (46%) appear to believe that while “warm” objects, or possibly living things, emit infrared radiation, “cool” ones, or possibly non-living things, do not. Specific questions would be necessary to determine whether cool living things, e.g., a lizard, or warm non-living things, e.g., a stove top, are thought to emit infrared radiation. This item also had a high rate of informal responses (12), suggesting many students found it difficult to choose an answer. It is also possible that some students did not link infrared radiation with “heat”. This could possibly be overcome by referring to heat in the item stem.

### 7.2.4 Conceptual area 2 – summary of findings

Evidence was found for existence of the following ideas among participants:

- Most energy received from the Sun is UV (item 6, 61%)
- Most heat leaving Earth’s surface is the Sun’s heat reflected (item 14, 50%)
- Most energy emitted by the Earth comes from human sources (item 14). Together with overestimation of carbon flows from fossil fuels in conceptual area one, this suggests a possible overestimation of outputs from human activities compared to natural processes. This may be due to two factors. First, human activities may be mentioned in education and the media more frequently than natural processes. Second, if students do not understand the concept of equilibrium, they may conclude that human outputs can only cause problems if they are relatively large in comparison with natural flows
- Students were more familiar with the concept of objects emitting infrared radiation in the context of a laboratory experiment than with
the idea of the Earth emitting heat (items 14 and 24). This may be due to their not associating “infrared radiation” with “heat”, or having seen or used infrared-detecting apparatus, as was observed during the pre-trial focus groups. However, 46% thought that only “warm” objects, or possibly living things, emit infrared radiation.

7.2.5 Conceptual area 3 – interactions between GHG and e.m.r. – items 11, 15, 16, 18, 21, 23

Conceptual area 3a – most of the gases that make up the atmosphere are transparent to visible light. Item 15

15. Most of the Sun’s energy:

A interacts with most of the molecules of Earth’s atmosphere 156, 68%
B only interacts with GHG in the Earth’s atmosphere 33, 14%
C isn’t affected by the Earth’s atmosphere at all 35, 15%

Discussion of conceptual area 3a

Most of the energy from the Sun is in the form of visible and near-infrared light. These wavelengths rarely interact, in processes that transfer energy, with either greenhouse gases or the oxygen and nitrogen that make up the bulk of the atmosphere. However, the concept of the atmosphere being transparent to most of the Sun’s energy is widely misunderstood. 73% of students think of most of the Sun’s energy as interacting with some or most atmospheric gases (Item 15, A+B). However, greenhouse gases did not feature prominently in this misconception: only 14% thought that interactions took place only with greenhouse gases. By far the largest
proportion of students, 68%, thought that interactions take place between most of the Sun’s energy and most of the Earth’s atmosphere.

*Conceptual area 3b – non-GH gases are transparent to IR. Item 16*

16. What is the REASON that nitrogen and oxygen do NOT cause the Earth to warm?

- **A** they don’t damage the ozone layer 82, 36%
- **B** they absorb infra-red (heat) rays but emit them again – they don’t trap them 88, 38%
- **C** they don’t absorb infra-red rays at all 48, 21%

*Discussion of conceptual area 3b*

36% of students appear to believe that greenhouse gases damage the ozone layer. However, the largest proportion, i.e., 38%, appear to believe that oxygen and nitrogen are not greenhouse gases because they re-emit the radiation they absorb. This suggests that these students believe greenhouse gases “work” by permanently trapping infrared radiation. This idea appears to be consistent with choosing option 15A, i.e., these students might think that most Solar radiation is absorbed by most atmospheric molecules, but that only greenhouse gases “hold onto” the radiation. Only 21% of students correctly thought that non-greenhouse gases do not interact with IR radiation.
Conceptual area 3c – GH gases absorb IR: this is the cause of the greenhouse effect. Item 21

21. What type of energy do all greenhouse gases interact with?

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<table>
<thead>
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<tbody>
<tr>
<td><strong>A</strong></td>
<td>infra-red</td>
</tr>
<tr>
<td></td>
<td>rays 27, 12%</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>ultra-violet</td>
</tr>
<tr>
<td></td>
<td>rays 44, 19%</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>visible light 9, 4%</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>more than one</td>
</tr>
<tr>
<td></td>
<td>of the above 117, 51%</td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>none of the</td>
</tr>
<tr>
<td></td>
<td>above 21, 9%</td>
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Discussion of conceptual area 3c

51% of participants thought that greenhouse gases interact with more than one band of the e.m.s. Possibly these students believe that greenhouse gases “trap” radiation as discussed for item 16. The next largest group (19%) thought that interactions took place with UV radiation: this might be related to the idea that greenhouse gases damage the ozone layer. These ideas are examined in Section 7.3.

Only 12% correctly identified infrared radiation as the type of energy all greenhouse gases interact with. However, this idea was more common than the ideas that greenhouse gases interact with only visible light (4%) or none of the types of radiation listed (9%).
Conceptual area 3d - GH gases absorb IR emitted by Earth. Items 11, 18

11. Greenhouse gases cause the Earth to warm up because:

A. they let heat rays in but don’t let them out 83, 36%
B. they allow the Sun’s rays in but absorb rays from Earth 25, 11%
C. they interact with all types of e.m.r., creating heat 9, 4%
D. they damage the ozone layer so more UV rays get in and heat up Earth 111, 48%

18. The energy absorbed by greenhouse gas molecules is MOSTLY:

A. reflected (bounced) off the Earth 57, 25%
B. emitted (given off) by the Earth 33, 14%
C. from human activity e.g., burning fossil fuels 88, 38%
D. directly from Sun 46, 20%

Discussion of conceptual area 3d

“Ozone-layer damage” seems to be the most common idea about the mechanism by which greenhouse gases cause the Earth to warm, with 48% of responses (item 11). The second most common idea, with 36% is that heat is “trapped” by greenhouse gases. In item 16 the idea of trapping was chosen by 38% while damage to ozone was chosen by 36%. Section 7.3 examines how many of these responses were from the same students.

A notable difference between items 11 and 16 is that half as many students chose the correct answer (B) for item 11 as answered item 16 correctly. Also, more students chose the “damage to ozone” for item 11 (D, 48%) than
for item 16 (A, 36%). It seems that the correct response to item 11 was unconvincing to the students. Based on the responses to items 15 and 16, this might indicate that students think of interactions between Solar radiation and the atmosphere as occurring “most of the time” i.e., for most gases and most frequencies. To these students, a response involving the Sun’s radiation passing through unaffected would be unconvincing.

Another possible reason for 11B being unconvincing is that it involves radiation from one source being unaffected while radiation from another source is absorbed. This may be unconvincing to students who do not understand the differences between radiation from the two sources, or who think that radiation from the Earth is just the Sun’s radiation reflected (see item 14).

Item 18 “tips off” participants with the information that greenhouse gases absorb energy, although it is possible that those who favour the idea of “ozone destruction” would agree that greenhouse gases require energy in order to do this. 38% of students, the largest proportion, thought that greenhouse gases absorb energy mainly released through human activity (C). This may be due to the prevalence of messages in education and the media about human activity releasing greenhouse gases, and the association between greenhouse gases, climate change and human activity. These ideas are explored in Chapter 8. Alternatively, these students may be unaware of the existence of the natural greenhouse effect.

20% thought greenhouse gases absorbed the Sun’s energy and 25% thought the absorbed energy was “bounced” off the Earth. The correct idea, that greenhouse gases interact with energy emitted mostly by the Earth, was held by only 14% of students – the smallest proportion. Further, item 18 does not specify the source of this “naturally emitted” heat. It is possible that participants who chose this response were thinking of heat emitted by discrete sources such as animals, volcanoes, hot springs etc., rather than infrared radiation emitted from all objects, i.e., black body radiation.
Conceptual area 3e – this is re-emitted in all directions - down as well as up. Item 23

23. When a molecule of greenhouse gas absorbs (takes in) heat, it

A rises into the ozone layer 79, 34%
B emits (gives off) the heat again 51, 22%
C creates more greenhouse gas molecules 54, 24%
D gives off a different type of energy 32, 14%

Discussion of conceptual area 3e

The most common response to item 23, with 34% of responses, involves the ozone layer (A). These students might believe that greenhouse gases damage the ozone layer and this is examined in Section 7.3 by comparing item 23 with items that mention ozone.

24% of students thought that greenhouse gases create more greenhouse gases (C). This misconception involves conservation of matter and the proportion of greenhouse gases in the atmosphere. These relationships are examined in Section 7.3. Note that this statement is technically true as rising temperatures create more water vapour, however this is due to rising surface temperatures rather than as a direct result of absorption of heat by greenhouse gas molecules.

22% of students correctly identified that heat energy absorbed by greenhouse gas molecules is re-emitted (B). Section 7.3 compares this with items 11 and 16, which address trapping or re-emission of radiation.

Item 23 did not include an option directly addressing the misconception that greenhouse gases “trap” heat: it may be desirable to include such an option.
in future research. However, as option B mentions re-emission of heat, the other three options can be considered to imply that heat is not re-emitted.

**7.2.6 Conceptual area 3 – summary of findings**

Evidence was found for existence of the following ideas among participants:

- Most of the Sun’s energy interacts with most molecules in Earth’s atmosphere (15A, 68%)
- Greenhouse gases interact with more than one band of the e.m.s. (item 21, 51%), or with UV radiation only (19%). This second idea may be related to “ozone layer” misconceptions.
- The Sun’s heat, and possibly radiation in general, is reflected off Earth rather than being absorbed and re-emitted. Only 11% of participants correctly thought that GHGs allow energy from the Sun in but absorb energy from the Earth (item 11). In item 14, 50% of students thought that most heat leaving Earth was the Sun’s heat reflected. In item 18, a total of 45% of students thought that the energy absorbed by GHGs originates from the Sun, either directly or reflected from Earth. Only 14% correctly thought that the energy absorbed by greenhouse gases is naturally emitted by the Earth (18B). Further, it is possible that these students were thinking of heat emitted by discrete, sensible non-human sources such as animals or volcanism, rather than intangible black body radiation.
- GHGs damage the ozone layer (item 16, 36%, item 11, 48%)
- GHGs trap heat by absorbing and not re-emitting it (item 16, 38%, item 11, 36%, item 23, 78%)
- GHGs create more of themselves (item 23, 24%). The most common response to item 23 (A, 34%) was that on absorbing heat, GHGs rise into the ozone layer. Together with items 11 and 16, this suggests that these students may believe GHGs damage the ozone layer.
- The energy absorbed by GHGs comes from human activity (item 18, 38%). Together with the idea that most of the energy emitted from the Earth comes from human activity (item 14, 29%), this suggests
an overestimation of relative impacts of human activities. This is explored in Section 7.3.

It should be noted that items 15, 18 and 23 were rated “unacceptable” according to their performance on the statistical measures of item quality, reported in Chapter 6.

### 7.2.7 Conceptual area 4 – proportions of greenhouse and non-greenhouse gases in the atmosphere – items 9, 10, 17, and 19

*Conceptual area 4a – Over 96% of the atmosphere consists of non-GHG.*

**Item 9**

9. How much of the atmosphere is greenhouse gases?

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>A</td>
<td>more than 30% (49, 21%)</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>between 5% and 30% (127, 55%)</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>less than 5% (50, 22%)</td>
<td></td>
</tr>
</tbody>
</table>

**Discussion of conceptual area 4a**

Overall, 76% of students overestimated the proportion of greenhouse gases in the atmosphere (A+B). Most students (55%) thought that the atmosphere comprises between 5% and 30% greenhouse gases.
Conceptual area 4b – the atmosphere also contains small amounts of CO₂, CH₄, O₃, N₂O and H₂O and CFCs, all of which are GH gases. Items 10, 19

10. Which of the following are ALL greenhouse gases?

A  carbon dioxide, methane, carbon monoxide 160, 70%
B  carbon dioxide, hydrogen, methane 19, 8%
C  carbon dioxide, methane, water vapour 45, 20%

19. How can a small percentage of greenhouse gases have a significant effect on climate?

A  it can’t. Greenhouse gases are only important at levels over about 5% 38, 17%
B  when greenhouse gases interact with the Sun’s rays they make more GHG 79, 34%
C  the Earth has a lot of atmosphere so a small % is a lot of molecules 103, 45%

Discussion of conceptual area 4b

Only 20% of students correctly identified water vapour as a greenhouse gas. This is significant because 80% of students will not understand the role that increased concentrations of water vapour play in climate feedback mechanisms. 70% thought carbon monoxide is a greenhouse gas, possibly because they are aware that it is a pollutant and harmful, and were
conflating different types of pollution. Alternatively, this option may have been seen simply as more plausible than the one containing water vapour. Only 8% chose the option that included hydrogen. Possibly this could be replaced with a more plausible distractor.

The correct option for item 19 was the most commonly chosen, with 45% of responses. The low rate of responses (17%) for 19A was surprising in light of item 9, in which most students overestimated the proportion of greenhouse gases. The most likely explanation for this is that the format of item 19 “tipped off” students to the fact that small concentrations of greenhouse gases do have a significant effect. 34% of students chose the response that involved greenhouse gases creating more greenhouse gases. In item 23, 24% of participants thought that greenhouse gases could multiply. Possible associations between these responses are explored in Section 7.3.

Option 19B contains two misconceptions: the concept of greenhouse gases multiplying and the concept of them interacting with the Sun’s (as opposed to the Earth’s) radiation. This could be corrected in future to say simply “radiation”; however this option was convincing to a large proportion of students, lending further weight to the idea, discussed in Section 7.2.6, that greenhouse gases are thought of as interacting with radiation from the Sun rather than from the Earth.

*Conceptual area 4c – water vapour is a variable component of the atmosphere and is the most abundant greenhouse gas. Item 17*

17. Which is the most abundant greenhouse gas (i.e., which one is there the most of)?

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>carbon dioxide 168, 73%</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>water vapour 25, 11%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>methane 31, 14%</td>
<td></td>
</tr>
</tbody>
</table>
Discussion of conceptual area 4c

73% of students thought that CO₂ is the most common greenhouse gas, the second most common choice being methane at 14%, which again suggests that methane is widely known to be a greenhouse gas. The importance of water vapour as a greenhouse gas does not appear to be understood, with only 11% choosing this correct response. This is a significant problem because of the role of water vapour in positive feedback mechanisms.

7.2.6 Conceptual area 4 – summary of findings

Evidence was found for the existence of the following ideas:

- Overestimation of the proportion of greenhouse gases in the atmosphere (item 9, 76%)
- Carbon monoxide is a greenhouse gas: possibly due to conflation of ideas of “pollution” (item 10, 70%) or lack of knowledge that water vapour is a greenhouse gas
- Only 20% correctly identified water vapour as a greenhouse gas (item 10), while only 11% identified water vapour as the most common greenhouse gas (item 17): this lack of awareness of the role of water vapour as a greenhouse gas has implications for the understanding of feedback mechanisms
- Greenhouse gases multiply when they interact with the Sun’s rays (item 19, 34%)
- Further evidence for the idea that Greenhouse gases interact with radiation from the Sun rather than from Earth (item 19, 34%): this was also discussed in conceptual area 3
7.2.7 Conceptual area 5 – feedback – items 25, 26 and 27

Conceptual area 5a – feedback can be negative. Item 25

25. Some types of cloud reflect the Sun’s rays back to space, so fewer rays reach the ground. If these clouds became more common due to global warming, how would it affect the climate?

A  it will get hotter, faster than before the clouds formed (make warming worse) 63, 28%
B  it will get hotter but more slowly than before (make warming less bad) 136, 59%
C  it won’t have any effect on climate change 26, 11%

Conceptual area 5b – or positive. Items 26 and 27

26. Ice and snow are white and reflect the Sun’s rays, but ground and water underneath are darker and absorb the Sun’s rays. When the climate gets warmer, ice and snow will melt. How will this affect the climate?

A  it will get hotter, faster than before the ice melted (make warming worse) 151, 66%
B  it will get hotter but more slowly than before the ice melted (make warming less bad) 60, 26%
C  it won’t have any effect on climate change 15, 7%
27. CO$_2$ is removed from the atmosphere when it dissolves in water e.g., oceans. Warmer water dissolves less carbon dioxide than colder water. What effect will this have on global warming?

- A the climate will get hotter, at a faster rate (make the warming worse) 135, 59%
- B the climate will still get hotter but more slowly (make the warming less bad) 53, 23%
- C it won’t have any effect on climate change 32, 14%

Discussion of conceptual areas 5a and 5b

In contrast to most of the other CCCI items, most students answered these three items correctly. This suggests that either they had previously learned about feedback mechanisms, or were able to reason correctly when given the relatively small amount of information contained in the item stems.

Item 25 concerned a negative feedback scenario. 59% of students answered item 25 correctly, 11% thought there would be no effect and 28% thought that the feedback would be positive. Items 26 and 27 concerned positive feedback. 66% answered item 26 correctly, 26% thought that the feedback would be negative and 7% thought there would be no change. Item 26 had the largest proportion of correct responses in this area: this may be due to students’ familiarity with the concept of light colours reflecting heat and dark colours absorbing it. Students are unlikely to have such direct experience of the other feedback mechanisms. With item 27, 59% answered correctly, 23% thought the feedback would be negative and 14% thought there would be no change.
7.2.8 Conceptual area 5 – summary of findings

- Most students correctly interpreted the effects of positive and negative feedback scenarios. This suggests either that they had previously learned about feedback or that they were able to use the limited information provided to deduce the correct response.
- The item with the highest rate of correct responses related to absorption of radiated energy by objects of different colours. Students would have everyday experience of this concept.
- “No change” was the least popular option for all three items. This may be because most students perceived that one change would lead to another, although some reasoned incorrectly about the type of change.

7.2.9 Conceptual areas 6 and 7 – equilibrium and conservation of energy – items 4, 7 and 20

Conceptual area 6 – equilibrium of energy: there is a balance of energy into and out of the Earth/atmosphere system. A net flow of energy into or out of the system leads to temperature change over time. Items 7 and 20

7. If the Earth gave out less energy than it receives from the Sun, then over time it would:

A use up the spare energy
  e.g., in photosynthesis and other processes 30, 13%

B gradually get hotter
  180, 79%

C store the spare energy but not get hotter 13, 6%
20. What happens to the energy from the Sun that is absorbed by the Earth?

A  less energy is sent back into space BECAUSE some is used up e.g., in photosynthesis 151, 66%
B  the same amount of energy is sent back into space 20, 9%
C  less energy is sent back into space BECAUSE the Earth is cooler than the Sun 52, 23%

Discussion of conceptual area 6

Items 7 and 20 performed very poorly according to the statistical measures reported in Chapter 6, and were rated “unacceptable”. Discrimination and point biserial coefficients for these items were well outside the recommended ranges, i.e., there was a lack of strong association between students answering these items correctly and achieving a high score on the entire test. This may be linked to the inconsistencies described below.

In items 7 and 20 students reasoned inconsistently about the relatively abstract concept of energy balance and temperature. In item 7, 79% of students reasoned correctly that if the Earth emitted less energy than it received, it would become hotter. However, in item 20 only 9% identified that the Earth emits the same amount of energy as it receives.

Students’ responses regarding photosynthesis were also inconsistent. Only 13% thought that energy would be used up in processes such as photosynthesis (7A), while 66% thought that energy from the Sun was “used up” in photosynthesis (20A). Together with the idea that plants use the Sun’s energy to create carbon atoms (item 2, 21%), this suggests a tentative conceptual model of photosynthesis, or a lack of understanding that the biomass on Earth would have to increase continually in order to maintain a difference between incident and emitted energy.
Very few students (item 7, 6%) thought that the Earth could store energy without getting hotter. It may be desirable to develop a more plausible option for this item in future research.

It is possible the correct response to item 20 seemed less plausible because it did not include a reason, while the two distractors did. This option could be adapted in future research to include a reason.

*Conceptual area 7 – conservation of energy: energy can change from one form into another but the total amount remains constant. Item 4*

4. A hot bath contains energy in the form of heat. After a while the water goes cold. What has happened to the heat energy?

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>it has changed to a different form but it’s still the same amount of energy</td>
<td>128, 56%</td>
</tr>
<tr>
<td>B</td>
<td>it has all been used up and doesn’t exist anymore</td>
<td>33, 14%</td>
</tr>
<tr>
<td>C</td>
<td>it has been partly used up so there’s less energy than before</td>
<td>65, 28%</td>
</tr>
</tbody>
</table>

*Discussion of conceptual area 7*

This item used language (“forms of energy”) that students could be expected to have encountered in recent years of science education. 56% of participants, the largest proportion, correctly identified that energy is conserved. However, 42% thought that the energy was totally or partially “used up, while 28% thought it was “partly” used up, possibly because they understood that the cold bathwater would still contain some energy.
7.2.10 - Findings for conceptual areas 6 and 7

- Evidence emerged that students had difficulty applying the law of conservation of energy. In item 4, 56% correctly applied the law of conservation of energy to a familiar situation (i.e., a hot bath). However, 42% thought that some or all of the energy had been “used up”

- The two items that addressed the Earth’s energy balance gave very inconsistent results. With item 20, there was strong evidence (66%) for the misconception that some of the Sun’s energy incident on the Earth is used up, e.g., in photosynthesis, however in item 7 only 13% chose this option. In item 7 most students (79%) identified that if the Earth received more energy than it emitted, it would heat up, while in item 20 only 9% identified that the Earth must emit the same amount of energy as it receives to maintain constant temperature. These inconsistent results suggest that students’ responses are heavily dependent on contextual cues in these items, and that students possibly hold tentative mental models about the Earth’s energy balance. Items 7 and 20 performed very poorly according to the statistical measures reported in Chapter 6.

7.3 Item response analysis part 2: item pairs

This section presents evidence for consistency in participants’ reasoning about concepts in the CCCI and for associations between ideas. This evidence allows further exploration of students’ mental models as well as providing additional evidence for or against the inferences drawn in Section 7.2. The findings presented in this section were derived from contingency tables listed in Table 7.2. Section 7.3.1 explains what contingency tables are and how I used them. The contingency tables themselves, and an explanation of how to read them, are given in Appendix 6.
7.3.1 Purpose and format of contingency tables

Concept inventories typically contain two or more items for each concept (see discussion of CI development in Chapter 5). If a student had a strongly developed idea about a concept, they would be expected to answer such questions consistently, whether their responses were correct or not. This section looks for evidence of such consistent reasoning in students’ responses to pairs of CCCI items that address the same concept, and addresses issues raised about hypothesised mental models in Section 7.3.2.

For example, two items that addressed the same concept might both be answered correctly by 50% of students. However, this result does not tell us how many of the correct responses to each item came from the same individuals. If a high proportion of students who answered the first item correctly, also answered the second item correctly, this suggests that these students have a strongly held understanding of the concept because their reasoning was consistent. However, if the 50% of students who answered the first item correctly chose a response containing a misconception to item 2, this would suggest that they do not have a strongly held understanding of the concept, because they did not reason consistently. This idea is illustrated in Figure 7.1.

![Venn diagrams illustrating consistent and inconsistent reasoning](image)

Figure 7.1: Venn diagrams illustrating consistent and inconsistent reasoning

In order to investigate how consistent participants were in reasoning about a concept, I generated contingency tables using JMP. These show the frequency distribution of responses to pairs of items. For example, a contingency table for items 1 and 2 would show the proportion of students who selected option A for item 1 and went on to choose option A for item 2; the proportion who chose 1A and 2B; the proportion who chose 1A and 2C
etc. The contingency table would also show the total proportion of students who chose 1A and 2A etc. Appendix 6 shows an exemplar contingency table with an explanation of how to read it.

For ease of interpretation, I rounded percentages to the nearest whole number and discarded informal responses, so percentages reported in this section typically add up to less than 100%.

### 7.3.2 Contingency tables in this section

I generated contingency tables for all pairs of items whose options included a concept in common. For example, items 11 and 16 both have options that include the idea of greenhouse gases damaging the ozone layer, while one of the options in item 23 mentions greenhouse gases rising into the ozone layer. A student who had a well-established misconception that greenhouse gases damage the ozone layer would be expected to choose the options that mention the ozone layer for all three items: the contingency tables test this.

For each contingency table the concept tested is stated, along with the items that address it. Notable response distributions are discussed. Table 7.2 lists the contingency tables in this section. Contingency tables that explore closely related ideas are grouped together in sub-sections.

#### Table 7.2: Contingency tables in Section 7.3

<table>
<thead>
<tr>
<th>Section</th>
<th>Items</th>
<th>Specific ideas addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3.3</td>
<td>3,22</td>
<td>Total amount of carbon on Earth over time</td>
</tr>
<tr>
<td></td>
<td>5,13</td>
<td>Source of carbon in fossil fuels and effect of their burning on the atmosphere</td>
</tr>
<tr>
<td></td>
<td>5,22</td>
<td>Carbon is created when fossil fuels are burned</td>
</tr>
<tr>
<td></td>
<td>13,22</td>
<td>Carbon in fossil fuel formation and burning</td>
</tr>
<tr>
<td>7.3.4</td>
<td>1,8</td>
<td>Relative importance of water as a reservoir in the carbon cycle</td>
</tr>
<tr>
<td></td>
<td>1,12</td>
<td>Water as a reservoir in the carbon cycle – ability of carbon dioxide to dissolve in water</td>
</tr>
<tr>
<td></td>
<td>8,12</td>
<td>Water as a reservoir in the carbon cycle – ability of carbon dioxide to dissolve in water</td>
</tr>
<tr>
<td>7.3.5</td>
<td>11,18</td>
<td>Source of energy leaving Earth, and mechanism of action of GHG</td>
</tr>
</tbody>
</table>
7.3.6 Proportion of GHGs in the atmosphere
- Relative size of human contributions to global carbon and energy flows
- Relative size of human contributions to global carbon flows and energy absorbed by GHGs
- GHGs create more GHGs
- GHGs trap radiation/damage the ozone layer
- GHGs damage the ozone layer
- Nature of energy from the Sun and its interactions with the atmosphere
- Mechanism of action of greenhouse gases and bands of e.m.s. that they interact with
- Interactions between greenhouse and non-greenhouse gases and different bands of the e.m.s.
- Nature of energy from the Sun and interactions between GHGs and different bands of the e.m.s.

7.3.8 Negative and positive feedback
- Positive feedback
- Negative and positive feedback

7.3.9 Equilibrium of energy

7.3.3 The carbon cycle – amount of carbon on Earth; source of carbon in fossil fuels and effect on atmosphere of fossil fuel burning – items 3, 5, 13 and 22

Items 3 and 22: total amount of carbon on Earth over time

Of the students who chose 3A (the total amount of carbon on Earth has increased over time), 78% also chose 22A, i.e., they were consistent in thinking that the amount of carbon on Earth has increased over time. However, the students who chose 3B (decreasing carbon) were much less consistent: they were almost equally divided between 22B (decreasing carbon) and 22A (increasing carbon). An explanation may be that the reason given in 22B was not as convincing as the reason in 22A. Of the students who chose 3C (constant carbon, correct response), over a third chose 22A (increasing carbon). This suggests that the idea: “burning fossil fuels causes an increase in carbon” may be more convincing than the idea: “burning fossil fuels does not change the amount of carbon”.

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Items 5 and 13: Source of carbon in fossil fuels and effect of their burning

There is some limited evidence of consistent reasoning that the carbon in fossil fuels originated in the Earth but had never been in the atmosphere before (5B), and that fossil fuel formation increased the amount of CO₂ in the atmosphere (13D). The largest proportion of students, 24%, chose these options. 52% of those who chose 13D also chose 5B, while 48% of those who chose 5B also chose 13D. This suggests a lack of understanding of the process of fossil fuel formation and the role that atmospheric carbon plays in this process.

Items 5 and 22: Carbon is created when fossil fuels are burned

There is some evidence of a relationship between 22A (total carbon is increasing now fossil fuels are being burned) and 5B (the carbon in fossil fuels was in the Earth but never in the atmosphere before): 34% of all students chose these two options. However, these options do not share a logical connection.

Conversely, there is only a weak relationship between 5A (carbon is created when fossil fuels are burned) and 22A, despite both containing the idea that burning fossil fuels creates carbon. 22% of students chose these two options and 72% of those who had chosen 5A also chose 22A. However only 32% of those who chose 22A had chosen 5A. This suggests the idea that burning fossil fuels creates carbon, is tentatively held by some students.

These results also lend weight to the interpretation that in answering item 22, students were thinking about carbon in the atmosphere rather than in the Earth as a whole, despite the clarification included in the question.

Items 13 and 22: Carbon in fossil fuel formation and burning

There is evidence of an association between the idea that burning fossil fuels increases the amount of carbon on Earth (22A), and the idea that fossil fuel formation increased the amount of carbon in the atmosphere (13D). 35% of students chose 22A and 13D, with 78% of those who chose 13D also choosing 22A, and 51% of those who chose 22A also choosing 13D. There is no obvious logic to this relationship. An explanation could be that
students associated fossil fuels with increasing atmospheric CO$_2$, or increasing carbon in general, or that they held tentative mental models about the distribution of carbon on Earth and the source of carbon in fossil fuels.

**Summary of findings for items 3, 5, 13 and 22**

- Evidence of consistent thinking that the amount of carbon on Earth has increased due to fossil fuel burning (items 3 and 22)
- Evidence of the idea that the carbon in fossil fuels originated in the ground rather than the atmosphere (items 5 and 13)
- Evidence of lack of firm conceptualisation of the process of fossil fuel formation, and the role of atmospheric carbon in this process. Responses to related items lack logical connections. Students may make “snap associations”, i.e., lacking logical reasoning between fossil fuels, and increasing carbon or increasing atmospheric CO$_2$ (items 3, 5, 13 and 22).

**7.3.4 CO$_2$ dissolving in water/role of water bodies in the carbon cycle – items 1, 8 and 12**

*Items 1 and 8: Relative importance of water as a reservoir in the carbon cycle*

The students who chose 8C (oceans as the smallest carbon source and sink) were equally split among 1A (44%) and 1B (45%), both of which show oceans as the smallest carbon reservoir. Only 9% of students who chose 8C also chose 1C, which shows oceans as the largest reservoir. These results show a consistent belief that oceans do not play a significant part in carbon stocks and flows.

However, of those who answered Item 1 correctly (oceans as the largest carbon reservoir, 1C), only 8% answered Item 8 correctly (fossil fuels as the smallest carbon flux). The largest proportion of students choosing 1C (63%) thought that land, oceans and fossil fuels were equally responsible for carbon fluxes (8B). This suggests that the proportion of the global carbon flow due to fossil fuel burning is over-estimated, even by students who understand the role of oceans as a carbon reservoir.
Items 1 and 12: Water as a reservoir in the carbon cycle: solubility of CO$_2$

Of those who chose 12A (the only option not to include CO$_2$ dissolving in water), 87% chose either 1A or 1B – both of which have oceans as a small reservoir in the carbon cycle. This suggests consistency in the idea that CO$_2$ and water do not interact significantly, therefore water bodies are not involved in the carbon cycle. Conversely, of those who answered Item 1 correctly (i.e., oceans are the largest carbon reservoir), 47% answered Item 12 correctly and in total, 79% chose an option that mentioned CO$_2$ dissolving in water. Again, this suggests consistent reasoning.

Items 8 and 12

The contingency table for these items suggests a lack of consistent reasoning about the inability of carbon dioxide to dissolve in water, in contrast to the findings from the contingency table for items 1 and 12. Options 8A, 8B, 12B and 12C all include the idea of CO$_2$ dissolving in water. Options 12A and 8C, by contrast do not include this idea. Therefore students who chose 12A, which does not include the idea of CO$_2$ dissolving in water, would be expected to choose 8C which does show oceans playing a significant role in carbon flows. However, there is no such evidence of a strong association between 8C and 12A. Only 14% of students chose 8C and 12A. Of the students who chose 12A, 60% chose 8C, which suggests some consistency. However, of the students who chose 8C, only 31% chose 12A.

Summary of findings from items 1, 8 and 12

• Evidence of consistent reasoning that oceans do not play a significant role in the carbon cycle. There is also some evidence of overestimation of the role of fossil fuel burning in planetary carbon flows (items 1 and 8)

• Evidence for students linking the concepts of carbon dioxide dissolving in water, and oceans as a carbon reservoir, is contradictory. Items 1 and 12 show evidence of consistent reasoning, but items 8 and 12 do not.
7.3.5 Sources of energy leaving Earth/absorbed by greenhouse gases – items 11, 14 and 18

*Items 11 and 18: Source of energy leaving Earth and mechanism of GHG*

Only 1% of students answered both items 11 and 18 correctly. The largest proportion, 26%, chose 18C (the energy absorbed by GHGs comes primarily from human activity) and 11D (GHGs damage the ozone layer). 52% of students who chose 11D went on to choose 18C, while 66% who chose 18C had chosen 11D. This suggests an association between the idea that greenhouse gases absorb heat released by human activity, and the ozone depletion misconception. However, most students (61%) who answered 18 correctly (B) also thought that GHGs damage the ozone layer, suggesting that this is a persuasive idea.

*Items 14 and 18: Source of energy leaving Earth and absorbed by GHGs*

These items address two misconceptions. First, that the heat involved in the greenhouse effect is the Sun’s heat reflected off the Earth’s surface (rather than being absorbed and re-emitted), and second, that the heat involved in the greenhouse effect is heat emitted by human activities. Because both items have four options, a smaller proportion of students can be expected to choose each option.

There is some evidence of consistent thinking about the nature of heat leaving the Earth’s surface. The largest proportion of students, 20%, chose 18A (GHGs react with energy reflected off Earth’s surface), and 14B (most of the heat leaving Earth is the Sun’s energy reflected). Of the students who chose 18A, 79% had chosen 14B, although only 39% who chose 14B went on to choose 18A. This suggests some evidence for a mental model where heat from the Sun is reflected off Earth rather than being absorbed and re-emitted. This is significant because the re-emitted energy has a lower wavelength than the incident energy, and greenhouse gases mostly interact with e.m.r. in the mid and far-infrared. Gautier et al. (2006) considered this idea fundamental to understanding the greenhouse effect.

