Storm chasing in the Australian Tropics: Is there a record of past tropical cyclones in Lake Eacham?

C Henderson-Matuschka

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Recommended Citation
Henderson-Matuschka, C, Storm chasing in the Australian Tropics: Is there a record of past tropical cyclones in Lake Eacham?, BEnvSci Hons, School of Earth & Environmental Sciences, University of Wollongong, 2018.
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Storm chasing in the Australian Tropics: Is there a record of past tropical cyclones in Lake Eacham?

Abstract
The occurrence of extreme events, such as tropical cyclones, can cause large amounts of landscape and ecosystem disturbance and leave a sedimentary or erosional 'signature' in the landscape. The knowledge of past disturbance events can be incredibly beneficial in deciphering the future responses of these events in a time of climate variability. While there has been considerable focus on the reconstruction of tropical cyclone activity with the use of coastal sedimentary sequences, little attention has been directed in assessing the suitability of paleo lakes as recorders of tropical cyclone occurrences. Maar lakes are considered to be ideal for paleoenvironmental investigations as the sediment sequences collected in their basin can be likened to continuous archives of the environmental history of the lake and its surrounds. This study proposes that Lake Eacham (17°17’S, 145°37’E, 746m.a.s.l.), a maar lake located on the Atherton Tablelands in Northeast Queensland, contains a ‘signature’ of tropical cyclones in its sedimentary record and is a likely candidate for future investigations to construct a record of past-tropical cyclone events for the region. To identify a tropical cyclone ‘signature’, Itrax XRF, grainsize and Loss-On-Ignition analyses data was used produce a facies classification for the 40cm sediment sequence collected from the lake. The analysis of the impact of past tropical cyclones from historical climate data was also undertaken to identify events that had impacted Lake Eacham. A sediment-influx signal characterised by increased grainsize, peaks of detrital elements (Fe, Si, Rb, Ti) and reductions in organic content was evident in facies units which were associated with tropical cyclone activity. However, the relationship between the response of the catchment and tropical cyclones is significantly more complex than first assumed. Considering this, there is indeed an observable tropical cyclone ‘signature’ within the stratigraphy of Lake Eacham, however further investigations will allow for greater understanding into the non-homogenous response of the catchment to such events.

Degree Type
Thesis

Degree Name
BEnviSci Hons

Department
School of Earth & Environmental Sciences

Advisor(s)
Sam Marx

Keywords
tropical cyclones, ecosystem disturbance, sedimentary or erosion, Maar lakes

This thesis is available at Research Online: https://ro.uow.edu.au/thsci/166
Storm chasing in the Australian Tropics: Is there a record of past tropical cyclones in Lake Eacham?

By

Christopher Henderson-Matuschka

A research report submitted in partial fulfilment of the requirements for the award of the degree of

BACHELOR OF ENVIRONMENTAL SCIENCE (HONOURS)

SCHOOL OF EARTH AND ENVIRONMENTAL SCIENCES, FACULTY OF SCIENCE, MEDICINE AND HEALTH

THE UNIVERSITY OF WOLLONGONG NSW, AUSTRALIA

October 2018
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Christopher Henderson-Matuschka

23rd October 2018
Acknowledgements

Firstly, a huge thank you must go to my university supervisor: Sam Marx, who never ceased to provide encouragement, ideas and brilliant feedback throughout the year.

Thank you to my supervisor from ANSTO, Craig Woodward, for firstly collecting the core, and then trusting it in my hands to tell its story. It was an incredible way to spend the past few months working on it. Thank you for guiding me through the lab work and data analysis throughout the year and always creating a relaxed environment to work in.

Thank you to the rest of the lovely people I had the pleasure of sharing a workspace at ANSTO, it seemed there was an endless supply of cake at morning tea every time I was up. Thank you to Patricia for everything involved with the ITRAX analysis. Thank you to also to Sabika and Atun for your guidance in the labs during the core dating processes.

Thank you to my family and friends for checking up on me and encouraging me to keep at it throughout the year.

Finally, to my fellow honours students, thank you for making this year enjoyable, it was an a pleasure to study around you all.
Abstract

The occurrence of extreme events, such as tropical cyclones, can cause large amounts of landscape and ecosystem disturbance and leave a sedimentary or erosional ‘signature’ in the landscape. The knowledge of past disturbance events can be incredibly beneficial in deciphering the future responses of these events in a time of climate variability. While there has been considerable focus on the reconstruction of tropical cyclone activity with the use of coastal sedimentary sequences, little attention has been directed in assessing the suitability of paleo lakes as recorders of tropical cyclone occurrences. Maar lakes are considered to be ideal for paleoenvironmental investigations as the sediment sequences collected in their basin can be likened to continuous archives of the environmental history of the lake and its surrounds. This study proposes that Lake Eacham (17°17’S, 145°37’E, 746m.a.s.l.), a maar lake located on the Atherton Tablelands in Northeast Queensland, contains a ‘signature’ of tropical cyclones in its sedimentary record and is a likely candidate for future investigations to construct a record of past-tropical cyclone events for the region. To identify a tropical cyclone ‘signature’, Itrax XRF, grainsize and Loss-On-Ignition analyses data was used produce a facies classification for the 40cm sediment sequence collected from the lake. The analysis of the impact of past tropical cyclones from historical climate data was also undertaken to identify events that had impacted Lake Eacham. A sediment-influx signal characterised by increased grainsize, peaks of detrital elements (Fe, Si, Rb, Ti) and reductions in organic content was evident in facies units which were associated with tropical cyclone activity. However, the relationship between the response of the catchment and tropical cyclones is significantly more complex than first assumed. Considering this, there is indeed an observable tropical cyclone ‘signature’ within the stratigraphy of Lake Eacham, however further investigations will allow for greater understanding into the non-homogenous response of the catchment to such events.
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1 Introduction

1.1 Introduction

There has been considerable scientific effort put into reconstructing the frequency and magnitude of previous extreme weather events outside of current weather records, i.e. reconstructing extreme weather events occurring before historic and/or instrument climate records. Extreme events can cause large amounts of landscape and ecosystem disturbance and leave a sedimentary or erosional “signature” in the landscape (Nott, 2004). The knowledge of past extreme weather events can be used to decipher the future responses of climate in certain regions; especially in the present-day climate where it is expected that climatic variability and increases in extreme rainfall, temperature and drought will continue intensify (Page et al., 2010; Pachauri & Reisinger, 2007). Paleoenvironmental research has been undertaken in Australia in attempts to fill this gap in the knowledge of the past climate of Australia. Extensive tropical cyclone records have been created in Australia using coastal sedimentary sequences (Nott, 2011; Hayne & Chappell, 2001) while other research has focused on changes in pollen assemblages (Haberle, 2005; Shulmeister, 1999) and corals (Hendy et al., 2002), to determine the behaviour and influence of past climatic regimes on the Australian continent at regional scales. To add to this body of research within Australia, this thesis examines the suitability of a paleo lake sediments as recorders of tropical cyclones, with the focus of identifying the ‘fingerprint’ that tropical cyclones may leave in the form of signature facies within the lake stratigraphy.

