Holocene Dust Transport to the Sub-Antarctic – Implications for the mid-latitude westerlies

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Holocene Dust Transport to the Sub-Antarctic – Implications for the mid-latitude westerlies

Abstract
Understanding the past behaviour of the Southern Hemisphere mid-latitude westerlies in the past is important due to their role in determining precipitation regimes on Southern Hemisphere land masses, advecting heat and influencing carbon cycling in the Southern Ocean and the transport of mineral and biological matter between continents. The aim of this study was to determine how the Southern Hemisphere mid-latitude westerly winds varied in their strength and intensity over the mid to late Holocene (~5500 cal yr BP to present). Australian dust transport to ombrotrophic (rainfall-fed) peat bogs on Campbell Island (52°34'S, 169°09'E) and Stewart Island (47°00'S, 168°50'E) was assessed. Ombrotrophic bogs grow above the surrounding hydrology and so are isolated from local contributions of sediment (fluvial or colluvial). Subsequently, the majority of mineral matter present in the cores analysed in this study was transported from the Australian mainland into the bogs by the westerly winds. Rates of dust deposition were determined by loss-on ignition analysis and the provenance of dust was determined using a mass balance approach which compared the chemistry of samples in the core to a range of over 250 potential source sediments. Rates of dust deposition and the provenance of dust were used to determine palaeo-aridity patterns on the Australian mainland, which were then used to infer the likely latitudinal position of westerly winds at particular points in time. Patterns of changing grain size were used to determine the changing intensity of the westerly winds. From ~5500-4000 cal yr BP, the results of this study indicate a southward displacement and weak nature of the westerlies. From ~4000-1700 cal yr BP, results indicate a northward displacement and strengthening of the westerlies. The westerlies remained in their northerly location after ~1700 cal yr BP, whilst wind intensity fluctuated. Results suggest that overall, the westerly winds have moved northward and increased in intensity since ~5500 cal yr BP.

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Sam Marx

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Holocene Dust Transport to the Sub-Antarctic – Implications for the mid-latitude westerlies

A thesis submitted in (partial) fulfilment of the requirements for the award of the degree of

INTERNATIONAL BACHELOR OF SCIENCE

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by

Crystal Wood

(School of Earth & Environmental Sciences)
(October, 2013)
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Abstract

Understanding the past behaviour of the Southern Hemisphere mid-latitude westerlies in the past is important due to their role in determining precipitation regimes on Southern Hemisphere land masses, advecting heat and influencing carbon cycling in the Southern Ocean and the transport of mineral and biological matter between continents. The aim of this study was to determine how the Southern Hemisphere mid-latitude westerly winds varied in their strength and intensity over the mid to late Holocene (~5500 cal yr BP to present). Australian dust transport to ombrotrophic (rainfall-fed) peat bogs on Campbell Island (52°34’S, 169°09’E) and Stewart Island (47°00’S, 168°50’E) was assessed. Ombrotrophic bogs grow above the surrounding hydrology and so are isolated from local contributions of sediment (fluvial or colluvial). Subsequently, the majority of mineral matter present in the cores analysed in this study was transported from the Australian mainland into the bogs by the westerly winds. Rates of dust deposition were determined by loss-on ignition analysis and the provenance of dust was determined using a mass balance approach which compared the chemistry of samples in the core to a range of over 250 potential source sediments. Rates of dust deposition and the provenance of dust were used to determine palaeo-aridity patterns on the Australian mainland, which were then used to infer the likely latitudinal position of westerly winds at particular points in time. Patterns of changing grain size were used to determine the changing intensity of the westerly winds. From ~5500-4000 cal yr BP, the results of this study indicate a southward displacement and weak nature of the westerlies. From ~4000-1700 cal yr BP, results indicate a northward displacement and strengthening of the westerlies. The westerlies remained in their northerly location after ~1700 cal yr BP, whilst wind intensity fluctuated. Results suggest that overall, the westerly winds have moved northward and increased in intensity since ~5500 cal yr BP.
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LIST OF ABBREVIATIONS

ENSO   El Niño Southern Oscillation
SAM    Southern Annular Mode
ITCZ   Inter-tropical Convergence Zone
ANSTO  Australian Nuclear Science and Technology Organisation
AMS    Accelerator Mass Spectrometry
ANTARES Australian National Tandem Research Accelerator
ICP-MS Inductively Coupled Mass Spectrometry
REE    Rare Earth Element
LREE   Light Rare Earth Element
HREE   Heavy Rare Earth Element
PSS    Potential Source Sediment
MUQ    Mud from Queensland
MDB    Murray-Darling Basin
1. INTRODUCTION

1.1 Introduction

In the mid-latitudes of the Northern and Southern Hemisphere, pole-equator temperature and pressure gradients result in distinct regions of westerly circulating air. In the Southern Hemisphere the westerly winds are located between ~30°S and ~60°S, with their modern core centred at ~50°S (Lamy et al. 2010; Fletcher & Moreno 2011). The latitudinal position and strength of these winds vary on seasonal (Hodgson & Sime 2010; Lamy et al. 2010; Varma et al. 2012), decadal to interannual (Knudson et al. 2011) and millennial to multimillennial timescales (Shulmeister et al. 2004; Lamy et al. 2010; Knudson et al. 2011; Varma et al. 2011). Changes in the position and intensity of the westerlies over the mid to late Holocene, at the latter timescale, are the focus of this study.

Variations in the strength and position of the westerly winds play a key role in determining climate dynamics and precipitation regimes on Southern Hemisphere landmasses between ~30°S and ~70°S, including drought prone regions in the mid-latitudes of Australia, New Zealand, South America and South Africa (Thresher 2002; Shulmeister et al. 2004; Fletcher & Moreno 2011; Saunders et al. 2012). A detailed knowledge of the past behaviour of the westerlies and their influence on palaeo-climate is necessary for predictions of future climate change (Saunders et al. 2012). The westerlies are also responsible for wind-driven upwelling of carbon-rich deep water in the Southern Ocean and play an important role in influencing global ocean circulation (Toggweiler & Samuels 1995; Sijp & England 2009) and carbon cycling (Moy et al. 2008; Hodgson & Sime 2010; Sigman et al. 2010). In addition, the transport of mineral and biological matter across Southern Hemisphere land masses by the westerly winds means their behaviour affects global radiation budgets (McTainsh 1989), atmospheric chemistry, bio-geochemical cycles (Arimoto 2001; Harrison et al. 2001; Ravi et al. 2011) and processes such as soil development (Alloway et al. 1992; Marx et al. 2009b).

Despite their importance, there are significant gaps in our understanding of past changes in the position and strength of the westerly winds, particularly through the mid to late Holocene. Whilst it is widely accepted that these winds varied in strength
and intensity (Mayr et al. 2007; Marx et al. 2009b; McGlone et al. 2010; Fletcher & Moreno 2011; Marx et al. 2011), and that these variations are closely linked to Holocene climate changes (Fletcher & Moreno 2011), a consensus on the exact nature and timing of these variations has not been reached.

For the mid-Holocene (7000-5000 cal yr BP), there are arguments for a northward migration and/or strengthening of the westerlies across southern South America (Moreno 2004), Australia (Shulmeister 1999b) and Africa (Holmgren et al. 2003); and for a southward migration and/or weakening of the westerlies in Australia (Moros et al. 2009). This is despite claims by Fletcher and Moreno (2011; 2012) that the westerly winds changed in a zonally symmetric manner at multi-millennial time scales until 5000 cal yr BP.

Fletcher and Moreno (2011; 2012) suggest that since 5000 cal yr BP, the westerlies have changed in a regionally asymmetric manner due to variability introduced with the onset of modern El Niño Southern Oscillation (ENSO) conditions. For the late Holocene (5000 cal yr BP – present), there are reports of both an equatorward (Lamy et al. 2001) and poleward migration of the westerlies (Varma et al. 2012). Low resolution palaeoclimate records from Australia, New Zealand and South America suggest an overall strengthening of the westerlies since 5000 cal yr BP (Bowler 1976; Shulmeister 1999a; Shulmeister et al. 2004), whilst other records from South America point to their weakening (Lamy et al. 2010). Higher resolution records from Australia and New Zealand have identified up to five changes in westerly wind strength/persistence and position over the mid to late Holocene (Marx et al. 2009b; Marx et al. 2011). Rather than asymmetric variation with the onset of ENSO, the inconsistency in these findings (along with inconsistency in reports for the mid-Holocene) has been attributed to shortcomings in the various methods used to reconstruct the westerlies (Lamy et al. 2010).

Approaches to reconstructing Holocene changes in the mid-latitude westerlies include global climate models (eg. Varma et al. 2012) and the use of several proxies for palaeo-precipitation regimes. Changing palaeo-precipitation patterns are used to infer changes in the position and/or strength of the westerly winds. Common proxies used include glacial behaviour (eg. Fletcher & Moreno 2011), pollen, (eg. Lamy et al. 2010), charcoal (eg. Mayr et al. 2007) and dust records (eg. Marx et al. 2009b).
Reasons for the lack of consensus between the results of different studies include the complex, indirect and diverse nature of these proxies, inadequate dating methods, discontinuous or short records and the interpretation of these records by different authors (Lamy et al. 2010; Moy et al. 2011; Fletcher & Moreno 2012). Additionally, these approaches have been unable to distinguish between changes in wind speed and intensity and many have been unable to distinguish between changes in wind speed and persistence. Furthermore, many are based on palaeoclimate records obtained from regions north of the modern core of the westerlies and so are reflective of boundary, rather than mean changes in the position and intensity of the wind.

In this study, the Australian contribution of mineral matter to a peat bog on Stewart Island (47°00’S, 168°50’E) and a peat bog on Campbell Island (52°34’S, 169°09’E) was used to assess relative changes in the position and intensity of the westerlies over the last 5500 years (mid to late Holocene). Campbell and Stewart Island are ideally situated to the southeast of Australia in the path of the westerly winds and close to their modern core which lies at ~50°S (D’Arrigo et al. 1995; McGlone et al. 2007). There is an absence of significant dust sources on the islands as many of the surfaces are covered in peats (Campbell 1981; McGlone & Wilson 1996) and they do not receive significant dust from mainland New Zealand. Additionally, the peat bogs from which the sediment cores for this study were extracted are ombrotrophic (rainfall fed). Ombrotrophic peats make excellent dust traps as they grow above the surrounding hydrology (Le Roux et al. 2004; Marx et al. 2008a; Marx et al. 2011; Le Roux et al. 2012) and their convexity means they are cut off from fluvial and groundwater sediment sources (Shotyk 1988). As a result, sources of dust to the study sites are likely to be the result of the westerly winds transporting dust from the Australian mainland, as evidenced by the transport of Australian dust to New Zealand’s South Island (Marx et al. 2009b).

Rates of dust deposition throughout time were determined by combusting samples from each core in a high temperature oven at 450°C. The difference in mass before and after combustion represents the amount of matter lost on ignition. Several studies have established loss on ignition as a simple and reliable method of determining the organic content of peat samples (Dean 1974; Konen et al. 2002; Salehi et al. 2011) and therefore enabling rates of mineral matter deposition to be
calculated. High rates of mineral matter deposition are associated with greater wind transport capacity (i.e. more persistent or stronger winds) or greater sediment availability (or a combination of the two) (Leslie & Speer 2006).

This study applies the trace element model developed by Marx et al. (2005c) to determine the likely provenance of this mineral matter deposited in the peat bogs. Australian dust is able to be distinguished from local New Zealand material based on its concentration of a number of a set trace elements known to be stable during entrainment, transport, deposition and post deposition (these include a number of Rare Earth Elements, and alkaline and earth alkaline elements) (Marx et al. 2005c). The source area of dust on the Australian mainland can be determined as individual river catchments tend to have uniform and distinguishable trace element patterns (fingerprints) that reflect the lithologies being eroded in their headwaters (Kamber et al. 2005). Based on established characteristics of the Australian dust transport system, the source areas of the dust were used to infer precipitation patterns and climate variability on the Australian mainland. Palaeo-precipitation patterns are used to infer the likely latitudinal position of the westerlies through the mid to late Holocene.

The size distribution of the retained mineral component of the cores was measured using a Malvern Mastersizer 2000, with particular attention paid to the frequency of particles in the long-range dust size range (5-25 µm). Dust size is a suitable proxy for westerly wind strength as the size of depositional dust is directly related to wind strength (Rea 1994; Derbyshire et al. 1997; Clemens 1998; Hesse & McTainsh 1999). Grain size is also a useful tool for distinguishing between changes in wind speed and persistence (Shulmeister et al. 2004). Grain size results were used to differentiate between changes in wind speed and intensity throughout the Holocene.

A robust age chronology (based on a total of 25 ¹⁴C dates) was developed for the sediment cores used in this study in an attempt to better constrain the timing of variations in wind position and intensity.
1.2 Objectives

The primary aim of this study is to determine how the latitudinal position and intensity of the Southern Hemisphere mid-latitude westerly winds varied during the mid to late Holocene (particularly since 5500 cal yr BP). Key objectives of this study include to:

1) Assess whether sites used in this study (Stewart Island and Campbell Island) yield useful palaeoclimate proxy data for the purpose of reconstructing past westerly wind regimes.
2) Quantify dust deposition rates at the study sites during the mid to late Holocene.
3) Determine the Australian contribution of dust to the study sites.
4) Determine the likely provenance of dust deposited at the study sites during the mid to late Holocene and to link changes in dust provenance to changes in the latitudinal position of the westerlies.
5) Assess changes in the grain size of the long-range dust size range (5-25um) during the mid to late Holocene and link these changes to varying wind strengths.
6) Integrate the results of this study with existing palaeoclimate records on the operation of the westerlies.

1.3 Thesis Scope and Structure

This study is primarily concerned with the Australian contribution of dust to Campbell Island and Stewart Islands as a means of measuring long-range dust transport. Whilst southern Africa is a potential (although unlikely) source of dust arriving at these islands, the long-range transport of South African dust is not considered in detail in this study.

The westerly winds are known to vary on multimillennial to seasonal timescales and many reconstructions of their behaviour date back to the late Pleistocene (eg. Fletcher & Moreno 2012). This study, however, focuses on multimillennial scale changes in the behaviour of the westerly winds throughout the mid to late Holocene (in particular, since 5500 cal yr BP). Only the relevant sections of the peat cores were analysed – the entirety of the Stewart Island and the top 260 cm of the Campbell Island core fell within the timeframe of this study.
The following chapter (Chapter two) provides a review of the relevant literature and establishes the context and significance of this study. Chapter three outlines the study sites from which the cores were extracted and the methods used to extract, process and analyse these cores. Chapter four summarises the results of this study. The relevance, validity and implications of these results within the context of the wider literature are discussed in Chapter five. Limitations of this study are also outlined in this chapter. Lastly, the conclusions of this study are presented in Chapter six.
2. LITERATURE REVIEW

2.1 Introduction

This chapter establishes the context and significance of this study with regard to the relevant literature. An evaluation of current knowledge about the behaviour of the Southern Hemisphere westerly winds throughout the Holocene and the methods used to obtain this knowledge is presented. Finally, due to its significance for the methods this study uses, the Australian dust transport system is reviewed.