Items 14C and 18C address the idea that human activity is responsible for the heat involved in the greenhouse effect; 15% of students chose these two
options. Of those who thought GHGs interact with heat from human activity (18C), 40% thought that most energy leaving the Earth came from human activity (14C), while 52% of those who chose 14C also chose 18C.

The association between options 14B and 18A, and between 14C and 18C, suggests that while many students misunderstand the main source of energy leaving the Earth, they do understand that GHGs interact with this energy.

However, another 40% of the students who chose 18C (GHGs interact with heat from human activity) also chose 14B (most energy leaving the Earth was the Sun’s energy reflected). If they were reasoning consistently, these students would think that most of the heat leaving the Earth does not interact with GHGs. Therefore they may think of the greenhouse effect as being entirely human-caused.

There was no evidence of consistency between the correct ideas that most of the energy leaving the Earth is naturally emitted (14D) and that GHGs absorb energy emitted by the Earth (18B). This lack of apparent trend may be due to the small proportion of students who chose these responses. Alternatively it is possible that very few students understand the concept of Earth emitting IR and this IR being absorbed by greenhouse gases.

**Items 8 and 14: Relative size of human contributions to carbon, energy flows**

Items 8, 14 and 18 all address the relative sizes of inputs from human activity. I looked for evidence of an association between students overestimating the relative size of human-caused carbon emissions in item 8, and the relative amounts of heat and greenhouse gases emitted by human activity in items 14 and 18.

There is evidence of an association between the idea that human activity is responsible for most of the heat leaving the earth (14C), and the idea that fossil fuel burning is responsible for a large proportion of carbon flows (8B and 8C). In total, 27% of students chose 14C and either 8B or 8C. Of the students who chose 14C, a total of 93% had chosen 8B or 8C, which both show fossil fuel burning responsible for a large proportion of total carbon
flows. Of the students who chose 8B or 8C (overestimation of human contribution to carbon flows), a total of 60% went on to choose 14C, suggesting some consistent overestimation of human contributions.

*Items 8 and 18: Human contributions to carbon flows and energy absorbed by GHGs*

There is evidence of an association between the options that overestimate human contributions to carbon flows (8B and 8C) and the idea that energy absorbed by greenhouse gases comes mostly from human activity (18C).

The largest two proportions of students chose 8C and 18C (19%) and 8B and 18C (16%). In total, 35% of students chose responses to items 8 and 18 that consistently overestimated human contributions to global matter or energy flows. Of the students who chose 18C, a total of 92% chose 8B or 8C while of those who had chosen 8B or 8C, a total of 87% went on to choose 18C.

*Summary of findings from items 8, 11, 14 and 18*

- Evidence for the idea that heat leaving the Earth’s surface, and the energy absorbed by GHGs, are both the Sun’s energy reflected from Earth’s surface (items 14 and 18), i.e., students do not appreciate that Earth absorbs Solar energy and re-emits at a lower frequency
- Evidence for association between the ideas that greenhouse gases damage the ozone layer, and that the energy they absorb is released mainly by human activity such as burning fossil fuels (items 11 and 18)
- Some evidence for the idea that heat leaving the Earth’s surface, and the energy absorbed by greenhouse gases, are both released mainly by human activity (items 14 and 18)
- Evidence of an association among overestimation of human contributions to three elements of the science of climate change: the carbon cycle; heat emitted by the Earth; and energy absorbed by greenhouse gases (items 8, 14 and 18).
7.3.6 Proportion of greenhouse gases in the atmosphere – items 9, 19 and 23

*Items 9 and 19: Proportion of greenhouse gases in the atmosphere*

There is evidence of consistent thinking about the proportion of the atmosphere comprised of greenhouse gases. Of the students who chose 19A (GHGs are only significant over 5%), 85% had chosen 9A or 9B (GHGs comprise over 5% of the atmosphere), i.e., they were consistent in their overestimation of the proportion of greenhouse gases in the atmosphere. Only 10% of those who answered 9 correctly chose 19A (the only option which directly contradicts the correct response to 9). 56% of those who answered 9 correctly also answered 19 correctly. Of the students who chose 9A (GHGs comprise over 30% of the atmosphere), the most common choice for 19 was B (creation of more greenhouse gas molecules). While incorrect, this reasoning is consistent.

A possible complication is that students might perceive 5% as “a small percentage”. This is unlikely because option 19A explicitly mentions 5%. However the wording of option 19C could be improved by replacing “a small percentage” with “less than 5%”, to make the distinction clearer.

Technically, the creation of more greenhouse gas molecules (19B) could refer to the creation of more water vapour due to rising temperatures, i.e., a positive climate feedback. If students understood this feedback mechanism, they would be expected to identify water vapour as a greenhouse gas. However, the contingency table for items 10 and 19 shows no association between students identifying water vapour as a greenhouse gas and believing that greenhouse gases create more of themselves. Therefore, it is unlikely that students who chose responses corresponding to “creation of more greenhouse gases” were thinking of the scientifically accepted idea of an increase in water vapour.

*Items 19 and 23: Greenhouse gases create more greenhouse gases*

Comparison of items 19 and 23 showed no evidence of consistent reasoning that GHGs create more of themselves (19B and 23C), suggesting that this idea is tentative rather than strongly developed.
Summary of findings for items 9, 19 and 23

- Evidence of consistent reasoning that greenhouse gases comprise more than 5% of the atmosphere (items 9 and 19)
- No evidence for consistent reasoning that greenhouse gases create more of themselves (items 19 and 23).

### 7.3.7 Mechanism of action of greenhouse gases; UV radiation and the ozone layer – items 11, 15, 16, 21 and 23

There is considerable evidence in the research literature for conflation of climate change and ozone depletion. I also found this in the pilot study reported in Appendix 1. Items 11, 16 and 23 explicitly mention the ozone layer, so I examined the contingency tables for these, for evidence of consistent reasoning. The pilot study also suggested that students who conflate climate change and ozone depletion, often assume that UV radiation is responsible for the warming. Therefore, I investigated relationships between items 6, 11 and 21, which mentioned UV radiation. I also included item 15 in this analysis as it specifically addresses greenhouse gas interactions.

**Items 11 and 16: Greenhouse gases trap radiation/damage the ozone layer**

These items contain two misconceptions: conflation with ozone depletion and the idea that greenhouse gases “trap” radiation. Both items contain four options rather than three, so the total percentage of students choosing each option would be expected to be smaller. However, some patterns are evident. The largest proportion of students, 23%, chose 11D and 16A (the “ozone damage” options). Further, 65% of students who chose 16A also chose 11D, and 48% who chose 11D also chose 16A. This suggests a firmly held misconception that greenhouse gases damage the ozone layer, among a minority of students.

There was some evidence of consistent thinking among a small minority of students, about the idea that greenhouse gases “trap” radiation. Only 15% of students chose 11A and 16B, the options corresponding to this idea. However, 42% who chose 11A chose 16B, while 40% who chose 16B chose
11A. There was no evidence of consistent thinking about the correct options 11B and 16C, suggesting that few students understand the mechanism of interactions between greenhouse gases and e.m.r.

**Items 11 and 23: Greenhouse gases damage the ozone layer**

The most common combination of responses (18%) was 11D and 23A: these both mention the ozone layer. 53% of students who thought that greenhouse gas molecules rise into the ozone layer after absorbing heat, also thought they cause warming by damaging the ozone layer. Of those who thought absorption of heat leads to creation of more greenhouse gases, 54% also thought that greenhouse gases destroy the ozone layer.

**Items 16 and 23: Greenhouse gases damage the ozone layer**

This contingency table, unlike the others, showed no evidence of consistent reasoning about damage to the ozone layer. This suggests either that ozone conflation is not a strongly held idea, or that the other options in item 16 were more plausible.

**Summary of findings from items 11, 16 and 23**

- Evidence for consistent conflation with ozone depletion (items 11 and 16; and items 11 and 23). However, the contingency table for items 16 and 23 shows no evidence for consistent reasoning involving the ozone layer
- Some evidence for the idea that on absorbing heat, GHGs create more GHGs, damaging the ozone layer (items 11 and 23)
- Some evidence for consistent reasoning that GHGs “trap” heat (items 11 and 16)

**Bands of the electromagnetic spectrum involved in the greenhouse effect – items 6, 11, 15 and 21**

This group of contingency tables focused on students’ ideas about what bands of electromagnetic radiation are received from the Sun, and are involved in interactions with greenhouse and non-greenhouse gases in the atmosphere.
Items 6 and 15: Energy from the Sun and interactions with the atmosphere

There is evidence of consistent thinking that most of the Sun’s energy is in the form of UV, and interacts with most of the atmosphere (15A and 6C). The largest proportion of students, 44%, chose these options. 72% of students who chose 6C also chose 15A, while 65% of those who chose 15A had chosen 6C, suggesting consistent reasoning among most students.

Items 11 and 21: Mechanism of GHGs and bands of e.m.s. they interact with

There is some evidence of association between the ideas that greenhouse gases interact with more than one band of e.m.s. (21D) and that they damage the ozone layer (11D). The largest proportion of students, 25%, chose these options. 51% of those who chose 11D chose 21D, while 49% of those who chose 21D had chosen 11D.

There is also evidence of association between the ideas that greenhouse gases interact with more than one band of the electromagnetic spectrum (21D) and let heat in but not out (11A). The percentages of students choosing these options were similar to those choosing 11D and 21D, suggesting a similar prevalence of this association. 20% of students chose 11A and 21D, with 54% of those choosing 11A also choosing 21D, and 38% of those who chose 21D also choosing 11A.

Items 15 and 21: Interactions between GHGs and non-GHG and e.m.s.

There is some evidence for association between the ideas that GHGs interact with more than one band of the electromagnetic spectrum (21D) and that the Sun’s energy interacts with most molecules of the atmosphere (15A). This suggests a “generalised” mental model, with interactions occurring between all types of gases and all types of radiation. 39% of students, the largest proportion, chose these options. 77% of those who chose 21D had chosen 15A, and 58% of those who chose 15A chose 21D.

Items 6 and 21: Energy from the Sun and GHG/e.m.s. interactions

There is evidence of association between the ideas that greenhouse gases interact with more than one band of the e.m.s. (21D) and that most of the energy Earth receives from the Sun is UV (6C). The largest proportion of
students, 33%, chose these two options. Of those who chose 6C, 54% also chose 21D and of those who chose 21D, 65% had chosen 6C.

There is a weaker association between the ideas that greenhouse gases interact with UV radiation (21B) and that most of the energy received from the Sun is UV (6C). The second largest proportion of students, 14%, chose these options. 73% of those who chose 21B had chosen 6C, however only 23% of those who chose 6C went on to choose 21B.

Summary of findings for items 6, 11, 15 and 21

- Evidence for the idea that most of the Sun’s energy is UV, and interacts with most of the atmosphere (items 6 and 15)
- Evidence for the idea that GHGs interact with more than one band of e.m.s., damaging the ozone layer; and for the idea that GHGs interact with more than one band of e.m.s. and let heat in but not out (items 11 and 21)
- Evidence for a “generalised” mental model of interactions where most molecules of the atmosphere interact with more than one band of the e.m.s. (items 15 and 21)
- Evidence of association between the ideas that most of the energy received from the Sun is UV radiation, and that GHGs interact with more than one band of the e.m.s. Weaker association between the ideas that most of the energy Earth receives from the Sun is UV, and that GHGs interact with UV radiation (items 6 and 21).

7.3.8 Feedback – items 25, 26 and 27

Items 25 and 26: Negative and positive feedback

There was a strong association between students answering these items correctly, despite one asking about positive feedback and another asking about negative feedback, which might be expected to confuse participants. The largest proportion, 42%, chose the correct response for both items. 71% of those who chose correctly for item 25 also did so for item 26, and 64% of those who chose correctly for item 26 also did so for item 25. However,
there was no strong association between choosing either the wrong type of feedback or “no effect”.

*Items 26 and 27: Positive feedback*

Similarly, there was a strong association between students answering these items correctly. 67% of those who answered item 26 correctly answered 27 correctly, and 75% of those who answered 27 correctly answered 26 correctly. Overall, 44%, the largest proportion, answered both correctly. There were no strong associations between choices of the wrong type of feedback, or of “no effect”.

*Items 25 and 27: Negative and positive feedback*

There was a strong association between correct responses for these items. 67% who chose the correct response for one of this pair of items also answered the other item correctly. Overall, 40% of students answered both items correctly.

*Summary of findings for items 25, 26 and 27*

- Evidence of consistent correct reasoning about positive and negative feedback scenarios.

7.3.9 *Equilibrium of energy – items 7 and 20*

It should be reiterated that these two items performed poorly in statistical measures of item performance. The response distributions for these items were inconsistent in that while 79% of students answered item 7 correctly, only 9% chose the correct response for item 20. The largest proportion of students, 55%, chose 7B (correct) and 20A (incorrect). Of those who answered 7 correctly, 70% went on to choose 20A and only 7% chose the correct answer for 20. This suggests that item 20’s distractors, especially 20A, were persuasive.

Also, of those who chose 7A, 67% chose 20A, i.e., they were consistent in their misconception that energy is used up in photosynthesis. This lends weight to the idea that option 20A is highly plausible to the high school students.
Summary of findings for items 7 and 20

- Evidence of inconsistent thinking about Earth’s energy balance. Most students agreed with the idea that if Earth emitted less energy than it receives it would get hotter, but also with the idea that Earth does emit less energy than it receives, because energy is used up, e.g., in photosynthesis.

7.4 Conclusions

7.4.1 Summary of findings from individual items

Table 7.3 summarises the most common ideas, in descending order of prevalence, from responses to individual items in Section 7.2. Items whose overall performance was rated “borderline” (δ) or “unacceptable” (ε) in the statistical evaluation of item quality, reported in Chapter 6, are indicated. Prevalence rates shown are the percentage of students who chose the relevant option or options. Given the evidence that the participants’ conceptual models are tentative and context dependent, these figures should be interpreted as tentative. The ideas listed correspond to responses chosen by 30% or more of participants. This figure, while arbitrary, corresponds approximately to the proportion of responses that could be expected if participants answered randomly, as most items had three options.

Table 7.3: Summary of common misconceptions and correct ideas from individual items; items rated “borderline (δ)” or “unacceptable” (ε) in the statistical evaluation of item quality are indicated

<table>
<thead>
<tr>
<th>Misconception</th>
<th>Rate</th>
<th>Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overestimation of contribution of fossil fuel-burning to global carbon flows</td>
<td>90%</td>
<td>8 (δ)</td>
</tr>
<tr>
<td>Overestimation of proportion of UV in Solar energy incident on the Earth</td>
<td>86%</td>
<td>6 (ε)</td>
</tr>
<tr>
<td>Oceans contain little if any carbon</td>
<td>81%</td>
<td>1</td>
</tr>
<tr>
<td>Water vapour is not a GHG</td>
<td>80%</td>
<td>10</td>
</tr>
<tr>
<td>If the Earth emitted less energy than it receives from the Sun, it would heat up</td>
<td>79%</td>
<td>7 (ε)</td>
</tr>
<tr>
<td>GHGs comprise more than 5% of the atmosphere</td>
<td>76%</td>
<td>9</td>
</tr>
<tr>
<td>Carbon dioxide is the most abundant GHG</td>
<td>73%</td>
<td>17</td>
</tr>
<tr>
<td>Burning fossil fuels has caused an increase in the Earth’s total</td>
<td>30-75%</td>
<td>3, 22</td>
</tr>
<tr>
<td>Statement</td>
<td>Percentage</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>CO is a GHG (conflation of types of pollution)</td>
<td>70%</td>
<td></td>
</tr>
<tr>
<td>Most of the energy from the Sun interacts with most of the molecules in the Earth’s atmosphere</td>
<td>68%</td>
<td></td>
</tr>
<tr>
<td>Melting of snow and ice will increase climate change</td>
<td>66%</td>
<td></td>
</tr>
<tr>
<td>The largest component of sunlight UV</td>
<td>61%</td>
<td></td>
</tr>
<tr>
<td>An increase in reflective clouds will slow climate change</td>
<td>59%</td>
<td></td>
</tr>
<tr>
<td>Warming oceans will increase climate change</td>
<td>59%</td>
<td></td>
</tr>
<tr>
<td>When a hot bath goes cold, the total amount of energy is unchanged</td>
<td>56%</td>
<td></td>
</tr>
<tr>
<td>CO$_2$ can escape from the atmosphere into space</td>
<td>51%</td>
<td></td>
</tr>
<tr>
<td>GHGs interact with more than one band of the e.m.s.</td>
<td>51%</td>
<td></td>
</tr>
<tr>
<td>Most of the heat leaving the Earth is energy from the Sun being reflected</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>The carbon in FF originated in soil or rock, not the atmosphere</td>
<td>49%</td>
<td></td>
</tr>
<tr>
<td>Oceans play a very limited role in carbon flows</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>Only “warm” or living things emit IR</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>CO$_2$ is removed from the atmosphere by rock formation and dissolving in water</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>GHGs damage the ozone layer</td>
<td>34-48%</td>
<td></td>
</tr>
<tr>
<td>The process of fossil fuel formation caused an increase in atmospheric carbon</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>The energy absorbed by GHGs is mostly the Sun’s energy (either direct or reflected from the Earth)</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>A small percentage of GHG is significant because it represents a lot of molecules</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>Energy can be partly or totally “used up”</td>
<td>42%</td>
<td></td>
</tr>
<tr>
<td>Some of the Sun’s energy received by the Earth is used up in processes such as photosynthesis</td>
<td>13-66%</td>
<td></td>
</tr>
<tr>
<td>Nearly all carbon on the Earth’s surface is in the atmosphere</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Plants get their carbon from the air</td>
<td>39%</td>
<td></td>
</tr>
<tr>
<td>Plants extract carbon for photosynthesis from the soil</td>
<td>38%</td>
<td></td>
</tr>
<tr>
<td>The energy absorbed by GHGs comes mostly from human activity e.g., burning fossil fuels</td>
<td>38%</td>
<td></td>
</tr>
<tr>
<td>GHGs trap IR radiation by absorbing and not re-emitting</td>
<td>36-78%</td>
<td></td>
</tr>
<tr>
<td>The process of fossil fuel formation did not change the amount of carbon in the atmosphere</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Most heat leaving the Earth is generated by human activities</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>The Earth emits less energy than it receives from the Sun</td>
<td>19-90%</td>
<td></td>
</tr>
</tbody>
</table>
## 7.4.2 Summary of findings from contingency tables

Table 7.4 summarises the ideas inferred from contingency tables in section 7.3. Estimated prevalence is the percentage of students who chose the relevant options for both of the items in the pair, i.e., the top number in the relevant contingency table cell. Again, this figure must be treated as an estimate. Rates are only shown where one option is being considered in each item. So for example in item 6, where 6B and C are taken together as “overestimation of the proportion of UV from the Sun”, I did not estimate a rate. Similarly, I did not attempt to estimate prevalence for findings involving more than one contingency table. As with Table 7.3, items which were rated “borderline” or “unacceptable” are indicated.

**Table 7.4: Summary of ideas inferred from contingency tables and estimated prevalence; items rated “borderline (δ)” or “unacceptable” (ε) in the statistical evaluation of item quality are indicated**

<table>
<thead>
<tr>
<th>Idea</th>
<th>Items</th>
<th>Estimated prevalence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burning fossil fuels has increased the total amount of carbon on Earth</td>
<td>3, 22</td>
<td>59%</td>
</tr>
<tr>
<td>Inconsistent reasoning about energy absorbed and emitted by Earth</td>
<td>7 (ε), 20 (ε)</td>
<td>55%</td>
</tr>
<tr>
<td>Energy from the Sun is mostly UV radiation, and interacts with most gases in the atmosphere</td>
<td>6 (ε), 15 (ε)</td>
<td>44%</td>
</tr>
<tr>
<td>Oceans do NOT play a significant role as reservoirs in the carbon cycle because CO₂ does not dissolve in water</td>
<td>1, 12, 8 (δ)</td>
<td>Contradictory findings</td>
</tr>
<tr>
<td>GHGs interact with more than one band of the e.m.s. and the Sun’s energy interacts with most of the atmosphere</td>
<td>15 (ε), 21</td>
<td>39%</td>
</tr>
<tr>
<td>Most of the energy from the Sun is UV and GHGs interact with more than one band of the e.m.s.</td>
<td>6, 21</td>
<td>33%</td>
</tr>
<tr>
<td>GHGs comprise at least 5% of the atmosphere</td>
<td>9, 19</td>
<td>N/A</td>
</tr>
<tr>
<td>GHGs damage the ozone layer</td>
<td>11, 16, 23 (ε)</td>
<td>Contradictory findings</td>
</tr>
<tr>
<td>GHGs “trap” heat, i.e., they do not re-emit it</td>
<td>11, 16, 23</td>
<td>N/A</td>
</tr>
<tr>
<td>Consistent reasoning about feedback scenarios</td>
<td>24, 25, 26</td>
<td>N/A</td>
</tr>
<tr>
<td>Lack of coherent conceptualisation of fossil fuel formation</td>
<td>5, 13,</td>
<td>N/A</td>
</tr>
</tbody>
</table>
and the role of atmospheric carbon in this process; association of fossil fuels with increasing carbon/CO₂

| Generalised overestimation of human contributions to global processes | 8 (δ), 14 (ε), 18 (ε) | N/A |

7.4.3 Conclusions and introduction to Chapter 8

Responses to individual items summarised in Table 7.3 gave the simplest way of identifying and estimating the prevalence of misconceptions. Responses to individual items also gave rise to possible models of students’ conceptual understanding: these were discussed in Section 7.2. In Section 7.3 I explored these ideas in more depth by looking for evidence of consistent reasoning and associations between ideas, using contingency tables. Findings from these were summarised in Table 7.4.

There is considerable evidence that students’ conceptual models are tentative, context-dependent and lack internal logic. For example, items 5, 13 and 22 suggest a lack of consistent reasoning about the movement of carbon during formation and combustion of fossil fuels.

Eight of the 27 items used to generate these findings performed poorly in statistical measures of item quality. The most common problem was low levels of association between students’ performance on these items, and on the test as a whole. Therefore it is important to corroborate these findings with data from another source.

In the next chapter, evidence to support or refute the findings listed in Tables 26 and 27 were sought in the focus group interview data.
CHAPTER 8 – STUDENTS’ IDEAS EXPRESSED IN POST-CI FOCUS GROUPS

This chapter serves three purposes:

• To describe the data collection and analysis methods for the post-CI focus group interviews;

• To present evidence that supports or refutes the main ideas inferred from CI responses, listed in Tables 7.3 and 7.4 of Chapter 7; and

• To explore reasons behind students’ CI response choices, thus providing a more detailed picture of what knowledge students possess and how well established this knowledge is.

Section 8.1 outlines the methods for data collection and analysis; Section 8.2 presents and discusses the focus group interview findings; and Section 8.3 summarises the chapter’s conclusions.

8.1 Participants and method

8.1.1 Data collection methods

Table 8.1: Post-trial focus groups – participants, interview length and activities

<table>
<thead>
<tr>
<th>School and date</th>
<th>Participants</th>
<th>Discussion time</th>
<th>Additional activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (suburban) 24th-25th November 2011</td>
<td>8 (all boys)</td>
<td>26 minutes (part 1) 32 minutes (part 2) Parts 1 and 2 took place on two consecutive days</td>
<td>Completing table of atmosphere/sunlight interactions Completing drawing of carbon flows Open-ended drawing activity</td>
</tr>
<tr>
<td>C (urban) 14th November 2011</td>
<td>13 (4 girls, 9 boys)</td>
<td>52 minutes</td>
<td>None</td>
</tr>
<tr>
<td>D (urban) 25th October 2011</td>
<td>5 (all girls)</td>
<td>1 hour 28 minutes</td>
<td>Completing drawings of carbon stocks and flows</td>
</tr>
<tr>
<td>F (rural) 21st November 2011</td>
<td>6 (3 girls, 3 boys)</td>
<td>47 minutes</td>
<td>Completing drawings of carbon stocks and flows</td>
</tr>
</tbody>
</table>
Table 8.1 summarises the post-CI focus group participants, and the activities that took place in addition to discussing concepts listed in the interview guide. Groups B and D completed a CI retest immediately before their focus group interviews. The discussion times shown in Table 8.1 do not include the time taken for retests.

The focus group interview guide was based on the CI item stems and was revised for each focus group to include questions that had arisen with previous groups. The focus group interview guide is in Appendix 7. Participants also completed a number of activities. These included: completing diagrams representing carbon reservoirs and fluxes (Appendix 8); completing a table to indicate which atmospheric gases interacted with which bands of the electromagnetic spectrum, and whether or not the gases were greenhouse gases; and, if time allowed, drawing their own diagrams to show their understanding of the mechanism of climate change. These activities helped participants to focus on the concepts under discussion and to recall their ideas (Koulaidis and Christidou 1999). All focus group interviews were audio recorded. In addition, I took field notes during the interviews. These were used to confirm my understanding of the audio recordings during data analysis.

It should be acknowledged that the post-CI focus group interviews were biased in favour of more academically capable students: of the four classes that took part in focus groups, three were selective, compared with six of the eleven classes that completed the CI. This was because, as with the CI, participating teachers selected which students to invite to focus groups. Most chose students from selective classes because the teachers considered they would contribute and benefit most from participation. Therefore it can be expected that the focus groups would express a higher rate of scientifically accurate ideas, and a lower rate of misconceptions, than were inferred from the CI data.
8.1.2 Data analysis methods

Data analysis consisted of five stages:

1. Transcription of audio recordings
2. Coding transcripts with inductively-derived codes
3. Mapping inductively-derived codes to CI findings
4. Grouping the coded transcript sections to produce a set of transcript segments for each of the CI findings
5. Generating frequency counts and writing commentary.

1. I transcribed each audio recording in full within a week of each interview. This allowed me to take advantage of my recollection of non-verbal communication and tone of voice, both of which convey additional information about students’ ideas.

2. I then coded the transcripts using an open-source text analysis tool Diment (2010). As with transcription, it was advantageous to complete this stage as soon as practicable, i.e., before the CI data was analysed. This meant that the codes had to be derived inductively rather than being based on CI findings. Each segment of conversation, usually consisting of several students’ comments and responses, was tagged with one or more codes. The full list of codes is given in Appendix 9.

3. Once the CI data was analysed I mapped the CI findings, shown in Tables 3 and 4 in Chapter 7, to the inductively derived codes. Twelve findings had no corresponding focus group data. This was because: (i) there was not enough time available to ensure full discussion of all items; and (ii) some findings from contingency tables contained ideas that were not anticipated and therefore not included in the interview guide. However, Most CI findings corresponded to between one and four codes.

4. I sorted the coded transcript segments according to which CI finding or findings they corresponded to, resulting in a set of transcript segments for each of the CI findings.
5. I carried out data reduction on these segments by grouping phenomenographically equivalent responses together and counting them, to give an indication of how common ideas were. These counts must be treated with caution because they included students who agreed with comments made by other students: it is possible that the students agreeing would not have made the statement if they had been interviewed individually. In addition, in some cases the number of students agreeing to a comment had to be estimated. However the counts serve as an estimate of the prevalence of ideas. Finally, I summarised the transcript segments and illustrated each summary with one or more quotations. The summaries and quotations comprise Section 8.2 below.

8.2 Post-CI focus group findings

In this section, corresponding focus group data are presented for the CI findings in Chapter 7. Table 8.2 summarises the findings from Chapter 7 that are discussed in this section. Findings from individual items and contingency tables that addressed the same concept were combined to avoid duplication: for example, findings 3a and 3b are both related to the role of oceans in the carbon cycle. Findings from Chapter 7 for which no focus group data was obtained, are not listed in Table 8.2 below, and are not discussed.

The findings are numbered for ease of reference, in approximate order of prevalence. For each finding, the relevant CI item(s) and the proportion of CI responses are shown. As in Chapter 7, items that performed poorly in statistical measures of item quality (Chapter 6) are indicated. The statements in brackets refer to inferences made from CI responses: these were discussed in the summaries of findings in Chapter 7.
<table>
<thead>
<tr>
<th>No.</th>
<th>Finding</th>
<th>Rate</th>
<th>Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Overestimation of contribution of fossil fuel burning to global carbon flows (lack of understanding of equilibrium or media/school focus on human activities)</td>
<td>90%</td>
<td>8 (δ)</td>
</tr>
<tr>
<td>2</td>
<td>Overestimation of proportion of UV in Solar energy incident on the Earth</td>
<td>86%</td>
<td>6 (ε)</td>
</tr>
<tr>
<td>3a</td>
<td>Oceans contain little if any carbon</td>
<td>81%</td>
<td>1</td>
</tr>
<tr>
<td>3b</td>
<td>Oceans play a very limited role in carbon flows (CO₂ does not dissolve in water)</td>
<td>46%</td>
<td>8 (δ)</td>
</tr>
<tr>
<td>4</td>
<td>Water vapour is not a GHG</td>
<td>80%</td>
<td>10</td>
</tr>
<tr>
<td>5a</td>
<td>If the Earth emitted less energy than it receives from the Sun, it would heat up</td>
<td>79%</td>
<td>7 (ε)</td>
</tr>
<tr>
<td>5b</td>
<td>Some of the Sun’s energy received by Earth is used up in processes such as photosynthesis (Inconsistent reasoning about energy absorbed and emitted by Earth)</td>
<td>13-66%</td>
<td>7(ε), 20 (ε)</td>
</tr>
<tr>
<td>5c</td>
<td>Earth emits less energy than it receives from the Sun (tentative mental models about Earth’s energy balance)</td>
<td>19-90%</td>
<td>7(ε), 20 (ε)</td>
</tr>
<tr>
<td>6</td>
<td>GHGs comprise more than 5% of the atmosphere</td>
<td>76%</td>
<td>9, 19</td>
</tr>
<tr>
<td>7</td>
<td>Carbon dioxide is the most abundant GHG</td>
<td>73%</td>
<td>17</td>
</tr>
<tr>
<td>8</td>
<td>Burning FF has increased Earth’s total amount of carbon/burning FF creates carbon atoms (tentative conceptual models about creation of elements/location of carbon reservoirs or “snap association” between FF burning and increasing carbon)</td>
<td>30-75%</td>
<td>3, 22</td>
</tr>
<tr>
<td>9</td>
<td>CO is a GHG (conflation of types of pollution/lack of awareness that water vapour is a GHG)</td>
<td>70%</td>
<td>10</td>
</tr>
<tr>
<td>10a</td>
<td>Most of the energy from the Sun interacts with most of the molecules in the Earth’s atmosphere</td>
<td>68%</td>
<td>15 (ε)</td>
</tr>
<tr>
<td>10b</td>
<td>GHGs interact with more than one band of the e.m.s.</td>
<td>51%</td>
<td>21</td>
</tr>
<tr>
<td>11</td>
<td>Melting of snow and ice will increase climate change (familiarity with dark objects absorbing heat)</td>
<td>66%</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Statement</td>
<td>Agree (%)</td>
<td>Unsure (%)</td>
</tr>
<tr>
<td>---</td>
<td>---------------------------------------------------------------------------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>12</td>
<td>An increase in reflective clouds will slow climate change</td>
<td>59%</td>
<td>25</td>
</tr>
<tr>
<td>13</td>
<td>Warming oceans will increase climate change</td>
<td>59%</td>
<td>27</td>
</tr>
<tr>
<td>14a</td>
<td>When a hot bath goes cold, total energy is unchanged</td>
<td>56%</td>
<td>4</td>
</tr>
<tr>
<td>14b</td>
<td>Energy can be partly or totally “used up” (difficulty applying the law of conservation of energy)</td>
<td>42%</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>CO₂ can escape from the atmosphere into space</td>
<td>51%</td>
<td>12</td>
</tr>
<tr>
<td>16a</td>
<td>Most of the heat leaving Earth is Sun’s energy reflected</td>
<td>50%</td>
<td>14 (ε)</td>
</tr>
<tr>
<td>16b</td>
<td>Most heat leaving Earth is generated by human activities (media/school focus on human activities)</td>
<td>29%</td>
<td>14 (ε)</td>
</tr>
<tr>
<td>17</td>
<td>The carbon in FF originated in soil or rock, not the atmosphere (“snap association” between FF and rock/lack of understanding of carbon flows/belief that plants get carbon from soil, or create it using sunlight)</td>
<td>49%</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>Only “warm” or living things emit IR (experience/association with “night vision goggles”)</td>
<td>46%</td>
<td>24</td>
</tr>
<tr>
<td>19</td>
<td>A small percentage of GHGs is significant because it represents a lot of molecules</td>
<td>45%</td>
<td>19</td>
</tr>
<tr>
<td>20a</td>
<td>FF formation increased atmospheric carbon (“snap association” between carbon and atmosphere/CO₂; lack of understanding of carbon flows)</td>
<td>45%</td>
<td>13</td>
</tr>
<tr>
<td>20b</td>
<td>FF formation did not change the amount of carbon in the atmosphere (belief that plants get their carbon from soil)</td>
<td>30%</td>
<td>13</td>
</tr>
<tr>
<td>21</td>
<td>The energy absorbed by GHGs is mostly the Sun’s energy, either direct or reflected from the Earth</td>
<td>45%</td>
<td>18 (ε)</td>
</tr>
<tr>
<td>22a</td>
<td>GHGs damage the ozone layer</td>
<td>34-48%</td>
<td>11, 16, 23 (ε)</td>
</tr>
<tr>
<td>22b</td>
<td>GHGs trap IR radiation by absorbing and not re-emitting</td>
<td>36-78%</td>
<td>11, 16, 23 (ε)</td>
</tr>
<tr>
<td>23</td>
<td>Nearly all carbon on Earth’s surface is in the atmosphere (limited knowledge of range of carbon compounds/carbon associated primarily with CO₂ or CO)</td>
<td>40%</td>
<td>1</td>
</tr>
<tr>
<td>24a</td>
<td>Plants get their carbon from the air</td>
<td>39%</td>
<td>2</td>
</tr>
<tr>
<td>24b</td>
<td>Plants extract carbon for photosynthesis from the soil</td>
<td>38%</td>
<td>2</td>
</tr>
</tbody>
</table>
For each finding in Table 8.2, post-CI focus group data are presented and discussed in Sections 8.2.1 to 8.2.24. Transcript segments are shown in italics. Each transcript segment is presented in a separate paragraph, with researcher’s questions and responses indicated where necessary for clarity.