Paleo lakes are ideal for investigations into past environmental conditions as they continuously accumulate sediments from their respective catchments and surrounds since their formation. The sediments collected in lakes can give great insight into the lake itself and its catchment by collecting biological remains, soils, other non-biological material from the catchment and the atmosphere (Bigler, 2007). Maar lakes are considered to be key-sites for paleoenvironmental studies as their sediments can provide high-resolution records of landscape and climate changes over long-term climatic cycles due to their relatively low sedimentation rates (Chassiot et al., 2018). These sediment sequences revealed in lakes can be likened to continuous archives of the environmental history of the lake itself and surrounds.

On the Atherton Tablelands in Northeastern Australia (17°20’S, 145°35’E), many maar craters are located across the landscape, which have now been filled by rainwater and have become maar lakes. Their formation is estimated to be of Quaternary age (Walker, 1999). Lake Eacham, the subject of this thesis, is one such maar lake located on the Atherton Tablelands, 8.5km northwest of the town of Malanda, QLD (17°35’S, 145°59’E). Like many maar lakes it no inflowing or outflowing streams, with
only small gullies delivering water to the lake during periods of high rainfall. The relatively undisturbed crater-rim and catchment, time of formation (within the Quaternary), sediment collecting characteristics combined with well documented and frequent tropical cyclone occurrences as well as extensive regional climatic records make it a likely candidate for extensive investigations into the construction of a record of past-tropical cyclone events for North Queensland.

Stemming from the characteristics of lakes and their often-continuous accumulation of sediments, the generalised hypothesis of the modes in which materials enter Lake Eacham and how these are deposited on the lake floor are depicted below (Figure 1). Muds and silts are deposited and accumulate on the lake floor during normal climatic conditions which can then be punctuated by coarser sands and plant fragments as result of disturbance events, such as tropical cyclones. During the process of extruding LEA3 from its’ casing, noticeable changes in the characteristics of sediment were observed. This included identification of sandy units abundant with plant fragments. By contrast, other units where comprised of fine muds and silts. The general composition of lake-bed sediments typically includes a heterogenous sediment matrix consisting of fine-grained clay and silt, siliceous materials as well a variable amounts of organic matter including leaves, wood and seeds (Lowe & Walker, 1997) (Figure 1A.). Coarse-grained layers, as observed in Eacham, potentially reflect high-energy sediment influx conditions due to the hydrodynamic relationship between the energy of discharge into lakes and the presence of coarser particles, as is often used as a proxy of paleoflooding in larger lakes with more extensive catchments and inflows (Schillereff et al., 2014). In the case of Lake Eacham, it’s very small catchment, and location in Northern Queensland imply these events are likely to reflect Tropical Cyclones.

Tropical cyclones have the potential to provide the mechanisms involved in depositing these observed sand layers and plant fragments due to the high intensity rainfall and severe winds that can be generated by such a system (Figure 1B.). The clastic material observed in the sandy layers of LEA3 show that Lake Eacham can be considered as an efficient repository for material eroded from the surrounding catchment in varying conditions. The relationship between the specific particle sizes and discharge, when considered against sedimentary records of lake basins, should enable the identification of large magnitude influx events as they are expected to appear as distinct layers of coarse material (Schillereff et al., 2014) (Figure 1C.). For this investigation, I consider this hydrodynamic relationship, but on a much smaller scale due to the absence of dedicated inflow streams into Lake Eacham, to investigate the hypothesis that these sandy layers and the organic materials also present within them represent disturbance resulting from tropical cyclone events.
1.2 Aims and Objectives

The aim of this study is to develop a record of past tropical cyclones from Lake Eacham and in doing so provide a long-term record of tropical cyclone activity in Northeast Queensland. The key objectives of the results of this study are to:

Figure 1: Generalised process of expected sediment delivery to Lake Eacham. Lake dimensions and sediment thicknesses are not to scale. (A.) Initial sediment characteristics during normal climatic conditions. (B.) Expected influx of organic materials and coarser sediments from tropical cyclone events due to the high intensity winds and rainfall. (C.) Hypothesised sedimentary sequence formed by the interplay of periods of calm climate activity and tropical cyclone occurrences.
• Analyse the core collected from Lake Eacham (LEA3) for various sedimentary, geochemical and biological proxies alongside historical climate data to identify a tropical cyclone signature and subsequently reconstruct a record of past tropical cyclone events for the region.

• Based on these finding above, decide on the suitability of the use of Lake Eacham for the reconstruction of tropical cyclone records and the potential for further investigations in this field to occur.
2 Literature Review

2.1 The Paleoclimate of Australia during the mid-to-late Holocene

Prehistoric storm events, including tropical cyclones, can be investigated in sedimentary systems such as lakes through use of geological and biological proxies. These can be used to establish a record of tropical cyclone frequency and intensity over past time periods. This assists in establishing longer baseline climate data trends by extending on the current, and relatively short, observational records that are currently available, which in Australia are generally <100 years in length. In addition to this, the relationships between tropical cyclone activity and climate variability can also be investigated, including the influences of teleconnections such as the El Niño Southern Oscillation (Walsh et al., 2016). By identifying the variations within tropical cyclone regimes and mechanisms in the past, more confident predictions of future storm regime and behaviour can be inferred which will greatly assist future risk assessments and identification of impacts on communities that may be affected by these storm events (Nott, 2004). Investigations of climate during the Holocene can provide crucial insight into the mechanisms controlling the Earth’s climate as this is understood to be a time comparatively stable boundary conditions (Gliganic et al., 2014), leading to better understandings of the variability of climates and the causes of short-term oscillations of climatic parameters. Climate variabilities in the Southern Hemisphere during the Holocene period have been investigated with the use of a wide range of environmental proxies including, but not limited to, tree rings (Cook et al., 1992), corals (Hendy et al., 2002; Gagan et al., 1998), lake cores (Mooney, 1997) and speleothems (Bar-Matthews et al., 2010).

Studies such as these not only contribute to understanding past climatic conditions, they can also form the basis for comparison of conditions both before and after major human interferences to highlight the extent to which humans have modified existing climate systems (Roberts, 2013).

2.1.1 Generalised Paleoclimate in Northern Australia during the Mid-to-Late Holocene

The Mid-to-late Holocene is of interest in understanding the Earth’s past climate characteristics and conditions as it was time of moderately stable boundary conditions (Wanner et al., 2008). Any variation in boundary conditions, such as the amounts of insolation received during the winter months, can have a considerable controlling effect over the positioning of the Intertropical Convergence Zone (ITCZ), a key driver of Australian monsoon intensity (Kuhnt et al., 2015). Several studies using both pollen and/or palaeohydrology have been undertaken to understand the past climatic conditions during the Holocene epoch, with a focus on sites on the Atherton Tablelands (Kershaw & Nix, 1988; Hiscock & Kershaw, 1992; Haberle, 2005). Maximum effective precipitation (EP) in Northern Australia occurred around 5000 BP with this period characterised by precipitation values...
200-1000mm higher and increases in temperature of 1-2°C from present-day values (Kershaw & Nix, 1988). Shulmeister (1999) also shows that Northern Australia experienced a precipitation maximum after 5000 years BP, marking the enhancement of the Walker Circulation system and commencement of modern El Niño – Southern Oscillation (ENSO) activity. A shift to more frequent ENSO activity resulted in drier conditions across Queensland (Turney & Hobbs, 2006).