Broad regions of westerly circulating air occur in the mid-latitudes of the Northern and Southern Hemisphere and are known as the mid-latitude westerlies. These winds are driven by pole-equator temperature and pressure gradients and are one of the three major global zonal circulations, alongside the trade winds and polar easterlies. In the southern hemisphere, the westerly zonal circulation prevails between ~30°S and ~60°S, with the modern core centred at approximately 50°S (Lamy et al. 2010; Fletcher & Moreno 2011). The southern hemisphere mid latitude westerlies are well developed due to strong temperature gradients between Antarctica and the Southern Ocean and the long wind run due to lack of landmasses between 40°S and 60°S (Shulmeister et al. 2004). They are the strongest time-averaged oceanic winds in the world (Hodgson & Sime 2010).

It is well established that the westerly winds migrate and change in intensity on a seasonal basis due to changes in sea surface temperatures (Hodgson & Sime 2010; Lamy et al. 2010; Varma et al. 2012). The present day location and speed of the westerly winds during the Austral summer (December-January-February) and winter (June-July-August) are shown in Figure 2.1. During the Austral summer the northern margin of the westerlies contracts toward the South Pole and the winds strengthen (Lamy et al. 2010; Varma et al. 2012). During the Austral winter the northern margin moves northward and the winds expand toward the equator and weaken (Lamy et al. 2010; Varma et al. 2012).
In addition to seasonal changes, the strength and position of the westerly winds vary over decadal to interannual to timescales, with variability controlled by coupled ocean-atmosphere phenomena such as the Southern Annular Mode (SAM) and El Nino-Southern Oscillation (ENSO) (Knudson et al. 2011). These phenomena adjust the position of atmospheric pressure systems that determine westerly airflow in the Southern Hemisphere (Karoly 1989; Hall & Visbeck 2002).

The westerly winds also vary over millennial to multimillennial time scales (e.g. Shulmeister et al. 2004; Lamy et al. 2010; Knudson et al. 2011; Varma et al. 2011). These long term variations in the strength and intensity of the westerly winds are thought to be caused by the effect of orbital cycles (Dodson 1998; Shulmeister 1999b), changes in seasonal insolation (Lamy et al. 2001; Lamy et al. 2010; Varma et al. 2012) and solar activity (Haigh 1996; Gray et al. 2010; McGowan et al. 2010; Varma et al. 2011) on climate and sea surface temperatures. Unlike the short term variations, there is very little consensus in the literature regarding the long term changes in the behaviour of these winds (Fletcher & Moreno 2012). This study focuses on long term changes in the latitudinal position and strength and persistence.
of the Southern Hemisphere mid latitude westerly winds throughout the mid to late Holocene.

2.2 Significance of the Southern Hemisphere westerly winds and understanding their behaviour.

The Southern Hemisphere mid-latitude westerly winds are a significant feature of the global climate system (Toggweiler & Russell 2008; Anderson et al. 2009). Changes in the strength and position of the mid latitude westerlies dominate climate dynamics and influence the precipitation regimes of Southern Hemisphere landmasses between ~30°S and 70°S, including the mid–latitude regions of Australia, New Zealand, South America and South Africa (eg. Thresher 2002; Shulmeister et al. 2004; Fletcher & Moreno 2011). The westerlies are the main means of advecting moisture into Southern Australia and changes in their nature are a major driver of wet and dry cycles over decadal to millennial scales (McGowan et al. 2010; Marx et al. 2011). Several studies have also noted the importance of these winds in controlling precipitation patterns along the southern Andes in South America in the Holocene and under current conditions (e.g. Lamy et al. 2001; Gilli et al. 2005). Due to the close link between the nature of the westerlies and precipitation (in both the past and present) an understanding of past changes in the westerly winds is important (Gilli et al. 2005). Accurate projections of future climate change (which are particularly important in regions susceptible to drought) are dependent on a detailed understanding of past climate changes and the processes driving them (McGowan et al. 2010; Saunders et al. 2012).

Through wind-driven upwelling of deep water in the Southern Ocean, the mid-latitude westerly winds play an important role in influencing global ocean circulation (Toggweiler & Samuels 1995; Sijp & England 2009). The upwelling of carbon-rich deep water, coupled with ocean biogeochemistry influences the exchange of CO₂ between the ocean and the atmosphere (Hodgson & Sime 2010; Sigman et al. 2010). Understanding changes in the position and intensity of these winds is significant due to their influence on whether the Southern Ocean acts as a net source or sink of atmospheric CO₂ (Le Quéré et al. 2007; Hodgson & Sime 2010). The recently observed intensification of these winds for example, is linked to the reduced effectiveness of the Southern Ocean as a CO₂ sink (Le Quéré et al. 2007).
In addition, the alignment of the westerlies with the Antarctic Circumpolar Current determines the amount of ocean meridional overturning circulation and plays a key role in determining whether the Earth is in glacial or interglacial conditions (Toggweiler & Russell 2008). The influence of the westerly winds on the global carbon cycle through deep water upwelling and their response to increased global atmospheric temperatures make the behaviour of the westerly winds a key variable in climate predictions (Knudson et al. 2011).

An understanding of past changes in the westerly winds is also significant due to the role they play in transporting mineral dust and biological matter across Southern Hemisphere landmasses (Marx et al. 2009b). For instance, the westerly winds have resulted in dust from the Australian mainland being transported toward New Zealand throughout the Quaternary to the present (Marx et al. 2005b), with several studies suggesting Australian dust deposition makes a significant chemical contribution to soils in New Zealand soil with potential implications for processes such as soil development (Alloway et al. 1992; Marx et al. 2009b). Atmospheric dust transport also plays an important role in affecting radiation budgets (McTainsh 1989), atmospheric chemistry and bio-geochemical cycles (Arimoto 2001; Harrison et al. 2001; Ravi et al. 2011).

Despite their importance, there are still notable gaps in our knowledge of past changes in the strength and position of the westerly winds. There are significant discrepancies in the dates and nature of changes in wind intensity/position reported in different studies (Fletcher & Moreno 2012; Kilian & Lamy 2012). Despite generalised reports of changes in their intensity and position, it is currently not known whether it is changes in the position or intensity of the westerlies that are driving the environment’s response (Marx et al. 2011).

2.3 Current knowledge of the behaviour of the westerlies throughout the Holocene

It is well established that these winds have varied in intensity and position throughout the Holocene (e.g. Mayr et al. 2007; Marx et al. 2009b; McGlone et al. 2010; Fletcher & Moreno 2011; Marx et al. 2011) and that variations are closely linked to Holocene climate changes (Fletcher & Moreno 2011). However, based on the existing literature it is not possible to draw a consensus as to the nature and timing of changes in
these winds. Previous studies have produced varying and often opposing results which are attributed to complicated relationships between the westerlies and proxies used to measure them, the diverse nature of the different proxies, discontinuous or short archives and inadequate dating methods (Lamy et al. 2010; Moy et al. 2011). The interpretation of palaeoclimate records (used as proxies for wind behaviour) by different authors is an additional reason often cited for the lack of consensus (Fletcher and Moreno, 2012).

For the early Holocene (11 000 – 8000 cal yr BP) there are arguments for a northward migration and/or strengthening of the westerlies in Southern South America (Veit 1996) and Australia (Dodson 1998; Gingele et al. 2007; Moros et al. 2009) and for a southward migration and/or weakening of the westerlies in southwest South America (Moreno & León 2003; Moreno 2004; Villa-Martínez & Moreno 2007), Australia and New Zealand (Shulmeister 1999b) and Africa (Holmgren et al. 2003).

For the mid-Holocene (7000 – 5000 cal yr BP) it has been argued that the westerlies migrated northward and/or that they strengthened across southern South America (Moreno 2004), Australia (Shulmeister 1999b) and Africa (Holmgren et al. 2003); and that they migrated southward and/or weakened in Australia (Moros et al. 2009).

Despite the varying nature of these results, in their hemisphere-wide synthesis of palaeoclimate data, Fletcher and Moreno (2011; 2012) provided evidence to suggest that the winds have changed in a zonally symmetric manner at multimillennial scales between 14000 and 5000 cal yr BP. They propose the winds have changed in a regionally asymmetric manner since 5ka cal yr BP due to the variability introduced with the onset of modern El Nino Southern Oscillation conditions (Fletcher & Moreno 2012). This has resulted in further variability in results between regions.

For the mid to late Holocene (5000 cal yr BP - present), there are similarly contradicting arguments for both an equatorward displacement of the westerlies (Lamy et al. 2001) and a Poleward displacement of the westerlies (Varma et al. 2012). Low resolution records from Australia and New Zealand have suggested an overall strengthening of the westerlies since 5000 cal yr BP (Bowler 1976; Shulmeister 1999b; Shulmeister et al. 2004) which agree with Markgraf’s (1993) findings of increased westerly wind strength in South America during this time period. Alternatively, the findings of Lamy et al. (2010) point toward a weakening of
the westerlies over this time. Although this could represent asymmetric variation in the winds with the onset of modern ENSO conditions (Fletcher & Moreno 2012), the inconsistency in these findings has been attributed to the limited number of palaeoclimate records past reconstructions have been based on and the fact interest in reconstructing westerly wind intensity is fairly recent (Lamy et al. 2010). Modern records show that the westerly winds have contracted Poleward and intensified since the 1970s (Tanaka & Chiba 2006).

Higher resolution records from Australia and New Zealand have identified between three (Marx et al. 2009b) and five (Marx et al. 2011) major shifts in the persistence, strength and position of the westerly winds over the mid to late Holocene (approximately the last 8000 years).

2.4 Approaches to reconstructing palaeo-mid-latitude westerlies

Global climate models have been used to simulate the behaviour of the westerly winds under changing levels of insolation throughout the Holocene (Varma et al. 2011; Varma et al. 2012). The models showed an overall strengthening and Poleward shifting of the westerlies under the influence of orbital forcing over the mid to late Holocene, with the exception of an equatorward shift during the Austral spring season (Varma et al. 2012). Centennial-scale periods of low solar activity caused equatorward shifts in the winds and periods of high solar activity were associated with poleward shifts in the winds (Varma et al. 2011). The output of different models have produced results generally in agreement with each other (Varma et al. 2012). However, this is likely attributable to the fact that insolation only was used as a forcing factor in these experiments. Consequently, their results must be treated with caution (Fletcher & Moreno 2011).

Due to the close link between the westerly winds and precipitation, most inferences on past changes in the westerly wind belt are based on palaeoclimate data which allow the reconstruction of past precipitation regimes. Common proxies for past moisture regimes used in previous studies include glacial advances, pollen and charcoal records and dust records.

Winter snow accumulation and precipitation is closely related to atmospheric circulation in temperate humid mountain ranges. Glacial advances (determined by
the dating of moraines) in New Zealand and South America have been linked to a northward migration and/or strengthening of the westerly winds, whilst glacial retreats have been linked to a southward migration and/or weakening of the westerly winds (Fitzharris et al. 1992; Shulmeister et al. 2004; Fitzharris et al. 2007; Fletcher & Moreno 2011). Whilst generalised changes are able to be pinpointed, the use of this proxy means data is limited to glaciated source areas and variations in wind speed are unable to be differentiated from wind intensity. Glacial proxies are also only able to measure change over a limited period of time as subsequent glacial advances overrides existing moraines meaning only the most recent advance or retreat in glacier accumulation can be measured (Shulmeister et al. 2004).

Several studies have used pollen records to infer changing vegetation patterns, and in turn, changing precipitation regimes over the Holocene (Rea 1994; Mayr et al. 2007; Lamy et al. 2010; Fletcher & Moreno 2011). Variations in precipitation regimes determined from the pollen records in these studies were attributed to variations in the strength and/or position of the westerly winds. For example, poleward migration of the westerlies results in weaker westerly flow over landmasses north of the modern core (~50°S), which decreases precipitation in western regions whilst allowing the incursion of easterly sourced precipitation from the east and thus increases precipitation in eastern regions. Equatorward migration of the westerlies results in stronger westerly flow over landmasses north of the modern core and the opposite effect to that described above is observed (Garreaud 2007; Hendon et al. 2007). (Fletcher & Moreno 2011) used this simple relationship to decipher past changes in the westerly winds based on data they obtained from existing pollen records.

Limitations of pollen studies stem from the fact pollen is an indirect proxy of wind strength/intensity – vegetation change records an indirect effect (i.e., rainfall patterns) of variations in wind strength/intensity (Shulmeister et al. 2004). Studies which have used charcoal records to establish past fire and precipitation regimes (Rea 1994; Fletcher & Moreno 2012) are similarly limited. In addition, palaeoclimate data derived from pollen and charcoal analysis is unable to be used to differentiate between wind strength and wind intensity (Rea 1994; Fletcher & Moreno 2011). The majority of these studies are based on palaeoclimate data that monitor the influence of the winds in areas north of their modern core (~50°S) (eg. Lamy et al. 2001) and
are unable to distinguish between changes in position and changes in wind speed/intensity (Fletcher & Moreno 2011). Many of the pollen-based palaeo-climate reconstructions that monitor changes in the westerly winds close to 50°S are based in South American countries in the South East Pacific such as Chile (Lamy et al. 2001; Villa-Martínez & Moreno 2007; Moy et al. 2008; Lamy et al. 2010) and Argentina (Markgraf et al. 2003; Gilli et al. 2005; Mayr et al. 2007). In addition, many of these studies describe the changing persistence of these winds rather than changes in their intensity/strength.

Dust records (from the deposition of fine-grained mineral particles transported by the wind) are another proxy that have been used to reconstruct changes in the Southern Hemisphere mid-latitude westerly winds throughout the Holocene (Marx et al. 2009b; Marx et al. 2011). In contrast to the other proxies, dust deposition records are a means of measuring both wind strength and position (Marx et al. 2011). Recent studies have used dust deposition in alpine peat bogs in the Snowy Mountains (Marx et al. 2011) and the South Island of New Zealand (Marx et al. 2009b). These studies used dust deposition rates and dust provenance results to infer patterns of aridity and climate variability in eastern Australia throughout the Holocene (Marx et al. 2009b; Marx et al. 2011). These results were used to reconstruct westerly wind regimes affecting the Australian mainland over this time. In addition to determining the provenance of dust, Marx et al. (2009b) measured the grain size of long-range travelled dusts to infer changes in wind intensity. However the study site (The Old Man Range, Central Otago, New Zealand) was located north of the modern core of the westerlies and hence results from this study are indicative of boundary conditions in the westerlies. Conclusive results on intensity versus position changes in the westerlies have therefore yet not been determined.