8.2.1 Finding 1 – Overestimation of contribution of FF-burning to global carbon flows (lack of understanding of equilibrium or media/school focus on human activities) – item 8, 90%

Focus group data provide evidence to support finding 1. Out of eleven students who compared the size of carbon flows from oceans, land and fossil fuel burning, nine overestimated carbon flows from fossil fuels, and seven of these thought that carbon flows from fossil fuel burning exceeded those from natural sources. However, only one student gave a reason:

*I don't know why I picked it B. They all looked equal and I knew a lot came from the oceans and I thought a lot came from us.*

Two students contradicted the misconception. Neither gave an explicit explanation, however, while one response was based on an instinctive feeling, the other gives the impression of being based on something learned:

*I didn't expect to get it right! I don't know [why I chose it] - I didn't have any thoughts like it would build up - I guess the Earth stuff would have more than a car but I didn't know so that seemed like the right one at the time.*

*It's a negligible amount that we're emitting from fossil fuel burning, but it's still affecting.*

One student explained how they chose the correct answer based on what they considered “climate sceptic” information:

*I should have thought about it relative to the other ones but you hear on those big scare campaigns against the carbon tax that our percentage of emitting carbon is tiny compared to cows farting and burping so I put the small one.*

The above reasoning suggests some students may believe that small contributions to global carbon flows are not capable of making a significant difference to the climate: this supports the inference made in Chapter 7.
8.2.2 Finding 2 – Overestimation of proportion of UV in Solar energy incident on the Earth – item 6, 86%

There is considerable evidence to support finding 2. “Sun safety” messages appear to be behind the dominance of UV in students’ minds. Twelve of nineteen students thought that UV comprised a greater proportion of radiation from the Sun than IR or visible light:

You see all the ads on TV “put sunscreen on or you'll die in 15min” and it's like they make a very big deal as if it's mostly UV.

You don't really hear about infrared or any of the others. I can’t name them.

Five thought that there were equal proportions of UV, IR and visible:

I think B [3 students] because the ozone layer absorbs UV which reduces the amount that hits the Earth, Infrared's heat and visible is light is only blocked by clouds.

While only two students chose the correct proportions:

I say A, because UV’s harmful to people and if it was the most it wouldn't work too well and we'd die [1 student agrees, one disagrees].

Two groups expressed astonishment when told the correct answer.

I guess it must be really strong then if there's that little and it still you need sunscreen and stuff.

However, three students showed evidence of deducing the correct answer by reasoning about the properties of different bands of e.m.r.:

Are ultraviolet rays more damaging than visible and infra-red rays?

Would a small amount of ultraviolet [pause] if there were two equal amounts of infra-red and ultraviolet, would UV be more damaging than IR?

[another group member, in response to the correct answer] Actually that doesn't surprise me because we talk about ultraviolet all the time but not everyone gets skin cancer - if it was a massive amount then everyone'd be dead.

Only one group recalled learning anything about the topic, however no-one in this group used the information to answer the question:

Wasn’t it in that graph [a sheet given out in science] of how the atmosphere blocks different types of e.m. radiation, and it dropped off at gamma?

Researcher: did you think about that when you answered the question? [laughter]
This is an example of very capable students not applying previously-learned information to answer a novel question, even though the context was the same.

8.2.3 Findings:

3a – Oceans contain little if any carbon – item 1, 81% and

3b – Oceans play very limited role in carbon flows (CO₂ does not dissolve in water) – items 1 and 8

Students in two groups expressed ideas corresponding to finding 3a:

*Oceans is the smallest, I don't think oceans have much, in comparison [with living things and atmosphere] [one student agrees]*

No post-CI focus group participants explicitly disagreed that CO₂ dissolves in water. However, this is unsurprising as item 27 of the CCCI gave this information. Two groups cited the CI as the source of their knowledge about this concept:

*Another question said that the oceans dissolved it. So you could go back to that.*

*Before I saw the question I didn't know that CO₂ could dissolve in water. [general agreement]*

Students in two groups had previously learned the information elsewhere: in the year 8 ESSA test, in a video about climate change at school and in a magazine:

*Oceans are a massive carbon sink - I read it in a magazine, carbon sinks in oceans, trees, peat bogs and swamps and stuff.*

Some students appeared able to apply their knowledge, suggesting that they had successfully learned the concept:

*[Researcher] who thinks there would be carbon in the oceans?  
It would be like the atmosphere, most of it is air, then there's that little 5% [sic]. In the ocean most of it's water, then there's all those little chemicals in it?  

*CO₂ would be found in the atmosphere, in the oceans. it's dissolved into the ocean.*

*[Researcher] so where did those animals and plants get their carbon from?  
From the water if they were living in the water.*
However, the following conversation suggests an incomplete or faulty understanding of the concept of substances dissolving:

[Student 1] Does carbon dissolve in the ocean, does it completely get rid of it then, or is it still in the ocean?
[Student 2] But there's carbon in living things, and living things in the ocean so it probably doesn't get rid of it completely, algae and stuff.
[Student 3] Like in the other question it dissolves it. But then if it dissolves it, it removes it.
[Student 4] Where does it remove it to? The equation's $H_2O$. There might be an $H_2OC$ sometimes.
[Student 5] I don't really know how it works.

The conversation below shows that these ideas were not fully understood, even among a group of students who had watched a video at school about the role of oceans in climate change:

[Researcher] How is carbon distributed?
[Student 1] Atmosphere
[Student 2] I thought mostly equal
[Student 3] I was tossing up between atmosphere and oceans
Oceans [2 students]
Researcher: What form would that be in?
[Student 2] Carbon dioxide
[Student 3] Just muck/stuff floating around

CI participants frequently stated that they had first learned that CO$_2$ dissolves in water while completing the CI. It appears therefore, that this information has been retained in students’ memory but not necessarily understood.

8.2.4 Finding 4 – Water vapour is not a GHG – item 10, 80%

It appears that water vapour is not widely known as a GHG. Of thirteen students, three disagreed that water vapour was a GHG. This was despite the fact that the CI contained this information, and several recalled the concept being raised in school. Two students provided reasons:

[Water vapour isn't a GHG] because it doesn't have carbon on it

We wouldn't think it would have a bad effect because water wouldn't have any aspects that could harm us.

Of the ten students who named it, three specified that they recalled it from the CI:
I remembered [water vapour was a GHG] from last time and I was confused, so I went and looked it up. [I found] that it was. And I was heaps confused.

Another two stated that they had completed a research project on it at school. One student, in another group, recalled seeing a list in a textbook: this student named CFCs as a greenhouse gas but did not identify water vapour.

8.2.5 Findings:

5a – If the Earth emitted less energy than it receives from the Sun, it would heat up – item 7, 79%

5b – Some solar energy received by Earth is used up in processes e.g., photosynthesis – items 7 and 20, 13-66% and

5c – Earth emits less energy than it receives from the Sun (tentative mental models about Earth’s energy balance) – items 7 and 20, 19-90%

Focus group responses mirrored the inconsistencies in the CI responses. When asked directly whether the Earth emits the same amount of energy as it receives from the Sun, no student thought that it would emit the same amount of energy, while 12 said less. Further, five of these students specified that the retained energy was used in photosynthesis:

[Student 1] [plants] absorb rays from the Sun and turn them into energy.
[Student 2] They convert it into food.

The following conversation shows that some students believe energy is used up in the process of photosynthesis. One student appears to believe that the energy is converted into matter in the form of glucose: another student corrects them. The final comment suggests that the student is aware that light plays a role in photosynthesis but does not know what this role is:

[Researcher] does any energy get used up in photosynthesis?
[Student 1] that's what I thought
[Student 2] not used up, just converted [1 student agrees] into glucose
[Student 3] it's energy, not matter [1 student agrees] you need the UV energy, the light energy to go into photosynthesis
[Researcher] what happens to that energy? when a plant absorbs some light in photosynthesis, what happens to the energy?
[Student 4] it's just stored
[Student 5] when it respires it makes the energy back
[Student 6] is it a catalyst for photosynthesis?
However, when asked what would happen if Earth emitted less energy than it receives from the Sun, 17 of 20 students identified that a change would occur. Of these, 14 correctly identified that Earth would get hotter:

*We'd get hotter and die out because we're not giving out all the Sun's energy and we're keeping in all the carbon and all the bad stuff as well as the good stuff.*

*Well, the energy emitted by the Sun like obviously comes down to the Earth to warm the Earth and then because of FF it gets trapped, yeah and then that's warming up the world gradually.*

One student thought that there would be an effect on the Sun:

*Would it die out? I don't know if I can explain - if we gave out less energy the Sun would die out because it needs give and take to survive as well. It burns hydrogen, I remember in science, and if we're not giving out things like hydrogen to the Sun it'll stop burning those and it'd die out into a white dwarf.*

**8.2.6 Finding 6 – GHGs comprise more than 5% of the atmosphere – items 9 and 19, 76%**

There is considerable focus group evidence to support finding 6. Of 26 students who responded, 13 thought that the atmosphere comprised over 5% GHGs, and four thought 30% or more:

*Like in the atmosphere most of it is air, then there's that little 5%.*

*Can I ask a question before I answer? How fast is the Earth's climate changing and becoming hotter? [discussion about rate of warming and change] 27% [greenhouse gases].*

The first quote above demonstrates how 5% may be considered by students to be only a small proportion of the atmosphere. The second shows that even with knowledge about the relatively slow rate of change, students may seriously overestimate the proportion of GHG. Together, these comments suggest that students may struggle to accept that atmospheric concentrations of the order of parts per million can have a significant effect on the climate. Nine students thought the atmosphere comprised less than 5% GHGs. Of these, three based their reasoning on knowledge, of varying accuracy, about the concentration of other atmospheric gases:
Below 5 cos we learned in science that the it's 75 or 90% is um ... air and there's a little bit of carbon dioxide I think it's 4% - and the rest is below. There's some that are one and the rest is below 1. It's on our laptop.

I think less than 5 because it's around 80% N and 20% O₂ so it's less than 1%, might be a little bit more. Got the figures from somewhere in science.

The variability of students’ knowledge about other atmospheric gases was demonstrated when the composition of the atmosphere was discussed with another group:

[Researcher] how much of the atmosphere is O₂?
[Student 1] 60%?
[Student 2] 2%
[Student 3] no idea

Two students had more accurate knowledge of the atmospheric concentration of CO₂:

Carbon dioxide is still like 0.001

I knew it was still really, really small number, I remember seeing it, probably in the same magazine, and thinking that's not much, but it still does ...

Thirteen students expressed surprise when told the actual concentration of CO₂ in the atmosphere:

[Student 1] Why's everyone so worried about it?
[Student 2] Cos a lot builds up over the long term
[Student 3] That's shocking
[Student 4] It'd be the same as the ultraviolet - we hear about it more, just cos it's more damaging.
[Student 4] I thought it would be a lot more [agreement] because they're talking about how GHGs are destroying our atmosphere, so I assumed it would be at least 25% if not more because that's what they're focusing on in climate change on the news "greenhouse gases are doing this/that" - but there's actually not that many.

Lack of knowledge of the composition of the atmosphere is one barrier to students’ understanding of this concept. It is clear, however, that students struggle to believe that a tiny percentage of GHGs could be capable of causing a significant problem. Also, students assume that a large amount of media and scientific concern must equal a large proportion of GHGs in the atmosphere. As one participant noted, this is analogous to students’ overestimation of the proportion of UV in Solar radiation incident on Earth.
8.2.7 Finding 7 – CO$_2$ is the most abundant GHG – item 17, 73%

The post-CI focus group data did not support finding 7. Of 24 students, 20 thought that water vapour was the most abundant GHG, one thought methane and three were not sure. However, as with the previous finding, it appears some of these students were making use of knowledge acquired from the CI, and that among the general student population this information may not be so widely known:

*We looked it up on the internet afterwards, and the next part of the test, it said that.*

Another two arrived at their answer through faulty reasoning:

*I was assuming there's lots of clouds, clouds are made of water vapour [1 student agrees].*

One student cited magazines as a source of information about this concept, while another learned the information:

*In the scare campaigns from the Liberals.*

This use of the term “scare campaign” implies that the student suspects the information is unreliable. I suggest that this demonstrates the need for educational experiences that address “climate sceptic” arguments.

8.2.8 Finding 8 – Burning fossil fuels has increased Earth’s total carbon/burning FF creates carbon atoms (tentative conceptual models about creation of elements/location of carbon reservoirs or “snap association” between FF burning and increasing carbon) – items 3, 5 and 22, 30-75%

The focus group data suggest that this misconception is likely to exist but is based on an instinctive reaction rather than a strongly held misconception, because many participants rejected the idea after some reflection.

Several students, including one entire group, did express the idea that burning fossil fuels increases the amount of carbon on Earth:

[Student 1] Over the life of the planet the total amount of carbon has increased [all agree].
[Student 2] Because forests are getting destroyed and factories are being built [several agree].
[Researcher] Where does that carbon come from?
Burning of FF increases the total carbon on Earth. Using cars - it converts it to carbon.

However, other students explained that carbon was moving into the atmosphere rather than increasing, and one student came to this realisation during the discussion:

[Researcher] What effect does burning FF have on the total amount of carbon?
Wait - actually in the Earth itself? including the atmosphere, oh alright. It goes from soil to atmosphere but it doesn't increase it, it's still the same amount of carbon.

I want to change my answer, it's still there in the fossil fuels but it's just in the air - so changing from increased to stayed the same.

**8.2.9 Finding 9 – Carbon monoxide is a GHG – conflation of different forms of pollution – item 10, 70%**

Of 20 students who named, or agreed with a named GHG, four identified carbon monoxide. However, this post-CI focus group data may underestimate the prevalence of finding 8, because it appears that by completing the CI, some students learned that carbon monoxide is not a GHG. Several students mentioned changing their answers to item 10 in light of information in the CI that water vapour is a GHG. As one student explained:

[Student 1] But it said later [in the CI] about water vapour so it confirmed that.

[Student 2] Actually I think I did change mine from carbon monoxide.

One student who chose carbon monoxide gave a reason:

[Student 1] I didn't agree that water vapour's a GHG. I chose carbon dioxide, carbon monoxide and methane.
[Student 2] Yeah but monoxide - it's just poisonous.
[Student 1] But more likely than water vapour.

Again, it should be emphasised that during the CI, all students had been exposed to the information that water vapour is a GHG.

Although the following comment does not mention carbon monoxide, it does confirm the existence of a conceptual link between a gas being a pollutant and being a GHG:

[GHGs are] bad stuff. Methane. Unwanted gases that damage the environment.
This may explain why so many students believe that carbon monoxide is a GHG. This could be investigated in more detail in future research.

8.2.10 Findings:

10a – *Most of the Sun’s energy interacts with most molecules in Earth’s atmosphere – item 15, 68% and*

10b – *GHGs interact with more than one band of the e.m.s. – item 21, 51%*

The focus group data, summarised in Table 8.3, provide limited evidence for findings 10a and 10b: only about 15% of focus group participants agreed with these ideas. The largest proportion, nearly 50% of those who responded, correctly identified that GHGs interact with IR radiation. This contrasts sharply with the CI data and suggests that the focus group participants may have a better understanding of this concept than most CI participants. However, four focus group participants specified that the interaction takes the form of reflection, while none discussed absorption and re-emission:

[Researcher] who thinks that GHGs absorb IR?
Do they just reflect it?

The reflection of the greenhouse gases - the infra red reflecting it back to Earth, causes the climate to warm up.

This suggests that even when students correctly identify the band of e.m.r. that interacts with GHGs, do not understand the nature of the interaction.

**Table 8.3: Summary of students’ ideas about interactions between different bands of e.m.r. and greenhouse and non-greenhouse gases.**

<table>
<thead>
<tr>
<th>Gas</th>
<th>IR</th>
<th>Visible light</th>
<th>UV</th>
<th>IR, UV and visible</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG</td>
<td>15 agree, of which 4 specify reflection</td>
<td>5 agree, none disagree</td>
<td>1 group agrees, 1 group disagrees</td>
<td>5 agree, none disagrees</td>
</tr>
<tr>
<td>Non-GHG</td>
<td>4 agree, 1 group disagrees</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GHG and non-GHG | 1 | 5 agree, none disagrees |
One student’s reasoning for believing that all bands of e.m.s. interact with GHGs demonstrates three misconceptions: (i) conflation with ozone depletion; (ii) the idea the GHGs are located in the ozone layer; and (iii) GHGs interact primarily with reflected energy from the Sun, rather than energy emitted from Earth. This third idea is further discussed in finding 21. The full quote is shown below:

*I think it reacts with ultraviolet and infra red and visible light. Just the ones that come to us from the Sun [agreement] because the Sun's rays have to make it through the ozone layer which has all these GHGs in it so they have to penetrate, they have to get through the GHGs so they interact that way.*

The following comment was not included in Table 8.3 as it does not specify what bands of the e.m.s. are involved. However, it also demonstrates conflation with reflection and ozone depletion, and demonstrates the tentative nature of the students’ knowledge:

*[Student 1]* Sunlight rays come in to the Earth and they should bounce back into space but with all the GHGs it's making like a barrier so a few of the Sun rays are released but a lot of them just bounce back onto the Earth [agreement]  
*[Researcher]* what do they bounce off?  
*[Student 1]* The ozone layer  
*[Student 2]* Other gases?

It is worth noting that the idea expressed above corresponds to item 15 option B “Most of the Sun’s energy only interacts with GHGs”, which was chosen by 14%, the smallest proportion of students.

The following comment shows an association between the concepts of IR radiation and climate change, based on the students’ knowledge that IR radiation is a form of heat energy:

*I think they interact with infra red and visible because greenhouse gases have something to do with climate change and getting hotter which is infra red I guess.*

Four students did not feel able to give an answer. Two of these specified the areas of knowledge that they thought were lacking:

*I don't fully understand UV - the only thing I know is they relate to cancer. Can't say anything about UV.*
I have no idea because I don't know what the interaction between the rays and GHGs do - and the effects.

The focus group data suggest that even though students might correctly identify that GHGs interact with IR, rather than other forms of radiation, they are likely to think of such interactions as reflection of the Sun’s energy rather than absorption and re-emission of IR emitted from the Earth. It also appears that students’ ideas about this conceptual area are tentative, with responses varying according to the form of questioning, and often contradicting earlier statements. Conversely, the detail in students’ responses relating to the ozone layer suggests that for those students, the ideas are firmly held.

8.2.11 Finding 11 – Melting of snow and ice will increase climate change – item 26, 66%

The focus group data support all of the findings relating to feedback scenarios, despite participants’ lack of familiarity with the concept of climate feedback mechanisms. Only five students, in one group, had heard of feedback in the context of climate change, and none recalled learning about other feedback mechanisms in science, e.g., body temperature regulation. One student recalled reading about the concept in magazines. However, the concept presented little difficulty when students were helped to reason through it:

*It makes so much sense [1 student agrees]*

All groups successfully deduced the effect of melting ice and snow:

*In the test it says how snow and ice reflect the Sun's heat which means that if the ice is melting it'd just be soil so it would absorb the heat and make the climate hotter, because there wouldn't be so much reflected heat.*

8.2.12 Finding 12 – An increase in reflective clouds will slow climate change – item 25, 59%

The effect of increased cloud cover caused the most difficulty of the feedback items, with three of fifteen students thinking there would be either no change or positive feedback. Two of these appear to be based on the
reasoning that if clouds can reflect the Sun’s rays back into space, they can also reflect heat from the Earth’s surface back to Earth. These responses might be caused by a lack of understanding of the different properties of solar and terrestrial radiation:

*It could be the same because it would also reflect off the ground as well. For heat that was trying to leave - it would reflect it back in.*

*So how come it's not balancing, with the amount of Sun rays being trapped and the amount being bounced back?*

Other students were able to extend their reasoning beyond the initial scope of the question:

[Student 1] It'd be negative, it'd cool the Earth down [2 students agree] cos there's more of them so it'd bounce off more, and wouldn't get to the Earth to heat it up.

[Student 2] And then the clouds would go away and it'd get hotter.

**8.2.13 Finding 13 – Warming oceans will increase climate change – item 27, 59%**

Three students in one group initially reasoned incorrectly about the effect of warming oceans, but were able to deduce the correct answer with some assistance:

[Student 1] It's going to get less - it's not going to be as bad.

[Student 2] A tiny bit, it'll still be worse but not as bad [1 agrees]

[Researcher] Cold water dissolves CO₂. If CO₂ dissolves in water, what does that do to the amount in the atmosphere?

[2 students] Decreases.

[Researcher] So if climate change makes oceans warmer and they can’t dissolve CO2 what effect would that have?

[2 students] Make it warmer.

The other three groups were able to explain their reasoning correctly without assistance:

[Researcher] Could any of those changes have an effect on climate change itself?

Yes cos there was the hotter water absorbs less carbon dioxide so there would be more in the air so it would keep going faster.
8.2.14 Findings:

14a – *When a hot bath goes cold, the total amount of energy is unchanged* – item 4, 56% and

14b – *Energy can be partly or totally “used up”* (difficulty applying the law of conservation of energy) – item 4, 42%

Focus group data support finding 14a but not 14b. Of 33 students, 13 stated explicitly that the amount of energy would stay the same:

[Student 1] Because energy can’t dissolve.
[Student 2] It's still there, it's just changed form.
[Student 3] Yes, cos if the heat goes, doesn't that mean it's been transferred, because it hasn't just disappeared [several students agree]

Another 15 students pointed out that the energy had changed form or moved elsewhere. These responses imply conservation of energy:

[2 students] It goes into the air/makes the air hot.

Converts [all agree]

However, five students thought some or all of the energy had disappeared, or “dissolved”. The response below suggests difficulty understanding that energy can change form or that heat energy is conserved when an object is no longer sensibly hot:

I thought if it was hot to start with then went cold something must have happened. It can't be the same energy if it's changed. Because if it was the same energy you'd have the same heat.

One group found this apparently simple question difficult to answer:

[It was confusing] because it was something so simple but we had no idea.

The other three groups recalled the law of conservation of energy and identified that it applied to this situation:

[Student 1] It's impossible [for the energy to vanish] - you can't destroy energy
[Student 2] Or create it.
[Student 3] It has to be converted from one form into another.
[Student 1] Yes that's a law apparently [all agree]. We learned about that in Year 8.
However it appears that some students, while being aware of the law, struggled to apply it:

[Researcher] What about "energy can be created or destroyed"? [vague agreement]
[Student 1] It can be created.
[Student 2] No, it can be changed or transformed.
[Student 1] You can create energy - friction, that's creating energy.
[Student 3] Solar.
[Student 2] But you're using energy.
[Student 1] But you're still creating energy.
[Student 2] That's transforming energy.

8.2.15 Finding 15 – CO₂ can escape from the atmosphere into space – item 12, 51%

The majority of comments did not support finding 15. Two students provided scientifically accurate reasons for disagreeing with the idea:

The Earth is pretty big, it'd have a lot of gravity a small amount might get out but it'd stay close.

I don't think there's CO₂ past our atmosphere, cos there's no oxygen. If it's a vacuum, does that mean there's no particles, no gases?

These comments suggest that rather than being a credible idea in itself, the concept may simply have been more convincing than the idea of CO₂ dissolving in water. Alternatively, some students might hold tentatively formed ideas about the conservation of matter or the carbon cycle, as the following comments suggest:

[Researcher] How does CO₂ get out of the atmosphere?
[Student 1] Through the ozone hole?
[Student 2] It can in small amounts it can but we're creating too much, so some is still leaving but we've created more than it's possible to leave.
[Student 3] If it gets in doesn't it [carbon] have a way of getting out?
[Student 4] But it's already here.

It is possible that to these students, the idea of carbon escaping into space may seem plausible.
8.2.16 Findings:

16a – Most of the heat leaving the Earth is energy from the Sun being reflected – item 14, 50% and

16b – Most heat leaving the Earth is generated by human activities – item 14, 29%

Table 8.4 summarises responses to the question: “Which are the biggest sources of heat coming from the Earth?”

<table>
<thead>
<tr>
<th>Source</th>
<th>Students agreeing</th>
<th>Students disagreeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Burning fossil fuels</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Sun’s rays reflected</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Naturally emitted</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

These provide evidence for finding 16a and, to some extent, 16b. As with the CI data, finding 16a was expressed by a larger proportion of students than 16b: additionally a large number of students disagreed with 16b. However, as the following conversation illustrates, there was considerable confusion about what was meant by “heat naturally emitted from the Earth”:

[Researcher] What about heat emitted naturally?
[Student 1] Wouldn't the radioactive core still be natural?
[Student 3] Is energy emitted by the Earth?
[Student 4] I still don't understand what that means. I didn't know anything about that.

I suggest that students’ understanding of heat “naturally emitted” by the Earth requires more investigation.
8.2.17 Finding 17 – The carbon in fossil fuels originated in soil or rock, not the atmosphere (“snap association” between fossil fuels and rock/ lack of understanding of carbon flows/belief that plants get carbon from soil, or create it using sunlight) – item 5, 49%

The knowledge that fossil fuels originate from living things appears to be relatively common as it was observed in all groups.

Dead organisms - when everything dies it decomposes and goes back to the earth and recycles carbon.

However, some students were unfamiliar or unhappy with this idea:

[Student 1] I just learned something new. It makes sense.
[Student 2] How's oil or gas made out of dead things? That's weird. [selective class]

There appear to be a number of misconceptions about the origin of fossil fuels as well as a lack of any knowledge:

[Researcher] Where did the carbon in fossil fuels originally come from?
Rocks [everyone], the ground

[Researcher] Who knows what coal originated from?
[Student 1] Diamonds, ashes, volcanoes, charcoal, when the Earth was formed, igneous rocks, from the heat in the middle of the Earth.
[Student 2] I don't really know what a fossil fuel is.

Student 1’s comment above, illustrates the association between fossil fuels and rock. Further, discussions showed that students lacked a clear understanding of the origin of carbon in fossil fuels.

Some students, while understanding the stages of the process of fossil fuel formation as separate events, had not consciously reasoned before that the carbon in fossil fuels originated from the atmosphere:

[Researcher] You all said plants take in carbon from the atmosphere so this carbon that's released by fossil fuels - if it came from living things, you think it came from the atmosphere, if you join up 2 or 3 things that you said. But, that's not what you said [in answer to the direct question] is it?

[Researcher] Where did that carbon come from originally?
[Student 1] Living things that were compressed
[Researcher] Where did they get their carbon from?
[Several] The atmosphere
[Researcher] So when you burn FF and that puts carbon in the atmosphere, that carbon was originally in the atmosphere?
A larger proportion of students either held misconceptions, or lacked knowledge of stages of the process of fossil fuel formation. The following comments demonstrate misconceptions as well as students’ acknowledged confusion and lack of information:

[Researcher] When you dig up coal, is the carbon in the coal then?
Yes [2 students]
No, it’s when you burn it, because it reacts [3 students]

Maybe [total carbon] has increased because from the time Earth began there wasn’t anything living but there is now. All living things have carbon.
[Researcher] Do they create it, or get it from somewhere else?
Get it from the ground?

See that's where I'm stuck, [living things] would have had to get it [carbon] from the atmosphere or from their food source which would have had to get it from somewhere.

CO₂, I don't know if it’s right or not. There's sources of carbon in CO₂, our body expels the carbon doesn't it, or is it oxygen, now I'm confusing myself. Somehow CO₂ just popped into my head.

Only one group had no difficulty identifying the atmosphere as the source of carbon in fossil fuels:

[Researcher] If the carbon in fossil fuels comes from plants and animals, where did they get it from?
The atmosphere [several]
[Researcher] How did it get from the atmosphere into animals and plants?
Photosynthesis and respiration [several]

A number of comments addressed the age of fossil fuels:

[Fossil fuels were formed] when the Earth was formed.

It was there when the Earth was formed, I mean it gradually formed over time, but all the elements were there.

But weren't the fossil fuels always there, but now that everyone’s burning them ...

It doesn't take millions of years to go into the trees but it takes millions of years to be compressed into coal. The whole cycle takes millions of years.
[Researcher] Is that something that you think about when people talk about fossil fuels being burned?
Not really [2 students].

In the second comment above it appears that the student thought of fossil fuels as forming from “ingredients” in-situ underground, as there is no mention of elements moving from place to place.
The final comment may sum up the situation for many students: they possess the elements of knowledge to understand the role of fossil fuel formation and burning in the carbon cycle, but they have not consciously tried to put these elements together.

8.2.18 Finding 18 – Only “warm”/living things emit IR – item 24, 46%

The focus group data provide evidence for finding 18. Even groups who had clearly been exposed to theory and experiments related to the concept, found it problematic.

At least one group had experienced the concept of IR emission first-hand in an investigation at school. However, they were not more successful than other groups in applying their knowledge. Three students, including two in the group who recalled using the apparatus in school, could not provide an answer to the question of whether a student, a lab bench, both or neither emit IR. Of thirteen students who answered, six said that only the student would emit IR. Of the seven who said that both would emit, three specified that the lab bench would emit very little IR:

[Student 1] They'd still emit heat, just not much.
[Student 2] I just put the student cos you wouldn't see the lab bench, it's only a tiny small bit.

[Student 1] I don't know! [if the bench emits IR] I think it would, because we had one last year.
[Student 2] Is that the ones that show the red? Wouldn't it show that it's cold, it'd be blue. So yes the bench does emit - just at a lower level than us.

One student was able to give a detailed scientific explanation of the phenomenon:

Everything emits IR cos nothing's at absolute zero then no molecules are perfectly still so they all have to be giving off a little bit of heat.

While another expressed the misconception that heat was only reflected rather than emitted:

Would they still emit heat or would they only reflect heat that's bouncing off them?
8.2.19 Finding 19 – *A small percentage of GHGs is significant because it represents a lot of molecules – item 19, 45%*

[Researcher] if GHGs are less than 1% how can that have a significant effect?
[Student 1] They can be spread out over a large area they don't have to be too thick to reflect the heat
[Student 2] It's all relative to the size, cos the Earth's so large [agreement] so 1 or 2% could be a lot.

[Researcher] How can less than 1% of GHGs have a big effect?
[Student 1] If I didn't know [the actual proportion], I would say they couldn't have a significant effect, because I thought there was a greater amount. But now knowing there's less than 1% I would say that they can have a significant effect because you only need a very very very small percentage to really effect the Earth.
[Student 2] Not knowing how much I would say that it would have an effect but the effect would be decreased - it wouldn't happen as quickly as they say it's happening at.

These comments suggest that students, when given information about the actual proportion of GHGs in the atmosphere, are able to provide reasons as to why a small percentage of GHGs could have a significant effect. The responses also suggest that the wording of item 19 did influence students who initially thought that GHG concentrations are over 5%. Therefore it may be desirable to replace option 19A with a more plausible distractor, or to alter the wording of the item so as to be less leading.

8.2.20 Findings:

20a – *The process of FF formation caused an increase in atmospheric carbon (“snap association” between carbon and atmosphere/CO2 – lack of understanding of carbon flows) – item 13, 45% and*

20b – *The process of FF formation did not change the amount of carbon in the atmosphere (belief that plants get their carbon from soil) – item 13, 30%*

The comment below appears to be evidence of a “snap association” between the concepts of fossil fuels and increasing carbon, i.e., a response based on a gut reaction rather than a strongly held misconception:

[Researcher] Plants growing, dying and getting buried, how would that affect the amount of C in the atmosphere?
Make more fossil fuels so make more carbon, more coal.
It is likely that these “snap associations” would be observed less commonly during focus group interviews, where students’ ideas were tested through discussion, than in CI responses.

The following comments are likely to be related to lack of knowledge about the nature of fossil fuels or the process of their formation:

[Researcher] What does fossil fuel formation do to the amount of CO₂ in the atmosphere?
Nothing

Wouldn't it balance each other out? It [a plant] dying and that carbon being taken out, but at the same time it's not around to take more carbon in, so it would stay the same.

However, two groups were able to correctly explain the effect of fossil fuel formation on the atmosphere, as the following conversations demonstrate.

There is also evidence that students had not thought about this before:

Reduces in the atmosphere [3 students] because it grows and absorbs it and dies and keeps it in the ground.

[Researcher] So if plants take carbon from the atmosphere and it ends up buried underground, what's the effect on the amount of carbon in the atmosphere?
Decreases [several]
You just have to think about it. I actually probably learned more on that test.

8.2.21 Finding 21 – The energy absorbed by GHGs is mostly the Sun’s energy (direct or reflected from the Earth) – item 18, 45%

There is considerable evidence for finding 21, with all but three of the 18 students specifying, or agreeing with, the Sun as the source of the energy that GHGs interact with. Of the three replies that did not specify the Sun, the final one may have referred to the Sun’s energy reflected from the Earth’s surface:

[Researcher] Everyone thinks it’s coming from the Sun? From the Earth?
[Student 1] Both.
[Student 2] Everywhere.
[Student 3] Reflected off Earth.

As with finding 10, there was a wide range of ideas. Of the 15 comments citing the Sun, two involved the trapping of UV radiation, one involved the absorption of heat, another described how GHGs reflected the Sun’s rays
back to Earth and two thought that all bands of e.m.r. from the Sun had to interact with GHGs in order to reach the Earth’s surface:

UV rays from the Sun, GHGs are trapping them.

GHGs take in more heat and like absorb the heat from the Sun.

Sunlight rays come in to the Earth and they should bounce back into space, but with all the GHGs it's making like a barrier so a few of the Sun rays are released but a lot of them just bounce back onto the Earth [agreement].

I think it reacts with ... the [e.m.r. bands] that come to us from the Sun [agreement] because the Sun's rays have to make it through the ozone layer which has all these greenhouse gases in it so they have to penetrate, well they have to get through the greenhouse gases.

It is not clear whether, by “trapping”, students mean that GHGs reflect radiation back to Earth, i.e., trapping it between the Earth’s surface and some barrier, or whether they conceptualise the energy as being stored within the molecules rather than re-emitted. The third comment above suggests the former meaning, with all bands of radiation from the Sun being reflected back to Earth by GHGs.