Pollen records from Lake Euramoo, also a maar lake located roughly 14km to the North of Lake Eacham in the highlands of the Atherton Tablelands, give an impression of past climatic conditions through the processes by which rainforest development had occurred in the region. From 5000-70 BP, the pollen assemblages reflect dryer, subtropical rainforest communities in response to warmer temperatures (Haberle, 2005). Infrequent but significant burning events (fires) resulted in a cycle of charcoal peaks occurring within the stratigraphy of the lake every 250-1000 years, signalling increases in disturbance to the surrounding rainforest over this time. Using the climate proxy records from the Western Pacific (Hayne & Chappell, 2001; Shulmeister & Lees, 1995), there is broad confidence in suggesting increased rainforest disturbance by fire events was potentially due to the influences of intensified El Niño Activity post ~5000 BP. The shift of the pollen assemblages from Lake Euramoo towards greater abundance of short-live taxa at this time is thought to represent more frequent El Niño disturbance events through increases in rainforest ecosystem turnover. In addition to this, increases in occupation of the region by aboriginal populations and the resource management techniques they utilised may have also contributed to the more prominent charcoal signals due to increased exploitation and intensification of the use of fire after 4000 BP, as displayed by evidence of swamp disturbance at Lynch’s Crater on the eastern edge of the Atherton Tableland in Queensland (Hiscock & Kershaw, 1992).

As ENSO activity across continued to influence the climate variability in the Late-Holocene, declines in EP in Northern Australia, as detailed in the more drought/fire tolerant pollen assemblages present in the Grotte Eylandt record from the Gulf of Carpentaria, have been indicated to have occurred from 3700 to 1000 BP, before stabilising to modern rainfall values (Shulmeister & Lees, 1995). Other late Holocene climate records convey a period of warm conditions, with greater frequency of El Niño events associated with increased fire occurrences and more pronounced periods of drought alternating with much shorter, wet La Niña events, similar to the oscillation patterns which influence the climate in the present day (Reeves et al., 2013).

2.1.2 The Medieval Warm Period and Little Ice Age events

The Medieval Warm Period (MWP) occurred from approximately 900-1300 AD (Mann, 2002a). This period of climatic history was characterised by the warmer temperatures experienced in Europe and
regions of the North Atlantic that were comparable and may have exceeded the temperatures experienced in the late 20th century (Mann, 2002a). Geological evidence indicates that glaciers throughout the mountains of Europe substantially retreated throughout this time relative to the behaviour of glaciers in later centuries (Grove & Switsur, 1994). This period of warmer conditions terminated as the general climate of the Northern Hemisphere became more moderate into the 15th century. This reduction in temperature led to significant expansion of mountain glaciers, especially in the alpine regions of the Northern Hemisphere between the 16th – mid 19th century. This period is now known to be the ‘Little Ice Age’ (LIA) (Mann 2002b).

Despite there being a considerable bodies of evidence for both the MWP and LIA climatic events in Europe and the Northern Hemisphere, the timing and extents of these is highly variable from region to region, making it difficult to reach confident conclusions in identifying synchronous events in other regions of the world. The is region to region variability is present when identifying evidence for both the MWP and LIA in the Southern Hemisphere, with studies in both New Zealand and South America amounting substantial evidence for the occurrence of these events in these regions (Cook et al., 2002; Lorrey et al., 2008). While only smaller-scale evidence can be demonstrated for either event within Australia (Barr et al., 2014; Marx et al., 2014) However, there are considerable uncertainties in the evidence for the presence of these events in the Southern Hemisphere and how they affected the climate of Australia with substantially more climate records needed to create a more coherent picture of the past climate changes over the last few hundred years (Bradly & Jones 1993).

2.2 Reconstructing past climate events from Lakes

There is considerable potential for records of past tropical cyclone activities to be inferred using sedimentary records collected from suitable lakes however, such records are currently scarce (Knutson et al., 2010). One of the key objectives of this study is to assess the suitability of Lake Eacham to create reconstructions of past tropical cyclone activity in Northern Queensland to assist in growing this body of information. Due to the volcanic origins of Eacham, the duration of time to which this lake has been present in the landscape and its closed catchment characteristics; it was hypothesised that Lake Eacham may contain a valuable record of tropical cyclone events from the mid-Holocene to present. Because of this, it is relevant to review the literature on the signals of paleoclimate and environmental change obtained from lakes. Lake sediments may preserve records of past climatic and hydrological conditions of the regions in which they are located due to their efficiency in acting as repositories for materials eroded from surrounding catchments (Bigler, 2007; Morellón et al., 2011). Due to this, the sediment in lakes may represent continuous environmental archives with a vast array
of proxies available to infer past paleoclimate and paleoenvironmental conditions, including biological, sedimentary and geochemical proxies.

For inquiries of climate-related information obtained from selected lake sediments, accurate dating is essential to provide a reliable chronology to base any further findings upon (Bigler, 2007). In some cases, sediments retrieved from lakes display ‘varves’, annually laminated sedimentary layers which can be utilised in creating an accurate chronology. However, these are not always often present in most environments, therefore additional dating techniques are required to create accurate chronologies. The most widely applied dating methods make use of the radioisotopes of lead ($^{210}\text{Pb}$, half-life 22.3 years) and radiocarbon ($^{14}\text{C}$, half-life 5730 years) (Appleby, 2002; Poluianov et al., 2016). Due to their respective half-lives, each method can only be used in certain conditions whereby $^{210}\text{Pb}$ dating can be applied to sediments <150 years old while $^{14}\text{C}$ dating is applicable for ages up to ~50,000 years. Combination of these two methods can, in some cases, produce relatively accurate age/depth models for sediments accumulating in lakes.

There are many opportunities to utilise some of the physical and geochemical properties of sediments as they can be related to various climatic variables (Bigler, 2007). The thicknesses of annually occurring layers (varves) in lakes can give insight into past rates of productivity or erosional inputs from lake catchments and be utilised in producing accurate chronologies as mentioned above (Bigler, 2007; Yamada, 2017). Textural analysis of the sediments in paleo lakes such as mineralogical compositions and grain size can yield insights into the origin and potential trajectories of material deposited into lakes. In paleoflood investigations, there are observed hydrodynamic relationships between particle size and discharge energy, resulting in the deposition of layers of coarse material which can be identified as higher-magnitude sediment influx events (Schillereff et al., 2014) or possibly events of large-scale disturbances. In addition to sedimentary analysis, the amounts organic content throughout the stratigraphy of paleo lake basins can indicate changes in the abundance of surrounding vegetation and thus, soil formation with the possible flow-on effects in changes erosion rates and the geochemistry of deposited materials to the lake, thus forming the basis for extensive multi-proxy evidence of past climates for some lakes (Chassiot et al., 2018). In addition to the physical and geochemical characteristics of paleo lake sediments, there are a wide range of biological indicators within lake sediments that can be utilised as indicators of past climate and catchment environments.