2.5 The Australian Dust Transport System

Because this study uses dust to reconstruct westerly circulation during the mid to late Holocene and Australia is the proximal major dust source to both the study sites (Campbell Island and Stewart Island) it is necessary to review the Australian dust transport system.

Australia is the driest continent on Earth (excluding Antarctica), with arid areas comprising approximately 40% of the landscape (Revel-Rolland et al. 2006). Dust
storms (defined as having a visibility <1000 m) are a common feature over much of arid central eastern Australia, with as many as 5 to 10 events year in some areas (McTainsh & Pitblado 1987). Consequently, Australia is argued to be the largest source of aeolian dust in the Southern Hemisphere (McGowan et al. 2005b; Tanaka & Chiba 2006) In addition to large visible dust storms, lower concentrations of dust are entrained near-constantly from dust source areas, a portion of which is exported from the Australian continent (Marx et al. 2005a). It is this long-range transport of dust which is the focus of this study. Long-range dust transport typically occurs associated with the passage of a cold frontal system across central and southern Australia (Sprigg 1982).

There are two main dust plume pathways out of Australia – the southeast and northwest dust transport corridors (Bowler 1976). The latter results in dust transport from central Australia over the Kimberly region of north western Western Australia and into Indian Ocean. The southeast dust transport corridor, which is the focus of this study, results in dust transport out of eastern Australia and into the Tasman Sea and Southern Ocean and potentially over the study sites on Stewart and Campbell Islands. It should be noted, however, that a number of other potential trajectories can occur (see McGowan & Clark 2008a) These dust transport corridors were first identified based on the pattern of longitudinal quartz dunes across the continent (Bowler 1976) and are shown in Figure 2.2, but have since been examined in greater detail from monitoring (Collyer et al. 1984; Arimoto et al. 1990; Marx et al. 2008b; Lavin et al. 2012), geochemical provenance of dust deposits (Marx et al. 2005d; McGowan et al. 2005b; Marx et al. 2009b; McGowan et al. 2012) and modelling (McGowan et al. 2000; McGowan & Clark 2008b) studies, in addition to observations (McTainsh & Pitblado 1987; Marx & McGowan 2005b). The latitudinal zone of dust transport in the southeast dust transport corridor extends from Townsville in North Queensland (19°04’S) to Macquarie Island in the Southern Ocean (54°30’S) (Hesse & McTainsh 2003). At latitudes 52°34’S and 47°00’S, Campbell Island and Stewart Island are positioned within this zone of dust transport. Evidence of the reach of Australian dust in the southeast transport corridor includes records of Australian dust deposition in the Tasman Sea (Hesse 1994), the Southern Alps of New Zealand (McGowan et al. 2005a; Marx et al. 2009b) and in Antarctic ice cores (Revel-Rolland et al. 2006). McGowan and Clark (2008a) created 8-day air mass trajectories
originating from Lake Eyre using available wind data and Hysplit - an air mass trajectory model run by NOAA. Their results showed Campbell and Stewart Island were well within the reach of air masses originating from Lake Eyre within this 8 day period.

There are three main types of dust transporting winds on the Australian continent that are associated with the passage of westerly systems from west to east across the continent - prefrontal northerlies, frontal westerlies and postfrontal south-easterlies (Sprigg 1982). The first type of wind involves hot northerlies which blow out of Central Australia before the passage of a front and the second type involves the westerlies associated with the passing of the front (Sprigg 1982). Both of these dust transporting winds could potentially transport dust to the studies sites. Post-frontal southeasterlies result is dust transport along the northwest corridor. The prevalence and effects of frontal systems are most pronounced in the southern regions of Australia, with the prefrontal northerlies being responsible for significant dust entrainment within the Lower Lake Eyre and Murray-Darling Basins (McTainsh 1989). When dust is lifted high enough by the prefrontal northerlies and frontal westerlies to reach the upper level westerlies, the dust may be transported offshore as it enters the southeast dust path (Figure 2.2).
At time scales relevant to this study, the two major environmental controls on dust entrainment are sediment availability and climatic controls (of which wind speed and direction and moisture are most important) (McTainsh 1989; Leslie & Speer 2006). In Australia, sediment availability appears to be the greatest limitation on dust transportation (Hesse & McTainsh 2003; Marx et al. 2005a; Marx et al. 2009b). Greater aridity does not necessarily equate to greater dust entrainment – although there is an established relationship of increased dust storm frequency with increasing aridity down to an average annual rainfall of 100-200mm, dust storm frequencies decrease in regions with average annual rainfalls less than 100mm (Goudie 1983). This is likely due to a lack of sediment supply to areas of wind erosion from rivers and river floodplains (McTainsh 1989). Consequently, it has been shown by Marx et al., (2005a; 2009a) that dust emissions from Australia are highest during periods of enhanced climate variability, where wet periods, which result in the recharge of dust sources with fine sediment, are followed by dry conditions.
Meteorological records indicate that the most active contemporary dust source areas are the Lake Eyre Basin and the western sector of the Murray-Darling Basin (Hesse & McTainsh 2003). The Lake Eyre Basin is Australia’s largest internal drainage basin spanning an area of 1.3 million km² (Revel-Rolland et al. 2006; Cohen et al. 2011). Ephemeral rivers in the northeast sector of the basin, including the Eyre and Diamantina River and Cooper Creek (Figure 2.3), contribute the largest discharge and sediment load into the lower parts of the basin. These rivers are sourced from the humid subtropics and are fed by sporadic monsoonal summer rains in tropical Queensland and the Northern Territory (Nanson et al. 2008). These rivers discharge toward Lake Eyre, depositing most of the sediment in the Simpson Desert Channel Country (Figure 2.3) in southwest Queensland and northern South Australia (McTainsh 1989). In their study of Australian dust deposition in New Zealand, (Marx et al. 2009b) interpreted periods of low rates of dust deposition as being the result of an active monsoon over the North of the Australian continent. The Inter-tropical Convergence Zone (ITCZ) and the westerlies would have been located further south (Marx et al. 2009b). The monsoon would have resulted in these rivers delivering substantial discharge and sediment loads into the lower parts of the basin and filling up Lake Eyre (meaning there was little opportunity for dust transport out of Australia). Periods of higher dust deposition were interpreted as representing a variable climate (where wet periods delivered sediment to the basin and dry periods allowed this sediment to be entrained) and Lake Eyre becoming ephemeral and subsequently becoming an active dust source (Marx et al. 2009b).

The Murray-Darling river system arises in the humid regions of the Main Dividing Range along the east coast and drains internally as it flows westwards through the semi-arid regions of New South Wales and South Australia before it reaches the sea (Figure 2.3) (McTainsh 1989). Much of the sediment load of the river system is deposited in the semi-arid regions through which it flows and there is minimal sediment load in the river when it reaches the sea (McTainsh 1989). The Murray River is fed by winter precipitation in the Snowy Mountains whilst the Darling River is fed by summer rainfall in southeast Queensland and northern New South Wales (McTainsh 1989). Unlike the rivers that drain into Lake Eyre, the Murray and Darling Rivers are perennial as they are fed by relatively high rainfall regions (McTainsh 1989). Periods of low dust transportation from the Murray-Darling Basin are linked to
enhanced westerly winds which advect moisture into south-eastern Australia and result in wet conditions (Marx et al. 2011). Period of greater dust transportation from the Murray-Darling Basin are linked to weakening of the westerly winds resulting in a more arid phase, likely with greater climate variability (Marx et al. 2011).

Figure 2.3 Map of eastern and central Australia showing the Lake Eyre and Murray-Darling drainage basins. Modified after Revel-Rolland et al. (2006).

Although similarly arid to the Lake Eyre and Murray-Darling drainage basins, the Western Australian deserts are not a major source of long-range aeolian dust (Prospero et al. 2002) as they are devoid of a substantial source of fine sediment.
2.6 Other potential sources of dust to study sites

Alongside Australia there are two other landmasses they may contribute dust to the study sites. These are New Zealand and southern Africa. In New Zealand’s South Island, dust transport is evidenced by substantial loess deposits than mantle the landscape downwind of the large braided river systems that drain the Southern Alps (Bruce 1973; Berger et al. 2002; Soons et al. 2002). Loess is more prevalent and thicker on the drier eastern side of the Southern Alps, but even on the super humid western side of the Southern Alps loess also occurs (Almond 1996). Although most loess dates from the Pleistocene, contemporary loess formation and dust transport (including dust storms) occur on both sides of the Southern Alps (Cox et al. 1973; McGowan et al. 1996; Marx & McGowan 2005a). Commonly, however, dust entrainment in South Island occurs during the passage of disturbed southerly and southwesterly flow and during föhn winds on both the east coast and, less commonly, the west coast (McGowan 1997; Marx & McGowan 2005a).

Mass trajectory modelling by Sturman et al. (1997) has shown the potential for dust transport from southern Africa to New Zealand. Forward and backward trajectories originating or ending up in the 850-800 hPa layer respectively were used to determine the westerly transport of air from the central interior of South Africa to New Zealand (Sturman et al. 1997). The mean transport plumes derived from these individual trajectories show that in winter (when the circumpolar vortex of the westerlies reaches its maximum equatorward extent) approximately 22% of air originating over Johannesburg reaches the central Tasman Sea south of New Zealand (Sturman et al. 1997). In summer this amount is negligible due to seasonal changes in the position of major circulation features such as the westerlies (Sturman et al. 1997). Whist these models demonstrate the possibility of inter-regional air transfer between southern Africa and New Zealand in the summer months, Sturman et al (2007) note that the large-scale transport of aerosols or trace gases between the two locations is unlikely. This can be attributed to the vast distance between South Africa and New Zealand. Consequently, South Africa is unlikely to be a significant source of dust to the study sites.
3. METHODS

3.1 Introduction

This chapter outlines the methods used to obtain and analyse the data for this study. It begins with a description of the two sites from which the peat cores in this study were extracted from. This is followed by an outline of how these cores were collected and sub-sampled and then a description of the various sediment analyses that were undertaken – moisture content, $^{14}$C dating, $^{210}$Pb dating, loss on ignition analysis, trace element concentration and grain size analyses. All methods described in this chapter were completed by the author with the exception of core collection, $^{210}$Pb dating and the final stages of the $^{14}$C dating process and the trace element concentration analysis which were completed by Sam Marx and Matt McGlone, Australian Nuclear Science and Technology Organisation (ANSTO) staff and staff at Trinity College’s Geochemical Fingerprinting Laboratory respectively.

3.2 Site Description

Dust records used in this study were obtained from peat cores extracted from Campbell Island (52°34’S, 169°09’E) and Stewart Island (47°00’S, 168°50’E) (Figure 3.1). These islands are ideally situated to the southeast of Australia in the path of the westerly winds (D'Arrigo et al. 1995; McGlone et al. 2007). The significance of these sites as islands lies in the fact they are remote from local sources of wind-blown sediment from nearby land masses.
3.2.1 Campbell Island

Campbell Island (52°34′S, 169°09′E) is an uninhabited, subantarctic island located in the cool, stormy waters of the Southern Ocean approximately 600km south of the New Zealand mainland (Figure 3.1). Campbell Island’s location is significant in that it lies close to the modern core of the westerly winds (~50°S). These westerly winds are strong and persistent on Campbell Island, with 70% of days having surface winds >7.5 m s\(^{-1}\) (McGlone et al. 2007). The dominance of the westerly winds on the island is shown in the wind rose (Figure 3.2) and wind speed/distribution graph (Figure 3.3) below.
Figure 3.2 Campbell Island Wind Rose constructed using WRPlot View™ 7.0 Software (Lakes Environmental 2011) based on climate data obtained from NIWA (2013).

Figure 3.3 Distribution of wind speeds and directions on Campbell Island. Wind speed/direction data obtained from NIWA (2013).
In addition to being windy, the climate is stormy, moist, cool, cloudy and highly oceanic (McGlone et al. 2007). The mean annual temperature is 7°C and there is little seasonal variation in temperature with average temperatures ranging from 4.9°C in July to 9.5°C in January (NIWA 2013). The average annual rainfall is approximately 1400mm, with a very high number of rain days, >250 wet days (>1mm/day) annually (NIWA 2013). The average relative humidity at 9am is 83% (NIWA 2013).

Campbell Island is the eroded eastern segment of a Pliocene volcanic complex spanning an area of 113km² (Campbell 1981). It lies on the margin of the Campbell Plateau – an area of continental crust 17-23 km thick (Adams 1962) extending south from the New Zealand mainland (Morris 1984). The surface geology of two thirds of the island consists of basaltic flows and volcanic intrusions, whilst schists, sedimentary conglomerates, mudstones, limestones, tuffs and breccias compose the remaining third (McGlone et al. 2007). The island was extensively glaciated at the height of the Last Glacial Maximum (McGlone et al. 1997). By 15 000 yr BP these glaciers had retreated and peat growth had begun, with the formation of significant peat soils beginning by 12 000 yr BP (McGlone 2002). Campbell Island’s surface is now almost entirely covered with thick (>1m) peats (Campbell 1981). Well humified peat soils (0.5-4m deep; >95% organic) are widespread in areas of moderate to well drained slopes and oligotrophic fibrous peat bogs up to 10m deep form in gently sloping valleys and on broad interfluves where drainage is impeded and fens of poorly consolidated peat occur on drainage runnels and flushes (McGlone et al. 2007). The occurrence of mineral soils is limited to fresh slips, cliffs, steep slopes >30°, outcrops and exposed tops above 400m (Campbell 1981). The terrain is hilly, with tall, steep cliffs cut by marine erosion on exposed coastlines to the west, and sloping ridges and long inlets in the sheltered east (McGlone 2002). The vegetation consists mainly of lowland Dracophyllum scrub from sea level to 200m and upland grassland, macrophyllous forbs and tundra at elevations greater than 200m (McGlone et al. 2007).

Following its discovery in 1810, the island’s resources were exploited. This included sealing, which occurred until about 1920 and a short episode of sheep farming that lasted from 1895 until 1931 (McGlone et al. 2007). These activities led to widespread burning and cutting of scrub (Wilmshurst et al. 2004). The island has been free of fire
since the 1930s (when farming ceased) and ungrazed since the elimination of feral sheep in the 1980s following which vegetation has recovered significantly (Wilmshurst et al. 2004; McGlone et al. 2007). Despite the climate rendering the island largely inhospitable and difficult to access, Campbell Island has attracted many scientific expeditions since the middle of the 19th century and a detailed record of post-glacial climate change exists for the island (McGlone 2002).