8.2.22 Findings:

22a – GHGs damage the ozone layer – items 11, 15 and 23, 34-48% and

22b – GHGs trap IR radiation i.e., they do not re-emit it – items 11, 16 and 23, 36-38%

There is evidence for finding 22a, with six of seventeen students mentioning, or agreeing with others mentioning the ozone layer:

Greenhouse gases burn the hole through, which means the sunlight - I thought it didn't directly come into the Earth, but through the ozone layer [3 students agree].

In addition, one student mentioned aerosol sprays. This may either be due to a misconception that aerosol sprays damage the ozone layer, or it may be correct information that they contain GHGs:

[Researcher] So you think about aerosols? What do they do?
It releases gas - it goes up [points]. It just keeps going up, stays up.
The data also provide evidence for finding 22b. Six students mentioned the concept of GHGs trapping energy:

Don't the gases form a blanket [“I remember doing this”] that is kind of protecting, lets stuff in but doesn't let the heat and stuff out, it's like a giant blanket.

GHGs trap heat energy from the Sun, they don't release it so it just stays in the atmosphere and heats up the Earth.

Of these, two incorporated the ozone layer into their reasoning:

[Researcher] Why do GHGs cause the Earth to warm up, what do they do?
The ozone layer - it traps the gases. Like a greenhouse, it keeps it warm, traps it in some area [making box shape with hands]

I think the Earth is going to get hotter because the IR rays aren't being rebounded back. They're just staying in the atmosphere because of the ozone layer.

Students in one group referred to GHGs reflecting heat back to Earth, rather than absorbing then re-emitting it:

[Researcher] So non-GHG don't interact with IR?
[Student 1] Oh no - they still heat up, they just release they don't reflect it back onto the Earth.
[Student 2] They don't reflect it back onto the Earth.
[Student 3] They don't absorb it.
[Researcher] Who thinks that GHGs absorb heat?
[Student 1] Yeah I think so.
[Student 2] Do they just reflect it?

The following conversation shows that even the group who chose the correct response to the CI item, did not actually understand the mechanism by which GHGs cause retention of energy in the atmosphere:

[Researcher] Most people chose "GHGs let heat rays in but not out" - how can they do that?
[Student 1] Are they polarised differently? Like one-way mirrors?
[Student 2] Maybe it's the critical angle at which it hits the layer of gas.
[Researcher] Have you been taught how GHGs trap the heat?
No [several].
The mechanism by which GHGs raise the temperature of the atmosphere was not understood by any focus group participants. One group, who evidently appreciated the wave nature of IR, attempted to use their knowledge of unrelated properties of waves to explain the phenomenon. Other students conflated the issue with ozone depletion, or thought the IR radiation was reflected off the GHGs. The idea that radiation could get in through the atmosphere but not out again, was known by some students but it is suggested that this information was rote memorised rather than understood, because the students were unable to explain it.

Explanations involving trapping, and involving the ozone layer, occurred at frequencies very close to those observed in the CI data. The focus group data, however, adds a layer of complexity to the CI data by suggesting that these explanations are sometimes conflated in students’ minds, and may also involve ideas of radiation being reflected, possibly from a discrete layer of gases. These concepts require exploration in more detail: CI items involving diagrammatic representations of atmospheric interactions may be useful for this.

8.2.23 Finding 23 – Nearly all carbon on Earth’s surface is in the atmosphere (limited knowledge of range of carbon compounds/carbon associated primarily with CO₂ or CO) – item 1, 40%

The focus group data support finding 23. Despite the majority of post-CI focus group participants knowing that CO₂ dissolves in water, the atmosphere was cited as the largest reservoir of carbon by 5 of 10 students who commented or agreed.

*I thought the atmosphere would be the biggest thing so I went with that, I guess atmosphere [1 student agrees].*

This included one student who had watched a video on the topic. It appears that this is a poorly understood concept:

*I wasn't sure about the first question [agreement].*
Of the students who recalled watching a video on the topic, two chose the oceans; one thought that carbon was equally distributed; and another could not decide between atmosphere and oceans. One student in another group thought living things had slightly more carbon than the atmosphere.

In order to gain more insight into how the students conceptualised carbon, they were asked:

(i) what words they associated with “carbon”;

(ii) what compounds contained it; and

(iii) what forms of carbon were found in living things.

Their responses provide more evidence for finding 23. Eight of the nine responses to the first question concerned CO$_2$ or other products of combustion. Clearly these images dominate students’ thinking about carbon. The complete list of responses is shown below:

\[\text{[Researcher]} \text{ What co you associate with the word "carbon"?} \]
\[\text{Smoke/emissions/factories/cars/gas [5 students].} \]
\[\text{CO$_2$/greenhouse gases [3 students].} \]
\[\text{Nothing/don’t know [3 students].} \]
\[\text{Carbon fibre.} \]

The second question elicited a wider range of responses, but again, fossil fuels and products of their combustion dominated, with 12 of the 18 compounds named. The suggestion “carbon pentoxide” implies that, for this student, all carbon compounds consist of carbon and oxygen, suggesting a very impoverished conceptualisation of carbon chemistry and a focus on gases. The comment about water also shows a misunderstanding of the process of dissolution. The complete list of responses is shown below:

\[\text{[Researcher]} \text{ Can anyone name any chemical compounds that contain carbon?} \]
\[\text{Carbon dioxide [5 students]} \]
\[\text{Carbon monoxide [3 students]} \]
\[\text{Carbon pentoxide} \]
\[\text{Coal/non-renewable sources/vehicle emissions [4 students]} \]
\[\text{Isn’t it in glucose?} \]
\[\text{Graphite} \]
\[\text{Diamonds} \]
\[\text{Steel} \]
It’s in water? Like in the other question it dissolves it. The equation's H₂O. There might be an H₂OC sometimes. I remember doing them [in science] but I don’t remember [2 students].

The following responses to the third question again show a limited understanding of carbon chemistry, a tendency to focus on CO₂ and a misunderstanding of the process and products of photosynthesis. Again, the complete list of comments is shown:

[Researcher] Do living things contain carbon?
Yes, probably [4 students] I don't know what form it's in.
In our blood. Air’s in our blood, like carbon dioxide would be in our blood.
Yes but not that much. Dioxide. When you breathe it out, that’s the waste.
Not just CO₂. It’s hard to explain because it’s mixed through with everything because not everything is pure like diamonds - they’re all compounds.
I kind of know about trees, how they take in stuff and give out oxygen.
Isn’t there a C in the glucose formula somewhere, plants have glucose in them and when you eat them they haven’t probably completed their photosynthesis so you’d probably get it through that. And then your meat would do the same thing. Yeah, we have glucose. Glucose is important for us.

8.2.24 Findings:

24a – Plants extract carbon for photosynthesis from the air – item 2, 39% and

24b – Plants extract carbon for photosynthesis from the soil – item 2, 38%

Thirteen students stated or agreed that plants get their carbon only from the air. Six did not elaborate, but the following comments indicate how students reasoned:

We take in oxygen from the air and put out carbon, because plants do the opposite.

Air [2 students] cos I thought they breathed it in in a way.

[Student 1] Don't the trees perform a chemical reaction to take the carbon out of the CO₂?
[Student 2] Photosynthesis. It releases oxygen so it takes away the carbon - it stores it. It goes into glucose - sucrose and starch. It goes into C₆H₁₂O₆

[FF formation] is going to reduce CO₂ [in the atmosphere] because it grows and absorbs it and dies and keeps it in the ground.

 Doesn't CO₂ [get removed from the atmosphere] through plants and photosynthesis. I don’t know if there are enough trees to get it all out.
Nine students thought that plants obtain carbon only from the soil or ground. Of these, three thought that the carbon was dissolved in water, suggesting that these students might see carbon dioxide as being dissolved out of the atmosphere and absorbed by plants through their roots. These students could be expected to understand that plant growth removes carbon from the atmosphere:

Soil [2 students] because of the rain, the rain comes from the atmosphere.

[Researcher] If plants get carbon from the soil what form is that carbon in? Dissolved through the water isn't it?

Three students, however, saw carbon for plant growth coming directly from the earth. One student used information from the CI to elaborate on her misconception:

Rocks are our main source of carbon: they're in the ground near the roots

They absorb nutrients from the soil - nutrients contain carbon [this group were able to give chemical formulas for photosynthesis reactants and products].

Dirt has carbon because [unclear] decomposes.

Nine students expressed the idea that plants get carbon from the Sun. These correspond to item 2 option C “they convert the Sun’s energy into new carbon atoms which didn’t exist before”. Two students stated that energy from the Sun was converted into glucose, and two stated that the Sun’s energy was converted into food. However, the idea that energy from the Sun can be converted into matter was challenged by other participants in the following exchanges:

[Student 1] Energy gets converted into glucose.
[Student 2] It's energy, not matter.

[Student 1] Nutrients and stuff so they can grow.
[Student 2] Food for themselves.
[Researcher] So can you take energy and turn it into chemicals?
Hmm.
Good question.
[Student 1] Using energy you can make chemicals.
[Student 2] Would there be energy in chemicals?
[Student 3] Using energy you can create reactions between chemicals but you couldn't [make matter].
So you think the energy makes new matter or not?
I don’t think so [2 students].

These exchanges suggest that some students may have tentative conceptual models regarding the role of sunlight in photosynthesis, and the ability of energy to generate matter on the scale of atoms.

In total, 14 students thought the carbon came from two sources: 11 students thought that plants obtain carbon both from the air and soil. None of these students explained their reasoning, suggesting their knowledge of this concept is tentative.

Two students thought the carbon came from the Sun and soil, while one cited the Sun and water:

If you were to weigh a plant and it was 50g and a week later it was 55g, where did that 5g come from?
Water?
Nutrients.
It's using the Sun and water to grow.
Depends on what type of plant it is.
I have no idea [third time this topic was raised].

Even among the group with the most detailed understanding of chemistry, there was uncertainty about the reactants and products of photosynthesis, while other students expressed misconceptions about the process:

You know about photosynthesis, [all - yes] what happens?
They absorb rays from the Sun and turn them into energy.
Water and glucose, carbon dioxide and the waste is oxygen.
They're taking in CO₂, glucose.
Glucose what's formed at the end - don't they take water and things from the Sun? [Photosynthesis] takes in carbon and releases oxygen.

These comments suggest that even among students who can recite the reactants and products of photosynthesis, there is confusion about the source of the reactants. This includes the idea that some of the matter for plant biomass is obtained from the Sun, which was expressed by a total of 11 students. It appears that the students have a well formed understanding that plants need something from the Sun, but don’t know what.
Water was mentioned as plants’ carbon source by a total of seven students, two of whom apparently mistook it for a product of photosynthesis, rather than a reactant. It is perhaps surprising that water is not mentioned more often, as students would be very familiar with the importance of water to plants. This may be due to a lack of appreciation that carbon dioxide can dissolve in water.

### 8.3 Summary and conclusions

#### 8.3.1 Summary of findings

Table 8.5 summarises the evidence supporting or refuting the CI findings, discussed in Section 8.2.

<table>
<thead>
<tr>
<th>No. and item(s)</th>
<th>CI Finding and rate</th>
<th>Post-CI focus group findings</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Item 8 (δ)</td>
<td>Overestimation of contribution of FF burning to carbon flows (lack of understanding of equilibrium or focus on human activities), 90%</td>
<td>9 out of 11 students overestimated carbon flows</td>
<td>Confirmed. Lack of understanding of equilibrium seems to be an issue</td>
</tr>
<tr>
<td>2 Item 6 (ε)</td>
<td>Overestimation of proportion of UV in Solar energy incident on Earth, 86%</td>
<td>12 out of 19 students thought most of the Sun’s energy is UV</td>
<td>Confirmed. “Sun safety” messages</td>
</tr>
<tr>
<td>3a Item 1</td>
<td>Oceans contain little if any carbon, 81%</td>
<td>Oceans seen as containing little carbon. Students unsure what form this would be in. CI cited as source of knowledge about CO₂ dissolving.</td>
<td>3a and 3b confirmed. Concept of carbon dissolving poorly understood.</td>
</tr>
<tr>
<td>3b Item 8 (δ)</td>
<td>Oceans play very limited role in carbon flows (CO₂ does not dissolve in water), 46%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Item 10</td>
<td>Water vapour is not a GHG, 80%</td>
<td>Even when information was provided it was not always recalled.</td>
<td>Confirmed. Water does not contain carbon/seem as not harmful</td>
</tr>
<tr>
<td>5a Item 7 (ε)</td>
<td>If Earth emitted less energy than it gains it would heat up, 79%</td>
<td>14/20 students thought if Earth emitted less energy it would get hotter 12/12 thought Earth emits less energy than it receives; 5/12 said energy</td>
<td>5a, 5b and 5c confirmed. Role of Sun’s energy in photosynthesis poorly understood.</td>
</tr>
<tr>
<td>5b Items 7 (ε)</td>
<td>Some of Sun’s energy received by Earth is used up in processes e.g., photosynthesis, 13-66%</td>
<td></td>
<td></td>
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<tr>
<td>and 20 (ε)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
<td>Percentage</td>
<td>Notes</td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------------------------------------------------------</td>
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<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>5c</td>
<td>Earth emits less energy than it receives from the Sun, (tentative mental</td>
<td>19-90%</td>
<td>models about Earth’s energy balance)</td>
</tr>
<tr>
<td>6</td>
<td>GHGs comprise &gt;5% of the atmosphere, 76%</td>
<td>13/26</td>
<td>Confirmed. 5% was considered a small amount. Media focus interpreted as large amount. Atmospheric composition not well known.</td>
</tr>
<tr>
<td>7</td>
<td>CO₂ is the most abundant GHG, 73%</td>
<td>20/24</td>
<td>Inconclusive. CI may have been source of information</td>
</tr>
<tr>
<td>8</td>
<td>Burning FF has increased Earth’s total carbon/burning FF creates carbon</td>
<td>Idea voiced initially but rejected after discussion</td>
<td>Confirmed – but probably a “snap association” rather than a conclusion based on reasoning.</td>
</tr>
<tr>
<td>9</td>
<td>CO is a GHG (conflation of types of pollution/lack of awareness that water</td>
<td>4/20</td>
<td>Confirmed. Possibly due to conflation with pollution.</td>
</tr>
<tr>
<td>10a</td>
<td>Most of Sun’s energy interacts with most molecules in Earth’s atmosphere,</td>
<td>5/33</td>
<td>10a, 10b not confirmed.</td>
</tr>
<tr>
<td>10b</td>
<td>GHGs interact with more than one band of the e.m.s. 51%</td>
<td></td>
<td>Wide range of ideas about interactions between atmosphere and e.m.s.</td>
</tr>
<tr>
<td>11</td>
<td>Melting of snow and ice will increase climate change (familiarity with dark</td>
<td>All groups successfully reasoned through the scenario</td>
<td>Confirmed. Concept of albedo widely known</td>
</tr>
<tr>
<td>12</td>
<td>An increase in reflective clouds will slow climate change, 59%</td>
<td>12/18</td>
<td>Confirmed.</td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
<td>Subitem</td>
<td>Notes</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>13 Item 27</td>
<td>Warming oceans will increase climate change, 59%</td>
<td>Three groups reasoned successfully</td>
<td>Confirmed.</td>
</tr>
<tr>
<td>14a Item 4</td>
<td>When a hot bath goes cold, total energy is unchanged, 56%</td>
<td>5/33 students thought some or all energy disappeared. Some difficulty applying law of conservation of energy.</td>
<td>14a Confirmed</td>
</tr>
<tr>
<td>14b Item 4</td>
<td>Energy can be partly or totally “used up” (difficulty with law of conservation of energy), 42%</td>
<td></td>
<td>14b Not confirmed.</td>
</tr>
<tr>
<td>15 Item 12</td>
<td>CO₂ can escape from atmosphere into space, 51%</td>
<td>Most comments disagreed</td>
<td>Not confirmed.</td>
</tr>
<tr>
<td>16a Item 14 (ε)</td>
<td>Most of the heat leaving Earth is Sun’s energy reflected, 50%</td>
<td>5 agreed and one disagreed with 16a</td>
<td>16a Confirmed</td>
</tr>
<tr>
<td>16b Item 14 (ε)</td>
<td>Most heat leaving Earth is generated by human activities (focus on human activities), 29%</td>
<td>2 agreed and 6 disagreed with 16b</td>
<td>16b Inconclusive. Naturally emitted heat not understood</td>
</tr>
<tr>
<td>17 Item 5</td>
<td>The carbon in FF originated in soil or rock, not the atmosphere (“snap association” between FF and rock/lack of understanding of carbon flows/belief that plants get carbon from soil, or create it using sunlight), 49%</td>
<td>Living things as the origin of FF widely but not universally known. FF associated with rocks/ground.</td>
<td>Confirmed. Stages of FF formation partially understood as separate events only. Movement of carbon not appreciated.</td>
</tr>
<tr>
<td>18 Item 24</td>
<td>Only “warm” or living things emit IR (experience/association with “night vision goggles”), 46%</td>
<td>6/13 thought a lab bench would emit no IR</td>
<td>Confirmed. More investigation required.</td>
</tr>
<tr>
<td>19 Item 19</td>
<td>A small percentage of GHGs is significant because it represents a lot of molecules, 45%</td>
<td>Students seem to have learned this information during the CI. Other responses suggest that 5% is seen as a “small proportion”</td>
<td>Confirmed. Students are able to reason successfully, however they are likely to overestimate the proportion of GHGs</td>
</tr>
<tr>
<td>Item 13</td>
<td>Item 13</td>
<td>Item 13</td>
<td>Item 13</td>
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</tr>
<tr>
<td>FF formation increased atmospheric carbon (“snap association” between carbon and atmosphere/CO$_2$. Lack of understanding of carbon flows), 45%</td>
<td>2 groups successfully deduced answer but evidence that they had not thought of it before</td>
<td>20a and 20b confirmed. Closely related to finding 17: separate events in FF formation understood but “big picture” not appreciated.</td>
<td>FF formation did not change the amount of carbon in the atmosphere (belief that plants get their carbon from soil), 30%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item 18</th>
<th>Item 18</th>
<th>Item 18</th>
<th>Item 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>The energy absorbed by GHGs is mostly the Sun’s energy, either direct or reflected from the Earth, 45%</td>
<td>15/18 students agreed finding 21. Energy seen as being “trapped”.</td>
<td>Confirmed. Wide range of ideas about nature of interaction between Sun’s rays and GHGs.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Items 11, 15(ε) and 23(ε)</th>
<th>Items 11, 16 and 23(ε)</th>
<th>Items 11, 15(ε) and 23(ε)</th>
<th>Items 11, 16 and 23(ε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHGs damage the ozone layer, 34-48%</td>
<td>GHGs trap IR radiation by absorbing and not re-emitting, 36-78%</td>
<td>6/17 mentioned ozone</td>
<td>6/17 mentioned trapping</td>
</tr>
<tr>
<td>22a and 22b confirmed. Wide range of incorrect ideas about mechanism; no correct ideas.</td>
<td>2/17 mentioned both</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item 1</th>
<th>Item 1</th>
<th>Item 1</th>
<th>Item 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearly all carbon on Earth’s surface is in the atmosphere (limited knowledge of range of carbon compounds/carbon associated primarily with CO$_2$ or CO), 40%</td>
<td>5/10 students agreed with finding 23. When asked to name carbon compounds, nearly all were gases.</td>
<td>Confirmed. Carbon widely associated with gases/smoke. Few non-gaseous compounds known.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item 2</th>
<th>Item 2</th>
<th>Item 2</th>
<th>Item 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plants get their carbon from the air, 39%</td>
<td>13 agreed with 24a</td>
<td>24a and 24b confirmed. Photo-synthesis not well understood.</td>
<td>9 agreed with 24b</td>
</tr>
<tr>
<td>Plants get carbon from the soil, 38%</td>
<td>9 thought plants get carbon from Sun</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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8.3.2 Discussion and conclusions

27 of the 33 CI findings for which post-CI focus group interview data were obtained, were corroborated by the data. The most significant emerging themes are:

- Overestimation of the proportion of sunlight that is UV. This is related to “sun safety” messages that emphasise the dangers of exposure to UV radiation from the Sun
- Wide range of incorrect ideas about interactions between GHGs and non-GHGs, and bands of e.m.r. These include:
  - GHGs interact with Sun’s energy rather than Earth’s;
  - GHGs interact with the Sun’s energy after reflection from Earth; and
  - GHGs are located in the ozone layer

These ideas sometimes appear to be conflated. No students were able to describe the mechanism of interaction correctly
- Students had not encountered the concept of feedback before in the context of systems. However they had little difficulty in applying it to the climate system when given minimal guidance
- Carbon is conceptualised primarily in gaseous form, as CO$_2$, CO and smoke, and is primarily associated with the atmosphere. Students have limited awareness of other carbon compounds
- Lack of understanding of concept of dissolution and lack of awareness of oceans as a carbon reservoir
- Lack of coherent conceptualisation of fossil fuel formation and the role of atmospheric carbon in this process. This is due to:
  - conceptual difficulties with process of photosynthesis; and
  - partial and disconnected understanding of the steps in the process

The concept that fossil fuels formed from living things is reasonably widely known, but the misconception that plants obtain carbon from soil, is also prevalent. This means that students would think of the carbon in fossil fuels as originating from soil
• Overestimation of human contributions to carbon flows. This appears to be related to lack of understanding of equilibrium, i.e., students do not understand how small imbalances can have a significant effect

• Overestimation of proportion of GHGs in the atmosphere due to media focus on the topic, and misconceptions about which gases are GHGs and why. Confusion with other forms of pollution

• Lack of understanding of Earth’s energy balance related to conceptual difficulties with process of photosynthesis

• Objects at room temperature are not seen as emitting e.m.r. It is not clear whether this is because they are not living or because of their temperature.

The implications of these for learning design are discussed in Chapter 9.

The quality of CI items derived from statistical measures, reported in Chapter 6, does not appear to affect the degree to which findings based on those items were backed up by focus group data. Of the 12 findings based on items whose performance was rated “borderline” (δ) or “unacceptable” (ε) in Chapter 6, 10 were confirmed. Of the 21 findings based on items whose performance was “acceptable”, “good” or “excellent”, 17 were confirmed.
CHAPTER 9 - CONCLUSIONS

9.1 Introduction

This chapter discusses the findings in relation to the research questions, the extent to which the methods employed adequately addressed the research questions, and the limitations of the findings. It then outlines implications for learning and teaching, and possible directions for future research.

Understanding the science of climate change is essential for citizens to make informed choices (Bord et al. 2000; Francis et al. 1993; McNeill & Vaughn 2010; Mason & Santi 1998; Shepardson et al. 2011). The Stage 5 compulsory curriculum in NSW (targeted for ages 14-16) and equivalent curricula nationally and internationally, represent the last opportunity in formal education settings for students to acquire this important knowledge. However, a significant body of research shows that students’ understanding of the science of climate change is incomplete and misconceptions are common. Further, this situation has persisted over 20 years.

To date, most research has taken a broad view, investigating students’ understanding of this complex topic as a whole. The research reported here explored possible underlying causes for students’ known difficulties with the topic. In order to achieve this, I identified key scientific concepts underlying the science of climate change, and investigated what students understand about these concepts. To explore the concepts in more depth, I focused on the mechanism of climate change rather than its effects or possible actions to remediate it.
9.2 Research question 1

The purpose of the study was to investigate NSW Stage 5 students’ understanding of the key scientific concepts required in order to understand the topic at a basic level. This involved deriving a valid, descriptive list of the key concepts underlying a basic but scientifically acceptable explanation of the mechanism of climate change. There are two steps in this process:

- determining the simplest scientifically acceptable explanation of the topic; and
- determining which concepts underlie this explanation.

The first step above was important because climate change is a highly complex, multidisciplinary field of study, so for Stage 5 students it must be presented in a simplified form. However, too much simplification could lead to inaccuracies as well as a failure to explain essential points.

Research question 1 was stated in Chapter 1 as follows:

What underlying scientific conceptual knowledge is required for students to make sense of a basic explanation of the mechanism of climate change?

9.2.1 Extent to which the method addressed research question 1

Summary of methods used

To produce a set of statements describing the key concepts underlying climate change, I synthesised results from a Delphi study with findings from a review of literature on students’ understanding of climate change. This was described in Chapter 4.

A total of eighteen experts took part in the Delphi study, which consisted of one qualitative round and two quantitative rounds. Participants included academics and researchers in climate science, and high school teachers who were experienced teachers of the topic. The Delphi study was successful in recruiting an appropriate number of participants: ten to fifteen participants was considered the minimum acceptable number by most authors.
The aim of the Delphi study was to identify about ten concepts because concept inventories usually address no more than ten concepts. However, the Delphi study resulted in identification of 29 concepts, and most participants rated most of these as “extremely important” or “very important”. This meant that the relative importance of concepts could not be differentiated. To overcome this, I asked participants in the final round to rank the ten most important items. By aggregating these rankings, I was able to identify the ten concepts considered most important by the participants.

In order to gain a second perspective on the topic, I conducted a literature review of 16 research publications focusing on conceptual understanding of the topic of climate change and involving, wherever possible, students similar in age to those in my study. From this I generated a second ranked list of concepts considered important by the authors. I produced a final ranked list of ten conceptual areas by synthesising the findings of the literature review and Delphi study. Both literature review and the Delphi method have methodological limitations. However, combining the two methods should enhance the validity of the resulting list of statements.

9.2.2 Comments on findings for research question 1

Summary of findings

The synthesis process resulted in descriptive statements of ten conceptual areas. In ranked order, with most important first, these were:

1. The carbon cycle and fossil fuels
2. The electromagnetic spectrum
3. Interactions between greenhouse gases and electromagnetic radiation
4. Natural climate variability in the past and relationship to CO₂ levels
5. The difference between weather and climate
6. Proportions of greenhouse and non-greenhouse gases in the atmosphere
7. Radiative forcing capacity of different greenhouse gases
8. Feedback
9. Equilibrium of energy
10. Conservation of energy

Validation of findings for research question 1

I compared my final list of conceptual statements to the Climate Literacy Network’s (2009), and Gautier et al.’s (2006) lists of essential knowledge: this comparison provided evidence to support the validity of my list. The Climate Literacy Network (2009) covered the broad topic of climate science for primary and secondary students, while the Gautier et al. (2006) focused on the mechanism of the greenhouse effect and is intended for undergraduate students. My list of conceptual areas covered all of the elements of the Climate Literacy Network’s (2009) list that related to climate change. In addition however, four conceptual areas from my list were either not included in the Climate Literacy Network’s (2009) list, or only covered in limited detail. This is likely due to the broad scope and intended age range of the Climate Literacy Network’s (2009) list. All three elements of Gautier et al.’s (2006) required knowledge had corresponding elements in my list.

According to McCaffrey and Buhr (2008), insufficient research has been carried out into the development of descriptions of required conceptual knowledge for climate science. Therefore, my findings for this research question may constitute a contribution to a neglected field of research.

9.2.3 Limitations of method for research question 1

I identified the following limitations:

• Although eighteen experts took part in the second round of the Delphi study, only four participants were recruited for the first round. This was most likely due to the time of year, when many academics and schoolteachers were unavailable. In order to address this problem, participants in the second and third rounds were invited to add conceptual areas that they considered were missing from the list resulting from round 1. Several participants did volunteer additional concepts, suggesting that this strategy was successful. However it is possible that the study was constrained to
some extent by the limited number of participants in round 1. Fifteen experts took part in the third round, however such attrition is common in Delphi studies.

- The Delphi study, while very successful in identifying conceptual knowledge important to the topic of climate change, was unsuccessful in identifying the simplest scientifically acceptable explanation of the topic. This was because each successive round resulted in participants identifying more underlying concepts and adding more detail. I addressed this by asking participants to rank the ten most important concepts, however, it should be acknowledged that this was not part of the original research design. Also, because the Delphi study was limited to three rounds, I was not able to obtain feedback from the participants on the validity of the ranked list. This failure to obtain explicit consensus is acknowledged as a weakness of the study. The failure to identify the simplest scientifically acceptable explanation of the topic may relate to the complex, multifaceted and deep expertise of the Delphi participants, as well as a lack of understanding by academics of what would be developmentally appropriate for high school students.

A notable strength of the Delphi method is that it resulted in clarification and refinement of the conceptual statements, helping to define exactly what knowledge of each concept was required. This contributed significantly to the process of creating CI items and focus group interview guides to address research question 2.

### 9.3 Research question 2

Research question 2 was stated in Chapter 1 as follows:

What do NSW Stage 5 students understand about these underlying scientific concepts?
9.3.1 Extent to which method used addressed research question 2

Summary of methods used

I used two data collection activities with NSW Stage 5 students:

- a concept inventory (CI), i.e., a qualitative, multiple choice diagnostic test with distractors based on known misconceptions; and
- semi-structured focus groups with CI participants.

As a large-scale data collection method, the CI had several advantages. The multiple choice format is familiar to students and requires little explanation. By contrast, my pilot study with concept mapping showed that although most students were able to produce a recognisable concept map after one hour of instruction, their maps conveyed less information about their knowledge than semi-structured interviews. While this may have been due to unfamiliarity with the concept mapping technique, it was also likely due to the absence of prompts, which helped students to recall their ideas. CIs overcome this problem because the item stems and options act as prompts. However, as with concept maps, CIs have the disadvantage of not collecting data about the reasons behind participants’ responses. Therefore it is necessary to supplement with methods such as interviews if the reasons behind responses are to be explored.

Development and validation of the CCCI

I based the method for development and validation of the climate change concept inventory (CCCI) on a review of literature on CI development and validation, focusing on CIs for science, mathematics and engineering. The purpose of this was to ensure rigour in the CI development and validation process, thus enhancing the validity of the instrument and its findings. In order to ensure that item distractors reflected known misconceptions, I conducted pre-trial focus group interviews with four groups of students, and reviewed literature on students’ ideas about the concepts identified in response to research question 1. The draft items were reviewed by a second group of students in order to ensure that the language was clear and unambiguous, and to begin exploration of reasons behind responses.
Data collection for research question 2

A total of 229 high school students completed the CCCI in this study. 68 undergraduate students also completed the CCCI; their results were used in supplementary statistical evaluation of the instrument.

I carried out semi-structured post-CI focus groups with four groups of students. The purpose of this was to provide data for validation of the CCCI by comparing students’ verbally expressed ideas with CCCI responses. In addition, the focus group interviews allowed students to discuss the reasons behind their ideas in depth, thereby addressing a limitation of the CCCI.

Performance of the CCCI

In the trial with high school students, seven of the items performed poorly on statistical measures of item performance, usually due to low discrimination (D) and point biserial coefficient (r_{pbs}) values. However, statistical measures did not reflect the degree to which CI findings were corroborated by focus group data. In fact, findings from items whose performance was rated “borderline” or “unacceptable” were corroborated slightly more often than findings from “acceptable”, “good” and “excellent” items. In addition, when trialed with undergraduates, most of the CCCI items performed well. Two possible reasons for this are outlined below.

First, the statistical measures D and r_{pbs} assess how a correct answer to an item contributes to a high overall score. Neither of these measures differentiates between distractors, i.e., all non-correct option choices are aggregated. This results in a loss of information, which is likely to cause poor values for statistical measures when the proportion of incorrect response is high. However, if misconceptions about a concept are prevalent, then it would be expected that a large majority of students would choose an incorrect option, accurately reflecting their current understanding of the concept. Second, these measures assess the extent to which an item discriminates between students whose knowledge of the topic is good, and those whose knowledge is poor. It is possible for an item to perform poorly in discrimination while still accurately reflecting students’ ideas. Smith et
al. (2008) stressed that psychometric criteria should not be applied uncritically to CIs, and pointed out that CI items with poor discrimination values provide useful information about students’ learning.

Overall, 81% of the CI findings for which focus group data were obtained, were corroborated; suggesting that despite the relatively poor statistical performance of the CCCI with high school students, it was useful as a method of collecting data that reflected the high school students’ ideas.

I carried out two measures of test reliability with high school students: test-retest, and Cronbach’s alpha. The Cronbach’s alpha value was below the minimal acceptable value. However the test-retest data suggested that there was a very small probability that students had chosen the same answers by chance for test and retest, which provides further evidence that students’ CI responses reflected their ideas. Cronbach’s alpha reduces all responses to “correct” or “incorrect” i.e., it does not discriminate between distractor choices, and so loses data. When the rate of distractor choice is high, then the rate of data loss is also high. This may explain the low Cronbach’s alpha value with high school students.

The CCCI was also trialed with a group of undergraduate students who had just finished an introductory unit of study on climate change. Almost all statistical measures of item performance were within required values. This lends further support to the idea that statistical measures were poor for the high school students primarily because of the high rate of distractor choice.

9.3.2 Comments on findings for research question 2

Summary of findings

I derived forty-five findings from the concept inventory data. Thirty-three of these findings had corresponding focus group data. Of these thirty-three, twenty-seven (81%) were corroborated by the focus group data. The most significant findings are summarised below, in approximate order of prevalence:

- Overestimation of human contributions to carbon flows
• Overestimation of the proportion of UV radiation in sunlight, possibly related to “sun safety” messages, e.g., in PDHPE at school
• Lack of awareness that CO₂ dissolves in water and that water bodies act as reservoirs in the carbon cycle
• Overestimation of proportion of greenhouse gases in the atmosphere; and misconceptions about which gases are greenhouse gases: carbon monoxide was widely thought to be a greenhouse gas while water vapour was not
• Lack of understanding of Earth’s energy balance
• Incomplete understanding of the concept of black body radiation
• A range of incorrect ideas about interactions between bands of electromagnetic radiation and greenhouse and non-greenhouse gases, including the ideas that greenhouse gases interact with energy from the Sun, and conflation with ozone depletion. No students were able to describe the mechanism of interaction correctly
• Students had not encountered the concept of feedback before but had little difficulty in applying it with minimal guidance
• Limited awareness of carbon compounds other than gases. This finding was derived only from focus group data, however it was supported by a considerable amount of evidence
• Lack of understanding of fossil fuel formation, the role of atmospheric carbon in this process, and the movement of carbon through the cycle as fossil fuels are formed then burned. This is due to:
  o tentative, faulty and incomplete understanding of underlying chemistry concepts;
  o incomplete or faulty understanding of the steps of the process of fossil fuel formation including photosynthesis; and
  o difficulty synthesising these steps.