These can include but not limited to plant and invertebrate macrofossils and pollens, which have been deposited throughout during the existence of the lake (Bigler, 2007). Macrofossils within lake sediments assist in reconstructing the paleoenvironment and vegetation species abundance for lake catchments through leaves, pollens and other parts of vegetation that may have entered lakes over
time through various taphonomic processes (Figure 2). With the identification of these fragments of vegetation and pollen assemblages that may also be present in lake sediments, identification of individual plant species is possible and in turn, possible predictions of the climatic conditions, such as the temperature and effective precipitation at that time can be made (Birks, 2001; Haberle, 2005). Terrestrial macrofossils that have been successfully deposited and preserved in lake sediments can also be utilised to assist in creating accurate chronologies for paleolake sedimentation as some deposited macrofossil material is suitable to undergo AMS radiocarbon dating (Birks, 2001) as was the case in this study of Lake Eacham.

![Figure 2: Illustration of the taphonomic processes allowing the preservation of plant macrofossil assemblages in a generalised lake setting (Source: Birks, 1980)](image)

2.2.1 Similar research case studies on other lakes and their responses to change

There is a large body of research in the field of paleoclimatology centred around the collection and investigation of sedimentary records from suitable lakes around the globe, as changes in geochemical and grainsize characteristics and other proxies reflect the responses of lakes to change. Lake Keilambete, a maar lake in south-western Victoria, Australia, has been subject to extensive research concerning the climatic oscillations of the last 2000 years through the results of pollen, charcoal, total carotenoids, magnetic susceptibility and composition of lake sediment investigations. In the period from 2000 to 1880 cal. BP, De Deckker (1982) describes a shift to higher sustained water levels for lake when compared to the lower levels from previous millennium. Suggestions of a period of higher levels of effective moisture in this time are confirmed as increased pollen concentrations of rush-like flowering plants and ferns display the response of vegetation in the surrounding catchment to a new climatic regime (Mooney, 1997). Increases in microscopic charcoals from 1880 and 1750 cal. BP can suggest additional occurrences of fires and a shift to a drying climate. In this same period, the representation of *Acacia* pollen also reflects the shift to dryer woodland communities within the surrounding catchment. As noted by Beaton (1983), the Aboriginal populations in south-western
Victoria were stable during this time and may be responsible for the increase in fire activity and therefore, a possible stimulus for increased representation of *Acacia* in the local catchment.

Lake Tutira, a closed lake on the North Island of New Zealand is such a lake containing a high-resolution sediment record of both natural and anthropogenically-induced changes of climates. There is comprehensive research at this lake linking the terrigenous deposits found in the lake as direct responses to rainfall-induced erosion from the surrounding, landslide-prone, watershed (Page et al., 1994). A sedimentary record of Cyclone Bola (1988), a large ex-tropical cyclone that caused extensive damage across New Zealand, was preserved in the lake, alongside a series of other similar major storms. The stratigraphic sequences identified in the core taken from Lake Tutira were matched to recent chronology through the analysis of storm rainfall records, pollen and diatom analyses, earthquakes and the onset of eutrophication in the lake (linked to land clearing).

The distinct stratigraphic sequences of the cores extracted from Lake Tutira reflect the landscapes response to change with 4 key sequences identified in Page et al., (1994). From the top of the core, large storms in 1988 and 1985 produced graded bedding sequences while the calmer periods before this sequence consisted of thin clay layers deposited during near-annual events. These layers alternate with black gyttja, formed due to decreases in water quality, growths of algae associated with eutrophication and the introduction of weeds to the vegetation surrounding the lake. A period of rapid events of sedimentation return with numerous examples of storm events through the formation multiple of graded beds. These sequences coincide with the conversion of large parts of Lake Tutira’s catchment to pasture during the arrival of Europeans and subsequent settlement in the 1880’s. These large pulses of sediment are believed to reflect the responses of the catchment to considerable changes in vegetation and land-use due to settlement of the region, as the sequence below that precedes this reflects pre-settlement conditions with lower sedimentation rates and reduced frequencies and size of graded beds within the lower section of the core. Lake Tutira has been the subject of an ongoing multi-disciplinary study to reconstruct and understand the long-term erosion history of the lake’s watershed (Trustrum & Page, 1992). This aids in gaining knowledge of the roles that storm events play in landscape evolution and the effects that land use and vegetation change has on sedimentation rates, and the responses of landscapes to both natural and anthropogenically forced changes in climate (Page et al., 2010).

Another example where lake sediments have been used to investigate the past comes from Lake Tirara on Mangaia in the Cook Islands. Analysis of a 4.3 metre peat sequence collected from the lake revealed insights into both long-term and short-term environmental changes over the last 3500 years, supported by variations in elemental profiles, grainsize data and diatom assemblages (Chagué-Goff et
Changes in the elemental profiles throughout the peat sequence enabled the distinction of biogenic and detrital phase responses, variations in organic matter and the identification of elements of marine origin in the lake. Steady increases in the amounts of clay associated with higher counts of detrital elements reflect the response of Lake Tirara to a period of increased erosion possibly due to the onset of human colonisation and/or more intense chemical weathering associated with a shift to a wetter climatic period. The peat sequence also recorded short-term events including tropical cyclones and/or heavy rainfall events. Broad peaks in detrital elements Iron (Fe), Silicon (Si), Rubidium (Rb) and Titanium (Ti) accompanied notable influx of sands and diatom assemblages dominated by freshwater species. While the occurrences of tropical cyclones and the associated responses of Lake Tirara as a result is specific to its surrounding environment of steep hills and weathered volcanic cone surroundings, the investigative approach undertaken by this study could be used to identify various input events of both material through both geochemical and microfossil signatures recorded within the lake (Chagué-Goff et al., 2016).

2.3 Past Tropical Cyclone Records

Studying prehistoric tempests or storms is known as Palaeotempestology which encompasses the investigations of major storm events which have occurred before documented climatic records (Walsh et al., 2016). Studies of this nature focus on reconstructing past extreme events by examining sedimentary evidence in the landscape, including storm deposits, or erosional impacts resulting from storm surges and wave action in coastal environments. With increasing attention in this field regarding the benefits of comparing regional climates pre and post anthropogenic disturbances, the numbers of tropical cyclone records that are being produced are becoming widespread, including studies in tropical Australia (Hayne & Chappell, 2001), southern and eastern United States (Liu & Fearn, 1993; 2000) and through the south Pacific islands (McLean, 1993). Records have been constructed by utilising both isotopes and sedimentary characteristics. (Nott, 2011). In some cases, the magnitudes of past storms can be estimated along with their frequency (Nott & Hayne, 2001). Although, as noted by Nott (2004), a large proportion of existing records tend to have been self-censored, whereby only the most extreme events have been recorded while evidence of others is destroyed by the most extreme events. Despite this, the long-term insights provided by these studies can give information on the frequencies of tropical cyclones or extreme storms in different regions while also determining whether the natural oscillations in the various mechanisms driving Earth’s climate have altered the frequency regimes of these events.