The core analysed in this study was collected from a peat bog near the summit of Mt Honey (Figure 3.4), which marks the highest peak on the Island at 570m above mean sea level (McGlone et al. 2007). The height of Mt Honey is significant in ensuring the peat bog receives maximum exposure to the westerly winds as a dust source and is ombrotrophic and not influenced by runoff and fluvial sources of sediment. Mt Honey is importantly located in the centre of the southern part of island, remote from local mineral matter associated with the cliffs and marine erosion in the exposed west. Low scrub and grassland are the dominant vegetation cover at the Mount Honey site (Figure 3.5). The surface peat overlies alkali olivine basalt lithology (Morris 1984).
3.2.2 Stewart Island

At 47°S, 168°E and with an area of only 1735km², Stewart Island (Rakiura) (Figure 3.6) is the southernmost and smallest of the three main islands of the New Zealand archipelago (Wilson 1987). Stewart Island lies less than 35km due south of the South Island across the shallow (<36m deep) Foveaux Strait (Brook 2009). The only township on the island, Oban, lies at the head of Halfmoon Bay on the northeast coast (Figure 3.6). It has a population of approximately 400 permanent residents (Heenan et al. 2009). This township comprises only 2% of the Island’s area (Beaven 2011) and many residents and visitors to the island remain within close proximity to the township for their entire stay (Usher 1953; Beaven 2011; Reis 2012). Since the cessation of a 70 year timber milling period in 1931, the island’s primary industries
have been fishing and tourism, both of which have had little impact on the environment (Wilson 1987). Consequently, Stewart Island remains a largely undisturbed wilderness (Wilson 1987). This is despite modifications by fire, logging and the introduction of browsing animals and predators (such as rats, cats and possums (Harper et al. 2005) occurring during 700 years of Maori and 175 years of European settlement (Wilson 1987).

Figure 3.6 Map of Stewart Island showing basic terrain height information and the location of Table Hill in the Tin Range (modified after Land Information New Zealand (2013a).

Importantly, Stewart Island lies in the direct path of the mid-latitude westerly winds and close to their modern core which lies at approximately 50°S (D’Arrigo et al. 1995). Like Campbell Island, westerly winds are strong and persistent on Stewart Island (NIWA 2013). The average wind speed recorded at the climate station at South West Cape (Figure 3.6) is 16.5m/s and over 82% of days have wind speeds greater than 7.5m/s (NIWA 2013). Wind data for the island is summarised in Figure 3.7 and Figure 3.8. These figures show that westerly quarter winds prevail.
Figure 3.7 Wind rose showing wind strengths and directions recorded at the Southwest Cape Climate Station, Stewart Island. Wind rose constructed using WRPlot View™ 7.0 Software (Lakes Environmental 2011) based on climate data obtained from NIWA (2013).

Figure 3.8 Distribution of wind speeds and directions on Stewart Island. Wind speed/direction data obtained from NIWA (2013).
Like Campbell Island, Stewart Island’s climate is cool temperate, highly oceanic and wet, with an annual rainfall range of 1000-3000mm (Murphy et al. 2012). Rainfall is evenly spread throughout the year with an average of 204 wet days annually (NIWA 2013). Stewart Island’s average annual temperature is 10.2°C. It lacks extremes of temperature and significant seasonal variation. For example, mean monthly temperatures range between 7.6°C in July to 13.1°C in February (NIWA 2013). The average relative humidity at 9am is 84% (NIWA 2013) and there is frequent cloud cover and persistent fog along the summits (Wilson 1987). Snow and significant frosts are rare at sea level whilst snow lies intermittently at high elevations and heavier frosts occur inland (Wilson 1987; McGlone & Wilson 1996).

The geology of the island is largely granite, however a band consisting of crossed of schists, marbles and quartzites occurs through the centre of the Island running west-east (Williams 1936). The island’s soils are typically boggy due to poor drainage and organic rich (Usher 1953). The majority of the island is covered with podocarp hardwood forest, particularly Dacrydium cupressinum, which exists in a complex mosaic with patches of scrub and minimal areas of open ground (McGlone & Wilson 1996). Above 200 m, vegetation consists largely of Dracophyllum scrub, while at high elevations (above 400 m) alpine grassland land and herb fields predominate. Evidence for glaciation during the LGM in the north of the island around the vicinity of Mt Anglem (Figure 9) is generally accepted (Brook 2009). However, unlike the extensive glaciation that occurred on Campbell Island, glaciation on Stewart Island was restricted to niche sites on the lee side of upland areas (Brook 2009). Evidence for glaciation at southern sites such as Mt Allen (Figure 9) is uncertain (Brook 2009). Widespread peat development on Stewart Island had begun by c. 10 000 BP (McGlone & Wilson 1996). Although patchy in the north of the Island, blanket peats are extensive in the south (McGlone & Wilson 1996) where they occur under low forest, scrub and heath vegetation types (McGlone 2002). Areas of basin peat are common, whilst raised peat bogs are very restricted in their extent (McGlone & Wilson 1996). The summit of Mt Anglem (at 980m asl), occurs in the rugged highlands in the northeast and marks the highest point on the island (D’Arrigo et al. 1995). Areas of high elevation also occur in the Tin Range - a 15km long, NNE-SSW oriented mountain range in the southeast of the Island (Brook 2009). These areas of
high relief are separated by a band or low-lying flats which stretch from Paterson’s Inlet to the west coast of the island (Wilson 1987).

The core used in this study was collected from a peat bog on a broad ridge top to the northeast of Table Hill (Figure 3.9) in the Tin Range. The Tin Range runs roughly southwest-northeast through the centre of Stewart Island. The highest points of the range consist of outcropping granite, while extensive peat occurs over broad flat surfaces below Table Hill. Periglacial features, such as gelifluction lobes, occur extensively on the steeper slopes. At 716m, the summit of Table Hill lies slightly below that of Mt Allen (750m) which is the highest peak in the Tin Range (Brook 2009). The position of this site on the ridge top is important in ensuring the mineral material arriving at the site is primarily atmospheric in origin. There is minimal capacity for fluvial or colluvial material to be transported upslope to the top of the ridge top, from where the core was extracted. Vegetation above the tree line at the Tin Range site consists of alpine herbs, sedges and tussocks. In boggy areas, including from where the studied core was collected, moss species prevail.

Figure 3.9 Photo looking to the north east of Table Hill. The arrow marks the position on the ridge top from which the core was taken. (Photo taken by Sam Marx).
3.3 Core Collection and sub-sampling

3.3.1 Campbell Island Core

A 6.5 m core was extracted from a peat bog (-52.576506, 168.137544) near the summit of Mount Honey, Campbell Island (Figure 3.4) using a 5 cm Russian D-section corer by Matt McGlone in 1999. The core was transferred from the corer into a semi-cylindrical plastic pipe. Plastic was tightly wrapped around the pipe to prevent the core drying out or becoming contaminated. The core was transported to, and stored at, Landcare Research, Lincoln, New Zealand, at approximately 4°C.

Sub-sampling of the core took place at the Landcare Research Institute in April 2013. One hundred and thirty eight non-contiguous sub-samples were taken at varying intervals (0.5-10 cm) throughout the length of the core. These sub-samples were 0.5 cm in width and were scooped out from the core using a 0.5 cm wide spatula from locations at which samples had been previously taken for pollen analysis by McGlone et al. (2010). Care was taken to avoid including sediment from the sides or bottom of the core (where the risk of contamination from other sediment sources is higher) within the sub-sample. The sub-samples were transferred into pre-weighed sealed plastic vials for shipment to Australia (where further analysis took place).

3.3.2 Stewart Island Core

A 35.4 cm sediment core was extracted from a peat bog located on a broad ridge top (-47.030262, 167.848955) to the northeast of Table Hill in Central Stewart Island (Figure 9) using a 10 cm Russian D-section corer by Sam Marx in February 2013. The core was transferred from the corer into a semi-cylindrical plastic pipe. Plastic was tightly wrapped around the pipe to prevent the core drying out and becoming contaminated whilst it was transported back to Australia. The core was stored at approximately 4°C at the University of Wollongong until it was sub-sampled.

Fine resolution contiguous sampling of the core took place at the University of Wollongong in May 2013. Thin sections from the edge and top of the core were scraped off prior to collecting samples to help reduce the risk of contamination in the samples. A scalpel was used to slice off sub-samples of the core into segments of
between 2 and 9 mm. The core was frozen before being sampled in order to preserve its stratigraphy. Small sections of the core were sampled at a time. As the core began to thaw out it was rewrapped in plastic and refrozen before further sampling took place. One hundred and one samples were taken in total and were transferred into pre-weighed labelled plastic vials.

3.4 Moisture Content

Each sample was weighed and then dried at 65°C for 48 hours. The samples were reweighed, with the difference in weight being reflective of moisture loss. The difference between the wet and dry weight of the samples was used to determine the moisture content through the cores.

3.5 Accelerator Mass Spectrometry (AMS) Carbon-14 dating

3.5.1 AMS Carbon-14 dating of Campbell Island Core

Nineteen radiocarbon ($^{14}$C) samples throughout the length of the Campbell Island core were dated by AMS radiocarbon ($^{14}$C) dating. The dating of these samples and their calibration is described in detail in (McGlone et al. 2010). As the peat was highly humified, bulk peat matter was dated. The OxCal calibration program (http://c14.arch.ox.ac.uk) was used to generate a sedimentation rate model which incorporated Markov Chain Monte Carlo sampling to produce a distribution of possible age solutions. Posterior probability densities were used to quantify the most likely age distributions, taking into account the deposition model and the actual age measurements made.

3.5.2 AMS Carbon-14 dating of Stewart Island Core

Four samples from the peat core were dated by AMS radiocarbon ($^{14}$C) dating at the Australian Nuclear Science and Technology Organisation’s ANTARES AMS Centre. Concentrated pollen from within the peat cores was dated as it is well established that radiocarbon dating concentrated pollen by AMS for Holocene deposits has the ability to provide more reliable ages than the dating of other sediment constituents such as bulk peat matter (Brown et al. 1989; Vandergoes & Prior 2006; Newnham et al. 2007). The pollen wall is thought to be impenetrable to sources of contaminants by younger carbon such as humic and fulvic acids that percolate downwards through
the peat profile (Newnham et al. 2007). This is particularly relevant in high rainfall environments (such as the high altitude regions of Stewart Island) where leaching of these acids would be more pronounced (Hammond et al. 1991; Vandergoes & Prior 2006).

Chemical pre-treatment of samples consisted of a range of procedures designed to concentrate the pollen and remove residual organic matter and other sediment constituents. Each sediment sample was gently homogenised with a mortar and pestle and then dispersed in an ultrasonic bath. The next step in ANSTO’s standard pretreatment of pollen samples is to sieve the samples through 150 µm mesh, discarding the >150 µm fraction. The <150 µm fraction is then retained and sieved through 5 µm filter cloth, with the sub 5 µm fraction discarded and the >5 µm fraction retained for 14C dating. However, the 150 µm sieve did not allow any sediment to pass through and so each sample was sieved at 300 µm and 5 µm. The 5-300µm fraction of each sample was washed in 10% HCl at 60°C for 30 minutes to remove carbonates and fulvic acids. Next, the samples were placed in 40% HF at room temperature overnight in order to remove silicates. The samples were then placed in 10% NaOH at 60°C for 1 hour and rinsed (this was repeated ten times) until all humic acid was removed. Heavy liquid separation (using a specific gravity of 2.1 g/ml) was carried out to separate inorganic matter from the lighter organic matter and pollen components. The samples were then washed with 2M HCl at room temperature for an hour in order to remove any atmospheric carbon dioxide that was absorbed by the sample during the NaOH washes. As the samples were so small, they were not purified further with sulfuric acid. The samples were then dried in combustion tubes at 60°C. Carbon dioxide was then extracted from the samples and each sample processed to graphite by ANSTO staff as per Hua et al. (2001).

The graphite was pressed into an aluminium cathode for 14C analysis using the Australian National Tandem Research Accelerator (ANTARES) (Lawson et al. 2000; Smith et al. 2010). At the ANTARES AMS centre, the 14C/13C ratio of the sample is compared with that of standard materials such as HOxI and ANU sucrose in order to determine the 14C content of the sample (Hotchkis et al. 1996; Tuniz et al. 2006). The δ14C dates were calibrated using Reimer and Reimer’s (2004) CALIBomb programme and Hua and Barbetti’s (2004) SH.1.14c dataset which is relevant for samples from the Southern Hemisphere.
3.6 Lead-210 dating

The quantity of unsupported $^{210}\text{Pb}$ at depths of 3.7 cm, 6.6 cm and 9 cm in the Stewart Island core was determined at ANSTO using the Pb-210/Cs-137 dating facility. The concentration of unsupported $^{210}\text{Pb}$ in sediment samples declines with age according to the radioactive decay law (Appleby & Oldfield 1983). Consequently, older sediments should contain less $^{210}\text{Pb}$. Assuming there has been a relatively constant net input of unsupported $^{210}\text{Pb}$ to a site (i.e., relatively consistent erosion and sedimentation rates), unsupported $^{210}\text{Pb}$ concentrations are a valid means of determining the relative age of sediment samples (Pennington et al. 1976). The unsupported $^{210}\text{Pb}$ concentrations were therefore used to determine the consistency of age with depth in the upper section of the Stewart Island core.

3.7 Loss on Ignition

After being dried, each sample was combusted to determine the amount of mineral material deposited in the core through time. Approximately 0.35 g of the dried samples from the Stewart Island core and the entirety of each sample from the Campbell Island core (due to the small size of these samples) were placed in pre-weighed, chemically inert, porcelain crucibles. The exact weight of material in each crucible was recorded and the samples were ashed in a high temperature oven at 450°C for approximately 12 hours. During ignition organic matter is oxidised to carbon dioxide and ash (Heiri et al. 2001). This temperature was chosen as it represented a balance between being high enough to promote maximum soil organic matter combustion whilst low enough to limit inorganic carbon combustion and undesirable effects on mineral matter such as driving off structural water from clays (Heiri et al. 2001; Salehi et al. 2011). After cooling in a desiccator, the samples were re-weighed and transferred into plastic vials for storage for further analyses. The difference in weight before and after combustion was used to determine the percentage of matter lost on ignition which has been proven as a reliable measure of the percentage of organic matter present in the sample (Dean 1974; Konen et al. 2002; Salehi et al. 2011). The material remaining after ignition consisted of mineral matter (dust) deposited in the peat. Using the volume of each sample (based on the radius of the d-section corer used to obtain the core), the amount of dust per volume of peat (g/m$^2$) was calculated. Then, using the age range of each sample segment,
the dust deposition rate in each core was calculated and reported in terms of the number of grams per square metre of peat per year (g/m²/year).