The carbon in plants, and in fossil fuels was often thought to come from soil or rocks.
Evaluation of students’ knowledge of the concepts

The responses to the CI suggest that Stage 5 students do not have enough accurate knowledge about the underlying concepts to understand the science of climate change. Although most students in the pilot study identified fossil fuels as the ultimate cause of climate change, none of the participants in this study were able to explain the mechanism correctly. I found high rates of misconceptions in all the conceptual areas tested by the CI.

Well-established and tentative conceptual models

It became clear during pre- and post-trial focus group interviews that there were some concepts that students had not considered before, e.g., the source of carbon in fossil fuels. They had to reason about such concepts for the first time during the interviews. The same situation may have occurred during the CI trials, i.e., participants had to reason about some concepts for the first time while answering the CI.

Further, for some concepts, students’ ideas appeared to be well-established, i.e., they appeared to have firm opinions of the science and were able to explain their reasoning. Two examples of such concepts were the proportion of greenhouse gases in the atmosphere, which students had thought about before, and feedback scenarios, which no student recalled encountering previously.

Students appeared to hold tentative understanding of other conceptual areas. In these cases, the participants were unable to explain the reasoning behind their ideas, frequently changed their minds, or stated that they were confused. Again this appeared to apply both for concepts that were “new” and for concepts that they had encountered previously. Rye et al. (1997) described such concepts as “‘loose’ in students’ cognitive structures” (p.547), and gave an example of a transcript excerpt in which the participant twice stated that she was confused. On a superficial level, students’ knowledge might appear to be well established, but probing students to reflect on their own and others’ ideas may reveal inconsistencies in
reasoning, result in confusion, or highlight instances in which students cannot explain why they believe an idea.

Table 9.1 shows examples of well-established and tentative ideas about key concepts. These have been further classified according to whether they may not have been previously encountered. As Table 9.1 shows, well-established ideas were conceptually less complex than tentative ideas.

Table 9.1 Proposed model of four types of knowledge about concepts underlying climate change

<table>
<thead>
<tr>
<th></th>
<th>Encountered previously</th>
<th>Encountered for the first time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well established ideas</strong></td>
<td>Proportion of UV in sunlight</td>
<td>Feedback</td>
</tr>
<tr>
<td></td>
<td>Proportion of greenhouse gases in the atmosphere</td>
<td></td>
</tr>
<tr>
<td><strong>Tentative ideas</strong></td>
<td>Interactions between greenhouse gases and e.m.r.</td>
<td>Fossil fuels’ source of carbon</td>
</tr>
</tbody>
</table>

Apparently well-established misconceptions are shown below. Students were able to explain their reasoning for these beliefs:

- Overestimation of the contribution of fossil fuel burning to carbon flows
- Overestimation of the proportion of UV in sunlight
- Underestimation of the role of oceans and water as carbon reservoirs
- Water vapour is not thought of as a greenhouse gas
- Overestimation of the proportion of greenhouse gases in the atmosphere
- Carbon monoxide thought to be a greenhouse gas
- The idea that Earth reflects the Sun’s radiation rather than absorbing and re-emitting it.

The contingency table for items 10 and 19 provided further evidence that participants did not think of water vapour as a greenhouse gas. If students had been aware that water vapour is a greenhouse gas, and that rising temperatures will cause more water to evaporate, then an association should have been observed between students who thought water vapour was a
greenhouse gas and those who thought that greenhouse gases could create more greenhouse gases. However, no such association was observed.

There were no CI items specifically addressing different forms of carbon, so the data for this finding came only from focus group interviews. However I included it because it provides a further perspective on students’ difficulties with chemistry concepts that are linked to climate change.

Students’ knowledge appeared to be tentative in the following conceptual areas:

- The process of photosynthesis, including the role of the Sun’s energy and plants’ source of carbon
- The nature of fossil fuels and the source of their carbon
- Carbon thought of only in terms of gases
- The nature of interactions of different bands of electromagnetic radiation with greenhouse and non-greenhouse gases in the atmosphere.

This “tentative knowledge” may consist of isolated, disjointed elements not linked to other elements of knowledge, as is needed for deeper understanding. These disjointed elements may result from rote learning, rather than being meaningfully learned (Ausubel 1963). This may explain the inconsistencies in students’ reasoning about these concepts during interviews. As such, it represents an opportunity for future research.

Comparison of this study’s findings with previous research

This study’s findings concurred with previous research findings regarding misconceptions about plants sourcing carbon from the soil, and students’ conceptual difficulties with basic chemistry concepts and their role in the carbon cycle. Additionally, I found similarities to Mohan’s (2009) findings regarding students’ difficulties with conservation of matter, namely the idea that sunlight is somehow converted into biomass by plants. However, I found the knowledge that fossil fuels originate from living things, to be more widespread than did Bodzin (2011).
Meadows and Weisenmeyer (1999) noted that there is internal logic in the commonly reported conflation with ozone depletion, in that students learn that the ozone hole allows UV to reach the Earth’s surface, they know from experience that the Sun’s rays are hot, so they conclude that a hole in the ozone layer would allow more heat through. This internal logic is typical of a well-established idea.

I identified little prior research on high school students’ ideas about the electromagnetic spectrum. Most of my participants, unlike those of the Institute of Physics (1998), were familiar with the idea that different bands of the e.m.s. are related. I did not identify any prior research on students’ ideas about the proportion of UV in Solar radiation so my finding may be a new addition to the body of knowledge of this topic. This finding also lends a further perspective on conflation with ozone depletion, i.e., if students believe that a large proportion of Solar radiation is ultra-violet, then they are likely to think that a hole in the ozone layer significantly increases the amount of solar radiation reaching Earth.

My study confirmed Gautier et al.’s (2006) finding that students (in their case, undergraduates) did not perceive the Earth as emitting electromagnetic radiation.

Regarding interactions between electromagnetic radiation and atmospheric gases, Comins (2003) reported the misconception that all electromagnetic radiation is able to pass through the Earth’s atmosphere. My findings did not agree with this: my participants expressed a range of ideas including that all solar radiation interacted with greenhouse and non-greenhouse gases.

9.3.4 Limitations of the method

The method used to address research question 2 had a number of weaknesses and limitations. These are discussed below:

• Because the first round of focus group interviews suggested that students’ ideas were either homogeneous or that their knowledge of a concept was sufficiently limited that no viable options could be
written, it was not possible to write items for the following conceptual areas:

- *The difference between weather and climate*
- *Natural climate variability in the past*
- *Radiative forcing capacity*

Omission of these conceptual areas from the CCCI must be considered a weakness of the study, and efforts must be made to include items for these conceptual areas in future versions of the CCCI. This would involve interviewing more students and continuing to review literature in order to identify sufficient misconceptions to write plausible distractors for items.

- Typically CIs undergo several cycles of development before they are considered in their final form (Libarkin & Anderson 2006). This study used the first draft version of the CCCI, because running multiple trials was beyond the scope of the study, and would have been too time consuming for schools.

- There was a bias in CI participants towards more academically capable students: six of the eleven participating classes were academically selective classes. This was due to participating staff choosing participants that they considered would participate actively and benefit most from the activity. Participating staff know the students best and their judgments are respected. However, the inferences made about participants’ ideas cannot be assumed to be representative of the wider student population. In order to overcome this weakness it would be necessary to trial the CI with a number of less academically capable classes. It is possible that less able students could have fewer firmly held ideas, whether correct or incorrect, about the concepts, and would therefore be more likely to guess responses, resulting in poor quality data. This would need to be tested, for example by validating the CI data with focus group interviews, and through the use of statistical techniques such as test-retest.
• The post-CI focus group interviews were biased to very academically capable students: three of the four participating classes were academically selective classes and one of these was an accelerated class. As with the CI participants, this bias was due to choices of participating staff. This may have resulted in more correct ideas and fewer misconceptions being expressed than would be expected in the general student population. However, there was strong agreement between ideas inferred from CI responses and ideas expressed by focus group participants, with 27 of 33 CI findings confirmed by focus group data.

• Not all concepts were discussed by all of the post-CI focus groups. This was due to time constraints at the host schools. Further data collection would be required in order to corroborate findings related to these concepts.

9.4 Implications for learning and teaching

This section discusses the findings listed in Section 9.3.3 that have implications for learning and teaching.

9.4.1 Overestimation of human contributions to carbon flows/proportion of greenhouse and non-greenhouse gases in the atmosphere

This is caused by:

• The belief that a “tiny” proportion of greenhouse gases in the atmosphere cannot have a significant effect (discussed below); and/or

• Possible lack of understanding of the concept of equilibrium.

Both these misconceptions would lead students to believe that if climate change is a real problem, then human inputs of greenhouse gases must be relatively large, therefore it is important to address both in the design of learning activities.
A number of students also expressed the idea that the amount of media focus on greenhouse gases had led them to believe that greenhouse gases must form a large proportion of the atmosphere.

Many substances are present in similarly “tiny” amounts in the human body, for example vitamins and trace elements, so this could be used as an introduction to the concept. Learning about the concept in two contexts may help to reinforce the idea as it gives students multiple opportunities to apply and test their understanding.

9.4.2 Overestimation of the proportion of UV radiation in Sunlight

This misconception was observed in 86% of CI responses, and was strongly corroborated by focus group participants’ comments. Both pre- and post-CI focus group participants explained that they based their reasoning on “Sun-safe” messages in primary school and PDHPE. They reasoned that if UV was so harmful as to require so much emphasis, then it must comprise a large proportion of the Sun’s energy.

This misconception resembles the overestimation of human carbon inputs and proportion of greenhouse gases described above. They can be described in the following general terms:

The assumption that in a system, the importance of an input is always determined by the relative amount of the input, and not weighted by the physical or chemical properties of the input.

This implies that the relevant physical properties of greenhouse gases and UV radiation must be addressed. I suggest that an explanation of these physical properties should be as simple as possible, while allowing students to reason logically about the phenomenon, thus avoiding the need for rote-memorisation. For example, explaining the proportion of UV from the Sun could be achieved by explaining that, for the same “amount”, UV radiation carries more energy than visible light and infrared. Two focus group participants independently came to this conclusion, suggesting that it would not be a troublesome concept for students to understand.
9.4.3 The ability of CO\textsubscript{2} to dissolve in water; role of oceans in the carbon cycle

Almost no students were aware, initially, that CO\textsubscript{2} dissolves in water, and this was reflected in their responses to items 1 and 8, which ask about terrestrial and marine carbon stocks and flows. However, when I asked about CO\textsubscript{2} in carbonated drinks, the focus group participants immediately grasped the concept, presumably because it was very familiar in that context. This may provide an accessible way of introducing it.

9.4.4 Earth’s energy balance/black body radiation

When asked directly, most students responded that if the Earth emitted less energy than it absorbs from the Sun, it would heat up. Therefore misconceptions about these concepts appear to be two underlying conceptual difficulties:

- The idea that energy is “used up” in photosynthesis, due to:
  - Misunderstanding of the role of sunlight in photosynthesis
  - Lack of understanding that plant biomass is at equilibrium, so that solar energy stored in chemical bonds is continually being released as those bonds are broken down
- Lack of understanding that the Earth emits longwave e.m.r.

The concept of equilibrium is a key scientific principle, spanning disciplines. It is required for understanding the effect of human contribution to carbon flows in this topic, described above. Explicit comparison of these two examples may help students identify similarities and hence deduce the key elements of the principle. Simple experiments to illustrate the principle would also be useful, e.g., growing plants and measuring the gain in biomass over time, or visiting mature bush land and observing the breakdown of biomass by decomposers.

One group of students reported using an IR detector to “see” IR radiation. This would provide a memorable way of introducing the idea of black body radiation. The idea that the Earth emits IR radiation is of central importance to understanding the greenhouse effect. However, black body radiation at
radio frequencies is of less immediate relevance to this topic, and teachers may choose not to discuss it, in order to minimise complexity.

9.4.5 The carbon cycle/diversity of carbon compounds/photosynthesis and fossil fuel formation/burning

All these concepts depend on sound understanding of basic chemistry principles, for example conservation of matter; the atomic model; the difference between atoms and molecules; and the principles of separating and joining atoms in chemical reactions. Students would benefit from increased awareness of the variety of carbon compounds, for example by making three-dimensional models of common carbon compounds in the environment, using modeling materials or software. The ubiquity of carbon as a basis for living things is essential to this topic, so emphasis should be given to carbon compounds that form the tissues of living things, i.e., carbohydrates, proteins and fats, and the percentage of different types of biomass which consist of carbon. The same approach could be used to visually represent how carbon atoms move from carbon dioxide to carbohydrate during photosynthesis; how the carbohydrate is changed during fossil fuel formation; and how carbon dioxide is formed during fossil fuel burning.

9.4.6 Greenhouse and non-greenhouse gases

The belief that water vapour is a non-greenhouse gas is problematic because it prevents students from understanding a key positive feedback mechanism. The belief that carbon monoxide is a greenhouse gas may be related to conflation of different forms of pollution. Both these misconceptions may be linked to the fact that students do not understand the mechanism by which greenhouse gases trap heat in the atmosphere. If students do not understand what greenhouse gases “do” they may attempt to reason by using prior knowledge about gases that they know to be harmful. Additionally, students who think of the greenhouse effect as entirely human-caused may assume that it is caused by gases associated with human activity, such as carbon monoxide. Alternatively, confusion may be caused
by the media tendency to refer to “carbon pollution”; a term that does not make clear which carbon compounds are pollutants and which are not.

Rote-learning greenhouse and non-greenhouse gases is unsatisfactory, while the detail of how bonds store energy is likely to be too complex for most Stage 5 students. However, students could identify common characteristics in the molecular structure of greenhouse and non-greenhouse gases, and derive simple rules to classify them. Such an activity would reinforce learning of chemical elements and compounds.

9.4 7 Feedback mechanisms
Feedback mechanisms do not appear to be taught as part of the science of climate change. Without awareness of the existence of climate feedbacks it is not possible to understand how small increases in greenhouse gases can lead to large climatic changes; so the absence of this concept in current learning materials and activities for climate change is an omission. However, CI and focus group participants were usually successful in working out the impact of the feedback scenarios provided, suggesting that this concept could be learned successfully by students of this age. The principle of feedback applies in other fields of science e.g., in homeostasis, which is in both the current NSW syllabus (NSW Board of Studies 2003a) and the National Curriculum (Australian Curriculum, Assessment and Reporting Authority 2012). It may be useful to explicitly identify similarities between feedback mechanisms in different science topics, in order to reinforce understanding of this important principle.

9.4 8 Scare campaigns
Academically capable students cited what they described as “political scare campaigns” as sources of information. These often rely on misinterpretation of accurate information, and depend on students being unaware of the faulty reasoning. It is important to engage with these sources of information and explicitly examine them, to identify which elements of information are accurate and where information is being misused or misrepresented. Some
of these sources of information rely on incorrect use of mathematics: critical analysis of these could be a useful activity for students’ numeracy.

9.4.9 Suggested sequence of concepts to be introduced

The summary that follows is an outline of suggested concepts that could be introduced in the order presented. However, further research would be needed to clarify this sequence in more detail.

1. Revision of chemistry concepts, making models of carbon-containing models and modeling the movement of carbon atoms through the carbon cycle, including fossil fuel formation and burning.

2. Substances do not have to be present in large amounts to be important, e.g., vitamins and trace elements in the human body; greenhouse gases in the atmosphere; and UV radiation in sunlight.

3. Physical mechanisms explaining why small amounts of greenhouse gases and UV radiation can have these disproportionate effects.

4. The ability of carbon dioxide to dissolve in water; the consequence of this given the volume of water in oceans; and the temperature-dependence of the phenomenon. Simple experiments with carbonated water and standard tests for CO₂ can be used to illustrate the phenomenon.

5. Dynamic equilibrium and the cumulative effect of small inputs to a system can be illustrated with experiments, e.g., adding and removing water from a basin, first in equal amounts then adding slightly more than is removed. The acidifying effect on oceans can be introduced at this stage. This leads into equilibrium of energy absorbed by, and emitted from Earth, which can be illustrated using IR-detection apparatus.

6. Feedback mechanisms: negative feedback mechanisms could be introduced as a living system’s way of maintaining equilibrium, thus linking to the previous concept, before introducing positive and negative climate feedback mechanisms.
7. “Scare campaigns”: using the concepts learned to critically examine some “climate sceptic” arguments.

**9.5 Future research**

Evaluation of the study’s design and implementation suggest a number of possible directions for future research activities, in order to address the study’s weaknesses and to explore questions that arise from its findings. These are listed below.

**9.5.1 Consultation with curriculum experts**

A limitation of the study was the lack of expert agreement on a scientifically acceptable explanation of the science of climate change that would be appropriate for the targeted audience. Follow-up studies with a larger group of experts who also have curriculum expertise may determine whether the list of conceptual statements could be improved. This would form the foundation for the further research directions described below.

**9.5.2 Further revision and testing to improve the draft CCCI**

This would include removing rarely-chosen distractors in the four and five option items; revising items with poor statistical performance and those whose findings were not corroborated by focus group data; and development of items for concepts that were not covered in the draft version due to lack of data about known misconceptions. Further data on students’ knowledge of these concepts would have to be collected, to develop plausible distractors. Chapter 7 also described some possible improvements to items. Testing of the revised CCCI with a wider range of students would enhance its validity as a diagnostic instrument. Testing with undergraduates completing a unit of study on introductory-level climate change and comparison with grades, would allow criterion-related validity to be tested.

**9.5.3 Additional interviews to enhance this study’s findings and further validate the CCCI; further research into potentially novel findings**

Individual interviews, while being less effective than focus group interviews in a number of aspects, would allow direct comparison of individual
students’ CI responses and their verbally expressed ideas. Therefore, both focus group and individual interviews may be beneficial.

Of particular interest are the findings from my study that disagreed with those of previous research, for example the idea that interactions take place between most of the Sun’s radiation and most gases in the atmosphere, and the finding that most students understand the relationship between different bends of the e.m.s. As explained in Chapter 2, I identified little prior research on students’ ideas about some conceptual areas. Therefore, further research would be useful in order to clarify the state of high school students’ knowledge of these concepts.

Also of interest are the conceptual areas where students’ ideas appeared to be tentative, in particular the wide range of misconceptions about interactions between atmospheric gases and electromagnetic radiation.

Finally, further investigation could be carried out into the hypothesised generalised overestimation of human contributions to greenhouse gases, carbon flows and heat emitted by the Earth.

9.5.4. Students’ drawings of climate change science
A number of participants produced drawings illustrating their understanding of the science of climate change. I did not incorporate these into the study as the sample was too small and did not reflect the range of students’ understanding and abilities. However, drawings have been used by a number of authors to investigate students’ ideas about climate change (e.g., Koulaidis and Christidou 1999): these were described in Chapter 2. Collecting an appropriately large and representative sample of drawings would provide a third perspective on students’ conceptual knowledge, thereby enhancing validity of the study’s findings.

9.5.5 Exploring the ways students apply their knowledge in context
This study illustrated the difficulties that students have in applying knowledge they have learned previously, e.g., conservation of energy, in a new context. Theories relating to how learners apply knowledge in new
contexts are complex (Lobato 2008; Rebello et al. 2005) and it would most likely be necessary to examine one conceptual area at a time in order to address the issues in sufficient depth.

9.5.6 Students’ sources of knowledge about the concepts underlying the science of climate change

It is important to determine where students obtain information, and how the information in these sources compares with their ideas expressed in this study. This may clarify whether students are accessing reliable and accurate sources of information, whether they are interpreting the information accurately, and whether their information sources cover all the key conceptual areas. This should enable informed decisions to be made regarding appropriate learning resources and activities for the topic. These should address existing misconceptions, fill in gaps in knowledge, help students learn to critically evaluate information about the science of climate change and assist them in integrating their knowledge of the underlying concepts, in order to make sense of the topic as a whole.

9.6 Wider applications of the CCCI

The concept inventory developed during the course of this research represents a first step toward the creation of a valid and reliable instrument that can be used in secondary and tertiary settings. The list of conceptual statements on which it was based was presented in a peer-reviewed publication at a science education conference. The development and validation of the first draft version, as used in this study, was reported in a peer-reviewed journal article. This draft version has also been used with my permission in a number of tertiary settings. It is hoped that future validation across a range of settings will enable further refinement, enhance the quality of this instrument and make a valuable contribution to the teaching of climate change in secondary and tertiary settings.
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APPENDIX 1 – PILOT STUDY REPORT – MAPPING STUDENTS’ IDEAS ABOUT CLIMATE CHANGE

A1.1 Statement of purpose
The purpose of this study was to use open-ended concept-mapping to investigate the knowledge structures and misconceptions about climate change held by students aged 14-16 (NSW Stage 5). Findings derived from qualitative and quantitative analysis of the concept maps were triangulated against knowledge communicated by students in semi-structured interviews. This research forms a pilot study for PhD research, the proposal for which was approved in August 2010.

A1.2 Research problem
Understanding climate change involves synthesising complex and abstract concepts such as frequency-dependent absorption of electromagnetic radiation and thermodynamic equilibrium. It is therefore a challenging phenomenon for students to conceptualise. The literature and personal teaching experience suggest that misconceptions, specifically conflation with stratospheric ozone depletion, are common. According to Rye et al. (1997) pre-existing misconceptions can hinder future learning so it is important to understand students’ knowledge structures, both to provide a starting point for building on existing knowledge, and to correct misconceptions. Ausubel (1968), cited in Novak and Gowan (1984) asserts that the most fundamental principle in education psychology is what the learner already knows. This view is in accordance with the basic principles of Constructivist Learning Theory (White & Gunstone 1992).

A1.3 Review of literature

A1.3.1 Concept-mapping as a tool for communicating understanding
Surveys, even with open-response questions, limit participants to responding to the researcher’s questions, so the researcher’s ideas frame and dominate the data-gathering process. Both Koulaidis and Christidou (1999)
and Rye et al. (1997) were interested in students’ ways of conceptualising rather than what facts they could recall. Both used concept-mapping embedded in interviews in order to give students the best opportunity for communicating all of their ideas, and demonstrating how they saw them to be related. Concept maps consist of concepts (usually nouns) arranged hierarchically according to inclusiveness and linked by lines, which must be labeled to show how the concepts are related (Figure A1.1).

![Figure A1.1: Part of a concept map for the topic of climate change](image)

Rye and Rubba continued to use concept-mapping to explore how students’ ideas were structured (Rye & Rubba 1998; Rye & Rubba 2002). They reported that students found concept-mapping in interviews assisted them in answering the interview questions. Taricani and Clariana (2006) describe open-ended concept maps as the “gold standard” for probing students’ knowledge structures (p.1). Kinchin et al., (2000) cited in Rye and Rubba (2002) state that “As an assessment tool, student-constructed … concept maps provide both qualitative and quantitative measures of understanding and have considerable potential for revealing changes in knowledge over time” (p.33). Rebich and Gautier (2005) emphasise the value of concept mapping in studying knowledge structures because “it allows an exploration of student knowledge at a sufficient level of complexity, does not presuppose that all students have mastered exactly the same material, and has been shown to create a more equitable assessment … for those … with test anxiety” (p.358). They also assert that it is a more efficient data
collection method than interviewing and point out that because maps are non-linear, they can show concept relationships that are difficult to convey in text. However Schultz (2009) who used concept maps to probe students’ ideas about climate change, suggested that they may have been too difficult for her Years 7 and 8 participants, and recommends further research into their use as a data-collection instrument.

**A1.3.2 Analysis of concept maps**

It is possible to place a value on a student’s understanding through scoring concept maps (Rye & Rubba 2002; Stoddart et al. 2000; Taricani & Clariana 2006; Yin et al. 2005). Novak and Gowan (1984) devised a method of scoring concept-maps in response to requests: “Scoring was in many respects irrelevant, for we were looking for qualitative changes in structure. But … we live in a numbers-oriented society” (p.97). They suggest the use of an expert map, against which to compare students’ maps. Since then many other rubrics have been devised, with different emphases on concepts and links. Stoddart et al. (2000) developed a method for scoring concept maps based on grounded theory, where students were following individual topics of open-ended enquiry. They calculated the percentage of scientifically accurate propositions and the percentage involving higher-order thinking (e.g. “how” or “why”). Reliability was evaluated by comparing marks generated by three researchers working separately. Stoddart et al. (2000) cite Bogdan and Biklen (2002), emphasising that “the process of carefully deriving categories which emerge from the data is as much part of the method as the final rubric itself. This is an inductive, qualitative method in which initial ideas are tested against the data through review, coding and categorisation of dominant themes.” (Stoddart et al. 2000 p.1231). Taricani and Clariana (2006) used a computer-based technique to score open-ended concept-maps, according to numbers of links and geometric distances between terms. Because all the participants had studied the same material, an expert map was used for the scoring procedure. Rebich and Gautier’s (2005) choice of concept-maps as a test instrument is significant because the focus of their study was
misconceptions about climate change and the effectiveness of a “mock climate change summit” in effecting conceptual change in undergraduate students. The authors note the significance of students’ existing ideas to the success of future learning. The students used concept-mapping software, received an hour of tuition prior to producing maps and were able to study maps for other topics. The authors used a rubric based on a number of existing rubrics; however, their aim was to assess evidence of conceptual change rather than to grade the maps. They concluded that concept-mapping “provided a valuable insight into … learning” that “may be used to inform the development of instructional materials” (p.364).

Literature on qualitative methods of concept-map analysis is less common than that for methods of scoring concept maps. Novak and Gowan (1984) and White and Gunstone (1992), who originated and developed the technique, express reluctance for scoring concept-maps, which they see as detracting from their purpose. Nevertheless, they do not explicitly describe a procedure for qualitative concept-map analysis. Koulaidis and Christidou (1999) do not describe how they analysed the concept-maps produced by their participants: it is not clear whether the concept-maps were recorded or simply used to help the students express their ideas verbally. Kinchin et al. (2000) used qualitative analysis based on the “shape” of concept-maps to assess levels of conceptual development among year 8 science students. Concept-maps were described as being chain-, spoke- or net-shaped, with net-shapes displaying the most sophisticated level of understanding. However, this approach would not provide a sufficient level of detail to satisfactorily describe students’ conceptual models. Van Zele et al. (2004) used qualitative analysis of concept mapping to investigate students' knowledge structures and misconceptions in physics. The authors claim that for the purpose of probing students' knowledge structures, qualitative analysis of concept maps yields more information than quantitative analysis of concept maps; and is more objective than qualitative analysis of students' responses to essay questions. They believe the method is appropriate for high school students.
Scoring rubrics are, by necessity, arbitrary and subjective (Rye & Rubba 2002). Reducing a concept-map to a set of values destroys information about what the student actually knows and does not know: one of Rye and Rubba’s (2002) concept maps demonstrated a more robust understanding than another but gained a lower score. The authors cited Novak and Gowan’s (1984) advice that researchers should experiment with values for rubrics. Ferry (1996) whose participants, like those of Stoddart et al., chose their own topics of enquiry, was not satisfied with the reliability achieved between two experienced teachers using Novak and Gowan’s (1984) method. To overcome the problems associated with giving a single value to a concept-map, the author used a method based on the work of Beyerbach (1988), cited in Ferry (1996) to give a multi-dimensional score.

A1.3.3 Teaching concept mapping
The method of instruction for producing concept-maps was informed by the work of White and Gunstone (1992), Novak and Gowan (1984), Ferry (1996) and Stoddart et al. (2000). According to Stoddart et al. (2000), who worked with students from years three to twelve, a minimum of 45 minutes is required for training. The authors recommend choosing a topic with which the participants are familiar, but which is unrelated to the research topic in order to allow the participants to focus on the process of producing a map. After introducing the components of a concept map, the researchers drew up a map on the blackboard. Following this, their participants were given a practice exercise to complete. Ferry (1996) combined parts of the methods used by Holley and Dansereau (1984), cited in Ferry 1996) and Gunstone and White (1992). Ferry (1996) cites Holley and Dansereau (1984), cited in Ferry (1996), who point out that the process of selecting key concepts “activates relevant knowledge” (p.235). This underlines the importance of the introductory session in helping the students to recall all that they know. Ferry also emphasised the importance of demonstrating to participants how a map is produced. According to Ferry (1996), Gunstone and White (1992) recommend using a familiar topic and a small number of concepts, so that participants can focus on the process of producing a
concepts in a concept map. Ferry, whose participants were using software to produce their maps, used a data projector to provide instruction on concept map production. Ferry’s participants received a review of their topic in a lecture, before producing their maps, and were provided with a set of key concepts.

Gunstone and White (1992) recommend encouraging participants to identify all possible links between concepts. They point out that more than one attempt will be necessary to produce a “good” map, and that providing positive feedback is essential. The authors also state that a suggested layout may be provided for the first map, but should not be provided for subsequent mapping exercises. Gunstone and White (1992) also emphasise the importance of making sure that students understand that there is no “correct answer” when constructing a concept map. Logically then, students should be told that it is not necessary either to include all the concepts on the core-concepts list, or to limit themselves to the concepts on the list.

A1.3.4 Conclusions

In order to design effective teaching and learning strategies, it is vital to uncover students’ pre-existing knowledge structures, but no satisfactory information about NSW students’ understanding of climate change has been identified in the literature. Concept mapping has a number of unique characteristics that enhance the ability of users to communicate their understanding.

A1.4 Theoretical framework

A1.4.1 Models of cognition and understanding

In order to study understanding it is necessary to theorise the elements from which understanding is built up. Bruning et al. (2004) describe concepts, propositions and schemata as the three “building blocks of cognition” (p.42) most closely associated with declarative knowledge. They assert that propositions which share elements are linked in long-term memory and that understanding and the ability to apply knowledge depend critically on the “quality of the [propositional] networks [learners] are able to create” (p.48).
In Paivio’s (1971, 1986a; cited in Bruning et al. 2004) dual coding theory, visual and verbal memories are coded independently. Visual memory is the stronger form and concepts coded under both systems are more readily recalled. This is significant because of the role that imagery plays in conceptual understanding in physics.

Gagné and White (1978) expanded Ausubel’s (1963) theory of meaningful verbal learning to include images, episodes, and intellectual skills. White and Gunstone (1992) add strings, motor skills and cognitive strategies, defining conceptual understanding as the set of propositions, strings, images, episodes and skills associated with a concept, so understanding is a multidimensional continuum and is never complete. White and Gunstone (1992) assert that their theory “is consistent with, and indeed owes much to, cognitive and constructivist theories of learning … learners construct their own meanings for the knowledge they acquire.” (p.13).

**A1.4.2 Constructivist learning theory**

Constructivist learning theory states that learners actively construct their own understanding. This process is essential for conceptual understanding (Dykstra et al. 1992). According to Driver (1983), learners cannot be expected to perceive connections between concepts or make and interpret observations in the same way as experts. This is because they make sense of information through conceptual frameworks that are developed through prior learning. Driver’s descriptions of “conceptual framework” (p.11), “causal frameworks” (p.64) and “theoretical perspective” (p.70) appear to be functionally equivalent to schemata in that they organise knowledge and focus attention on relevant aspects of observations.

**A1.4.3 Schema theory**

Bruning et al. (2004) define schemata as hypothesised structures formed when elements of knowledge are meaningfully linked and assert that they are central to the construction of new knowledge. They store numerous related concepts, propositions and procedures; serve to organise knowledge and focus attention on relevant stimuli; and are necessary for
comprehension, assimilation and recall of new information. Because meaning rather than actual information is remembered, schemata play a vital role in how information is encoded: “In this way schema theory supports a constructivist view of learning” (Bruning et al. 2004 p.51). Schemata may result in either enhanced meaning or in distortion because they form the “lenses” through which learners perceive and process information, therefore critically underpinning future learning.

A1.5 Research paradigm

The study was carried out within the pragmatic paradigm (Creswell 2002; Tashakkori & Teddlie 1998). Pragmatism is concerned with finding solutions to problems (Cherryholmes 1992) and the choice of method and relationship between researchers and participants is determined by what achieves the purpose of the study (Creswell 2002; Mertens 2005). Pragmatists focus on what is effective rather than what is true or real: this position aligns with the philosophy underlying physics where models and theories are judged by their usefulness rather than whether they represent any sort of objective reality (Gregory 1988).

A1.6 Research questions

What pre-existing ideas, knowledge and misunderstandings do students aged between 14 and 16 bring to the topic of climate change, and how do they perceive the relationships between these ideas?

- What conceptual models of climate change do students communicate in concept-maps?
- How do these conceptual models compare under quantitative analysis?
- How do these conceptual models compare with students’ verbally expressed understanding of the topic during semi-structured interviews?
A1.7 Data Collection

A1.7.1 Method
A non-selective public high school participated in the research. The participating students were in their first term of Year 9, and had not yet studied climate change in Stage 5 science. Three classes of 25, 30, and 26 students took part in the concept-mapping exercise, making a total of 81 participants. Each class participated in two lessons, each of one hour duration. During the first lesson, I introduced the method of producing a concept map, and participants made their own map for the science topic they were studying at the time. Little time was available to me for taking field notes during lessons but I made more detailed notes immediately afterwards. These notes included variations on planned activities, unforeseen problems, participants’ response to activities, levels of engagement and ability to carry out activities, and are summarised below.

A1.7.2 Lesson 1: Teaching concept mapping

Introduction

The lesson started with a five-minute introduction during which participants were reminded of the purpose of the research; the fact that the activities were optional and did not form part of their assessment; that there were no right or wrong answers and that their own ideas were what was wanted. I also explained that concept mapping could be used for any topic and may be of value to them as a revision aid.

Demonstration of producing a concept map

I demonstrated how to make a concept map on the topic of ecology, which all students should have studied in Stage 4, i.e., Years 7 or 8. Participants were asked to suggest possible concept words related to the topic and the researcher used four of these to draw up the start of a map on the board, showing how it was important to link each new word to the previous ones as it was added, rather than putting all the words down and then making links. Following this, the participants were shown two pre-prepared OHP
transparencies that illustrated two possible further stages of a concept map for the topic.