From an Australian perspective, the reconstruction of tropical cyclone events in both Northeast Queensland and Western Australia have largely been focused on the analysis of parallel sand beach
ridges believed to have been formed during cyclonic events where wave action and ocean surges combine to transport coarse sediments onto the coastline and deposit this above normal tidal levels. From these events a series of parallel ridges can accrete, with the ridge ages decreasing from the most landward ridge towards the coastline. Studies undertaken in Australia at various locations including Shark Bay, Western Australia (Nott, 2011) and both Curacoa Island and Cowley Beach in Northeast Queensland (Hayne & Chappell, 2001; Nott et al., 2009) have focused on dating the time of formation of sand beach ridges as they are perceived to be indicators for the occurrence of tropical cyclone events. Events responsible for ridge formation at Shark Island were believed to be between categories 2-4 in strength. The ages collected from the ridges, formed over a 6000-year period, form an average occurrence interval for moderately intense tropical cyclones of 190 to 270 years, which is believed to be a similar interval to tropical cyclone activities recorded in Northeast Queensland (Nott, 2011).

Based on the 5000-year Curacoa Island record, that the rate of progradation and frequency of tropical cyclone deposits had not changed over this time span. There is some paleoclimatic evidence suggesting that changes in climate had occurred over this time-period, characterised by warmer and wetter conditions between 4000-7000 years ago with sea temperatures also about 1°C warmer (Kershaw 1983; Gagan et al., 1998), raising questions over the extent to which such changes in climate can effect tropical cyclone frequency and intensity, which is particularly relevant to the present trends of global warming (Hayne & Chappell, 2001). While no change in overall tropical cyclone frequency was observed at Curacoa Island, the record obtained from Cowley Beach record indicates that high intensity tropical cyclone events have occurred more frequently than previously implied by the short historical tropical cyclone record (Nott et al., 2009), giving early indications of the possible impacts on tropical cyclone activity when the paleoenvironmental evidence noted above is considered. The incorporation of more records constructed from similar ridge formations, if available, on both the Northeastern and Northwestern coastlines of Australia regularly impacted by tropical cyclones will aid to build further understanding of the frequencies and intensities of tropical cyclone events on regional scales than what can be currently extrapolated from current limited historical records (Nott et al., 2009).

Currently, studies into the prehistoric records of tropical cyclones are largely restricted to the latter half of the Holocene period (last 5000-6000 years) as is the case for the records reported above. These studies are limited to the period where sea-levels were similar to current levels, causing any tropical cyclones preceding this time to form at lower sea levels, making it likely that any sediment deposits associated with these previous events were likely to have been disturbed during the sea-level rises during the Holocene (Nott, 2004). Investigations of tropical cyclones in lakes, however, which are not directly affected by sea level rise, have the ability to extend tropical cyclone records.
3 Study Area

3.1 Regional Setting

Lake Eacham (17°17’S, 145°37’E, 746m.a.s.l.) is a maar lake, that is – a volcanic crater lake. It is located 65km South-Southwest of Cairns, QLD Australia on the Atherton Tablelands (Figure 3). The lake has been included within the Wet Tropics World Heritage Area (since 1988), and now forms part of the Crater Lakes National Park which includes nearby Lake Barrine. Despite only being 0.5 km\(^2\) in area, the maximum depth of the lake is relatively deep at 63m. The crater rim is characterised by a mean height of 36m with its inner rim creating a small catchment of 0.29 km\(^2\) relative to the area of the lake. Almost all the catchment is covered by rainforest except for a small portion allocated for tourist amenities and recreational facilities. The catchment slope has an average gradient of 18° (Walker, 1999). There are no streams into or out of Lake Eacham. Water in the lake may be lost into underlying rock units, through the crater wall or by evaporation (Walker, 1999). Water levels do not remain stable within the Lake as there is fluctuations of up to 4 metres between the wet and dry seasons (Walker, 2000; DNPSR, 2012–2018).

![Figure 3: Regional setting of Lake Eacham in Northeast Queensland (Source: Breuer et al., 2000)](image_url)
3.1.1 Settlement and Land practices of the region

The southern region of the Atherton Tablelands was first settled by Europeans in 1886 AD after a preliminary survey conducted in that year. Based on this, the region was subdivided into a series of farm blocks and settled. Shortly after, the natural beauty and recreational significance of the Lake Eacham was realised and in 1888, was proclaimed a scenic reserve, which resulted in the vegetation of the crater’s inner rim remaining virtually undisturbed, reserved from vegetation clearing activities (Walker, 1999). Powered boats were used on the lake until 1934 when the lake and surrounding forest became a national park. While boating activities ceased, development of the shoreline with small jetties, diving platforms, changing facilities and recreational areas were constructed from 1943 onwards by the Commonwealth of Australia for use by Australian Military Forces personnel and members of the public (DNPSR, 2012–2018). The forests in the region surrounding the lake was initially cleared for agricultural uses, but the catchment of the lake itself was not subject to any serious clearing or disturbance. This was due to difficulties in timber harvesting in times of early settlement of the area and subsequent protection legislation (Walker, 2000). Today, Lake Eacham and its surrounding catchment remain protected from clearing within the Crater Lakes National Park. Much of the land in the region has been developed for agricultural including Banana, Avocado, Mango and Sugar production as well as for beef and dairy cattle. In 2015, the gross value production for the regions industries was over $552 million. (Department of Agriculture and Fisheries, 2015).

3.1.2 Climate

The climate of tropical northern Australia is greatly influenced by the interaction between the Australian Summer Monsoon (AMS) and the south-east trade winds (Suppiah, 1992). The Atherton Tablelands experience hot and humid summers and mild dryer winters with the mean annual rainfall at Malanda, QLD (17°35’S, 145°59’E, 8.5km southwest of Lake Eacham) 1680mm. The dominant source of precipitation for the region is the Southeast Trades which are occasionally interspersed by northwesterly monsoonal flows and associated tropical cyclones which result in highly intense, but infrequent rainfall events during the summer months when the intertropical convergence zone (ITCZ) shifts to its’ most southerly extent (Godfred-Spenning & Reason, 2002). From December to March, the monsoon trough is relatively close to the area of Lake Eacham resulting in hot humid conditions that increases risks of thunderstorms developing on the inland ranges and formation of tropical cyclones in the Coral Sea. This period is responsible for mean minimum and maximum temperature ranges between 18 and 29˚C and monthly mean rainfall totals between 151 and 348mm. This period is responsible for over 80% of the annual mean precipitation totals for regions of the Australian Tropics (Bureau of Meteorology, 1988a). Between May to October the region is under the influence of the
sub-tropical ridge bringing milder and dryer conditions. Winter is characterised by mean minimum and maximum temperatures between 10 and 27°C with frosts occurring occasionally in times of weak trade winds and low cloud cover. Rainfall is considerably less with monthly mean rainfall totals ranging between 19 and 59mm. The tropical cyclone season is usually confined between December and April with majority of tropical cyclone impacts recorded in North Queensland (Bureau of Meteorology, 1988a). Under the influences of El Niño events, significant decreases in summer precipitation occurs, with totals typically 150-300mm below the seasonal averages due to the northward movement of the ITCZ (Dai and Wigley, 2000).