3.8 Trace Element Concentration

The trace element concentration of the dust samples was measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the Geochemical Fingerprinting Laboratory, Trinity College, Dublin using the approach of (Eggins et al. 1997) and (Kamber 2009). It has already been demonstrated that this approach is capable of measuring trace element concentrations at typically >1% error for most elements (Marx & Kamber 2010b).

The reproducibility of trace element concentrations in standards run as unknowns alongside the samples analysed in this study was used to confirm the reliability of the trace element results obtained from ICP-MS. The standards digested and analyses in this study were BHVO-2, AGV-2 and SCo-1. In each case the mass of material digested was 10 mg, which is close to the mass of samples from the Campbell Island core (1-10 mg). The reproducibility of the standards therefore provides a suitable measure of the quality of the results of the ICP-MS analysis.

The homogeneity of the samples (and hence the usefulness of analysing such a small sample size) was assessed by comparing a replicate of one of the Stewart Island Samples (TR6B-51). The relative standard deviation between the concentration of trace elements for each replicate was established and elements with the highest relative standard deviations (>12%) were deemed unsuitable to be used in determining dust provenance.

A total of 25 samples – 11 from the Campbell Island core, 11 from the Stewart Island core and 3 samples containing local sources of sediment from Stewart Island were analysed. Due to the small size of the Campbell Island samples (the average mass of mineral matter for each sample was 6.7 mg) between two and four adjacent samples were combined to form each of the 11 specimens submitted for trace element analysis from this core.

The relative trace element concentration of the analysed samples was used to determine the proportion of dust in the samples and the likely provenance of the dust, as per (Marx et al. 2005c), (Marx et al. 2009b) and (Marx & Kamber 2010b).
Different dust producing regions can have unique trace element ‘fingerprints’ which make it possible to provenance Australian dust using this approach (Kamber et al. 2005; Marx & Kamber 2010b). The trace element chemistry of the core was compared to the trace element chemistry of each potential source sediment (PSS). The chemistry of PSSs was located in an existing database of >250 samples collected from the major dust producing regions in Australia, as well as local loess and fluvial samples from New Zealand by Marx et al. (2009b).

The provenance of dust in the core was determined using the mass balance model of Marx et al. (2005c), where the concentrations of the most conservative lithologically controlled trace elements (i.e., La, Be, Ta, Pr, Nb, Nd, Sm, Eu, Gd, Tb, Sc, Dy, Y, Ho, Ti, Co and Ga) in the core were compared to those in every PSS from:

\[
\Sigma_D = \sum_{i=1}^{n} \left| \left( \frac{E_{d(i)} \times En}{\Sigma E_D} - 1 \right) \right|
\]

where \(\Sigma_D\) is the degree of match (0 = a perfect match) between a dust and a particular PSS. In this equation \(En\) is the number of trace elements used and \(E_{d(i)}\) is the concentration difference of a particular trace element in a dust and the PSS. \(E_{d(i)}\) is calculated as:

\[
E_{d(i)} = \frac{(E_{pss(i)} / E_{dust(i)}) + (E_{dust(i)} / E_{pss(i)})}{2}
\]

The subscripts PSS and dust refer to the trace element concentration in the PSS and core dust sample respectively. \(\Sigma E_D\) is the sum all the individual \(E_{d(i)}\) values:

\[
\Sigma E_D = \sum_{i=1}^{n} E_{d(i)}
\]

Based on the strong link between the westerly winds and dust availability and transport from the Australian mainland (see section 2.5), the dust provenance results were used to infer changing weather and frontal conditions affecting the Australian mainland. In turn, variations in the latitudinal position of the westerly winds were proposed.
As the dust in each sample from the core can potentially be derived from different regions, the mixing model developed by Marx et al. (2009b) was used to quantify the likely percentage of local sediment or New Zealand derived dust and far-travelled dust from Australia in the core. In this mixing model the closest matching Australian PSS and the closest matching local or New Zealand PSS are normalised against the dust sample. The degree of mixing of the two respective regions and how much this mixing reduced the $\Sigma_D$ was used to determine the relative contribution of Australian and local/New Zealand dust to the core.

3.9 Grain Size Distribution

The grain size distribution for each remaining sample was measured using a Malvern Mastersizer 2000, at the School of Earth and Environmental Sciences, University of Wollongong. The Mastersizer 2000 uses laser diffraction to measure particle size by measuring the intensity of light scattered as a laser beam passes through a dispersed sediment sample (Malvern Instruments Worldwide 2013). For non-symmetrical grains, the equivalent spheres method is used to estimate grain size - the diameter of a sphere with an equivalent property (e.g. mass or volume) to the particle is used to define particle size (Malvern Instruments Worldwide 2012). The samples were firstly left in water overnight to help disaggregate grains. Immediately prior to grain size analysis, the samples were placed in an ultrasonic bath for 30 minutes followed by 2 minutes by the ultrasonic probe in the Mastersizer to further break up any sediment aggregates.

To test the sensitivity of the instrument, samples of varying masses of homogenised, fine grained sediment were analysed by the Mastersizer. The masses of these sediment samples were 2, 1, 0.5, 0.25, 0.2, 0.1, 0.02, 0.01, 0.009, 0.008, 0.007, 0.005 and 0.004 g. The similarity of the grain size results for the measurement of different amounts of material was determined. The grain size results from the larger sediment masses were compared to the smaller ones in order to determine the reliability of the Mastersizer for measuring samples as small as those from the Campbell Island core.

Due to their small size, the entirety of each sample from the two cores was analysed. The average grain size distribution of each sample was determined from the average
of five consecutive measurements by the Mastersizer. Results were reported as a percentage of sand, silt and clay and were then presented and analysed by constructing frequency distribution curves of the range of grain sizes for each sample. These grain size results were then able to be used as a proxy for relative wind speed over time (Hesse & McTainsh 1999).
4. RESULTS

This chapter presents the moisture content, age-depth, mineral matter deposition, trace element/provenance and grain size results are in Sections 4.1, 4.2, 4.3, 4.4 and 4.5 respectively. Subsections in each section detail these results for both the Campbell Island and Stewart Island core.

4.1 Moisture Content

The moisture content of the peat in the Campbell Island core increased sharply with depth until a depth of ~50 cm (Figure 4.1). Deeper in the core, despite small fluctuations, the moisture content remained relatively constant with increasing depth. Overall, moisture accounted for 89.08% of the content in the Campbell Island core.

The moisture content of the peat in the Stewart Island core was highest at a depth of ~5cm. Below 5cm, moisture decreased slightly with depth (Figure 4.1). With an average moisture content of 43.76%, the peat in the Stewart Island core was much drier than that in the Campbell Island Core.

4.2 Core Age-Depth Relationships

4.2.1 Campbell Island Core

For the Campbell Island core the returned carbon-14 dates of McGlone et al. (2010) yielded a coherent age-depth relationship, that is, the core displayed increasing age with depth. The radiocarbon ages (including the 1 sigma standard deviations), calibrated ages and depths at which these ages occur in the Campbell Island core are shown in Table 4.1. The age depth model was best described by a third order
polynomial fit, which explained 99.44% of the variance in the calibrated ages (Figure 4.2). The lowermost date returned an age of 14 558 cal yr BP (Table 4.1) implying that peat began growing on Campbell Island during the late Pleistocene. As this study is only concerned with dust deposition after 5500 cal yr BP, only the top ~290 cm of the core was analysed in detail. Therefore a second age-depth model was constructed for this period of the core only. It is shown in Figure 4.3 and used a third order polynomial fit for calibrated dates from the top 290cm of the core (<5 500 cal yr BP in age). This curve explained 99.93% of the variance in the calibrated ages and was used to calculate dust deposition rates through the core. This age model, however, returned negative dates for the top 11.5 cm of the core. Subsequently, an age model was constructed for the top 36cm. This age model was constructed based on the assumption that the age at the peat at the top of the core (depth=0 cm) was 0 cal yr BP. This data point was added in order to prevent the age model returning negative dates for the youngest material at the top of the core. This age-depth model is shown in Figure 4.4. The fitted curve is a second polynomial function which explains 99.26% of the variance in the calibrated ages.

Table 4.1 Depths, radiocarbon and calibrated ages for Campbell Island core

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>^14C age ± 1σ</th>
<th>Modelled Age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>313±42</td>
<td>243</td>
</tr>
<tr>
<td>36</td>
<td>839±43</td>
<td>709</td>
</tr>
<tr>
<td>41</td>
<td>974±32</td>
<td>825</td>
</tr>
<tr>
<td>55</td>
<td>1208±39</td>
<td>1115</td>
</tr>
<tr>
<td>86</td>
<td>1870±37</td>
<td>1781</td>
</tr>
<tr>
<td>110</td>
<td>2457±45</td>
<td>2397</td>
</tr>
<tr>
<td>160</td>
<td>3415±56</td>
<td>3540</td>
</tr>
<tr>
<td>210</td>
<td>4035±54</td>
<td>4403</td>
</tr>
<tr>
<td>290</td>
<td>4968±50</td>
<td>5625</td>
</tr>
<tr>
<td>380</td>
<td>5889±53</td>
<td>6727</td>
</tr>
<tr>
<td>415</td>
<td>6285±45</td>
<td>7236</td>
</tr>
<tr>
<td>450</td>
<td>7309±50</td>
<td>8075</td>
</tr>
<tr>
<td>510</td>
<td>8391±54</td>
<td>9444</td>
</tr>
<tr>
<td>525</td>
<td>8866±51</td>
<td>10093</td>
</tr>
<tr>
<td>545</td>
<td>9941±55</td>
<td>11288</td>
</tr>
<tr>
<td>565</td>
<td>10585±57</td>
<td>12373</td>
</tr>
<tr>
<td>585</td>
<td>11278±60</td>
<td>13133</td>
</tr>
<tr>
<td>590</td>
<td>11528±70</td>
<td>13278</td>
</tr>
<tr>
<td>650</td>
<td>12445±76</td>
<td>14558</td>
</tr>
</tbody>
</table>
Figure 4.2 Age-depth curve for the calibrated radiocarbon dates for the entire Campbell Island Core. The fitted curve is a third order polynomial function.

Figure 4.3 Age depth curve for the calibrated radiocarbon dates from the top 290 cm of the core. The fitted curve is a third order polynomial function. A linear function similarly returns a strong fit. The $R^2$ value of a linear trend line on this graph is 0.991.

Figure 4.4 Age depth curve for the calibrated radiocarbon dates from the top 36 cm of the core. A data point at a depth of 0 cm and age of 0 cal yr BP was included. The fitted curve is a second order polynomial function.
4.2.2 Stewart Island Core

The carbon-14 dates for the Stewart Island core (Table 4.2) do not yield a coherent age-depth model. Each pollen concentrate sample contained modern carbon. The depths, radiocarbon ages (including error at 1 sigma standard deviations) and calibrated ages of the pollen dated in the Stewart Island core are shown in Table 4.2. Ages were calibrated using Reimer and Reimer’s (2004) CALIBomb programme.

Table 4.2 Depths, radiocarbon and calibrated ages for Stewart Island core

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>percent Modern Carbon± 1σ</th>
<th>Conventional radiocarbon age (cal yr BP)</th>
<th>Cal AD age range</th>
<th>Relative area under probability distribution at 2 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>99.59±0.54 Modern</td>
<td>1809.05-1925.96</td>
<td>0.78173</td>
<td></td>
</tr>
<tr>
<td>12.4</td>
<td>113.19±0.48 Modern</td>
<td>1992.68-1996.15</td>
<td>0.871733</td>
<td></td>
</tr>
<tr>
<td>18.9</td>
<td>111.08±0.46 Modern</td>
<td>1995.29-1996.82</td>
<td>0.693199</td>
<td></td>
</tr>
<tr>
<td>26.9</td>
<td>114.60±0.45 Modern</td>
<td>1990.17-1993.88</td>
<td>0.859837</td>
<td></td>
</tr>
</tbody>
</table>

The calibrated dates and the age-depth model they produce (Figure 4.5) imply an age-reversal has occurred within the peat core. The oldest material in the core dates back to 1809.05-1925.26 cal yr AD and this material is located near the peat surface. The three samples from deeper in the core yield younger calibrated ages which are very similar to each other and imply the material deeper than 12.4 cm is roughly the same age.

![Figure 4.5 Age-depth curve for the calibrated dates for the Stewart Island core. The fitted curve is a fifth order polynomial function. The average of the calibrated age ranges were used in this graph.](image)

Figure 4.5 Age-depth curve for the calibrated dates for the Stewart Island core. The fitted curve is a fifth order polynomial function. The average of the calibrated age ranges were used in this graph.

The unsupported $^{210}\text{Pb}$ in samples from the top 9 cm of the core (Table 4.3) confirm the age-reversal that is apparent from the calibrated radiocarbon dates. As shown in
Figure 4.6, the top sample has a smaller quantity of unsupported $^{210}\text{Pb}$ than the sample it overlies.

Table 4.2 Depths, supported and unsupported $^{210}\text{Pb}$ Concentrations for the Stewart Island core

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Supported $^{210}\text{Pb}$ (Bq/kg)</th>
<th>Unsupported $^{210}\text{Pb}$ (Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>3±1</td>
<td>158±7</td>
</tr>
<tr>
<td>6.6</td>
<td>5±1</td>
<td>201±9</td>
</tr>
<tr>
<td>9</td>
<td>4±0</td>
<td>64±3</td>
</tr>
</tbody>
</table>

Figure 4.6 Diagram showing the concentration of unsupported $^{210}\text{Pb}$ with depth. The peak in the concentration of unsupported $^{210}\text{Pb}$ occurs in the middle of the core.

4.3 Mineral Matter Deposition

4.3.1 Campbell Island Core

The material remaining after combusting the samples consisted of mineral matter deposited in the peat. The age-depth model was used to determine the quantity of mineral matter deposited in each square metre of peat per year (g/m$^2$/yr). As shown in Figure 4.7, dust deposition in the Campbell Island core has decreased overall since 5500 cal yr BP. Three broad phases of dust deposition were identified – the first lasting from ~5500-4000 cal yr BP, the second lasting from ~4000-1700 cal yr BP and the third from 1700 BP to present (Figure 4.7). Each successive phase is characterised by a marked reduction in the deposition of mineral matter in the core.
Figure 4.7 Diagram showing major variations in the mass of mineral matter deposited per square metre of peat each year (g/m$^2$/yr) since 5500 cal yr BP in the Campbell Island core. Three phases of dust deposition are marked on the figure – a period of high dust deposition beginning at 5500 cal yr BP (phase 1), followed by a period of slightly lower dust deposition beginning at 4000 cal yr BP (phase 2) and a period of even lower dust deposition beginning at 1700 cal yr BP (phase 1).