*Practice concept map*

Computers were not available for all students to use individually, so concept maps for the practice activity and for data collection were made on paper, as for Schultz’ (2009) and Stoddart et al’s (2000) participants. Each participant was provided with a sheet of A3 paper and a pile of small pieces for writing concept words on. The topic for the practice map was the science topic currently being studied by the participants. The three classes were working on different topics, so each class produced practice maps on a different topic.

For the practice map made by the first class, a set of fifteen pre-prepared concept words and an exemplar map were provided. Before distributing these, I asked participants to suggest possible concept words and found that their suggestions corresponded closely with the prepared words. However, during the mapping activity I found that participants focused on ensuring that they had a complete set of the prepared words and on arranging all of these on their map, and that they rarely added any concept words of their own. By the end of the hour, only one or two participants considered themselves finished. Several had arranged their concepts but not glued them down or drawn any linking arrows. I concluded that providing a set of concept words led to conformity and stifled individual thinking, so for the second and third classes’ practice maps, I asked students to suggest concept words and these were used as the core concepts for the practice mapping activity. No exemplar map was prepared. Participants working together succeeded in compiling a list of 15 to 18 relevant concept words in only a few minutes. I instructed them to write the concept words they wanted to use on the small pieces of paper, then arrange them on the A3 sheet, finally gluing them down when they were satisfied with the arrangement and adding appropriate linking words.
The first and third classes continued working on their practice maps until the end of the period. Participants in the second class indicated that they had completed their maps about fifteen minutes before the end of the period, so this time was used to show the introductory video on climate change.

**A1.7.3 Lesson 2: Making the concept map for climate change**

During the second lesson, participants produced their maps on the topic of climate change. These sessions took place within a week of the first sessions. At the start of the session, I returned practice maps made during the first session to participants. I showed a short video on the topic of climate change (National Geographic 2007) and distributed stimulus sheets. These contained scientifically accurate information about the mechanism and projected impacts of climate change as well as social issues related to the topic. Details of these are given below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Source</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>The greenhouse effect</td>
<td>Diagram with numbered arrows and explanatory text underneath</td>
<td>The national academy of sciences</td>
<td><a href="http://www.pewclimate.org/docUploads/images/greenhouse-effect_012907_085209.gif">http://www.pewclimate.org/docUploads/images/greenhouse-effect_012907_085209.gif</a></td>
</tr>
<tr>
<td>Global warming kids page</td>
<td>Text in Q&amp;A format</td>
<td>Pre centre on global climate change</td>
<td><a href="http://www.pewclimate.org/global-warming-basics/kidspage.cfm">http://www.pewclimate.org/global-warming-basics/kidspage.cfm</a></td>
</tr>
</tbody>
</table>

I also provided participants with a sheet of tips for producing concept maps, which reiterated the advice given during the first session.
Again, I emphasised that the purpose of the research was to get the participants’ own ideas, and that the video and information sheets were intended to help them focus on the topic, recall everything they know and to help them generate a list of concept words. I emphasised that their maps were not expected to be copies of the supplied information.

I asked participants to note down possible concept words while watching the video. After watching the video, they were asked to volunteer words from their lists and these were written on the board. Participants were reminded that their maps did not have to contain all of these words or be limited by them, and that they should not include words they did not know the meaning of. As with the practice sessions, participants readily volunteered 18-20 concept words. Because they had struggled to label the links on their practice concept maps, I provided examples of linking words on the board. I asked participants to suggest further possible linking words for this list, and were able to do so. Levels of participant engagement during production of climate change concept maps were high. Participants in the second and third classes were asked to rate the level of difficulty of the concept-mapping task on a scale from one to five, and write their rating on their map. In total, participants constructed 50 recognisable concept maps.

**A1.7.4 Selection of participants for interview**

In order to provide triangulation for all levels of understanding it was necessary to interview participants whose maps suggested limited, moderate and sophisticated understanding of the topic. It was intended that students should be interviewed as soon as practicable following the mapping activity, so that the topic and the concept-mapping activity would be as fresh in their memories as possible. Therefore, detailed analysis of maps prior to selection of potential interviewees was not practicable. Instead, I sorted the maps into four levels of complexity based on numbers of concepts, structure (numbers of branches and cross-links). Several maps were classified as of limited complexity: these had seven or fewer concepts and either a linear, star-shaped or very simply-branched structure. At the opposite end, a number of maps stood out as being extensive and complex in structure, with a large
number of branches and with cross-links, which were absent from the limited maps. Once maps had been sorted, students from across the range of complexity, boys and girls, were asked if they wanted to participate in interviews. Out of 15 interviews, three of the students originally selected declined to be interviewed: in these cases students who had produced maps of similar complexity agreed to be interviewed instead.

**A1.8 Data analysis methods**

The objective of data analysis was to determine what ideas participants expressed in their concept maps, and how these compared with the ideas expressed in interviews. As the video shown during the concept mapping session was considered to be the most significant factor likely to have influenced participants’ concept maps, I also analysed the video content. Data processing and reduction for the interviews and video involved conversion of recordings into lists of propositions that could be categorised and compared. For the concept maps, less processing was required to produce lists of propositions. Data analysis was carried out on Word documents. At each stage, a new file was created so that the complete process could be audited subsequently and findings derived from the processed data could be confirmed. For example, it may be necessary to check the exact wording of an utterance that led to it being coded under a particular phrase. The analysis focused on participants’ ideas about the cause and mechanism of climate change. The stages of data analysis are described below.

**A1.8.1 Interview data**

*Stage 1*

I transcribed the interviews in full after listening to each one twice. In some cases, I considered participants’ hesitation or confidence to be a significant part of the data (Hesse-Biber & Leavy 2006). This information was included in the transcript. This inclusion was helped by the fact that the I transcribed interviews soon after they had taken place. Sections of dialogue were extracted that related to causes, effects, prevention of climate change, or
which assessed participants’ own understanding and the extent to which they considered the map reflected their understanding. Minor paraphrasing was then carried out, e.g., removal of verbal tics and conversion of questions/answers to statements. For example:

*Researcher:* So do you know anything about the gases from fossil fuels, and that sort of stuff?

*Participant:* No.

Was converted to:

Don’t know anything about the gases from fossil fuels.

The following shows the results for one participant. The researcher’s voice is given in brackets.

“I don’t know all that much about climate change. I know some things, but don’t know if it’s right or not”.

“Is global warming caused by gases from fossil fuels? I don’t know if that’s right or wrong. I just wrote that because that’s what my friend had”.

“Don’t know anything about the gases from fossil fuels”.

[Researcher reads from the concept map “greenhouse gases change the atmosphere and they’re going to change forests and stuff”.

<confident> “I know that – about greenhouse gases and carb … the bad stuff coming out, the carbon dioxide coming out cars, and destroying the ozone layer and that’s causing the sun to heat up more because of the ozone layer. It goes straight through, and it’s melting the ice, and the sea’s rising. Is that ok?”

“CO₂ destroying the ozone layer, then you get more heat from the sun because there’s less protection from the sun, and that’s causing the ice in the Arctic and Antarctica to melt”.}
[Researcher: When the ozone layer gets destroyed ultraviolet radiation gets in]

“Is that from the sun?”

“Global warming, is it caused by the sun, and the ultraviolet”.

“I’ve learned about [radiative forcing], but I forgot that, I knew that. It lets it in but it won’t let it out and then that’s why it’s getting hotter, that’s why the earth’s more polluted”.

“We learned, not the big, technical words. Just, the rays get in, can’t get out, type of thing”.

“I don’t know that much about fossil fuels!”

Stage 2

The segments of transcript were re-arranged according to the following themes, which were chosen after examination of the data: causes, effects, prevention, confidence in their own knowledge, other. At this stage, segments of transcript from individual students were kept together under headings so that it was possible to see which ideas belonged to a single student.

Stage 3

In order to analyse participants’ ideas about the causes of climate change, I copied all the utterances grouped under “causes” into the left hand column of a table with separate rows for each students’ utterances. The right hand column contained a “translation” i.e., a list of participants’ ideas expressed in as simple a proposition as possible without distorting the apparent meaning of the participants’ talk. E.g., some students said only that climate change was caused by greenhouse gases. Others said this and also named specific greenhouse gases and/or said where they came from and elaborated on what they did in the atmosphere. The processed data for the same participant is shown in Table A1.2. This approach was informed by phenomenenography (Marton 1981). According to this theory, there is a finite
number of qualitatively different ways of understanding a phenomenon, and phenomenography seeks to classify and compare these.

Table A1.2: Interview participants’ utterances and corresponding propositions

<table>
<thead>
<tr>
<th>Original utterance</th>
<th>Propositions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is global warming caused by gases from fossil fuels? I don’t know if that’s right</td>
<td>NONE</td>
</tr>
<tr>
<td>or wrong. I just wrote that because that’s what my friend had</td>
<td></td>
</tr>
<tr>
<td>Don’t know anything about the gases from fossil fuels.</td>
<td>NONE</td>
</tr>
<tr>
<td>I know this one – about greenhouse gases and carb ... the bad stuff coming out, the</td>
<td>CO₂ is a pollutant that comes from cars</td>
</tr>
<tr>
<td>carbon dioxide coming out cars, and destroying the ozone layer and that’s causing</td>
<td>CO₂ destroys the ozone layer</td>
</tr>
<tr>
<td>the sun to heat up more because of the ozone layer. It goes straight through, and</td>
<td></td>
</tr>
<tr>
<td>it’s melting the ice, and the sea’s rising. Is that ok?</td>
<td></td>
</tr>
<tr>
<td>CO₂ destroying the ozone layer. Global warming, Is it caused by the sun, and the</td>
<td>Direct heating from the sun</td>
</tr>
<tr>
<td>ultraviolet</td>
<td>Global warming caused by UV</td>
</tr>
<tr>
<td>It lets it in but it won’t let it out and then that’s why it’s getting hotter, that’s</td>
<td>Rays can get in but can’t get out</td>
</tr>
<tr>
<td>why the earth’s more polluted.</td>
<td></td>
</tr>
<tr>
<td>We learned, not the big, technical words. Just, the rays get in, can’t get out, type of thing.</td>
<td>Rays can get in but can’t get out</td>
</tr>
</tbody>
</table>

Stage 4

Using the right hand column i.e., the summarised propositions as propositions from all fifteen participants were then sorted according to theme. Some propositions, e.g., “carbon dioxide is a greenhouse gas” or “climate change is caused by greenhouse gases”, were identical or close to identical, and could simply be counted. Other propositions were categorised under headings e.g.,

Sources of CO₂

CO₂ comes from deforestation and burning fossil fuels

CO₂ is a pollutant that comes from cars

CO₂ is emitted by machines and things people build
CO₂ is an emission

**A1.8.2 Concept map data**

*Stage 1*

The equivalent of the interview transcripts was made by transcribing the propositions directly from the maps with no editing except for clarity e.g., adding verbs to unlabelled links to create propositions, e.g., “Greenhouse gases (cause) climate change”. Added verbs were in brackets to distinguish them form verbs added by the participants. It was not necessary to replicate the first stage of data reduction as for the interview process, where participants’ talk was summarised as propositions. This is because concept maps by their nature communicate ideas using little or no redundant language, so there was very little need to re-word or standardise language.

*Stage 2*

Propositions were rearranged under the headings of causes, effects, prevention and other, and repeated propositions removed.

*Stage 3*

For the causes theme, I categorised and sorted sub-themes, and counted propositions in the same way as for the interview data. Themes were not chosen to be identical to those in the interview data, rather they were allowed to emerge from the data.

**A1.8.3 DVD transcript analysis**

I transcribed, coded and categorised the DVD soundtrack in the same way as the interview data, and made frequency counts.

**A1.8.4 Ensuring quality in data analysis**

All stages of data analysis were at least double-checked, both to ensure that no mistakes or omissions had been made, and also to re-evaluate the data and coding decisions. I listened to all recordings twice before starting transcribing so that any unclear areas could be identified and resolved.
read finished transcripts while listening to the recording to confirm accuracy and completeness. Transcripts were compared with the file containing coded sections to ensure that no dialogue relating to themes under investigation had been missed. In order to check the sorting process I printed the files and physically crossed off propositions to confirm that none had been missed. This process allowed me to consider the raw data afresh and re-evaluate original categorisations.

**A1.8.5 Displaying results using concept maps**

In order to show logical relationships between categories, I used a concept map rather than a table to summarise the data on causes of climate change. I used propositions from the file for interview data and the file for concept map data to generate concept maps. Propositions were copied directly into concept boxes only in a minority of cases. Most of the propositions were constructed on the map in the form: concept → link → link, with a number in brackets at either the concept or link to indicate the number of responses.

**A1.9 Results and discussion**

**A1.9.1 Summary and discussion of findings**

Figures A1.2 and A1.3 show the concept map summary of the interview data and concept map data on participants’ understanding of the cause of climate change.

Although the majority of participants linked climate change to greenhouse gases and were able to name greenhouse gases or their sources, none gave an account of the mechanism of climate change that corresponded to the scientifically understood version. Two participants described their understanding as “rays get in but can’t get out”, which is the closest reference to the scientifically understood version. However both these participants also conflated climate change with damage to the ozone layer.
When asked to explain their understanding of how greenhouse gases cause climate change, most participants, and all of those who offered a mechanism, blamed the phenomenon on damage to the ozone layer. Of the eleven participants who voiced this idea, two may have been influenced by leading questions, as they agreed that ozone might be involved but were unable to elaborate on the idea:

Researcher: What are people doing that’s causing global warming?

Participant: Um … cutting down trees, …
Researcher: And what happens when they cut down trees? Do you know what kind of effect that would have? No? Ok, do you know what’s happening in the atmosphere?

Participant: No

Researcher: What do you think’s going to happen to temperatures?

Participant: … they … will rise?

Researcher: Do you know why?

Participant: <shakes head - negative>

Researcher: Ok, do you think it’s got anything to do with the ozone layer?

Participant: Yeah ...

Researcher: Ok, can you tell me anything about that?

Participant: Not really

In these cases, it seems unlikely that the participants really hold the belief that climate change is related to ozone depletion. However, this leaves nine out of fifteen participants who clearly did hold this belief and in most cases described their understanding in detail. This contrasts with the lack of elaboration of the scientifically accepted mechanism. One more participant responded to my suggestion that ozone was related to climate change, but in this case there was little doubt that the participant was not unduly led:

Participant: Like, I don’t know how to explain it, I don’t know what it’s called.

Researcher: It’s not the ozone layer is it?

Participant: Yeah, that!

One participant appeared to link the burning of fossil fuels directly with a rise in temperature:

Researcher: Do you know what’s causing it?

Participant: Global warming with greenhouse gases. Fossil fuels being burnt, pollution.

Researcher: What sort of pollution?

Participant: Like, smoke, yeah.

Researcher: Do you know how that pollution causes the climate to change?
Participant: It sort of, I don’t know really how to explain it. The air, like, it warms up, expands around, heats up.

Researcher: That’s interesting. So you say pollution causes the air to heat up.

Participant: Yeah, and temperatures to rise.

Given that the participants will be very familiar with the idea that burning fuel gives out heat, it is perhaps surprising that the idea that global warming is caused directly by the heat generated from burning fossil fuels, is not more widespread. However, there was evidence both in the concept map and the interview data, of a belief in the idea of direct heating, usually caused by increased solar input following damage to the ozone layer:

Researcher: I’ll write that down, it’s interesting what you said. <writing> CO2 destroying the ozone layer, then you get more heat from the sun?

Participant: Yeah, because there’s less, like, protection from the sun.

Methane, originating from cattle, was discussed in detail by one interview participant, and was included in four maps, two of which gave cattle as the source. This information was not included in the video and the level of detail volunteered by the interviewee suggests that it was not rote-learned elsewhere, but was a topic the participant felt strongly about:

“I heard the Amazon is being ripped to shreds for cows and stuff to be raised in it, to then be killed. Cows also create methane a whole ton, so that’s destroying the atmosphere as well. And things are just being ripped down to make room for these fast food things. Human demand as well, the earth just wants more and more and more of it as its population goes up and its people’s wants increases so they need to tear down more and more forests to get enough room for the cows. And it’s not only the fast food industry, but its things like mining, with fossil fuels, we’re going to run out of those and it’s not going to be cool”.

Joint negotiation of meaning invariably occurred during interviews. Hesse-Biber and Leavy (2006) discuss the potential significance of the phrase “do you know what I mean?” (p.346). This phenomenon was noted when one
participant tried to communicate her understanding of the mechanism of climate change:

“Is like, climate change, isn’t there like a big thing that opens up. Like a greenhouse, oh, yeah that. <she seems to have remembered something here!> Do you get what I mean though?”

It also became apparent that whether or not a participant really understood a concept was not clear-cut: for example, participants may have written a proposition on their concept map but when asked about it, they often could not elaborate, or said they had understood at the time but could not remember now, or asserted that they had copied this information from a partner. This raises the question of whether an individual’s understanding of a complex topic can be considered as fixed and unchanging, even when the individual is not currently learning about the topic. In some cases, participants said more than once during the interview that they did not know anything about the cause of climate change, but later described an alternative concept in detail in response to probing about what specifically happens in the atmosphere to cause global warming.

Only one student mentioned deforestation as a cause of climate change in their interview; this contrasts with the concept map data where one in five participants cited this. This suggests that the video shown during the mapping activity influenced participants. I suggest that in the absence of the video few of the participants would have volunteered this information, as only one concept map included a mechanism for the link between climate change and deforestation:

“Chopping down trees builds up carbon dioxide levels because trees breathe out oxygen and take in carbon dioxide”

**A1.9.2 Comparison of categories of understanding: concept map and interview data**

The categorisation shown in Table A1.3 is informed by the work of Koulaidis and Christidou (1999) and Andersson and Wallin (2000). Categories are listed in approximate order of increasing complexity, with
the simplest categories towards the top and the most complex toward the bottom. Categories which are equivalent or similar are aligned horizontally. Percentages of participants expressing the category are given in brackets.

Table A1.3: Categories of understanding of the cause of climate change

<table>
<thead>
<tr>
<th>Categories from concept maps</th>
<th>Categories from interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cause or mechanism (20%)</td>
<td>Cause but no mechanism (26.3%)</td>
</tr>
<tr>
<td>Cause but no mechanism e.g., CO2, fossil fuels, methane (46%)</td>
<td></td>
</tr>
<tr>
<td>Greenhouse gases trapped in the atmosphere (10%)</td>
<td>Build-up of pressure in the atmosphere (6.7%)</td>
</tr>
<tr>
<td>Links cause e.g., CO2, fossil fuels, methane, to changes in the atmosphere (14%)</td>
<td>Burning fossil fuels heats the atmosphere (6.7%)</td>
</tr>
<tr>
<td>The sun is heating up the Earth (2%)</td>
<td></td>
</tr>
<tr>
<td>Links cause to damage to the atmosphere (6%)</td>
<td>Greenhouse gases cause changes to the ozone layer (13.4%)</td>
</tr>
<tr>
<td>Links cause to holes in the ozone layer (2%)</td>
<td>Greenhouse gases damage the ozone layer, letting in more of the Sun’s rays, causing heating (33.5%)</td>
</tr>
<tr>
<td></td>
<td>Greenhouse gases cause damage to the ozone layer, letting in more UV radiation (13.4%)</td>
</tr>
</tbody>
</table>

A1.10 Conclusions

This research suggests that open-ended concept mapping as a data-collection activity does not serve to provide as detailed insight into participants’ knowledge structures as interviews: in particular it was not effective at uncovering participants’ misconceptions. This was also found by Schultz (2009), who suggested that more research be carried out on the use of concept maps as a learning assessment tool. However, according to a large number of researchers, this use of concept mapping is unproblematic.
(Rye & Rubba 1998; Rebich & Gautier 2005; Novak & Gowin 1984; Novak 1990; Stoddart et al. 2000). I suggest that further literature review and research is required to resolve this apparent contradiction.

The study’s findings also raise the questions: why is conflation with ozone-depletion such a common idea, and why do so few students come to understand the scientifically accepted model? Various reasons have been put forward for the high rate of misconceptions, including psychological or socio-cultural explanations (Devine-Wright et al. 2004), however the future research will continue to focus on cognitive factors. Rye et al. (1997) cite higher awareness of the issue of ozone depletion, and the fact that both issues are human-induced and affect the atmosphere. Koulaidis & Christidou (1999) inferred that misconceptions about the nature of solar radiation may contribute to conflation of climate change and ozone depletion, and recommended that learning addresses the properties of the electromagnetic spectrum. Hansen (2009), Andersson and Wallin (2000) and Mason and Santi (1998) cited the complexity of the topic and the conceptual appeal of a “barrier” keeping harmful radiation out. Österlind (2005) described the difficulties that Year 9 students encountered when applying knowledge from other contexts to understand climate change. The PhD research which leads from this study aims to explore these issues in more depth by determining the scientific concepts needed to understand climate change and assessing students’ knowledge of, and ability to apply, these in context.

It is possible that the topic may be inherently too complex for many students at NSW Stage 5 to understand fully. Hansen (2009) noted that “Even in a condensed and popularised version the complex greenhouse and climate system is demanding both for teachers and students in secondary education” (p.399). Such a finding would have implications for curriculum designers.
APPENDIX 2 – CLIMATE CHANGE CONCEPT INVENTORY AS USED IN TRIALS

INSTRUCTIONS

1. Put a CIRCLE round the BEST answer to each question
2. If you change your mind, CROSS OUT your first answer and CIRCLE the new answer.
3. If you don’t understand a word or question, PUT YOUR HAND UP
4. THIS IS NOT A TEST!! DON’T COPY YOUR NEIGHBOUR – JUST PUT WHAT YOU THINK.
   Your answers will NOT affect your course results!

1. Most of the Earth’s carbon is in rocks. Which of the following images BEST represents the relative amounts of carbon in the other parts of the Earth? (larger circle = more carbon)

2. When plants make new roots, stems and leaves, where do they get the carbon from?

   A  they absorb it from the air
   B  they absorb it from the soil
   C  they convert the Sun’s energy into new carbon atoms which didn’t exist before
3. Over time since the Earth first formed until now, the total amount of carbon on the planet, including its atmosphere, has:
   A increased
   B decreased
   C stayed the same

4. A hot bath contains energy in the form of heat. After a while the water goes cold. What has happened to the heat energy?
   A it has changed to a different form but it’s still the same amount of energy
   B it has all been used up and doesn’t exist anymore
   C it has been partly used up so there’s less energy than before

5. When fossil fuels are burned, carbon is added to the atmosphere. Where did this carbon originally come from?
   A it was created when the fossil fuels were burned – it did not exist before
   B it was in the Earth but had never been in the atmosphere before
   C it was in the atmosphere a long time ago

6. The following graphs show different types of energy emitted (given off) by the Sun. Which graph BEST shows the amounts of each type of energy emitted by the Sun?

7. If the Earth gave out less energy than it receives from the Sun, then over time it would:
   A use up the spare energy e.g. in photosynthesis and other processes
   B gradually get hotter
   C store the spare energy but not get hotter
8. Which of the following diagrams BEST shows movement of carbon into, and out of the atmosphere? (The WIDER the arrows, the MORE carbon is moved in or out).

A

B

C

9. How much of the atmosphere is greenhouse gases (gases that make the Earth warmer)?

A more than 30%
B between 5% and 30%
C less than 5%

10. Which of the following are ALL greenhouse gases?

A carbon dioxide, methane, carbon monoxide
B carbon dioxide, hydrogen, methane
C carbon dioxide, methane, water vapour

11. Greenhouse gases cause the Earth to warm up because:

A they let heat rays in but don’t let them out
B they allow the Sun’s rays in but they absorb rays coming from the Earth
C they interact with all types of electromagnetic rays (e.g. infra-red, ultra-violet and visible light), creating heat
D they damage the ozone layer so more ultra-violet rays get in and heat up the Earth
12. Carbon dioxide can be removed from the atmosphere by plants, through photosynthesis. What OTHER ways can it be removed from the atmosphere?

A when rocks such as limestone form AND escaping from the atmosphere into space
B by dissolving in water AND escaping from the atmosphere into space
C when rocks such as limestone form AND dissolving in water

13. What effect did the process of fossil-fuel formation have on the amount of carbon dioxide in the atmosphere?

A it decreased the amount of carbon dioxide in the atmosphere
B it did not change the amount of carbon dioxide in the atmosphere
C the fossil fuels were formed when the Earth formed, and it didn’t yet have an atmosphere
D it increased the amount of carbon dioxide in the atmosphere

14. Heat that leaves the Earth’s surface is MOSTLY:

A heat from radioactive rocks and heat from the centre of the Earth
B heat from the Sun reflected (bounced) off the Earth’s surface
C heat emitted through human activity e.g. burning fossil fuels
D heat emitted (given off) naturally by the Earth

15. Most of the Sun’s energy:

A interacts with (is affected by) most of the molecules of Earth’s atmosphere
B only interacts with greenhouse gases in the Earth’s atmosphere
C isn’t affected by the Earth’s atmosphere at all
16. What is the REASON that nitrogen and oxygen do NOT cause the Earth to warm?
A  they don’t damage the ozone layer
B  they absorb infra-red (heat) rays but then emit them again – they don’t trap them
C  they don’t absorb infra-red rays at all

17. Which is the most abundant greenhouse gas (i.e., which one is there the most of)?
A  carbon dioxide
B  water vapour
C  methane

18. The energy absorbed by greenhouse gas molecules is MOSTLY:
A  reflected (bounced) off the Earth
B  emitted (given off) by the Earth
C  from human activity e.g., burning fossil fuels
D  directly from the Sun

19. How can a small percentage of greenhouse gases have a significant effect on climate?
A  it can’t. Greenhouse gases are only important at levels over about 5%.
B  when greenhouse gases interact with the Sun’s rays they make more greenhouse gases
C  the Earth has a lot of atmosphere so a small percentage is a lot of molecules.

20. What happens to the energy from the Sun that is absorbed by the Earth?
A  less energy is sent back into space BECAUSE some is used up e.g., in photosynthesis
B  the same amount of energy is sent back into space
C  less energy is sent back into space BECAUSE the Earth is cooler than the Sun

21. What type of energy do all greenhouse gases interact with?
A  infra-red rays
B  ultra-violet rays
C  visible light
D  more than one of the above
E  none of the above
22. The total amount of carbon on Earth, including its atmosphere, since the planet first formed has
A remained constant for most of the time but is increasing now that fossil fuels are being burned
B slowly decreased because when carbon dioxide absorbs heat, it rises and escapes from the atmosphere
C stayed the same because burning fossil fuels doesn’t affect the total amount of carbon on Earth

23. When a molecule of greenhouse gas absorbs (takes in) heat, it
A rises into the ozone layer
B emits (gives off) the heat again.
C creates more greenhouse gas molecules
D gives off a different type of energy

24. Students used an infra-red radiation detector to measure radiation given off by a student and a laboratory bench. What did they find?
A neither student nor bench emits infra-red radiation
B both the student and lab bench are emitting infra-red radiation
C only the student emits infra-red radiation

THE LAST THREE QUESTIONS ARE ABOUT SOME THINGS THAT MIGHT HAPPEN DUE TO CLIMATE CHANGE – AND WHETHER THESE THINGS WILL HAVE AN EFFECT ON THE CLIMATE

25. Some types of cloud reflect the Sun’s rays back to space, so less of the Sun’s rays reach the ground. If these clouds were to become more common due to global warming, how would it affect the climate?
A it will get hotter, faster than before the clouds formed (make the warming worse)
B it will get hotter but more slowly than before (make the warming less bad)
C it won’t have any effect on climate change

26. Ice and snow are white and reflect the Sun’s rays, but the ground and water underneath is darker and absorb the Sun’s rays. When the climate gets warmer, ice and snow will melt. How will this affect the climate?
A it will get hotter, faster than before the ice melted (make the warming worse)
B it will get hotter but more slowly than before the ice melted (make the warming less bad)
C it won’t have any effect on climate change
27. Carbon dioxide is removed from the atmosphere when it dissolves in water e.g., oceans. Warmer water dissolves less carbon dioxide than colder water. What effect will this have on global warming?

A. the climate will get hotter, at a faster rate (make the warming worse)
B. the climate will still get hotter but more slowly (make the warming less bad)
C. it won’t have any effect on climate change
APPENDIX 3 – ETHICS AND SERAP APPROVAL LETTERS

Approval letters are shown from the University of Wollongong Human Research Ethics Committee for the Delphi study, and from the Department of Education and Training Student Engagement and Program Evaluation Bureau (SERAP) for data collection with high school students.
Dear Mrs Jarrett

I refer to your application to conduct a research project in New South Wales government schools entitled Investigating secondary school students' understanding of climate change. I am pleased to inform you that your application has been approved. You may now contact the Principals of the nominated schools to seek their participation. You should include a copy of this letter with the documents you send to schools.

This approval will remain valid until 18/01/2012.

The following researchers or research assistants have fulfilled the Working with Children screening requirements to interact with or observe children for the purposes of this research for the period indicated:

<table>
<thead>
<tr>
<th>Name</th>
<th>Approval expires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lorna Jarrett</td>
<td>21/12/2011</td>
</tr>
</tbody>
</table>

I draw your attention to the following requirements for all researchers in New South Wales government schools:

- School Principals have the right to withdraw the school from the study at any time. The approval of the Principal for the specific method of gathering information for the school must also be sought.
- The privacy of the school and the students is to be protected.
- The participation of teachers and students must be voluntary and must be at the school's convenience.
- Any proposal to publish the outcomes of the study should be discussed with the Research Approvals Officer before publication proceeds.

When your study is completed please forward your report marked to Manager, Schooling Research, Department of Education and Training, Locked Bag 53, Darlinghurst, NSW 2010.

Yours sincerely

Dr Max Smith
Senior Manager
Student Engagement and Program Evaluation
7 April 2011
## APPENDIX 4 – PRE-TRIAL FOCUS GROUP INTERVIEW GUIDE

**School:** ____________  **No. students:** _____  **Date:** ______________

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Explain what you think fossil fuels are.</td>
</tr>
<tr>
<td>2</td>
<td>Do they contain carbon?</td>
</tr>
<tr>
<td>3</td>
<td>Where does the carbon in them come from?</td>
</tr>
<tr>
<td>4</td>
<td>How long ago were they made?</td>
</tr>
<tr>
<td>5</td>
<td>When fossil fuels are burned, what is released? Where does the CO2 come from?</td>
</tr>
</tbody>
</table>
| 11 | Where is carbon found on our planet?  
   - can carbon move form one part of the planet to another? |
| 6 | What processes take CO2 out of the atmosphere? |
| 7 | Are these processes natural or caused by humans? |
| 8 | What processes put CO2 into the atmosphere? |
| 9 | Are these processes natural or caused by humans? |
| 10 | What happens to the total amount of carbon on Earth over time?  
   - In the atmosphere?  
   - In other parts of the planet? |
| 12 | What is the connection between IR, UV and visible light? |
| 13 | What is electromagnetic radiation?  
   - What is the electromagnetic spectrum? |
| 14 | What does the Sun emit?  
   - Which does the Sun emit most of? (UV, visible, IR?) |
| 15 | What happens to this radiation when it reaches the Earth? |
| 16 | Does the Earth emit any radiation? |
| 17 | How is the radiation emitted by the Earth different from the radiation from the Sun? |
| 18 | If an object is at 15°C (cool to the touch) does it emit radiation? |
| 19 | Can a gas emit radiation?  
   - If the Earth has been absorbing energy from the Sun for millions of years, why doesn’t it keep getting hotter and hotter?  
   - If you park a car in the sun it gets hot. If you left it all day would it keep getting hotter and hotter without stopping? Could it melt?  
   - Have you heard of night-vision goggles? How do they work? |
<p>| 20 | What do greenhouse gases do? |
| 21 | How do they warm up the planet? |</p>
<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>What are the most important ones?</td>
<td></td>
</tr>
<tr>
<td>Why are greenhouse gases different from other gases in the atmosphere?</td>
<td></td>
</tr>
<tr>
<td>What happens when visible light meets a greenhouse gas?</td>
<td></td>
</tr>
<tr>
<td>What happens when IR meets a greenhouse gas?</td>
<td></td>
</tr>
<tr>
<td>What happens when UV meets a greenhouse gas?</td>
<td></td>
</tr>
<tr>
<td>What happens to the energy absorbed by GHGs?</td>
<td></td>
</tr>
<tr>
<td>How much of the atmosphere is greenhouse gases?</td>
<td></td>
</tr>
<tr>
<td>What greenhouse gas exists in the greatest quantities?</td>
<td></td>
</tr>
<tr>
<td>Do any greenhouse gases occur naturally?</td>
<td></td>
</tr>
<tr>
<td>Where do these natural GHGs come from?</td>
<td></td>
</tr>
<tr>
<td>Whereabouts in the atmosphere are greenhouse gases found?</td>
<td></td>
</tr>
<tr>
<td>Why are some greenhouse gases considered &quot;worse&quot; than others?</td>
<td></td>
</tr>
<tr>
<td>Do all greenhouse gases have the same impact?</td>
<td></td>
</tr>
<tr>
<td>Do all GHGs absorb the same amount of radiation?</td>
<td></td>
</tr>
<tr>
<td>Do all GHGs stay in the atmosphere the same amount of time?</td>
<td></td>
</tr>
<tr>
<td>Can you explain the difference between weather and climate?</td>
<td></td>
</tr>
<tr>
<td>Some years it's hot and sunny on the Easter weekend, other years it's</td>
<td></td>
</tr>
<tr>
<td>rainy. Why is this?</td>
<td></td>
</tr>
<tr>
<td>Has the climate been different in the past?</td>
<td></td>
</tr>
<tr>
<td>What causes the climate to change?</td>
<td></td>
</tr>
<tr>
<td>Do you know what is meant by feedback?</td>
<td></td>
</tr>
<tr>
<td>Can you give any examples of feedback?</td>
<td></td>
</tr>
<tr>
<td>What’s the difference between positive and negative feedback?</td>
<td></td>
</tr>
<tr>
<td>How does the fridge stay at a constant temperature?</td>
<td></td>
</tr>
<tr>
<td>If you have a sink with a leaky plug, how do you keep the water level</td>
<td></td>
</tr>
<tr>
<td>constant?</td>
<td></td>
</tr>
<tr>
<td>What happens if you turn the tap up/down?</td>
<td></td>
</tr>
<tr>
<td>If you fill a bath with hot water, why does it gradually cool down?</td>
<td></td>
</tr>
<tr>
<td>When you watch TV what happens to the ELECTRICAL energy USED BY THE</td>
<td></td>
</tr>
<tr>
<td>TV?</td>
<td></td>
</tr>
<tr>
<td>What happens after you turn the TV off?</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 5 – STATISTICAL MEASURES OF TEST AND ITEM PERFORMANCE

This appendix contains a detailed description of the theory underlying statistical tests commonly used to evaluate CI performance. These were listed in Table 5.6. It also tabulates the values of the tests used to evaluate the CCCI. These data are discussed in Chapter 6.