3.1.3 Vegetation

There is a well-marked zonation of emergent plant species around the margin of Lake Eacham, that is within the crater. At the water’s edge, bands of Phragmites can be observed with Colocasia and Hibisus populating the inner landward zone around the lake. On the inner crater rim, the moderately fertile basaltic soils host a complex notophyll vine forest (Tracey, 1982) characterised by varying trunk sizes and canopy levels with many epiphytes and vines. Species associated with this type of forest can include Flindersia bourjotiana, Austromuellera trinervia and Grevillea baileyana. In the wider region around Lake Eacham, the soils transition to less-fertile soils; resulting in changes to the characteristics of vegetation. The rainforest that covers the region around Lake Eacham is considered more structurally ‘simple’ with an Acacia spp. canopy and other emergent species. Low species diversity and uniform trunk sizes are also noted as the forests recover from past disturbance vegetation clearing (DNPSR, 2012–2018). Most of the forest that is present around Lake Eacham is protected within the boundaries of the Crater Lakes National Park and has escaped major disturbance due to the land-clearing and subsequent agricultural activities that have encroached close to the lake during settlement of the area (Walker, 1999).

3.1.4 Geology

The region in which Lake Eacham has formed is part of the Atherton Basalt province which Stephenson et, al., (1980) believe to be of Tertiary to Quaternary in age. The mineralogy of this basalt is predominantly clinopyroxene, plagioclase and olivine. The volcanic basalts which makeup this province erupted over a variety of basement rocks of Devonian to Early Permian age, including metamorphosed sediments and granitic rocks (Locsey & Cox, 2003). Additional volcanic activity has occurred in the region leading to the formation of a series of maar lakes which now dot the landscape of the Atherton Tablelands, including Lake Eacham. The formation of a maar lakes is the result of activity from maar-diatreme volcanos. These volcanos form when magma begins to rise through
feeder dykes towards the surface. As the magma continues to rise closer to the surface it can interact with groundwater, creating an explosion and eruption which breaks through the surface and forms a crater (Lorenz, 2003). Following the eruption, the maar crater fills with groundwater and surface water due to the undercutting of the previous valley floor (Figure 4) (Lorenz, 2003). The eruption and formation of the maar crater in which Lake Eacham now lies is estimated to have occurred 12,000 years ago (DNPSR, 2012-2018).

Figure 4: Schematic diagram of a maar-diatreme volcano showing its feeder dyke, root zone and overlying cone-shaped diatreme (Source: Lorenz, 2003)
4 Methods

4.1 Core Collection and Sampling

One core was collected from Lake Eacham (17°17’S, 145°37’E, 746m.a.s.l.) in Northern Queensland, Australia on the 14th of June 2011. The 40cm LEA3 core was collected from the middle of lake at a depth estimated to be ~60 m using a Gravity Corer. Gravity corers are designed for use in areas of soft, unconsolidated sediment, relying on its own weight for substantial penetration via freefall into the lake floor. Once the corer had reached the lake floor, a small weight was released down the cable tethered to the corer to close an air valve to create a vacuum to subsequently pull the captured sediment back to the surface of the lake. The LEA3 core was then extruded and subsampled at 0.5cm intervals on the shore of Lake Eacham using an extrusion plate and spatula to scrape sediment into Whirl-paks® sample bags. The first 1cm of this core was utilised for analysis of chironomids shortly after collection and was not available for use in this study. The remaining samples were kept sealed and chilled until further analysis of the sediment began in June 2018.

4.2 Chronology

The chronology of LEA3 was determined using 210Pb activity through alpha spectrometry for the last ~150 years and Accelerator Mass Spectrometry (AMS) STAR accelerator radiocarbon dating (14C) for macrofossil samples. These dating techniques were performed using the lab facilities at ANSTO. The results from these were then compiled to produce an age depth model for the LEA3 core

4.2.1 210Pb Dating

A total of 13 subsamples were taken from LEA3 for 210Pb dating. For each subsample, approximately 1.5 g of dry weight sample was analysed to determine 210Pb decay profiles using the alpha-spectrometry at ANSTO. The technique of 210Pb (half-life 22.3 years) dating allows for the dating of recent sediments (0-150 years) (Appleby, 2002). The activities of these sources are can be determined using the alpha spectrometry to calculate the decay in excess 210Pb activities to determine the rate of sediment accumulation. The change in 210Pb activity was determined by measuring the total activity of 210Pb and its two components, the ‘supported’ and ‘unsupported’ 210Pb activity in the subsamples. Supported 210Pb activity is assumed to be in secular equilibrium from the concentration parent radionuclide 226Ra, while unsupported 210Pb activity is derived from atmospheric flux (Appleby, 2002), where supported 210Pb is determined from measured 226Ra activity and total 210Pb from its granddaughter 210Po. Ages were determined using both CIC (constant initial concentration) and CRS (constant rate of supply) age models. Comparisons were made between the two with the CRS ages
utilised in the age/depth model as the unsupported $^{210}$Pb decay curve was non-monotonic (Binford, 1990).

4.2.2 $^{14}$C Dating

Leaf and twig fragments were obtained from 2 subsamples of LEA3 at 20.75 and 34.25cm to undergo radiocarbon analysis by Accelerator Mass Spectrometry. Before undergoing analysis, the subsamples were pre-treated using the acid – alkali – acid (AAA) protocol before radiocarbon analysis on the STAR accelerator at ANSTO. Radiocarbon dating is a widely used method for determining the ages of materials up to ~ 50,000 years. Carbon-14 ($^{14}$C) is a radioactive isotope of Carbon and is produced in the upper atmosphere in neutron form as a product of cosmic rays. The interaction of these neutrons with oxygen results in the formation of carbon dioxide which is then distributed into the food chain through use by plant life during photosynthesis on the Earth’s surface. Through this, $^{14}$C is constantly being exchanged throughout the environment through plants and animals until an organism dies. At this point, exchange of $^{14}$C ceases and remains within the organism, making it possible to date the age of $^{14}$C due to its radioactive decay at a half-life of 5730 years (Poluianov et al., 2016). The radiocarbon ages determined for this study were calibrated using the Southern Hemisphere SHCal13 calibration curve (Hogg et al., 2013). As discussed later, the ages returned from this were eventually excluded from use in the final age model for the core. The percentages of modern carbon >97% and the $^{14}$C ages associated with this meant the $^{14}$C cal. BP ages derived from the SHCal13 calibration curve were associated with large ranges of uncertainty, impacting on the reliability of the later created age/depth model.

4.3 Loss-On-Ignition

A total of 78 subsamples of 1 cm$^3$ were taken from each 0.5cm increment of the LEA3 core for Loss-On-Ignition (LOI) analysis. The LOI analysis procedure involves recording the initial weights of the crucibles to be used. Each subsample was then placed into a specific crucible and then re-weighed. These samples were then dried at 60°C and then re-weighed to determine the moisture content for each subsample. Next, the samples were combusted in a furnace at 550°C for 12 hours. Following this, the samples were then re-weighed and then transferred to small vials for storage. From the weights recorded, the percentages of organic content for each sample could be calculated. The results of this were interpreted in Microsoft Excel then displayed visually using the “C2” program to show the variation in organic content through the stratigraphy of the LEA3 core.
4.4 Dry Bulk Density

The 78 subsamples used for (LOI) were also used to calculate Dry Bulk Density through LEA3. This was achieved by dividing the total dry weight of sample by the sample volume (1cm³). The results of this were interpreted in Microsoft Excel then displayed visually using the “C2” program to show the variation dry bulk density through the varying stratigraphy of LEA3.