Dust deposition (g/m$^2$) with depth is shown in Figure 4.8 and show a very similar pattern to dust deposition with time, with the same three phases of mineral matter deposition identifiable. A prime difference is that the recent sharp increase in mineral matter deposition near the surface of the core (from a depth of approximately 20 cm) became more apparent when mineral matter deposition was plotted with depth (as opposed to age).
Figure 4.8 Diagram showing variations in the mass of mineral matter deposition per square metre of peat (g/m$^2$) with depth in the Campbell Island core. Three phases of dust deposition are identified. A sharp increase in mineral matter deposition occurs at the end of phase 3.

4.3.2 Stewart Island Core

Due to the incoherence of the age-depth model constructed for the Stewart Island core, only the mineral matter deposition per square metre of peat and its variance with depth were able to be considered. As shown in Figure 4.9, the amount of mineral matter deposited in the peat fluctuates significantly, although shows a general increase with depth. Mineral matter deposition per area of peat was the lowest in the top 5 cm of the core. Unlike for the Campbell Island core, distinct phases of mineral matter deposition were unable to be identified.

The average mass of mineral matter per square metre of peat in the Stewart Island core was 268.69 g/m$^2$. This was significantly higher than the average mass of mineral matter per square metre in the Campbell Island core (40.79 g/m$^2$).
4.4 Trace Element Concentrations in the Studied Sores

4.4.1 Reliability of Trace Element Data

The reproducibility of trace element concentrations in standards run as unknowns alongside the samples analysed in this study was used to confirm the reliability of the trace element results obtained from ICP-MS. Three standards - BHVO-2, AGV-2 and SCo-1- were digested and analysed as part of this study. In each case the mass of material digested was 10 mg, which is close to the mass of samples from the Campbell Island core (1-10 mg). The reproducibility of the standards therefore provides a more direct measure of the quality of data presented here. The standards measured in this study, are presented alongside the long term 100 mg values reported by Marx and Kamber (2010a) and the 10 mg digestions reported by Babechuk et al. (2010) in Table 4.4. The concentrations of standards determined compare well with those in the literature, hence confirming the reliability of the trace element results. For the elements of most interest in this study, i.e., the Rare Earth Elements (REE), differences in concentration between this study and those reported in Marx and Kamber (2010a) and Babechuk et al. (2010) are typically ~1 to 2 ppb.
Table 4.4 Trace element concentrations (ppb) of standards. The results from standards in this study are compared to standards reported in Marx & Kamber (2010a) and Babechuk et al. (2010).

<table>
<thead>
<tr>
<th>BHVO-2</th>
<th>THO-10 mg (this study)</th>
<th>THO-10 mg (this study)</th>
<th>THO-10 mg (this study)</th>
<th>SKO-10 mg (this study)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7Li</td>
<td>443.7</td>
<td>449.1</td>
<td>462.2</td>
<td>514.7</td>
</tr>
<tr>
<td>9Be</td>
<td>920</td>
<td>996</td>
<td>0.92</td>
<td>1058</td>
</tr>
<tr>
<td>45Sc</td>
<td>31464</td>
<td>32064</td>
<td>0.98</td>
<td>31,800</td>
</tr>
<tr>
<td>49Ti</td>
<td>147980</td>
<td>164430</td>
<td>0.90</td>
<td>16,270</td>
</tr>
<tr>
<td>51V</td>
<td>281327</td>
<td>314465</td>
<td>0.89</td>
<td>310,200</td>
</tr>
<tr>
<td>53Cr</td>
<td>286578</td>
<td>298688</td>
<td>0.96</td>
<td>299,600</td>
</tr>
<tr>
<td>59Co</td>
<td>43361</td>
<td>45267</td>
<td>0.96</td>
<td>45,120</td>
</tr>
<tr>
<td>60Ni</td>
<td>112770</td>
<td>117772</td>
<td>0.96</td>
<td>116,700</td>
</tr>
<tr>
<td>65Cu</td>
<td>116079</td>
<td>125716</td>
<td>0.92</td>
<td>117,400</td>
</tr>
<tr>
<td>66Zn</td>
<td>110118</td>
<td>102749</td>
<td>0.97</td>
<td>103,800</td>
</tr>
<tr>
<td>71Ga</td>
<td>20596</td>
<td>21057</td>
<td>0.98</td>
<td>21,000</td>
</tr>
<tr>
<td>75As</td>
<td>717</td>
<td>664.1</td>
<td>1.08</td>
<td>725</td>
</tr>
<tr>
<td>85Rb</td>
<td>8996</td>
<td>9139</td>
<td>0.98</td>
<td>9153</td>
</tr>
<tr>
<td>86Sr</td>
<td>386820</td>
<td>394298</td>
<td>0.98</td>
<td>392,600</td>
</tr>
<tr>
<td>89Y</td>
<td>23649</td>
<td>24284</td>
<td>0.97</td>
<td>24,320</td>
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|            | 4130                   | 39.4                   | 0.91                   | 34.7                   | 0.91                   |

|            | 1093.9                 | 109.3                  | 0.91                   | 43.3                   | 0.91                   |

|            | 4130                   | 39.4                   | 0.91                   | 34.7                   | 0.91                   |
In order to assess the homogeneity of the samples themselves, a replicate of one of the Stewart Island samples was analysed (sample TR6B-51). The standard deviation between the replicates for most trace elements was less than 10% (Figure 4.10). Elements with the highest relative standard deviations (>12%) between the replicates (i.e. Sn, Sb, Zn, Cr, Th, Mo, Cs and Ni) were excluded from further analyses. With the exception of Th and Cs, these elements are often affected by pollution and cannot be used to determine dust provenance in samples which post-date the Industrial Revolution, while Cs is soluble and therefore highly mobile in peats (Marx et al., 2009; 2010).

Figure 4.10 Relative standard deviation in the concentration of trace elements between the two replicate samples from the Stewart Island core.
Elements that are known to be mobile and showed mobility toward the top or the bottom of the core were also excluded from further analyses. These elements included Sr, Rb, Cs, U, W and Li. The concentration of these elements (both alone and as a ratio with La) with depth shows they were all mobile toward the surface of the core (Figure 4.11). La (a refractory element) is unaffected by internal core processes and any variability in its concentration with depth can be attributed only to variation in the source of the sediment (Shotyk et al. 2001). Considering the ratio of mobile elements (or polluting elements) with is a means of demonstrating that their enrichment in parts of the core is due to the mobile (or polluting) nature of the element and not simply the results of increased trace element deposition (as a whole) in the core (Shotyk et al. 2001; Marx et al. 2011).
Figure 4.11 Behaviour of particular mobile elements – Sr (A), Rb (B), Cs (C), U (D), W (E) and Li (F) – with depth in the Campbell Island core. Their ratio with La (an element unaffected by internal core processes) is plotted to confirm their mobility.

In addition to mobile elements, elements affected by pollution were also excluded from the set of trace elements used to determine the provenance of dust in the core. These elements included W (which is also mobile, Figure 4.10), Pb, Ni, Cu, V, Sn, and Mo (Figure 4.12).
Additional elements not used to determine the dust provenance included Hf and Zr and the Heavy REEs (HREE) (Ho, Er, Tm, Yb and Lu) as they are enriched in heavy minerals which are less susceptible to atmospheric dust transport. The concentrations of these elements are therefore likely to be relatively low in the core compared to their source location. Barium was excluded due to its heterogeneity in carbonates (in addition to its solubility) and Ce was excluded as it is affected by redox and shows systematic depletion with depth (as a ratio with La) in the Campbell Island core.
Figure 4.13 shows the average abundance of trace elements in the Campbell Island core normalised against MUQ – a trace element normalisation determined from the composition of weather upper continental crust from alluvial sediments in Queensland, Australia (Kamber et al. 2005). Elements significantly high or low in abundance were excluded (eg. Tl and Li) for use in determining the provenance of material deposited in the core as their behaviour is likely to be affected by internal core processes, such as wetting and drying, pollution or density sorting.

4.4.2 Comparison of concentration of stable elements in Campbell Island core and potential source areas

The elements deemed suitable for use in determining the provenance of dust were La, Be, Ta, Pr, Nb, Nd, Sm, Eu, Gd, Tb, Sc, Dy, Y, Ho, Ti, Co and Ga. Particular attention was paid to the variation in REEs throughout the core – as these are known to be the most stable during entrainment, transport, deposition and post deposition and their concentration in the core is therefore most indicative of source lithology (Marx et al. 2005b).

Examples of the concentration of selected REEs with depth are shown in Figure 4.14. There are three distinct regions of the core – each with its own trace element chemistry. These regions are near the surface of the core (the top 2 samples analysed by ICP-MS), the middle of the core (the middle 7 samples), and at the bottom of the core (the bottom 2 samples). The variability in the REE trace element chemistry of these three groups for regions in the Campbell Island core is shown in Figure 4.15. The REE trace element chemistry of the bottom of the core differs markedly from that in the middle and top. The bottom of the core is enriched in all
REEs relative to MUQ, whilst the middle and top of the core are depleted in most REEs relative to MUQ. The bottom of the core has a roughly equal concentration of REEs normalised with MUQ, with the exception of a negative Eu anomaly and positive Er anomaly. The middle and top of the core, on the other hand, are relatively enriched in light REEs (LREEs) compared to heavy REEs (HREEs). The middle and top of the core do not have the negative Eu anomaly, but have a similar positive Er anomaly to the samples at the bottom of the core. Overall, these results imply that the chemistry of mineral material in the base of the core is different to that in the middle and upper parts of the core. As ombrotrophic peats develop through time they become increasingly cut off from the surrounding surface hydrology, e.g., they develop domed surfaces. Consequently, material at the base of the core is typically reflective of local inputs to the bog, either weathered from the bedrock, or alluvial material washed into the site. By contrast once the bog becomes truly ombrotrophic the mineral matter is typically dominated by dust (Shotyk et al. 2001; Marx et al. 2009b). For this reason, the bottom two samples from the Campbell Island core were included in the dust provenance model as a local potential sediment source.

Figure 4.14 Concentration of La and Gd (REEs) with depth in the Campbell Island core. These diagrams show three broad regions with distinct chemistry – the top of the core, middle of the core, and bottom of the core.
Figure 4.15 Diagram showing the variability in REE chemistry for the three regions of the Campbell Island Core. The trace element chemistry for the bottom of the core is derived from the bottom two samples of the core.

The REE chemistry of local sediment on Stewart Island are presented in Figure 4.16. The Dough Boy Bay and Table Top samples had quite similar REE chemistry – they were both relatively enriched in LREEs with a negative Eu and positive Er anomaly. They were both included in the dust provenance model as potential locally sourced end members to the Stewart Island and Campbell Island sites. The main difference evident in the chemistry of these three samples is that TR-01 contained a positive Eu anomaly. This sample was excluded from the dust provenance model.

Figure 4.16 Concentration of REE MUQ normalised for three potential (local) sources of sediment to the Stewart Island core.

4.4.2.1 Provenance Results for the Campbell Island Core

Using the dust provenance model of Marx et al. (2005c), the most likely source of sediment deposited in the bog was determined. Potential sources of material to the
bog include Australian sourced dust, dust sourced from the New Zealand mainland and locally generated and transported sediment. The degree of match between a potential source sediment (PSS) and a sediment extracted from the core can be expressed using $\Sigma_D$, the sum of the all the differences in trace element concentration between a core sediment and a PSS. PSS with lower $\Sigma_D$ more closely resemble the chemistry of the core sediment and are therefore more likely to be the source of that material.

Overall the chemistry of samples from the Campbell Island core matched Australian PSS more closely than either local or New Zealand PSS. This is shown in Figure 4.17 where the difference between each element in the closest matching Australian PSS and the closest local or New Zealand PSS are shown plotted against a core sediment. For instance, in all of the samples except the one from the bottom of the core, the sum of difference between the concentration of Tb and Nb in the core and in local or New Zealand PSS was much higher than the sum of differences between the core and the range of Australian PSS (Figure 4.17, A-G). Dust from near the surface of the core most closely resembled the chemistry of dust in the Eyre Peninsula, whilst dust in the middle depth range of samples from the core resembles the chemistry of dust in the lower Murray-Darling Basin (MDB) and south central MDB and dust deeper in the core resembled dust in the Riverina and lower MDB regions. The sum of differences for the Australian sediment sources were higher for the deepest samples (at ages of ~3850 and ~5200 cal yr BP).
Figure 4.17 Sum of differences between the REE chemistry of the core sediment and the most likely Australian and local dust source regions. The most likely dust source regions for the samples at the following depths/ages are shown - 8.5 cm (A), 10.5 cm (B), 13.5 cm/50 cal yr BP (C), 17.5 cm/157 cal yr BP (D), 25.5 cm/370 cal yr BP (E), 54.5 cm/1110 cal yr BP (F), 109.5 cm/2410 cal yr BP (G), 179.5 cm/3850 cal yr BP (H) and 259.5 cm/5200 cal yr BP (I).
The degree of match between sediment from the Campbell Island core and Australian PSS through time is shown in Figure 4.18. Lower sum of differences indicated a closer match between the trace element chemistry of the core and a particular source area. Overall the lower MDB was the main source of dust in the core.

From ~14 560 cal yr BP to ~14 500 cal yr BP, the most likely sources of sediment are located on the Darling River in the upper MDB. At ~5200 cal yr BP closest matching sediments were located in the upper and lower MDB. It is important to note, the sum of differences for between the core and potential source areas is quite high until ~5200 cal yr BP. At ~3850 cal yr BP, the closest matching sediments were from the lower MDB only. At ~2410 cal yr BP, sediments deposited in the core most closely resembled those from the upper and lower MDB, whilst at ~1110 cal yr BP most closely resembled those from the lower MDB. For sediments deposited between ~370 and ~157 cal yr BP, the major dust source regions were the lower Lake Eyre basin and upper and lower MDB. The dust deposited near the surface (at 8.5 and 10.5cm depth) was likely sourced from the lower Lake Eyre and lower MDB (Figure 4.18)
Figure 4.18 Sum of differences between the chemistry of Campbell Island core samples and potential source regions in southeast Australia at the top of the core (A and B), ~50 cal yr BP (C), ~157 cal yr BP (D), ~370 cal yr BP (E), ~1110 cal yr BP (F), ~2400 cal yr BP (G), ~3850 cal yr BP (H), ~5200 cal yr BP (I), ~14 500 cal yr BP (J) and ~14 560 cal yr BP (K).
As the dust in each sample from the core can potentially be derived from different regions, the mixing model developed by Marx et al. (2009b) was used to quantify the likely percentage of local sediment or New Zealand derived dust and far-travelled dust from Australia in the core. The results of this mixing model indicate that Australian dust dominates much of the top 259.5 cm of the core (the portion of the core containing dust deposited since ~5200 cal yr BP). Australian dust accounted for over 97% of the mineral matter in the samples deposited since ~3850 cal yr BP (179.5 cm deep) but only 58.25% of the sample deposited ~5200 cal yr BP (259.5 cm deep) (Figure 4.18). This supports the sum of differences results presented in Figure 4.18 which show the dust in the core is less closely matched to Australian provenance regions at this point in time. In addition, the chemistry of this sample implied it contained a substantial proportion of New Zealand derived loess, which matched the chemistry of the core sediment more closely than locally derived sediment.