A5.1 Statistical tests used to evaluate CI performance

This section elaborates on the theoretical background of the statistical tests commonly used to evaluate CIs, and discusses how these have been used by researchers.

A5.1.1 Whole-test measures: reliability and internal consistency

Miller (1995) explained that there are two sources of variation in test scores: real differences between people sitting the test, and random experimental error. He defined test score reliability as the ratio of true variance (due to differences between people sitting the test) to total variance. In other words, reliability measures illustrate how much of the variation in test results is due to measurement error (Steif & Dantzler 2005). Miller (1995) stressed that reliability of an instrument depends on the population being tested and the test conditions: for example, a test will have a higher reliability when administered to a population with more genuine variance, than with a population of similar ability.

Miller (1995) described three types of method for estimating reliability:

- test-retest: the same test is administered on two occasions;
- alternative forms: this is the same as test-retest, but rather than using the same test twice an alternative form, addressing the same content, is used for the second administration; and
- internal-consistency, which requires the test to be completely homogeneous, i.e., “all unique variance is measurement error” (p.261).
Bardar et al. (2006) stressed that CI results scores should be generalisable to a larger set of possible items, i.e., performance on a CI should predict performance on other questions related to the topic. According to the authors, this can be evaluated by determining how consistent students’ performance was across individual items or subsets of the CI, using internal consistency measures.

Test-retest

Ding et al. (2006) criticised test-retest as a measure of reliability, claiming that students might remember items, study for the retest or re-sit under different conditions, thereby making this method impractical for determination of reliability. Instead, they suggested the use of Kuder-Richardson 20. Similarly, Allen (2006) claimed that remembering items might lead to over-estimates of reliability.

Smith et al. (2008) cited Crocker and Algina (1986) in support of their use of test-retest data to calculate a mean coefficient of stability for their CI. However it appears that instead of testing a population of students twice, they tested two similar groups of students and compared their results.

The procedures required for collecting test-retest data are incompatible with development procedures for most concept inventories. Test-retest data-collection requires participants to complete the test twice under as similar conditions as possible, so that all variation between test and retest scores is due to experimental error (Miller 1995). However, CIs are usually developed for a taught subject, with participants enrolled on the subject at the time. It would be difficult to obtain test-retest data that did not involve participants learning something about the subject. Given the availability of internal consistency measures as a proxy for reliability, it is understandable that test-retest is not generally used. However, my research design, in which the CI was not being developed for a particular unit of study, enabled collection of test-retest data within normal teaching time, with a reasonable level of confidence that participants had not studied the topic in between tests. This raised the possibility of having a second reliability measure.
against which to compare the internal consistency measure. The method and results of analysis of the test-retest data are given in Chapter 6.

Internal consistency methods: split half, Cronbach’s alpha and Kuder-Richardson 20

Allen (2006) explained the popularity of internal consistency measures of reliability as follows: they require only one administration so (i) they are cheaper (and less burdensome to participants), and (ii) they avoid the issue of students acquiring knowledge between tests, or remembering items during the retest.

The most popular internal consistency methods according to Miller (1995) are Cronbach’s alpha and the split half method.

The split half method involves splitting the items into two groups and calculating the correlation of the two groups. It has been criticised because of the arbitrary nature of the split and the fact that different splits will give different estimates (Miller 1995). The author asserted that as Cronbach’s alpha is more robust, there is no reason to use the split half method.

One way to overcome the arbitrary nature of the split half method would be to average the reliabilities for a number of splits. Cronbach (1951) established that Cronbach’s alpha ($\alpha$) is identical to the average value of all possible split half reliabilities.

$$\alpha = \frac{k}{k-1} \left(1 - \frac{\sum V_i}{V_{\text{test}}} \right)$$

where:

- $\alpha$ is Cronbach’s $\alpha$
- $k$ is the number of items on the test
- $V_i$ is the variance of each question
- $V_{\text{test}}$ is the total score variance of the entire test

(Cronbach’s (1951) notation)
Allen (2006) cited Cronbach’s (1951) formula above and noted that for dichotomous items (i.e., those in which the score is either zero or one), $V_i$ reduces to $pq$, and the formula becomes identical to Kuder-Richardson 20.

Steif and Dantzler (2005) used Cronbach’s alpha to establish reliability. However they did not state a source for this measure, or state a minimum acceptable value. Bardar et al. (2006) described Cronbach’s alpha as “a standard measurement of internal consistency for dichotomously scored tests” (p.7). They provided the formula and agreed with Gray et al. (2005) that Cronbach’s alpha should be greater or equal to 0.7. Both authors cited sources for this value.

According to DeVellis (2003) and Allen (2006), Kuder-Richardson 20 (K-R 20) is a simplified form of Cronbach’s alpha suitable for dichotomous (i.e., right or wrong) data. Allen (2006) gave the formula for K-R 20 as follows:

$$ r_{tt} = \frac{k}{k-1} \frac{\sigma_t^2 - kpq}{\sigma_t^2} $$

where:

- $k$ is the number of items in the test
- $r_{tt}$ is the reliability of the test
- $\sigma_t^2$ is the total score variance for the test
- $p$ is the proportion of students who answer each item correctly
- $q$ is the proportion of students who answer each item incorrectly

Kuder-Richardson 20 was used by Anderson et al. (2002), Ding et al. (2006) and Nottis et al. (2009). Gray et al. (2005) also mentioned its use with dichotomous data. Nottis et al. (2009) used split half and Kuder-Richardson 20 to establish reliability.

Miller (1995) pointed out that the less homogeneous a test is, the lower the estimate of reliability an internal consistency measure such as Cronbach’s alpha or the Kuder-Richardson 20 will give. In other words, on measures of
internal consistency rather than repeatability, low scores can mean either a non-homogeneous test or an unreliable one. CIs typically measure understanding of a number of concepts while psychological tests are intended to measure a single trait. Therefore, while a good psychological test should be homogeneous, a good concept inventory could not be expected to be, as good understanding of one of the concepts might not imply good understanding of others.

However, Miller (1995) also asserted that “generally speaking, a test that is homogenous will be internally consistent, but a test that is internally consistent is often not homogenous” (p.267). This suggests that measures of internal consistency can “badly under-estimate reliability” (p.270) of concept inventories, which are non-homogeneous. Similarly, Gray et al. (2005) described Kuder-Richardson 20 and Cronbach’s alpha as conservative estimates of reliability for test results. Therefore, it should be stressed that these measures give a lower limit rather than an absolute value of reliability for a CI, and a low value does not necessarily mean that the CI is unreliable.

Miller (1995) pointed out that adding more items increases reliability if the additional items are positively correlated to the existing ones: “test reliability increases with test length when a test is internally consistent, whether the test is homogenous or not” (p.268). However, there are practical limits on the number of items that can be included in a CI (Rowe & Smaill 2007).

_Ferguson’s delta_

Ferguson’s delta was used by Allen et al. (2004) and Ding et al. (2006) to calculate the extent to which a test discriminates between students, i.e., produces a wide range of scores. However, according to Terluin et al. (2009) the value of Ferguson’s delta depends on the population of test takers and does not provide any useful information about an instrument.
A5.1.2 Single-item measures: item difficulty, discrimination and point biserial coefficient

These three measures are used to evaluate the suitability of individual items.

*Item difficulty, $P$*

$$P = \frac{N_1}{N}$$

Where $N_1$ = number of correct responses; $N$ = total number of students who attempted the question.

Ding et al. (2006) cited Doran’s (1980) assertion that there are a number of criteria for acceptable $P$ values. According to Bardar et al. (2006), a wide range of item difficulties is desirable for a test designed to assess effectiveness of learning activities. Anderson et al. (2002) cited Kaplan and Saccuzzo’s (1997) advice that optimum difficulty is halfway between all students choosing the correct response and the probability of a student choosing the right response by chance. This gives an optimum value of 0.63 for four options and 0.67 for three items. However they also point out that in order to discriminate between students of different ability, tests must have items with a range of difficulty.

Bardar et al. (2006) considered it desirable that questions should be answered correctly by between 20% and 80% of students, while Richardson et al. (2003) recommended item difficulty in the 0.4-0.6 range.

*Item discrimination, $D$*

Discrimination is based on the correlation between answering an item correctly and getting a high score on the test overall. According to Ding et al. (2006), item discrimination shows how much a single item distinguishes between students with strong and those with weak mastery of the topic. For example, a question which is usually answered correctly by low-scoring students is probably problematic. The discrimination index varies from -1 to +1 and the closer it is to 1, the more an item discriminates between students of different overall ability (Steif and Dantzler 2005).
To calculate discrimination for an item, it is first necessary to calculate the total score for each participant, and the median score. The responses are then divided into two groups: “high score” and “low score” (defined in more detail below). For each item, the number of correct responses in the “high score” and “low score” groups are counted.

Data can be divided into two groups as follows:

- $D_{50}$, where “high” scores are above the mean and “low” scores are below the mean. This method uses all the available data.
- $D_{25}$, $D_{27}$ and $D_{33}$ where data from the top and bottom ranges (either quartiles, 27% or 33%) are used, and the data in the middle range are discarded.

The formulas for $D_{50}$ and $D_{25}$ are shown below (Ding et al. 2006):

$$D_{50} = \frac{N_h - N_l}{(N/2)}$$

Where:

- $N_h$ is the number of correct responses to an item by students whose total score was above the median
- $N_l$ is the number of correct responses to an item by students whose total score was below the median

$$D_{25} = \frac{N_{top25\%} - N_{bottom25\%}}{(N/4)}$$

Where:

- $N_{top25\%}$ is the number of correct responses to an item by students whose total score was in the top 25%
- $N_{bottom25\%}$ is the number of correct responses to an item by students whose total score was in the bottom 25%

Allen (2006) explained that discrimination is important because if highly knowledgeable students are more likely to answer each item correctly, the test as a whole produces a wide range of scores, i.e., it differentiates well between students of differing ability.
Richardson et al. (2003) aimed for a minimum discrimination index of 0.40 for all items. Steif and Dantzler (2005) recommended that the discrimination index should exceed 0.3 for all questions.

Ding et al. (2006) explained the advantages and disadvantages of different ways of calculating item discrimination. The 50%-50% uses problematic “unstable” data in the middle of the range and therefore can underestimate discrimination, while the 25%-25% reduces the probability of underestimating discrimination, but at the expense of neglecting half of the dataset. Other authors have used 33%-33%. For example, Smith et al. (2008) cited Doran (1980) in their use of 33%-33%. Similarly, Steif and Dantzler (2005) defined discrimination index as how students in the top third for total score performed on any particular question when compared with students who scored in the bottom third. According to Allen (2006) the optimum split uses the top and bottom 27%: this is likely to yield results close to the 25%-25% split.

**Point biserial coefficient (r_{pbs})**

Allen (2006) gave the formula for r_{pbs} as follows:

\[ r_{pbs} = \frac{\bar{y}_c - \bar{y}_i}{S_t} \sqrt{p_i q_i} \]

where:

- \( y_c \): is the average test score of people who got the item correct
- \( y_i \): is the average test score of people who got the item incorrect
- \( S_t \): is the standard deviation of scores
- \( p_i \): is the proportion of students who got the item correct
- \( q_i \): is the proportion of students who got the item incorrect

Ding et al. (2006) stated that r_{pbs} is sometimes referred to as the reliability index for each item, and measures how consistent each item is with the test as a whole, i.e., the correlation between students’ scores on each item and their total score. As with item discrimination, r_{pbs} varies between -1 and +1, with higher values corresponding to stronger correlation between item score and total test score. According to the authors r_{pbs} is different from
discrimination, in that discrimination measures how well an item discriminates between students with strong and those with weak mastery of the topic.

Conversely, Bardar et al. (2006) appeared to imply that the two are the same: “Item discrimination, which measures how well an item differentiates between examinees who score relatively high or low on the entire inventory, is generally a more insightful statistic than item difficulty. The point biserial correlation coefficient, \( r_{pbs} \) (Crocker & Algina 1986), represents the correlation between a dichotomous variable (correct = 1; incorrect = 0) and a continuous variable—in this case, the item score and the overall test score” (p.107). Similarly, Allen (2006) described the \( r_{pbs} \) as “another measure of item discrimination” (p.30).

Anderson et al. (2002) used \( r_{pbs} \) values to determine discriminability. Smith et al. (2008) and Ding et al. (2006) cited Kline (1986) in support of 0.2 as a minimum acceptable value for \( r_{pbs} \); however Ding et al. (2006) added that it is unrealistic to insist that all items meet this criteria, and suggested that a small number of items with \( r_{pbs} <0.2 \) can remain in a test.

\textbf{A5.2 Data for individual item measures used to evaluate the CCCI}

This section tabulates the data obtained for item difficulty, discrimination (D50 and D25), point biserial coefficient with associated p value, number of informal responses (i.e., either no option or more than one option chosen) and Cronbach’s alpha with item deleted.

The data for Cronbach’s alpha with item deleted are presented together in Tables A5.2 and A5.4, because these data are interpreted in relation to each other, rather than with reference to a fixed value.

For the remaining statistical measures, items are grouped according to conceptual area covered. For each item, a phrase summarising the concept is given. Measures flagged yellow were below the minimum value recommended in literature but greater than 0.1; those flagged pink were less
than 0.1, i.e., well outside the recommended range. The p value associated with the \( r_{\text{obs}} \) values shows whether the total scores of students who answered an item incorrectly are statistically significantly lower than the total scores of students who got the item correct. Table A5.1 shows the results for high school students.

**Table A5.1: Individual item measures grouped by conceptual area – high school students**

**Conceptual area 1: The Carbon Cycle and Fossil Fuels**

**1 (a) There is a fixed amount of carbon on Earth:**

<table>
<thead>
<tr>
<th>Item number and conceptual content</th>
<th>( P )</th>
<th>( D_{25} )</th>
<th>( D_{50} )</th>
<th>( r_{\text{obs}} ) and ( p ) value</th>
<th>I.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Total amount of carbon on Earth, including its atmosphere, since the planet first formed: increased, decreased or constant?</td>
<td>0.16</td>
<td>0.34</td>
<td>0.23</td>
<td>( r_{\text{obs}} = 0.465, p&lt;0.0001 )</td>
<td>3</td>
</tr>
<tr>
<td>22. Total amount of carbon on Earth, including its atmosphere, since the planet first formed: increased, decreased or constant? with reasons.</td>
<td>0.20</td>
<td>0.31</td>
<td>0.26</td>
<td>( r_{\text{obs}} = 0.4469, p&lt;0.0001 )</td>
<td>8</td>
</tr>
</tbody>
</table>

**1 (b) it is cycled among the atmosphere, biosphere, soils, ocean and rocks.**

| 1. Relative amounts of carbon in the atmosphere, oceans and soil/living things. | 0.17 | 0.14 | 0.13 | \( 0.2343, p=0.0001 \) | 5 |

**1 (c) There are both natural and human-induced sources and sinks of greenhouse gases: Items 2, 8 and 12**

| 2. When plants make new roots, stems and leaves, where do they get the carbon from? | 0.39 | 0.32 | 0.27 | \( 0.3043, p=0.0001 \) | 3 |
| 8. Relative sizes of carbon fluxes into, and out of the atmosphere from fossil fuel burning, oceans and land/plants. | 0.08 | 0.11 | 0.1 | \( 0.2164, p=0.001 \) | 5 |
| 12. What other ways, apart from photosynthesis, can carbon dioxide be removed from the atmosphere? | 0.48 | 0.34 | 0.3 | \( 0.333, p<0.0001 \) | 7 |
1 (d) Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle: Item 13

<table>
<thead>
<tr>
<th>Item number and conceptual content</th>
<th>$P$</th>
<th>$D_{25}$</th>
<th>$D_{50}$</th>
<th>$r_{pb}$ and $p$ value</th>
<th>I.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>13. Effect of the process of fossil-fuel formation on the amount of carbon dioxide in the atmosphere.</td>
<td>0.11</td>
<td>0.12</td>
<td>0.06</td>
<td>0.2389, $p=0.0003$</td>
<td>2</td>
</tr>
</tbody>
</table>

1 (e) Burning fossil fuels returns this carbon to the cycle: Item 5

5. Where did the carbon in fossil fuels originally come from? | 0.2 | 0.25 | 0.27 | 0.4128, $p<0.0001$ | 3 |

Conceptual area 2 - Electromagnetic spectrum:

(a) The Sun emits mostly visible radiation: Item 6

6. Proportions of UV, IR and visible light emitted by the Sun | 0.11 | 0.04 | 0.09 | 0.1299, $p=0.0497$ | 8 |

(b) The Earth emits mostly IR: Items 14 and 24

14. Origin of majority of heat leaving the Earth’s surface | 0.12 | 0.07 | 0.07 | 0.1206, $p=0.0685$ | 7 |
24. Is IR emitted by a student or a laboratory bench? | 0.25 | 0.13 | 0.19 | 0.1889, $p=0.0041$ | 12 |

Conceptual area 3 - Interactions between greenhouse gases and e.m.r.:

3 (a) Most gases that make up the atmosphere are transparent to visible light: Item 15

15. What gases in the atmosphere does most of the Sun’s energy interact with? | 0.16 | 0.07 | 0.1 | 0.0425, $p=0.522$ | 5 |

3 (b) Non-GH gases are transparent to IR: Item 16

16. Why nitrogen and oxygen do not cause the Earth to warm. | 0.22 | 0.17 | 0.15 | 0.1757, $p=0.0077$ | 11 |

3 (c) GH gases absorb IR: this is the cause of the greenhouse effect: Item 21

21. Which bands of the electromagnetic spectrum all GHGs interact with. | 0.12 | 0.22 | 0.19 | 0.3262, $p=0.0001$ | 11 |
(d) GH gases absorb IR emitted by Earth: Items 11, 18

<table>
<thead>
<tr>
<th>Item</th>
<th>Question</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>p value</th>
<th>p value</th>
<th>Conceptual area</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Why GHGs cause the Earth to warm: atmosphere/radiation interactions.</td>
<td>0.11</td>
<td>0.14</td>
<td>0.14</td>
<td>r0.2595,</td>
<td>p&lt;0.0001</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>Source of energy absorbed by GHG molecules: Sun/Earth/human activity.</td>
<td>0.15</td>
<td>0.07</td>
<td>0.04</td>
<td>r0.0479,</td>
<td>p=0.4708</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

(e) This is re-emitted in all directions - down as well as up: Item 23

<table>
<thead>
<tr>
<th>Item</th>
<th>Question</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>p value</th>
<th>p value</th>
<th>Conceptual area</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>What a molecule of GHG does after it absorbs heat.</td>
<td>0.24</td>
<td>0.07</td>
<td>0.09</td>
<td>0.116</td>
<td>p=0.0798</td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

Conceptual area 4 - Proportions of greenhouse and non-greenhouse gases in the atmosphere:

<table>
<thead>
<tr>
<th>Item number and conceptual content</th>
<th>P</th>
<th>D_{25}</th>
<th>D_{50}</th>
<th>r_{p,hs} and p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. How much of the atmosphere is GHGs?</td>
<td>0.22</td>
<td>0.37</td>
<td>0.26</td>
<td>0.3396, p&lt;0.0001</td>
</tr>
<tr>
<td>10. Which are all GHGs?</td>
<td>0.20</td>
<td>0.21</td>
<td>0.19</td>
<td>0.2871, p&lt;0.0001</td>
</tr>
<tr>
<td>19. How can a small percentage of GHGs have a significant effect on climate?</td>
<td>0.4</td>
<td>0.22</td>
<td>0.15</td>
<td>0.2152, p=0.001</td>
</tr>
<tr>
<td>17. Most abundant GHG.</td>
<td>0.11</td>
<td>0.21</td>
<td>0.13</td>
<td>0.2905, p&lt;0.0001</td>
</tr>
</tbody>
</table>

Conceptual area 5 - Feedback:

<table>
<thead>
<tr>
<th>Item</th>
<th>Question</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>p value</th>
<th>p value</th>
<th>Conceptual area</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>If reflective clouds were to become more common due to global warming, how would it affect the climate?</td>
<td>0.60</td>
<td>0.39</td>
<td>0.28</td>
<td>0.3343,</td>
<td>p&lt;0.0001</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>26</td>
<td>How will the melting of reflective ice and snow affect the climate?</td>
<td>0.67</td>
<td>0.23</td>
<td>0.27</td>
<td>r0.2543,</td>
<td>p&lt;0.0001</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>27</td>
<td>Warmer water dissolves less carbon dioxide than colder water. What effect will this have on global warming?</td>
<td>0.61</td>
<td>0.35</td>
<td>0.35</td>
<td>0.3779,</td>
<td>p&lt;0.0001</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

Conceptual area 6 – Equilibrium of energy:

<table>
<thead>
<tr>
<th>Item</th>
<th>Question</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>p value</th>
<th>p value</th>
<th>Conceptual area</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>If the Earth gave out less energy than it receives from the Sun, what would happen to its temperature?</td>
<td>0.81</td>
<td>0.07</td>
<td>0.17</td>
<td>0.1419,</td>
<td>p=0.0318</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>20</td>
<td>Balance between energy from the Sun absorbed and emitted by Earth.</td>
<td>0.09</td>
<td>0.02</td>
<td>0.04</td>
<td>0.0375,</td>
<td>p=0.5724</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>
Conceptual area 7 – Conservation of energy:

4. A hot bath contains energy in the form of heat. When the water goes cold what has happened to the heat energy?

<table>
<thead>
<tr>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td><strong>0.4263</strong></td>
<td>10</td>
<td>0.4098</td>
<td>20</td>
<td>0.4401</td>
</tr>
<tr>
<td>1</td>
<td>0.4183</td>
<td>11</td>
<td>0.4115</td>
<td>21</td>
<td>0.4012</td>
</tr>
<tr>
<td>2</td>
<td>0.4122</td>
<td>12</td>
<td>0.4060</td>
<td>22</td>
<td>0.3768</td>
</tr>
<tr>
<td>3</td>
<td>0.3746</td>
<td>13</td>
<td>0.4172</td>
<td>23</td>
<td>0.4443</td>
</tr>
<tr>
<td>4</td>
<td>0.4195</td>
<td>14</td>
<td>0.4324</td>
<td>24</td>
<td>0.4317</td>
</tr>
<tr>
<td>5</td>
<td>0.3840</td>
<td>15</td>
<td>0.4491</td>
<td>25</td>
<td>0.4051</td>
</tr>
<tr>
<td>6</td>
<td>0.4302</td>
<td>16</td>
<td>0.4321</td>
<td>26</td>
<td>0.4228</td>
</tr>
<tr>
<td>7</td>
<td>0.4387</td>
<td>17</td>
<td>0.4068</td>
<td>27</td>
<td>0.3939</td>
</tr>
<tr>
<td>8</td>
<td>0.4167</td>
<td>18</td>
<td>0.4470</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.3867</td>
<td>19</td>
<td>0.4346</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A5.2 lists the data for Cronbach’s alpha with item deleted, for high school students. Table A5.2: Values of Cronbach’s alpha when individual items are deleted from the CCCI, for high school students. The first value is for the entire 27 item test

Table A5.3 presents P, D_{50}, D_{25}, r_{pbs} and I.R data for undergraduates. It follows the same format as school student table, but descriptive phrases have been shortened to avoid unnecessary repetition. Measures outside the recommended range are flagged in the same way as for school students.

Table A5.3: Individual item measures grouped by conceptual area - undergraduates

**Conceptual grouping 1: The Carbon Cycle and Fossil Fuels**

1 (a) There is a fixed amount of carbon on Earth:

<table>
<thead>
<tr>
<th>Item number and conceptual content</th>
<th>P</th>
<th>D_{25}</th>
<th>D_{50}</th>
<th>r_{pbs} and p value</th>
<th>I.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Total amount of carbon on Earth: increased, decreased or constant?</td>
<td>0.50</td>
<td>0.63</td>
<td>0.44</td>
<td>0.6147</td>
<td>0</td>
</tr>
</tbody>
</table>
22. Total amount of carbon on Earth: increased, decreased or constant? with reasons.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.57</td>
<td>0.60</td>
<td>0.53</td>
<td>0.6293</td>
<td>p&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 (b) it is cycled among the atmosphere, biosphere, soils, ocean and rocks.

1. Relative amounts of carbon in atmosphere, oceans and soil/living things.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.61</td>
<td>0.44</td>
<td>0.25</td>
<td>0.3732</td>
<td>p=0.0024</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 (c) There are both natural and human-induced sources and sinks of greenhouse gases: Items 2, 8 and 12

2. Source of carbon for plant biomass

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.67</td>
<td>0.38</td>
<td>0.13</td>
<td>0.3095</td>
<td>p=0.0128</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8. Relative sizes of carbon fluxes into, and out of the atmosphere from fossil fuel burning, oceans and land/plants.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.22</td>
<td>0.25</td>
<td>0.22</td>
<td>0.3071</td>
<td>p=0.0136</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

12. Natural carbon sinks

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.71</td>
<td>0.25</td>
<td>0.16</td>
<td>0.3473</td>
<td>p=0.0049</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 (d) Fossil fuels contain carbon that was part of living things millions of years ago. The process of burial took this carbon out of the atmosphere-ocean-biosphere cycle: Item 13


<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.56</td>
<td>0.44</td>
<td>0.16</td>
<td>0.3435</td>
<td>p=0.0055</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 (e) Burning fossil fuels returns this carbon to the cycle: Item 5

5. Where did the carbon in fossil fuels originally come from?

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.51</td>
<td>0.38</td>
<td>0.19</td>
<td>0.3875</td>
<td>p=0.0016</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conceptual area 2 - Electromagnetic spectrum:

6. Proportions of UV, IR and visible light emitted by the Sun

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
<td>0.06</td>
<td>0.00</td>
<td>0.0309</td>
<td></td>
</tr>
<tr>
<td></td>
<td>p=0.8087</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) The Earth emits mostly IR: Items 14 and 24

14. Origin of majority of heat leaving the Earth’s surface

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.13</td>
<td>0.25</td>
<td>0.19</td>
<td>0.3738</td>
<td>p=0.0023</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

24. Is IR emitted by a student or a laboratory bench?

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.39</td>
<td>0.54</td>
<td>0.31</td>
<td>0.4212</td>
<td>p=0.0005</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conceptual area 3 - Interactions between greenhouse gases and e.m.r:

3 (a) Most gases that make up the atmosphere are transparent to visible light: Item 15

<table>
<thead>
<tr>
<th>Item number and conceptual content</th>
<th>P</th>
<th>D25</th>
<th>D50</th>
<th>r_{psi} and p value</th>
<th>I.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>15. Which gases e.m.r. interacts with.</td>
<td>0.11</td>
<td>0.13</td>
<td>0.10</td>
<td>0.2301 p=0.0673</td>
<td>1</td>
</tr>
</tbody>
</table>

3 (b) Non-GH gases are transparent to IR: Item 16

| 16. Why nitrogen and oxygen do not cause the Earth to warm. | 0.57 | 0.25 | 0.16 | 0.2559 p=0.0412 | 0   |

3 (c) GH gases absorb IR: this is the cause of the greenhouse effect: Item 21

| 21. Bands of the e.m.s. all GHGs interact with. | 0.50 | 0.58 | 0.32 | 0.5381 p<0.0001 | 4   |

(d) GH gases absorb IR emitted by Earth: Items 11, 18

| 11. Why GHGs cause the Earth to warm. | 0.53 | 0.25 | 0.25 | 0.395 p=0.0012 | 1   |
| 18. Source of energy absorbed by GHG molecules. | 0.27 | 0.32 | 0.16 | 0.3139 p=0.0115 | 3   |

(e) This is re-emitted in all directions - down as well as up: Item 23

| 23. What a molecule of GHGs does after it absorbs heat. | 0.51 | 0.20 | 0.14 | 0.2142 p=0.0892 | 4   |

Conceptual area 4 – GHGs and and non-GHGs in the atmosphere:

| 9. Proportion of GHGs in atmosphere | 0.42 | 0.44 | 0.38 | 0.531 p=0.0001 | 0   |
| 10. Which are all GHGs? | 0.67 | 0.44 | 0.13 | 0.3309 p=0.0076 | 0   |
| 19. How can a small percentage of GHGs have a significant effect? | 0.69 | 0.59 | 0.20 | 0.4572 p=0.0001 | 3   |
| 17. Most abundant GHGs. | 0.58 | 0.38 | 0.13 | 0.3281 p=0.0081 | 1   |

Conceptual area 5 - Feedback:

<p>| 25. Effect of increased reflective clouds on climate. | 0.72 | 0.42 | 0.39 | 0.5048 p=0.0001 | 7   |</p>
<table>
<thead>
<tr>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td>0.7656</td>
<td>10</td>
<td>0.7615</td>
<td>20</td>
<td>0.7538</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.7592</td>
<td>11</td>
<td>0.7580</td>
<td>21</td>
<td>0.7484</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.7627</td>
<td>12</td>
<td>0.7603</td>
<td>22</td>
<td>0.7419</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.7429</td>
<td>13</td>
<td>0.7612</td>
<td>23</td>
<td>0.7692</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.7586</td>
<td>14</td>
<td>0.7584</td>
<td>24</td>
<td>0.7561</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.7585</td>
<td>15</td>
<td>0.7641</td>
<td>25</td>
<td>0.7507</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.7764</td>
<td>16</td>
<td>0.7666</td>
<td>26</td>
<td>0.7590</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.7615</td>
<td>17</td>
<td>0.7621</td>
<td>27</td>
<td>0.7621</td>
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</tr>
<tr>
<td>8</td>
<td>0.7619</td>
<td>18</td>
<td>0.7620</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.7489</td>
<td>19</td>
<td>0.7538</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

27. Effect of warmer water on climate.  
<table>
<thead>
<tr>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.87</td>
<td>0.13</td>
<td>0.17</td>
<td>0.3595</td>
<td>p=0.0035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.62</td>
<td>0.20</td>
<td>0.20</td>
<td>0.3281</td>
<td>p=0.0081</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conceptual area 6 – Equilibrium of energy:

7. If the Earth gave out less energy than it receives from the Sun, what would happen to its temperature?  
<table>
<thead>
<tr>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td>0.32</td>
<td>0.06</td>
<td>0.3152</td>
<td>p=0.0112</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20. Balance between energy from the Sun absorbed and emitted by Earth.  
<table>
<thead>
<tr>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21</td>
<td>0.39</td>
<td>0.26</td>
<td>0.4609</td>
<td>p=0.0001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conceptual area 7 – Conservation of energy:

4. When bath water goes cold what has happened to the heat energy?  
<table>
<thead>
<tr>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>Item dropped</th>
<th>New α value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>0.31</td>
<td>0.16</td>
<td>0.3766</td>
<td>p=0.0022</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A5.4 lists the data for Cronbach’s alpha with item deleted, for undergraduates.

**Table A5.4: Values of Cronbach’s alpha when individual items are deleted from the CCCI, for undergraduates. The first value is for the entire 27 item test**
APPENDIX 6 – CONTINGENCY TABLES DISCUSSED IN CHAPTER 7

This Appendix contains the contingency tables discussed in Section 7.2 of Chapter 7.

How to read the contingency tables

Table A6.1: Example of format of contingency table

<table>
<thead>
<tr>
<th>Total %</th>
<th>1A text</th>
<th>1B text</th>
<th>1C text</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2A text</td>
<td>23</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>2B text</td>
<td>5</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>2C text</td>
<td>10</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>25</td>
<td>55</td>
</tr>
</tbody>
</table>

80% of students who chose 1A went on to choose 2A – suggests association between concept contained in 1A and concept contained in 2A.

25% of all students chose 1A and 2B.

Numbers in black in bottom row ie:
10+7+2=19 = total % of

Numbers which are shown in the same colour, add up to 100%.

Table A6.1 above illustrates the layout of the contingency tables. The top row shows the options for item 1 and the left-hand column shows the options for item 2.

The rest of the cells each contain three numbers. The top number (coloured black) is the percentage of students who chose both the corresponding options, so the top numbers in the entire table add up to 100% (minus informal responses and rounding errors). In the example above, 25% of students chose both 1B and 2B (indicated in the table); while 2% chose 1C and 2C.
To find the total percentage of students who chose an option, add the top number in each row (for options in rows) or column (for each option in columns. E.g., the percentage of students who chose 1C in the example above is 16+2+2 = 18%, while the number choosing 2A is 23+20+16 = 59%.

The middle number in each cell (coloured light, medium and dark blue) shows the percentage of students who chose the corresponding option from the item shown in columns, and also the corresponding option from the item shown in rows, i.e., the middle numbers in each column add up to 100%. This is illustrated by examples below.

For example, in Table A6.1 above, 23% of all students chose 1A and 2A. 80% of the students who chose 1A also chose 2A and 68% of the students who chose 2A had chosen 1A. This suggests evidence for consistent reasoning about the concept contained in these options. 25% of all students chose 1B and 2B; however only 24% of the students who chose 1B also chose 2B, while 35% of the students who chose 2B had chosen 1B. This suggests that the students made no association between the concept contained in 1B and the concept contained in 2B.