4.5 Grainsize Analysis

Grains size analysis was undertaken on each of the 78 subsamples through Subsamples of approximately 2 cm³ were collected and digested at 60°C using 10% hydrogen peroxide (H₂O₂) solution. This was gradually increased to a 30% H₂O₂ solution to completely dissolve all organic components of the sediment. The samples were placed in an ultrasonic bath for 15 minutes and were then then sieved to remove and collect any clasts >1mm. The clasts collected were counted and a concentration of >1mm clasts was calculated. The digested subsamples were analysed using a Malvern Mastersizer 2000 laser diffraction particle sizer at ANSTO. The statistical analysis of the distributions in particle size was facilitated with the use the GRADISTAT version 8.0 software package for Microsoft excel (Blott, 2010). The results of this were tabulated in excel and then visualised using the program “C2” to demonstrate changes in grainsize throughout the stratigraphy of the recreated core.

4.6 Geochemistry

The geochemical analysis of LEA3 was undertaken using the Itrax micro-XRF Core Scanner at the Institute for Environmental Research, Australian Nuclear Science and Technology organisation (ANSTO). The scanner has the capability to rapidly and conveniently acquire data for important physical and chemical properties for sediment cores without being destructive. Before elemental detection, each Whirl-pak® bag containing 0.5cm interval sub-samples were subject to X-radiography to initially determine the abundance of large clasts that may be present in the various layers of the core. Elemental detection was then undertaken with the use of the Molybdenum (Mo) tube x-ray source as it is known to produce great excitation for a range of elements that are of interest in environmental research applications (Croudace et al., 2006). To allow for this analysis to occur, small windows were cut into the Whirl-pak® bags containing each sample. This allows the XRF detection system to not be disrupted by the plastic layer of the bags so the ‘counts’ of the various elements contained in the sediments are like when a complete core is scanned. Elemental data from the XRF scan was taken at a step size of 200µm for each sub-sample. The data produced from this was processed using Microsoft Excel. Firstly, elements counts <100 counts per second (CPS) where removed from the dataset and were then normalised by the division of the individual counts with the
ratio of incoherent and coherent molybdenum (Mo Ratio) to normalise CPS values against to the water/organic content of for each subsample.

4.7 Multivariate facies analysis

A cluster analysis was performed to separate the recreated core stratigraphy into different facies with similar geochemical and sedimentary characteristics. Within the Itrax data, highly correlated variables ($R^2 > 0.9$) were omitted to reduce the redundancy within the cluster analysis. The grainsize data utilised included concentration of clasts >1mm, Folk & Ward statistics and the component breakdown of sand, silt and clay components. Organic Content was also included. All data was centred and standardised before the analysis took place. The Mo ratio was not used as a variable this analysis due to its characteristics of indicating water content in sediments. Due to the length of time the sediments had been in storage (2011-2018), it was not guaranteed that the moisture content had varied equally across the 78 subsamples, possibly impacting on the groups identified cluster analysis. Cluster analysis was performed with the software “PAST” (Hammer et al., 2001) using Ward’s method, (that is, the Euclidean (dis)similarity measure), and was unconstrained. This later criterion was used as the aim of this analysis was to identify layers in the stratigraphy that are alike. A principle components analysis (PCA) was also performed using the software package CANOCO to display the differences in geochemistry and sedimentology between the various facies’ groups created in the cluster analysis.

4.8 Analysis of the impact of past tropical cyclones on Lake Eacham

Analysis of past cyclone events and climate station data was undertaken so that the core stratigraphy could be compared with known tropical cyclones in order to determine whether Lake Eacham contains a tropical cyclone record. A record of past tropical cyclones that were likely to have affected the site was obtained from the Australian Tropical Cyclone Database, maintained by the Bureau of Meteorology. A boundary around Lake Eacham was created to identify tropical cyclones tracks that had passed between 15-19°S and 143-147°E (Lake Eacham 17°17’S, 145°59’E) and thus may have impacted on the lake catchment (Figure 5). A boundary of this size was created as the impacts and rainfall associated with various tropical cyclones can be spatially variable and are rarely homogenous (Yu et al., 2015). The data from the tropical cyclone database was filtered spatially to determine the tropical cyclones which had passed within the latitude and longitude criteria. Landfalling tropical cyclones often bring very heavy rainfall to the affected region and can be an indicator system intensity, therefore, rainfall data was collected for the days in which tropical cyclones had entered the boundary around Lake Eacham from the Malanda Post Office Weather Record Station (17°35’S, 145°59’E 762 m.a.s.l.) This climate station was selected due to its proximity to Lake Eacham (8.5km southwest) and
its operation lifespan from 1916 – 28th February 2011, with rainfall records available from 1920. Both the tropical cyclone and rainfall data was compiled, analysed and displayed using Microsoft Excel.

Figure 5: Boundary criteria for the analysis of impact of past tropical cyclones on Lake Eacham
5 Results

5.1 Chronology

5.1.1 \(^{210}\)Pb Dating

The returned \(^{210}\)Pb Activity (total, supported and unsupported) and ages are displayed in Table 1. The activity of \(^{210}\)Pb was considerably low across all samples dated. Total \(^{210}\)Pb activity gradually decreased towards zero with slight fluctuations, particularly between 2.25cm, 4.25cm and 6.25cm (58.45 ± 2.67, 18.53 ± 1.04 and 64.04 ± 2.61 Bq/kg respectively). The uppermost sample returned \(^{210}\)Pb activity at 73.99 ± 3.37 Bq/kg (1.25cm) while the lowest sample (35.25cm) returned \(^{210}\)Pb activities at levels considered background (1.01 ± 0.49 Bq/kg).