The deposition of Australian dust (and the total dust deposition) throughout the core is shown in Figure 4.19. When compared to total dust deposition in the core, Australian dust deposition is relatively lower in the first phase and initial stages of the second phase (Figure 4.20).

Figure 4.19 Australian contribution of dust to the Campbell Island Core since 5500 cal yr BP compared to total dust deposition.
4.4.3 Dust Provenance Results for the Stewart Island Core

Due to the inconsistent age model for Stewart Island, variations in trace element chemistry with depth in the core are meaningless and therefore in-depth results for the chemistry of this core are not presented. Worth noting, however, are the results from the mixing model. It was determined that, averaged over the length of the core, Australian dust contributes ~24.16% of the mineral matter material in the bog. The contribution of Australian material relative to total mineral matter is therefore much lower in the Stewart Island core than in the Campbell Island core.

4.5 Grain Size Results

4.5.1 Sensitivity of Malvern Mastersizer for small sample masses

The reliability of the Malvern Mastersizer for analysing small masses of material (like the small masses of mineral matter in the Campbell Island core samples) was assessed based on similarity of results obtained for different masses of homogeneous sediment samples. Variability in results (such as mean grain size) was introduced when the sample size is below 0.007 g (Figure 4.21). The average mass of mineral matter in the Campbell Island samples was ~0.007 g (and 0.27 g for the Stewart Island samples). Consequently, these samples are at the limit of resolution for the Mastersizer and the results must be treated with caution.
4.5.2 Grain Size Results for the Campbell Island Core

The average grain size of mineral matter for the entire Campbell Island core was 27.75 µm. The average grain size has increased overall since ~5 500 cal yr BP (Figure 4.22). A peak in grain size occurred around 1000 cal yr BP, followed by a general decrease in grain size between 1000 and 237 cal yr BP and then a significant increase in mean grain size after ~237 cal yr BP (Figure 4.22).

The particle size distributions show two main frequency modes – a finer grained mode (mode 1) centred at approximately 10-30 µm and a coarser grained mode (mode 2) with particle diameter >100 µm (Figure 4.23). The grain size of the finer mode is closest to the size range of long-range dust (Prospero 1999; Marx et al. 2009b) whereas the coarse mode is toward the upper limit of material transported long distances as dust. Changes in the particle diameter of the finer grained mode throughout time in the core are shown in Figure 4.24. The size of this finer grained
mode varied with depth/age in a different manner to the mean grain size, with a minimum in grain size occurring ~4000-5500 cal yr BP (during the first phase of dust deposition) and increased grain size between 4000 and 1700 cal yr BP (during the second phase of dust deposition). Several fluctuations occurred in the third phase of dust deposition, with a lower grain size between 1700 and ~700 cal yr BP, followed by increased grain size until ~550 cal yr BP, after which grain size decreased (Figure 4.24). This differs from the increase in mean grain size at this time (Figure 4.22).
Figure 4.23 The frequency (as a percentage of volume) of particle diameters at selected depths/ages from the Campbell Island core. These grain size distribution at 19.5 cm/~200 cal yr BP (A), 30.5 cm/~500 cal yr BP (B), 59.5 cm/~1250 cal yr BP (C), 94.5 cm/2000 cal yr BP (D), 139.5 cm/3000 cal yr BP (E), 187.5 cm/4000 cal yr BP (F) and 279.5 cm/5500 cal yr BP (G).
Figure 4.24 Variation in the particle size of mode 1 (fine grained mode) with depth (A) and age (B) in the Campbell Island core. The fitted curves are sixth order polynomial functions and explain 45.8% of variation in grain size.

4.5.3 Grain Size Results for the Stewart Island Core

The average grain was significantly larger in the Stewart Island core (51.41 µm). However the incoherent age model for the Stewart Island core means the variation of grain size with depth in this core is meaningless and therefore detailed grain size results for this core are not presented.
5. Discussion

This chapter presents a discussion of the results presented in the preceding chapter. An analysis of the contribution of long-range dust to the study sites and variation in the flux of this long-range dust flux over time are presented in sections 5.1 and 5.2 respectively. Section 5.3 contains an analysis of varying grain size and wind intensity over time. A summary of how the findings of this study compare with the findings of others is found in section 5.4.

5.1 Contribution of long-range dust to the study sites

5.1.1 Contribution of long-range dust to the Campbell Island core

The three main groups of potential end members in the Campbell Island core are far-travelled Australian dust, sources local to Campbell Island and nearby islands such as New Zealand and far-travelled South African dust. The trace element ‘fingerprints’ of South African dust sources have not been documented like those of Australia and local sources to Campbell Island core have been by Marx et al (2009b; 2011). The dust provenance model used in this study was therefore used under the assumption that South African dust had not been deposited in the core. This assumption was supported by the fact large-scale transport of South African dust to Campbell Island is unlikely (Sturman et al. 1997). Similarly, samples of local sources of sediment on Campbell Island were unable to be attained within the timeframe of this study. Subsequently, the bottom two samples from the core were interpreted as being reflective of local potential sediment sources and were included as local PSSs in the mass balance model used to determine provenance. This assumption was based on the fact the trace element chemistry of the bottom of the core was markedly different from the rest of the core (Figure 4.15) and that the dust in the bottom of the core was likely deposited before the peat bog had grown above the surrounding hydrology (that is, before the peat bog had become isolated from fluvial and colluvial sources of sediment) (Shotyk et al. 2001; Marx et al. 2009b).

Far-travelled Australian dusts contributed to the majority of mineral matter in the core. Long-range Australian dust accounted for almost all of the mineral matter in the top 179.5 cm of the core (after ~3850 cal yr BP). As indicated by the trace element results, the contribution of far-travelled Australian dust as a percentage of total dust...
deposition in the core was lower between ~5200 and ~3850 cal yr BP (Figure 4.20). This implies that there was a greater deposition of local dust sources (for example from mainland New Zealand) in the core at this time. Marx et al. (2009b) reported a similarly lower percentage of Australian dust being transported to New Zealand at this time.

The enrichment of Pb in the top ~20 cm of the core (Figure 4.12) is likely to be sourced from lead smelting operations in Australia that began in 1889 at the lead smelter of the Broken Hill Associated Smelters Pty Ltd (BHAS) at Port Pirie in South Australia (the closest Pb smelter to Campbell Island). Broken Hill sourced Pb has been found extensively as a contaminant throughout the Southern Hemisphere (Bollhöfer & Rosman 2000; Bollhöfer et al. 2005) and is transported alongside dust (Marx et al. 2008b; Marx et al. 2010). It is also the main source of Pb to Antarctica where its accumulation also dates from the 1890s (Vallelonga et al. 2002). Broken Hill derived Pb was used extensively as an additive in petrol which further facilitated its widespread contamination signature. An increase in the concentration of other pollutant metals, e.g. Cu, Ni, Sb and Sn, in the top of the core are also indicative of the timing of industrial development in the Australian region.

The lower MDB is the major source area of dust throughout the core, with dust from the Lake Eyre and upper MDB also contributing dust at stages of the late Holocene (Figure 4.18) The samples from the bottom of the core (deposited ~14500 and ~14 560 cal yr BP) are quite different in their trace element chemistry to the rest of the core. These samples could represent increased local fluvial and colluvial sediment deposition, and/or local weathered saprolite in the peat bog before it became ombrotrophic and grew above the surrounding hydrology (Shotyk et al. 2001; Marx et al. 2009b). Importantly however, the trace element chemistry is more similar to the trace element ‘fingerprints’ of the variety of Australian source regions than local sediment sources, indicating that Australian dust deposition still formed a significant portion of mineral matter in the core at this time.

The results of this study show that Australian dust has been deposited at Mount Honey, Campbell Island since 5 500 cal yr BP (as well as possibly prior to this time as well). In addition to studies of Australian dust deposition in the Tasman sea (Hesse 1994), New Zealand (McGowan et al. 2005a; Marx et al. 2009b) and in
Antarctic ice cores (Revel-Rolland et al. 2006) these findings provide further evidence for the transport of Australian dust toward islands to the south east of the continent in Bowler’s (1976) south eastern dust transport corridor. Whilst rates of Australian dust deposition on Campbell Island have not been previously reported, the findings of this study are in line with past reports that Australian dust transport makes a significant contribution the sedimentary environment downwind of the continent (eg. Alloway et al. 1992; Marx et al. 2009b). The fact the percentage of Australian dust contribution to the core is so high implies that this dust likely has a very important influence on soil development and geochemical cycles. The influence of Australian dust is particularly important in alpine regions (such as Mount Honey) where the inputs of local sediments are low (Marx et al. 2009b).

5.1.1 Contribution of long-range dust to the Stewart Island Core

Overall, Australian dust accounted for only 24.16% of total dust deposition in the Stewart Island core. This implies that the study site was affected by local sources of sediment to a greater extent than the study site at Campbell Island. This result differs markedly from the higher percentages of Australian dust deposition on the South Island of New Zealand by Marx et al. (Marx et al. 2009b) and is quite surprising given the proximity of the island to mainland New Zealand.

5.2 Dust Flux Through Time

5.2.1 Dust flux through time in the Campbell Island core

As this study is concerned with the behaviour of the westerlies since ~5 500 cal yr BP, only dust deposition since ~5 500 cal yr BP is considered. Three phases of Australian dust deposition in the Campbell Island core were identified. The rate of dust deposition, considered in conjunction with the provenance of dust during each of these phases has implications for the likely position of the westerlies.

In general, the two major controls of dust entrainment are sediment availability and the presence of wind to transport this sediment (McTainsh 1989; Leslie & Speer 2006). In Australia, the greatest limitation on dust transportation is sediment availability (Hesse & McTainsh 2003; Marx et al. 2005a; Marx et al. 2009b). Sediment availability is highest when the climate is variable – for example, wet periods (which deliver sediment to major drainage basins) are followed by drier
periods when this sediment is entrained and transported – and lowest when the conditions in the source region are wet (Marx et al. 2005a; Marx et al. 2009a). The provenance of dust arriving at the core gives further meaning to estimates of palaeo-aridity in eastern Australia. In summary, when the Lake Eyre basin is ‘active’ as a dust source, conditions in the Lake Eyre basin are dry and the Australian monsoon (which feeds the rivers in the Channel Country that run into Lake Eyre of sediment) was likely located further north of the Australian continent. Periods of low dust emissions from Lake Eyre indicate that the Australian monsoon was more active, feeding the rivers that run into the Lake Eyre basin and filling up Lake Eyre (Marx et al. 2009b). Magee et al. (2004) similarly note the effectiveness of lake levels in Lake Eyre as a proxy for the location of the Australian monsoon and Inter-Tropical Convergence Zone (ITCZ). High rates of dust deposition from the Murray-Darling Basin are associated with dry or variable climatic regimes whilst low rates of dust deposition are associated with wet periods when the westerlies were stronger or further north allowing in greater moisture being advected into south eastern Australia (Marx et al. 2011). The Australian dust transport system was discussed in greater detail in Section 2.5.

The first phase of Australian dust deposition identified in this study (~4000 – 5500 cal yr BP) is characterised by relative low rates of dust deposition compared to the second phase (Figure 4.19). At this point in time, the major source of dust was the lower MDB. Conditions in the lower MDB basin were likely dry at this time – as the westerlies are the prime means of advecting moisture into south eastern Australia (McGowan et al. 2010; Marx et al. 2011), changes in their position can be linked to wet and dry periods in the MDB. Lower rates of dust transport, by comparison to the second deposition phase and fact dust was sourced predominantly from the lower MDB can be attributed to weaker westerly flow or the westerlies being positioned further south of the Australian continent. Lake Eyre was not an active dust source at this point in time, implying that conditions in Lake Eyre were wet, likely due to an active monsoon over the north of the continent. As discussed by Marx et al. (2009b), this would have meant the ITCZ and baric ridge were located further south over the Australian continent, in turn, forcing the westerlies to be moved to a more southward position. These results vary only slightly from those of Marx et al. (2009b) who reported this shift in the position of the westerlies to have occurred between 7800
and 4800 cal yr BP. Importantly, these results also confirm reports of wetter than present conditions between ~10 000 and ~5000 cal yr BP from studies of Australian lake sediments (Nott & Price 1994; Magee & Miller 1998; Johnson et al. 1999) and reports of a southern location of the ITCZ and monsoon at ~6000 cal yr BP (Quigley et al. 2010). Importantly, these findings are in line with the results of Magee et al. (2004) who showed, based on sediment cores, that Lake Eyre experienced a lacustral stage from ~12000 - ~ 4000 cal yr BP, before it began to dry.

The second phase of Australian dust deposition (4000-1700 cal yr BP) was characterised by higher dust deposition rates than in phase 1. The provenance of only one sample from within this time frame was determined in this study and so this study does not show variability in dust source regions within this phase. Like in phase 1, the lower MDB was the main source region of dust in the core. At this time central Australian dust sources, including from near the lower Lake Eyre basin and regions in the northern MDB (such as along the Darling River) were beginning to become active. This corresponds well with the reports that Lake Eyre began to dry out ~4000 cal yr BP (Magee et al. 2004) and implies a less active monsoon and northward positioning of the ITCZ and westerlies over this time period. Marx et al. (2009) similarly reported a northward positioning of the core at this time – they proposed this northward positioning extended from 4800-900 cal yr BP.

The third phase of dust deposition (~1700 cal yr BP – 370 cal yr BP) is characterised by lower relative rates of Australian dust deposition, with the exception of the sharp increase in dust deposition from ~200 cal yr BP to present. At the ~1100 cal yr BP, the results of this study show that the major dust source region was the lower MDB. Lake Eyre was not an active source of Australian dust at this time. It is unlikely that Lake Eyre switched off as dust source, but rather the contribution of material from the MDB increased to the point where it was the dominate dust source being transported to the Southern Ocean.