The bottom number in each cell (coloured light, medium and dark red) is the percentage of students choosing the corresponding option from the item shown in rows, who also chose the corresponding option from the item shown in columns, i.e., the bottom numbers in each row add up to 100%. For example, in Table A6.1, 68% of those who chose 2A had chosen 1A; while 20% of those who chose 2A had chosen 1B. This suggests that the students made an association between the concepts in 1A and 2A, but not between the concepts in 1B and 2A.
Table A6.2: List of contingency tables in Appendix 6, showing the section in Chapter 7 where each one is discussed

<table>
<thead>
<tr>
<th>Section</th>
<th>Table</th>
<th>Items</th>
<th>Specific Ideas Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3.3</td>
<td>A6.3</td>
<td>3,22</td>
<td>Total amount of carbon on Earth over time</td>
</tr>
<tr>
<td></td>
<td>A6.4</td>
<td>5,13</td>
<td>Source of carbon in fossil fuels, and effect of their burning on the atmosphere</td>
</tr>
<tr>
<td></td>
<td>A6.5</td>
<td>5,22</td>
<td>Carbon is created when fossil fuels are burned</td>
</tr>
<tr>
<td></td>
<td>A6.6</td>
<td>13,22</td>
<td>Carbon in fossil fuel formation and burning</td>
</tr>
<tr>
<td>7.3.4</td>
<td>A6.7</td>
<td>1,8</td>
<td>Relative importance of water as a reservoir in the carbon cycle</td>
</tr>
<tr>
<td></td>
<td>A6.8</td>
<td>1,12</td>
<td>Water as a reservoir in the carbon cycle – ability of carbon dioxide to dissolve in water</td>
</tr>
<tr>
<td></td>
<td>A6.9</td>
<td>8,12</td>
<td>Water as a reservoir in the carbon cycle – ability of carbon dioxide to dissolve in water</td>
</tr>
<tr>
<td>7.3.5</td>
<td>A6.10</td>
<td>11,18</td>
<td>Source of energy leaving Earth and absorbed by GHGs</td>
</tr>
<tr>
<td></td>
<td>A6.11</td>
<td>14,18</td>
<td>Source of energy leaving Earth and absorbed by GHGs</td>
</tr>
<tr>
<td></td>
<td>A6.12</td>
<td>8,14</td>
<td>Relative size of human contributions to small carbon and energy flows</td>
</tr>
<tr>
<td></td>
<td>A6.13</td>
<td>8,18</td>
<td>Relative size of human contributions to large carbon flows and energy absorbed by GHGs</td>
</tr>
<tr>
<td>7.3.6</td>
<td>A6.14</td>
<td>9,19</td>
<td>Proportion of GHGs in the atmosphere</td>
</tr>
<tr>
<td></td>
<td>A6.15</td>
<td>19,23</td>
<td>GHGs create more GHGs</td>
</tr>
<tr>
<td>7.3.7</td>
<td>A6.16</td>
<td>11,16</td>
<td>GHGs trap radiation/damage the ozone layer</td>
</tr>
<tr>
<td></td>
<td>A6.17</td>
<td>11,23</td>
<td>GHGs damage the ozone layer</td>
</tr>
<tr>
<td></td>
<td>A6.18</td>
<td>16,23</td>
<td>GHGs damage the ozone layer</td>
</tr>
<tr>
<td></td>
<td>A6.19</td>
<td>6,15</td>
<td>Nature of energy from the Sun and its interactions with the atmosphere</td>
</tr>
<tr>
<td></td>
<td>A6.20</td>
<td>11,21</td>
<td>Mechanism of action of greenhouse gases and bands of e.m.s. that they interact with</td>
</tr>
<tr>
<td></td>
<td>A6.21</td>
<td>15,21</td>
<td>Interactions between greenhouse and non-greenhouse gases and different bands of the e.m.s.</td>
</tr>
<tr>
<td></td>
<td>A6.22</td>
<td>6,21</td>
<td>Nature of energy from the Sun and interactions between GHGs and different bands of the e.m.s.</td>
</tr>
<tr>
<td>7.3.8</td>
<td>A6.23</td>
<td>25,26</td>
<td>Feedback</td>
</tr>
<tr>
<td></td>
<td>A6.24</td>
<td>26,27</td>
<td>Feedback</td>
</tr>
<tr>
<td></td>
<td>A6.25</td>
<td>25,27</td>
<td>Feedback</td>
</tr>
<tr>
<td>7.3.9</td>
<td>A6.26</td>
<td>7,20</td>
<td>Equilibrium of energy</td>
</tr>
</tbody>
</table>
Table A6.3: Contingency tables items 3 and 22

<table>
<thead>
<tr>
<th>Total %</th>
<th>Col %</th>
<th>Row %</th>
<th>22 A: constant for most of the time but increasing due to fossil fuels</th>
<th>22 B: decreased - CO₂ escapes from atmosphere</th>
<th>22 C: same - burning fossil fuels doesn’t affect total carbon on Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>59</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>3A:</td>
<td>increased</td>
<td></td>
<td>87</td>
<td>52</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>79</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>3B:</td>
<td>decreased</td>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>33</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>44</td>
<td>39</td>
<td>17</td>
</tr>
<tr>
<td>3C:</td>
<td>stayed the same</td>
<td></td>
<td>6</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>10</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td>6</td>
<td>58</td>
</tr>
</tbody>
</table>

Table A6.4: Contingency table for items 5 and 13

<table>
<thead>
<tr>
<th>Total %</th>
<th>Col %</th>
<th>Row %</th>
<th>13A: fossil fuel formation decreased CO₂ in the atmosphere</th>
<th>13B: did not CO₂ in the atmosphere</th>
<th>13C: the fossil fuels were formed when the Earth first formed</th>
<th>13D: increased CO₂ in the atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A:</td>
<td>carbon created when fossil fuels burned</td>
<td></td>
<td>6</td>
<td>9</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35</td>
<td>29</td>
<td>26</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19</td>
<td>29</td>
<td>7</td>
<td>43</td>
</tr>
<tr>
<td>5B:</td>
<td>carbon in the Earth but never in atmosphere before</td>
<td></td>
<td>6</td>
<td>14</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35</td>
<td>49</td>
<td>63</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>29</td>
<td>11</td>
<td>48</td>
</tr>
<tr>
<td>5C:</td>
<td>carbon was in the atmosphere a long time ago</td>
<td></td>
<td>5</td>
<td>6</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>21</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>31</td>
<td>4</td>
<td>40</td>
</tr>
</tbody>
</table>

Table A6.5: Contingency table for items 5 and 22

<table>
<thead>
<tr>
<th>Total %</th>
<th>Col %</th>
<th>Row %</th>
<th>22A: total carbon constant most of time but increasing due to fossil fuel burning</th>
<th>22B: decreased - CO₂ escapes from atmosphere</th>
<th>22C: same - burning fossil fuels doesn’t affect total carbon on Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A:</td>
<td>carbon is created when fossil fuels are burned</td>
<td></td>
<td>22</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td>38</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>72</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>5B:</td>
<td>carbon in fossil fuels was in Earth but never in atmosphere before</td>
<td></td>
<td>34</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>5C:</td>
<td>carbon in fossil fuels was in atmosphere long time ago</td>
<td></td>
<td>12</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>62</td>
<td>7</td>
<td>31</td>
</tr>
</tbody>
</table>
### Table A6.6: Contingency table for items 13 and 22

<table>
<thead>
<tr>
<th>Total %</th>
<th>22A: total C constant most of time but increasing due to fossil fuel burning</th>
<th>22B: decreased - CO\textsubscript{2} escapes from atmosphere</th>
<th>22C: same - burning fossil fuels doesn’t affect total carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13A: fossil fuel formation CO\textsubscript{2} in atmosphere</td>
<td>9</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>29</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>13B: did not CO\textsubscript{2} in the atmosphere</td>
<td>20</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>7</td>
<td>24</td>
</tr>
<tr>
<td>13C: fossil fuels formed when Earth formed, and it didn’t have an atmosphere</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>13D: increased CO\textsubscript{2} in the atmosphere</td>
<td>35</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>29</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>6</td>
<td>14</td>
</tr>
</tbody>
</table>

### Table A6.7: Contingency table for items 1 and 8

<table>
<thead>
<tr>
<th>Total %</th>
<th>8A: oceans, land &gt;&gt;&gt; fossil fuels</th>
<th>8B: oceans = land = fossil fuels</th>
<th>8C: fossil fuels, land&gt;&gt;&gt; oceans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A: atmosphere&gt;&gt;&gt; living things&gt; oceans</td>
<td>3</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>41</td>
<td>50</td>
</tr>
<tr>
<td>1B: living things&gt; atmosphere&gt; oceans</td>
<td>3</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>38</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>1C: oceans&gt;&gt;&gt; atmosphere= living things</td>
<td>1</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>63</td>
<td>24</td>
</tr>
</tbody>
</table>

### Table A6.8: Contingency table for items 1 and 12

<table>
<thead>
<tr>
<th>Total %</th>
<th>12A: limestone formation and escaping into space</th>
<th>12B: dissolving in water and escaping into space</th>
<th>12C: limestone formation and dissolving in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A: atmosphere&gt;&gt; living things&gt; oceans</td>
<td>10</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>49</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>1B: living things&gt; atmosphere&gt; oceans</td>
<td>11</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>28</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>1C: oceans&gt;&gt;&gt; atmosphere= living things</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>32</td>
<td>47</td>
</tr>
</tbody>
</table>
### Table A6.9: Contingency table for items 8 and 12

<table>
<thead>
<tr>
<th>Total %</th>
<th>12A: limestone formation and escaping into space</th>
<th>12B: dissolving in water and escaping into space</th>
<th>12C: limestone formation and dissolving in water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8A: oceans, land &gt;&gt;&gt;fossil fuels</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8B: oceans = land = fossil fuels</td>
<td>35</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>8C: fossil fuels, land&gt;&gt;&gt;oceans</td>
<td>60</td>
<td>38</td>
<td>43</td>
</tr>
</tbody>
</table>

### Table A6.10: Contingency table for items 11 and 18

<table>
<thead>
<tr>
<th>Total %</th>
<th>18A: energy absorbed by GHGs is reflected off the Earth</th>
<th>18B: emitted by the Earth</th>
<th>18C: from human activity</th>
<th>18D: directly from the Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11A: let heat rays in but not out</td>
<td>12</td>
<td>4</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>11B: allow Sun’s rays in but absorb rays from the Earth</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>11C: interact with all types of e.m.r. creating heat</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>11D: damage the ozone layer so more UV gets in and heats the Earth</td>
<td>6</td>
<td>9</td>
<td>26</td>
<td>7</td>
</tr>
</tbody>
</table>

### Table A6.11: Contingency table for items 14 and 18

<table>
<thead>
<tr>
<th>Total %</th>
<th>14A: heat leaving Earth’s surface is from radioactive rocks/centre of Earth</th>
<th>14B: from Sun reflected off Earth’s surface</th>
<th>14C: from human activity e.g., burning fossil fuels</th>
<th>14D: emitted naturally by Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18A: energy absorbed by GHGs is reflected off the Earth</td>
<td>1</td>
<td>20</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>18B: emitted by the Earth</td>
<td>14</td>
<td>39</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>18C: from human activity e.g., burning fossil fuels</td>
<td>2</td>
<td>15</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>18D: directly from the Sun</td>
<td>36</td>
<td>30</td>
<td>52</td>
<td>38</td>
</tr>
</tbody>
</table>

366
### Table A6.12: Contingency table for items 8 and 14

<table>
<thead>
<tr>
<th>Total %</th>
<th>8A: oceans, land &gt;&gt;&gt; fossil fuels</th>
<th>8B: oceans = land = fossil fuels</th>
<th>8C: fossil fuels, land&gt;&gt;&gt; oceans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14A: heat leaving Earth is mostly from radioactive rocks and heat from the centre of the Earth</td>
<td>&lt;1  3  2</td>
<td>5  8  5</td>
<td>7  57 36</td>
</tr>
<tr>
<td>14B: heat is mostly from the Sun reflected (bounced) off the Earth’s surface</td>
<td>4  24 21</td>
<td>53 54 47</td>
<td>9  47 43</td>
</tr>
<tr>
<td>14C: heat is mostly emitted through human activity e.g., burning fossil fuels</td>
<td>1  11 16</td>
<td>16 26 34</td>
<td>4  39 54</td>
</tr>
<tr>
<td>14D: heat is mostly emitted (given off) naturally by the Earth</td>
<td>2  4  5</td>
<td>26 10 10</td>
<td>19 38 42</td>
</tr>
</tbody>
</table>

### Table A6.13: Contingency table for items 8 and 18

<table>
<thead>
<tr>
<th>Total %</th>
<th>8A: oceans, land &gt;&gt;&gt; fossil fuels</th>
<th>8B: oceans = land = fossil fuels</th>
<th>8C: fossil fuels, land&gt;&gt;&gt; oceans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18A: energy absorbed by GHGs is reflected off the Earth</td>
<td>2  14 8</td>
<td>26 31 18</td>
<td>9  54 33</td>
</tr>
<tr>
<td>18B: emitted (given off) by the Earth</td>
<td>2  4  8</td>
<td>21 10 17</td>
<td>12 30 55</td>
</tr>
<tr>
<td>18C: from human activity e.g., burning fossil fuels</td>
<td>3  16 19</td>
<td>32 37 50</td>
<td>7  42 50</td>
</tr>
<tr>
<td>18D: directly from the Sun</td>
<td>2  9  9</td>
<td>21 20 20</td>
<td>9  43 46</td>
</tr>
</tbody>
</table>

### Table A6.14: Contingency table for items 9 and 19

<table>
<thead>
<tr>
<th>Total %</th>
<th>19A: GHGs are important only at levels &gt;5%.</th>
<th>19B: GHGs interact with Sun’s rays making more GHGs</th>
<th>19C: Earth has a lot of atmosphere so a small % is a lot of molecules.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9A: &gt; 30%</td>
<td>4  10  6</td>
<td>24 30 14</td>
<td>18 49 29</td>
</tr>
<tr>
<td>9B: 5% - 30%</td>
<td>10 17 26</td>
<td>61 51 58</td>
<td>18 32 47</td>
</tr>
<tr>
<td>9C: &lt; 5%</td>
<td>2  7  12</td>
<td>13 19 27</td>
<td>10 30 56</td>
</tr>
<tr>
<td>Total %</td>
<td>23A: when a GHG molecule absorbs heat it rises into the ozone layer</td>
<td>23B: emits the heat again</td>
<td>23C: creates more GHG molecules</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------------------------------------------------</td>
<td>--------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Row %</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19A: GHGs are important only at levels &gt; 5%</td>
<td>8</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>19B: GHGs interact with Sun’s rays making more GHGs</td>
<td>11</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>19C: Earth has a lot of atmosphere, so small percentage is a lot of molecules.</td>
<td>14</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

| Table A6.16: Contingency table for items 11 and 16 |
|---------|---------------------------------------------------------------|--------------------------|-------------------------------|----------------------------------------|
| Total % | 16A: don’t damage the ozone layer | 16B: absorb IR rays but then emit them again | 16C: don’t absorb IR at all |
| Col % | 16A: don’t damage the ozone layer | 16B: absorb IR rays but then emit them again | 16C: don’t absorb IR at all |
| Row % | 16A: don’t damage the ozone layer | 16B: absorb IR rays but then emit them again | 16C: don’t absorb IR at all |
| 11A: let heat rays in but don’t let them out | 9 | 15 | 10 |
| 11B: allow Sun’s rays in but absorb rays coming from Earth | 3 | 7 | 1 |
| 11C: they interact with all types of e.m.r. creating heat | 1 | 1 | 1 |
| 11D: damage the ozone layer so more UV gets in and heats Earth | 23 | 15 | 9 |

| Table A6.17: Contingency table for items 11 and 23 |
|---------|---------------------------------------------------------------|--------------------------|-------------------------------|----------------------------------------|
| Total % | 23A: rises into the ozone layer | 23B: emits the heat again | 23C: creates more GHG molecules | 23D: gives off different type of energy |
| Col % | 23A: rises into the ozone layer | 23B: emits the heat again | 23C: creates more GHG molecules | 23D: gives off different type of energy |
| Row % | 23A: rises into the ozone layer | 23B: emits the heat again | 23C: creates more GHG molecules | 23D: gives off different type of energy |
| 11A: heat rays in but not out | 14 | 7 | 7 | 6 |
| 11B: allow Sun’s rays in but absorb rays coming from Earth | 2 | 4 | 3 | 1 |
| 11C: interact with all types of e.m.r., creating heat | 0 | 2 | 1 | 1 |
| 11D: damage the ozone layer so more UV gets in and heats up Earth | 18 | 9 | 13 | 6 |

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### Table A6.18: Contingency table for items 16 and 23

<table>
<thead>
<tr>
<th>Total %</th>
<th>23A: GHG rises into the ozone layer</th>
<th>23B: emits the heat again</th>
<th>23C: creates more GHG molecules</th>
<th>23D: emits a different type of energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16A: non-GHGs</td>
<td>12.</td>
<td>7</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>don’t damage the ozone layer</td>
<td>35</td>
<td>33</td>
<td>43</td>
<td>25</td>
</tr>
<tr>
<td>16B: they absorb IR but then emit it again</td>
<td>15.</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>16C: they don’t absorb IR at all</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table A6.19: Contingency table for items 6 and 15

<table>
<thead>
<tr>
<th>Total %</th>
<th>15A: Sun’s energy interacts with most molecules of atmosphere</th>
<th>15B: only interacts with greenhouse gases in atmosphere</th>
<th>15C: isn’t affected by atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6A:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR=visible</td>
<td>7</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>&gt;&gt;&gt;UV</td>
<td>71</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>6B:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR=UV =visible</td>
<td>14</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6C:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV&gt;visible</td>
<td>44</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>&gt;IR</td>
<td>72</td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>

### Table A6.20: Contingency table for items 11 and 21

<table>
<thead>
<tr>
<th>Total %</th>
<th>21A: GHG interact with IR</th>
<th>21B: with UV light</th>
<th>21C: more than one of the above</th>
<th>21D: none of the above</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11A: GHGs let heat rays in but not out</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>11B: they allow Sun’s rays in but absorb rays coming from Earth</td>
<td>3</td>
<td>1</td>
<td>&lt;1</td>
<td>5</td>
</tr>
<tr>
<td>11C: they interact with all types of e.m.r., creating heat</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>2</td>
</tr>
<tr>
<td>11D: they damage the ozone layer so more UV gets in and heats up Earth</td>
<td>5</td>
<td>11</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>11E:</td>
<td>41</td>
<td>57</td>
<td>44</td>
<td>49</td>
</tr>
</tbody>
</table>

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### Table A6.21: Contingency table for items 15 and 21

<table>
<thead>
<tr>
<th>Total %</th>
<th>21A: GHG interact with IR</th>
<th>21B: they interact with UV</th>
<th>21C: visible light</th>
<th>21D: more than one of the above</th>
<th>21E: none of the above</th>
</tr>
</thead>
<tbody>
<tr>
<td>15A: Sun’s energy interacts with most molecules of atmosphere</td>
<td>8</td>
<td>11</td>
<td>3</td>
<td>39</td>
<td>3</td>
</tr>
<tr>
<td>70</td>
<td>59</td>
<td>67</td>
<td>77</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>17</td>
<td>4</td>
<td>58</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>B: only interacts with GHGs in the atmosphere</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>27</td>
<td>22</td>
<td>8</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>6</td>
<td>27</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>C: isn’t affected by the atmosphere at all</td>
<td>3</td>
<td>3</td>
<td>&lt;1</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>14</td>
<td>11</td>
<td>13</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>17</td>
<td>3</td>
<td>43</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

### Table A6.22: Contingency table for items 6 and 21

<table>
<thead>
<tr>
<th>Total %</th>
<th>21A: GHG interact with IR=visible&gt;&gt;&gt;UV</th>
<th>21B: they interact with IR=UV=visible</th>
<th>21C: UV&gt;visible&gt;IR</th>
<th>21D: more than one of the above</th>
<th>21E: none of the above</th>
</tr>
</thead>
<tbody>
<tr>
<td>6A: IR=visible&gt;&gt;&gt;UV</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>33</td>
<td>11</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>12</td>
<td>54</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>6B: IR=UV=visible</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>44</td>
<td>20</td>
<td>33</td>
<td>21</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>16</td>
<td>5</td>
<td>42</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>6C: UV&gt;visible&gt;IR</td>
<td>6</td>
<td>14</td>
<td>1</td>
<td>33</td>
<td>5</td>
</tr>
<tr>
<td>48</td>
<td>73</td>
<td>33</td>
<td>65</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>23</td>
<td>2</td>
<td>54</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

### Table A6.23: Contingency table for items 25 and 26

<table>
<thead>
<tr>
<th>Total %</th>
<th>25A: it will get hotter, faster than before the clouds formed</th>
<th>25B: it will get hotter more slowly than before the ice melted</th>
<th>25C: no effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>26A: it will get hotter, faster than before the ice</td>
<td>17</td>
<td>42</td>
<td>6</td>
</tr>
<tr>
<td>melted</td>
<td>62</td>
<td>71</td>
<td>54</td>
</tr>
<tr>
<td>26B: it will get hotter, but more slowly than before the ice melted</td>
<td>8</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>30</td>
<td>23</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>52</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>26C: no effect</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>60</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
Table A6.24: Contingency table for items 26 and 27

<table>
<thead>
<tr>
<th>Row %</th>
<th>27A: it will get hotter, at a faster rate</th>
<th>27B: it will get hotter but more slowly</th>
<th>27C: no effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>26A: it will get hotter, faster than before the ice melted</td>
<td>44</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>70</td>
<td>31</td>
</tr>
<tr>
<td>26B: it will get hotter, but more slowly</td>
<td>11</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>23</td>
<td>62</td>
</tr>
<tr>
<td>26C: no effect</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>27</td>
<td>13</td>
</tr>
</tbody>
</table>

Table A6.25: Contingency table for items 25 and 27

<table>
<thead>
<tr>
<th>Row %</th>
<th>25A: it will get hotter, faster than before the clouds formed</th>
<th>B: it will get hotter more slowly than before</th>
<th>C: no effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: it will get hotter at a faster rate</td>
<td>14</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>49</td>
<td>67</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>67</td>
<td>9</td>
</tr>
<tr>
<td>B: it will still get hotter, but more slowly</td>
<td>8</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>18</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>47</td>
<td>17</td>
</tr>
<tr>
<td>C: no effect</td>
<td>4</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>56</td>
<td>9</td>
</tr>
</tbody>
</table>

Table A6.26: Contingency table for items 7 and 20

<table>
<thead>
<tr>
<th>Row %</th>
<th>20A: less energy sent back because some used up e.g., in photosynthesis</th>
<th>20B: same amount sent back</th>
<th>20C: less sent back because Earth is cooler than Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>7A: use up spare energy e.g., in photosynthesis</td>
<td>9</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>7B: gradually get hotter</td>
<td>55</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>65</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>69</td>
<td>7</td>
<td>21</td>
</tr>
<tr>
<td>7C: store spare energy but not get hotter</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>38</td>
<td>38</td>
</tr>
</tbody>
</table>
APPENDIX 7 – POST-CI FOCUS GROUPS
INTERVIEW GUIDE

1. Show a copy of the CI: any questions that they didn’t understand what they were being asked?
2. Most of Earth’s carbon is in rocks. What amount of carbon do you think is in the atmosphere, oceans and living things?
3. What do you think of when you hear the word "carbon”?
4. Carbon in living things – what forms is it in?
5. Carbon in the oceans – what forms is it in?
6. (a) What compounds can you name that contain carbon?
   (b) Where are these compounds found?
7. When plants make roots/stems/leaves, where do they get the carbon from?
8. Carbon from the soil – what form does this come in?
9. Does photosynthesis have an effect on the mount of carbon in the atmosphere? Is this something they have thought about?
10. Since the Earth first formed until now, what has happened to the total amount of carbon on the planet, including its atmosphere?
11. What could cause the amount of carbon on the planet to change?
12. Does burning FF cause the amount of C on the planet to increase?
13. A hot bath contains energy in the form of heat. After a while the water goes cold. What has happened to the heat energy?
14. (a) Have you heard about “conservation of energy”?
   (b) Have you heard of “energy can’t be created or destroyed”?
15. When FF are burned, carbon is added to the atmosphere. Where did this originally come from?
16. If FF are made of remains of animals and plants, where did they get their carbon from?
17. What effect did the process of FF formation have on the amount of CO₂ in the atmosphere?
18. What do they know about the e.m.s.?
19. Is UV the same as ultraviolet?
20. What bands are given off by the Sun and how much relatively of each?

21. If Earth gave out less energy than it receives from the Sun, then over time what would happen?

22. Carbon in/out of atmosphere from FF; plants/soils; oceans: is it clear what the diagram shows?

23 (a) What processes move C around the carbon cycle?
(b) What process could cause the UP arrows form plants/soils and oceans?
(c) What processes cause the DOWN arrows?
(d) How much C do we release compared to these natural flows (DRAW ARROWS IN ON DIAG)

24 (a) How much of the atmosphere is GHGs (gases that make Earth warmer)?
(b) Where did they learn about this?

25 (a) Greenhouse gases - HOW MANY CAN YOU NAME?
(b) Where did they learn about these gases?

26. What are clouds made of? Do they play a part in global warming?

27 (a) Why do GHGs cause the Earth to warm up? I.e., why are they different from a non-GHGs?
(b) How can a GHG let the same type of ray in but not out?

28. (a) What ways apart from photosynthesis can CO2 get out of from the atmosphere?
(b) What parts of the C cycle remove CO2 from the atmosphere?
(c) Can CO2 escape into space?
(d) Can CO2 dissolve in water? Did they know this before?
(e) Can CO2 get taken up into rocks? How? Did they know this before?

29 (a) What are the sources of heat that leave the Earth?
(b) How much relatively of each?

30. What happens to energy from the Sun that reaches the Earth?

31(a) HOW DOES most of the Sun’s energy interact with Earth's atmosphere?

<table>
<thead>
<tr>
<th>UV</th>
<th>Visible</th>
<th>IR</th>
<th>X rays</th>
<th>Radio</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH gases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non GHGs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(b) What do they understand by “interact”? Same as “absorb”? What else could it mean in this context?

32. What is the REASON that N₂ and O₂ do NOT cause Earth to warm?

33. Which is the most abundant GHG (i.e., which is there the most of)?

34 (a) What kind of energy do GHGs interact with?
   (b) Where does most of this energy come from? What is emitting it?
   (c) What happens when a GHG absorbs energy?

35. How can a small percentage of GHGs have a significant effect on climate?

36. What happens to the energy from the Sun that is absorbed by the Earth?

37 (a) How is energy "used" in photosynthesis? What happens to the energy?
   (b) How is it stored?
   (c) Why does this not cause the Earth to get warmer?

38. What happens when plants die/decay/are eaten?

39. What type of energy do all greenhouse gases interact with?

40. What has happened to the total amount of carbon on Earth, including its atmosphere, since the planet first formed?

41. When a molecule of GHGs absorbs (takes in) heat, what does it do?

42 (a) What is IR radiation?
   (b) What is it emitted by - living things/warm things?

43 (a) Have you heard about feedback in science? (apart from “getting feedback”)?
   (b) Heard of in climate change?
   (c) Biological systems example – what happens when you exercise? What effect does this have?
   (d) Some types of cloud reflect Sun’s rays back to space, so less Sun’s rays reach the ground. If these clouds became more common due to global warming, how would it affect the climate?
   (e) Ice/snow are white and reflect Sun’s rays, but the ground and water underneath is darker and absorb Sun’s rays. When the climate gets warmer, ice/snow will melt. How will this affect climate?
   (f) CO₂ is removed from the atmosphere when it dissolves in water e.g., oceans. Warmer water dissolves less carbon dioxide than colder water. What effect will this have on global warming?
APPENDIX 8 – DIAGRAMS OF CARBON RESERVOIRS AND FLUXES COMPLETED BY POST-CI FOCUS GROUP PARTICIPANTS

The following images were created by students during the post CI focus groups.

Figure A8.1: Carbon reservoir diagrams created by post CI focus group participants
Figure A8.1 shows carbon reservoir diagrams and Figure A8.2 shows carbon flux diagrams. These were made and modified by students on Omnigraffle (2012) during the focus group interviews. Students changed the size of the circles (labeled “original”) to show their ideas of the relative sizes of the carbon reservoirs and fluxes.

Three students worked separately on the carbon reservoir diagrams in Figure A8.1, while the carbon flux diagram in A8.2 was a joint effort by the same group of students.

Figure A8.2: Carbon flux diagram jointly created by post CI focus group participants
# APPENDIX 9 – POST-CI FOCUS GROUPS

## QUALITATIVE DATA ANALYSIS CODES

Table A9.1 lists the data analysis codes used to label transcript segments, with a description of the type of comment the code applies to, the number of transcript segments corresponding to the code and an exemplar transcript segment.

### Table A9.1: Codes, descriptions of codes, number of corresponding transcript segments and examples of segments for post CI focus group transcripts

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>No.</th>
<th>Example transcript segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>Associations between FF and other concepts. Nature and origin of FF. Effects of FF formation and burning.</td>
<td>27</td>
<td>[Researcher] where did the C in FF originate from?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- from the dead things</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- how's oil or gas made out of dead things? That's weird.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- I don't really know what a FF is</td>
</tr>
<tr>
<td>C is</td>
<td>Nature of carbon. Associations between carbon and other concepts. What chemical forms carbon occurs in.</td>
<td>19</td>
<td>[Researcher] what co you associate with the word &quot;carbon&quot;?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- smoke</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- CO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- greenhouse gases</td>
</tr>
<tr>
<td>C where</td>
<td>Where in the Earth (atmosphere, hydrosphere, biosphere and geosphere) carbon is found. Movement of carbon between atmosphere, hydrosphere, biosphere and geosphere</td>
<td>45</td>
<td>I thought the atmosphere would be the biggest thing so I went with that, I guess atmosphere</td>
</tr>
<tr>
<td>Human contrib</td>
<td>Relative size and importance of outputs (carbon, carbon dioxide, heat, energy) from human activities in relation to those from natural processes. Assumption that all outputs are human-caused rather than natural. Energy absorbed by GHGs is mainly from humans (implying that the greenhouse effect is entirely not natural)</td>
<td>12</td>
<td>I should have thought about it relative to the other ones but you hear on those big scare campaigns against the carbon tax that our amount of % of emitting C is tiny compared to cows farting and burping so I put the small one.</td>
</tr>
<tr>
<td>Plants</td>
<td>Where plants get their carbon /energy from. Other comments explicitly about plants.</td>
<td>24</td>
<td>[Researcher] Plants take in carbon: where to they get it from?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Soil because of the rain, the rain comes from the atmosphere</td>
</tr>
</tbody>
</table>
- Air cos I thought they breathed it in in a way
- Wouldn't it be through the Sun's rays as well, through photosynthesis?

| Cons of matter | Creation or destruction of atoms e.g., plants creating matter from Sun's energy, carbon being created when FF are burned, GHGs being created. | 14 | Researcher: what do [plants] turn [energy from the Sun] into?
- nutrients and stuff so they can grow
[Researcher] so can you take energy and turn it into chemicals?
- Hmmm, good question |

| Total C | Any processes bringing carbon onto the planet or allowing it to escape (as opposed to creation or destruction). | 9 | [Researcher] does burning FF cause the amount of carbon on the planet to increase?
- no [several]
- converts it into different forms
- yes, slightly |

| Sun’s energy | Nature of energy received from Sun e.g., what bands of e.m.r. Any comment explicitly referring to energy from Sun | 18 | Whenever you hear about the Sun, you always hear about ultraviolet rays and how you've got to protect yourself so I thought that meant that's the one it gives the most of |

| e.m.r. | Understanding of the nature of e.m.r. i.e., that IR, UV and visible light are different related | 11 | I don't know! [if the bench emits IR]
I think it would, because we had one last year
- Is that the ones that show the red? Wouldn't it show that it's cold, it'd be blue |

| Interact | Interactions between atmospherics gases (GH or non-GH) and different bands of e.m.r.: in terms of what interacts with what. Source of energy that GHGs interact with (e.g. Sun, Earth, human activity) | 16 | - GHGs rise into the atmosphere and react with the Sun's rays or stop them or hold them or something
- and stay there
- GHGs take in more heat and absorb the heat from the Sun. And the radiation. |

| GHGs do | The mechanism by which greenhouse gases cause warming. What they do that non-GHGs don’t do. | 13 | [Researcher] why do GHGs cause the Earth to warm up?
- the ozone layer - does it trap it? - it traps the gases. I think. Like it's a greenhouse, so it keeps it warm, traps it in some area |

| Ozone | Any comment explicitly mentioning ozone/ozone layer | 10 | GHGs are going up into the atmosphere and EMR can penetrate through the atmosphere and so they're kind of interacting there and it causes a hole in the ozone layer or something like that. The way they interact it's not good. So it |
Earth’s energy

Nature and origin of energy leaving the Earth’s surface. Any comment about energy leaving the Earth’s surface.

9

[Researcher] What are the sources of heat coming from Earth?
- the core [several]
- and reflection from the Sun
- things that we've done, fuel that we've burned

Energy balance

Balance between energy coming into and leaving Earth. Comments about conservation or equilibrium of energy

15

[Researcher] If Earth puts out less energy than it takes in, is it going to get hotter or use up that spare energy?
- going to get hotter [several]
- it might convert it into …

GHGs abund

Proportion of the atmosphere that is greenhouse gases. Relative abundance of different greenhouse gases.

10

[Students express surprise at actual CO₂ concentration]
- why's everyone so worried?
- cos a lot builds up over the long term
- it'd be the same as the UV - we hear about it more, just cos it's more damaging.

GHGs are

Which chemical species are GHGs and which aren’t

10

Researcher: who can name a GHG?
methane [straightaway]
carbon dioxide -oh
carbon monoxide
water vapour, it was in the paper

Pollution

Comments about pollution in general terms. Conflation between climate change and unrelated pollutants

2

[Researcher] what do we mean by GHGs?
- Bad stuff. Methane. Unwanted gases that damage the environment

Feedback

All comments describing understanding of feedback mechanisms

11

[Researcher] melting ice caps - what effect will that have?
In the test it says how snow and ice reflect the Sun's heat which means that if the ice is melting it'd just be soil so it would absorb the heat and so it'd make the climate hotter, because there wouldn't be so much reflected heat.