Since ~370 cal yr BP, the Lake Eyre has been an active source of dust to Campbell Island, implying either drier or more variable conditions in central Australia possibly associated with a northerly location of the monsoon, ITCZ and westerlies. These results are in line with modern observations of dry conditions in Lake Eyre at this time. Lake Eyre was dry between 1840 (when it was discovered) and 1949, when the
first flooding was observed (Kotwicki & Allan 1998). Although it is important to note, the isolated nature of Lake Eyre means it is possible there were simply no people around to observe other flooding events (Kotwicki & Allan 1998). Since 1949, a sequence of several wet and dry spells have been observed (Kotwicki & Allan 1998). This climate variability can be attributed to ENSO variability, with flooding events generally linked to the La Nina phase of ENSO (Kotwicki & Allan 1998).

There are three main potential explanations for the dramatic increase in Australian dust transport to the study sites from ~200 cal yr BP to present. The first potential explanation is that the Australian monsoon, ITCZ and westerlies were located further north over the Australian continent, resulting in dry conditions conducive to dust transport in Lake Eyre. This explanation contradicts modern records which show a recent poleward migration of the westerlies (Tanaka & Chiba 2006). The lower MDB was also a source of sediment to Campbell Island at this time. A rapid increase in the rate of dust from the MDB deposited in a peat bog in the Snowy Mountains after 200 cal yr BP was similarly noted by Marx et al. (2011). This implies the increased rate of dust transport may be due to conditions affecting the MDB, rather than Lake Eyre.

As dust transport is known to be highest when the climate is variable (Marx et al. 2005a; Marx et al. 2009a), the second potential explanation is that the observed climate variability in Lake Eyre (after 1949) and similar climate variability in MDB, resulted in greater dust supply and transport from these regions, increasing dust transport rates around this time. It is important to note that one of the main limitations of using dust records to infer palaeo-aridity is that increased dust deposition due to climate variability (occurring due to ENSO) is unable to be inferred from increased dust deposition due to aridity alone (Marx et al. 2009b). The lower MDB was also a source of sediment to Campbell Island at this time. A rapid increase in the rate of dust from the MDB deposited in a peat bog in the Snowy Mountains after 200 cal yr BP was similarly noted by Marx et al. (2011). This implies the increased rate of dust transport may be due to conditions affecting the MDB, rather than Lake Eyre (although a contribution from Lake Eyre is implied from the geochemistry).

The third potential explanation is that this increase in dust deposition is not related to climate and is instead due to increased rates of erosion introduced with the onset of
European land clearing and agricultural practices in arid and semi-arid Australia (Marx et al. 2011). Livestock farming and land clearing also occurred on Campbell Island at this time, however, on a relatively small scale (McGlone et al. 2007). Given that Australian dust was modelled to account for ~97% of dust deposition in the core at this time, human induced increased erosion on Campbell Island itself, is a less likely contributor to the increased dust deposition rates in the core. Additionally, the provenance results in the most recent section of the core confirm modern meteorological records that indicate the Lake Eyre Basin and MDB are the most active contemporary dust source areas on the Australian continent (Hesse & McTainsh 2003).

5.2.2 Dust flux through time in the Stewart Island core

Potential age reversals in the Stewart Island core meant variations in dust deposition and provenance over time were unable to be measured. The most notable finding from studying the Stewart Island core is therefore the young nature of the peat. Alpine peats characteristically accumulate very slowly. For example, a 1m long core collected by Marx et al. (2011) from the Snowy Mountains, Australia, and a 0.6 m core collected by McGlone et al. (1997) from the Old Man Range, New Zealand date back to 5880 cal yr BP and 9490 cal yr BP respectively. Sedimentation rates in the Snowy Mountains and Old Man Range were therefore 0.017 cm/yr and 0.006 cm/yr respectively. By contrast the Tin Range core analysed in this study had a sedimentation rate of 0.243 cm/yr.

A potential reason for the young nature of the core is the windiness on the island. The average wind speed at South West Cape, a location to the southwest of the study site (Figure 3.6) is 16.5 m/s (59.4 km/hr) (NIWA 2013). The average maximum daily gusts recorded on the island are 80.85 km/hr and gusts as high as 183.6 km/hr are recorded at the South West Cape climate station (NIWA 2013). Given the exposed location of the ridge top from which the core for this study was extracted from, it is likely wind speeds are similarly high at the study site. Although conditions on Stewart Island are quite wet, often with the average rainfall between 2000 and 2500 mm/yr (McGlone & Meurk 2000), the drying influence of the winds on days without rain could lead to dust transport from the peat bog. Hence wind-blown sediment deposited in the bog and peat being formed could be blown away during
dry periods. However, as this does not explain the high sedimentation rate, the wind may be possibly causing overturning of sediment in the core, rather than blowing it all away.

Another potential explanation for the overturned and young nature of the peat core are the activities of burrowing animals on Stewart Island. Burrowing animals that live on the island include the native Kiwi (Sales 2005) and exotic animals such as Norway Rats (Harper et al. 2005). Rabbits were introduced with European settlement before being eradicated from the island between 1948 and 1950 (Department of Conservation 2004). Kiwi habitats are widespread on Stewart Island, including locations from the coastline to alpine environments such as where the studied core was extracted from (Harper 2009). Rabbits and Norway Rats are less likely to inhabit cold, high altitude, alpine environments (Department of Conservation 2004; Harper et al. 2005) and so likely had less impact on the nature of sediments at the study site.

5.3 Variations in Wind Intensity Inferred From Grain Size Results

Whilst the particle diameter of many long-range transported sediments is usually less than 10 µm (Prospero 1999), studies have reported the long-range transport of dust with particle sizes up to 25 µm (Marx et al. 2009b; Jeong et al. 2013). With an average particle diameter of 27.75 µm, the size of dust transported to the Campbell Island study site was therefore close to the upper limit of diameter size for long-range dust transport.

The average particle diameter (Figure 4.22) in the Campbell Island core increased overall since ~5500 cal yr BP, with the exception of decreased particle diameter between ~600 and ~200 cal yr BP. A dramatic increase in overall mean particle diameter occurred after 200 cal yr BP. This overall increase supports claims by other studies of an overall increase in westerly wind intensity since ~5000 cal yr BP (eg. Bowler 1976; Shulmeister 1999b; Shulmeister et al. 2004). The increase in mean grain size after ~200 cal yr BP implies that a fourth potential explanation for the unusually high rates of dust deposition after this time could be due to increased wind strength, allowing the transport of larger particles.
The average particle diameter of the fine grained mode (Figure 4.23) shows a more variable pattern over time. As this mode is closer to the usual size of long-range dust transport (Prospero 1999; Marx et al. 2009b; Jeong et al. 2013), the changing particle size of the mode is potentially a more accurate means of inferring wind intensity. This is particularly because the coarser grained mode is often as large as 300 µm, which is well above the range of sizes of sediment transported long distances in the atmosphere atmospheric dust transport (Prospero 1999; Jeong et al. 2013). The sample sizes did not visually appear to have any individual sediment grains this large, and hence this mode may be attributed to the aggregation of sediments whilst they were being analysed. Similar to the overall mean grain size, the grain size of the fine grained mode has increased overall since ~4500 cal yr BP, supporting claims of increased westerly intensity since ~5000 cal yr BP (eg. Bowler 1976; Shulmeister 1999b; Shulmeister et al. 2004).

Overall, in the first phase of dust deposition, the particle diameter of the fine grained mode was smaller than the rest of the core. This coincided with lower rates of dust deposition. Particle diameter decreased until ~4500 cal yr BP, before it then increased overall for the rest of phase 1, and the rest of the core. Other studies have reported an increase in westerly wind strength starting ~5000 cal yr BP (eg. Bowler 1976; Shulmeister 1999b; Shulmeister et al. 2004), which is similar to the findings of this study. During phase 1, the findings of this study show the ITCZ and westerly winds were located in a more southerly location (compared to present). Grain size results imply this southward position of the westerlies was occurred at a time when the westerlies were weaker than at present (Figure 4.24). This differs from the findings of models which show that, in general, southward migrations of the westerlies are linked to the westerlies being stronger, whilst northward migrations of the westerlies are linked to their expansion and weakening (eg. Varma et al. 2011; Varma et al. 2012).

In the second phase of dust deposition, the results of this study show that when the westerly winds were at this more northern location (as indicated by dust provenance results), they were stronger, also contradicting the relationship of position and intensity noted by Varma et al. (2011; 2012). Varma et al. (2011; 2012) noted that the westerlies generally contract and increase in intensity when they move southward and generally expand and weaken as they move toward the equator.
In phase 3, provenance results suggest the winds were similarly located at a northerly location, i.e. the Lake Eyre Basin was a dust source which implies that the Australian monsoon and westerlies were located further north resulting in dry conditions. Grain size was lowest (~27µm) at the beginning of this phase (~1700-700 cal yr BP). It then increased until ~550 cal yr BP (when it was ~32 µm), after which it decreased again till the present (at ~27.5 µm) (Figure 4.24). This implies intermittent strengthening and weakening of the westerlies over this time. Importantly, the reduction in the fine mode indicates the westerlies decreased in intensity after ~550 cal yr BP, whilst the average mean grain size at this time indicates they were becoming stronger (Figure 4.22). The decrease in the grain size of the fine grained mode over this time period is supported by the decrease in grain size of Australian dust deposited in New Zealand since 900 cal yr BP by Marx et al. (2009b), confirming a likely weakening of the westerlies since 900 cal yr BP.

It is important to note that the sample masses of the Campbell Island core were so small that they were close to the resolution limit of the Mastersizer 4.20 (Figure 4.21). Grain size results from this core therefore need to be treated with caution.

The average grain size of mineral matter in the Stewart Island core was 51.41µm and was therefore well above the usual size range for dusts travelled long distances (Prospero 1999; Marx et al. 2009b; Jeong et al. 2013). This supports the provenance results of this study which also show that local mineral matter made a more substantial contribution to dust in the core than in the Campbell Island core.

### 5.4 Comparison of the results of this study with existing records

Overall, the results of this study are generally in agreement with previous studies of Australian dust emissions during the mid to late Holocene (eg. Marx et al. 2009a; Marx et al. 2011). The timing in the changes in rates of dust deposition through time, dust provenance and grain size reported in this study broadly match those of Marx et al. (2009b; 2011). Despite this, there is some variability in the timing of deposition phase shifts between these studies. For example, Marx et al.(2009a) reported that the westerlies migrated northward between 4800 and 900 cal yr BP whilst this study proposes that this northward shift began at ~4000 cal yr BP, lasting till the present. Overall, however, the dates are similar. Importantly, the palaeo-aridity conditions inferred from dust deposition for the Lake Eyre Basin are generally in line with
existing palaeoclimate records for this region (Nott & Price 1994; Magee & Miller 1998; Johnson et al. 1999; Magee et al. 2004). Namely, wet conditions between 5500 and 4000 cal yr BP, largely dry conditions between ~4000 and 1700 cal yr BP and the dry and variable climate condition since 1840.

The results of this study can also be compared to the results of studies which have used a variety of methods in a variety of locations. This study implies a southward displacement and/or weakening of the westerlies in Australia during the mid Holocene (~5500–~5000 cal yr BP) as was similarly suggested by Moros et al. (2009) using oxygen-isotope records of planktonic foraminifer species in a deep sea sediment core off South Australia. Whilst Moros et al. (2009) did not differentiate between changes in position and intensity, the results of this study imply that the westerlies were displaced southward as well as being weaker. Results from Campbell Island are in disagreement, however, with those of Moreno (2004) and Holmgren et al. (2003) which suggest a northward displacement and/or stronger nature of the westerlies at this time in South Africa.

For the mid to late Holocene (~5000 cal yr BP - present), the results of this study are in agreement with a number of other studies which have implied that the westerlies increased in strength after ~5000 cal yr BP (e.g. Bowler 1976; Markgraf 1993; Shulmeister 1999b; Shulmeister et al. 2004). However, the Campbell Island core implies that the increase in westerly intensity occurred slightly later at~4500 cal yr BP. The northward displacement of the westerlies over the late Holocene reported in this study confirms the results of Lamy et al.’s (2001) geochemical and clay mineral based study in South America. The results of this study, however, disagree with the modelling results of Varma et al. (2012) which suggest that the westerlies were displaced poleward over this time.

Overall, the results of this study do not support the relationship between wind strength and intensity proposed by the modelling results of Varma et al. (2011; 2012). Whilst modelling results have suggested the southern hemisphere westerlies increase in intensity when they move southward and decrease in intensity when they move northward (Varma et al. 2011; Varma et al. 2012), the findings of this study imply that westerly wind strength and latitudinal position can vary independently. For
instance during the first phase of dust deposition reported in this study the westerlies were displaced southward and were possibly weaker than at present.
6. CONCLUSION

The results of this study confirm that the Southern Hemisphere mid-latitude westerly winds have varied in their latitudinal position and intensity since ~5500 cal yr BP. The significant contribution of long-range Australian dust to the total dust deposition in the Campbell Island core, coupled with the age span of this core mean the Campbell Island core yielded useful palaeoclimate proxy data for the purpose of reconstructing past westerly wind regimes. The incoherent age model for the Stewart Island core (and fact the material in the core was so young) and greater flux of local and New Zealand sediments to the Stewart Island site meant this location did not yield useful proxy data for inferring conditions of palaeo-aridity on mainland Australia, and in turn, the position of the westerlies. For this reason, conclusions about westerly wind strength and intensity in this study were based only on proxy data obtained from the Campbell Island core.

Rates of Australian dust deposition and the provenance and grain size of dust in the Campbell Island core pointed toward three key phases of mineral matter deposition and westerly behaviour, which compare well with several existing palaeoclimate records. From ~5500-4000 cal yr BP, the results of this study indicate a southward displacement and weak nature of the westerlies. From ~4000-1700 cal yr BP, results indicate a northward displacement and strengthening of the westerlies. The westerlies remained in their northward location after ~1700 cal yr BP, whilst wind intensity fluctuated. Overall the results of this study are similar to many existing records which suggest an overall northward migration and strengthening of the westerly winds throughout the mid to late Holocene. This study is unique in that changes in westerly position were interpreted separately to changes in westerly position.

Like the proxies used in methods in existing studies, dust provenance is an indirect proxy for palaeo-aridity and the nature of the westerly winds. Palaeo-aridity conditions are used to infer the likely position of the westerly winds, and so many existing reports (as well as the changes reported in this study) are based on the interpretation of these palaeo-aridity records by individual authors. However, as the results of this study compare well with many published reports of varying wind
intensity at this time (obtained from similar studies as well as different studies), the usefulness of dust as a proxy for wind strength and intensity is confirmed.
7. REFERENCES


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