\[
\begin{array}{cccccccccc}
\text{Lab Code} & \text{Depth Mid-point (cm)} & \text{Dry Bulk Density (g/cm}^3\text{)} & \text{Cumulative Dry Mass (g/cm}^3\text{)} & \text{Total }^{210}\text{Pb (Bq/kg)} & \text{Supported }^{210}\text{Pb (Bq/kg)} & \text{Unsupported }^{210}\text{Pb (Bq/kg)} & \text{Unsupported }^{210}\text{Pb Decay corrected (Bq/kg)} & \text{CIC Age (years)} & \text{CRS Age (years)} \\
U928 & 1.25 & 0.3 & 0.375 ± 0.08 & 76.82 ± 3.33 & 2.98 ± 0.45 & 73.84 ± 3.36 & 73.99 ± 3.37 & 5.04 ± 1.16 & 4.87 ± 1.35 \\
U929 & 2.25 & 0.3 & 0.675 ± 0.08 & 60.98 ± 2.64 & 2.65 ± 0.33 & 58.33 ± 2.66 & 58.45 ± 2.67 & 9.08 ± 1.44 & 8.83 ± 2.76 \\
U930 & 4.25 & 0.3 & 1.275 ± 0.08 & 21.21 ± 0.98 & 2.71 ± 0.34 & 18.50 ± 1.04 & 18.53 ± 1.04 & 17.15 ± 2.18 & 13.63 ± 2.96 \\
U931 & 6.25 & 0.3 & 1.875 ± 0.08 & 66.63 ± 2.59 & 2.72 ± 0.33 & 63.90 ± 2.61 & 64.04 ± 2.61 & 25.22 ± 3.02 & 19.62 ± 3.22 \\
U932 & 8.25 & 0.3 & 2.475 ± 0.08 & 44.48 ± 1.79 & 2.90 ± 0.34 & 41.58 ± 1.83 & 41.67 ± 1.83 & 33.29 ± 3.88 & 30.64 ± 3.78 \\
U933 & 10.25 & 0.3 & 3.075 ± 0.08 & 27.02 ± 1.18 & 2.82 ± 0.32 & 24.20 ± 1.22 & 24.25 ± 1.22 & 41.36 ± 4.77 & 40.02 ± 4.35 \\
U934 & 12.25 & 0.3 & 3.675 ± 0.08 & 14.37 ± 0.69 & 3.23 ± 0.34 & 11.14 ± 0.77 & 11.16 ± 0.77 & 49.43 ± 5.66 & 46.31 ± 4.78 \\
U935 & 14.25 & 0.3 & 4.275 ± 0.08 & 31.68 ± 1.34 & 2.92 ± 0.32 & 28.76 ± 1.38 & 28.82 ± 1.38 & 57.50 ± 6.56 & 55.07 ± 5.45 \\
U936 & 16.25 & 0.3 & 4.875 ± 0.08 & 18.46 ± 0.85 & 2.70 ± 0.29 & 15.76 ± 0.89 & 15.80 ± 0.90 & 65.57 ± 7.46 & 69.64 ± 6.81 \\
U937 & 18.25 & 0.3 & 5.475 ± 0.08 & 8.17 ± 0.39 & 2.70 ± 0.29 & 5.47 ± 0.49 & 5.48 ± 0.49 & 73.64 ± 8.36 & 79.24 ± 7.89 \\
U808 & 20.25 & 0.328 & 6.103 ± 0.08 & 12.20 ± 0.71 & 5.25 ± 0.55 & 6.95 ± 0.90 & 6.95 ± 0.90 & 82.09 ± 9.31 & 87.69 ± 8.98 \\
U809 & 29.25 & 0.205 & 8.501 ± 0.07 & 4.79 ± 0.29 & 2.25 ± 0.24 & 2.53 ± 0.37 & 2.53 ± 0.37 & 114.34 ± 12.92 & 141.62 ± 20.72 \\
U810 & 35.25 & 0.263 & 9.905 ± 0.07 & 5.26 ± 0.26 & 4.25 ± 0.41 & 1.01 ± 0.49 & 1.01 ± 0.49 & 133.23 ± 15.04 & - \\
\end{array}
\]

Table 1: \(^{210}\)Pb activity and dates. Samples are relative to July 2018

Figure 6 shows supported (left) and unsupported (right) \(^{210}\)Pb activities used to calculate \(^{210}\)Pb ages. The supported \(^{20}\)Pb displays similar values of activity through the top 20cm of the core (e.g. U928=2.98 ± 0.45 – U937=2.70 ± 0.29; Table 1). However, at greater depths (18.25cm), the supported \(^{210}\)Pb activity becomes more variable and higher. The cause of this increased variability could be due
to influx sediments with differences in supported $^{210}$Pb activity entering the lake. The unsupported $^{210}$Pb activities suggest a generally exponential trend of decay, as expected for radioactively decaying elements. However, there is considerable variability in $^{210}$Pb decay rates in the upper portion of the profile. The decay trend begins to flatten between depths of 16.25-35.25cm.

Two age models were used to calculate the ages from the $^{210}$Pb data, the Constant Initial Concentration (CIC) and Constant Rate of Supply (CRS) age models, as outlined by Appleby (2001). The CIC model assumes that concentrations of $^{210}$Pb will remain constant regardless of variations in sedimentation rates. Discrepancies can occur when there is variation in the initial $^{210}$Pb concentrations due to events such as land-use changes. The key assumptions of the CRS age model are that unsupported $^{210}$Pb is in a constant rate of supply to the sediments through time (Appleby and Oldfield, 1978). Given this model assumes the constant fallout of $^{210}$Pb, it also assumes that no post-depositional mixing occurs, therefore making this model better suited to studies based upon water bodies that have not been subject to large amounts of sediment disturbance (Corcoran and Kelley, 2006). Both the CIC and CRS models have been plotted in Figure 7, with both exhibiting linear trends ($R^2 = 0.98$, $R^2 = 0.91$ respectively).

Figure 6: Supported (left) and unsupported (right) $^{210}$Pb activity throughout each subsample dated from LEA3
5.1.2 $^{14}$C Dating

The results of the two samples submitted for $^{14}$C dating are presented in Table 2. The uppermost age, from a depth of 20.5-21cm, is $245 \pm 25$ yrs BP, while the lower age, at 34-34.5cm, is $170 \pm 25$ yrs BP.

<table>
<thead>
<tr>
<th>Lab Code</th>
<th>Depth (cm)</th>
<th>$\delta^{(13)}$C per mil</th>
<th>percent Modern Carbon</th>
<th>Radiocarbon Ages</th>
<th>Age CE</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>pMC</td>
<td>1σ yrs BP</td>
<td>1σ yrs BP</td>
</tr>
<tr>
<td>OZX217</td>
<td>20.5-21</td>
<td>-25.9 +/- 0.1</td>
<td>97.02 +/- 0.28</td>
<td>245 +/- 25</td>
<td>227 +/- 77</td>
</tr>
<tr>
<td>OZX218</td>
<td>34-34.5</td>
<td>-26.5 +/- 0.1</td>
<td>97.90 +/- 0.28</td>
<td>170 +/- 25</td>
<td>139 +/- 139</td>
</tr>
</tbody>
</table>

5.1.3 Age/Depth Model

During the creation of the Age/Depth model for LEA3, the decision was made to omit the two $^{14}$C dates. The returned dates were considered to have too greater uncertainties which would greatly impact of the age model. Consequently, the age model was developed using only $^{210}$Pb ages. A CRS age model was used as it accounts for more variability in the natural environments and was chosen for this study as it is considered the best model to calculate $^{210}$Pb ages when the unsupported $^{210}$Pb
decay curve is non-monotonic (Binford, 1990). Figure 8 shows the depth model constructed by fitting a 2nd order polynomial function to the (Constant Rate of Supply) CRS generated $^{210}$Pb ages. Based on the errors given to 1σ, determined from the CRS model, 2nd order polynomial functions were also fitted to the upper and lower age estimates respectively.

![Figure 8: Age/Depth model constructed using $^{210}$Pb ages calibrated by CRS age model with lower, median and upper ages (AD) plotted by depth (cm) based on error thresholds](image)

5.2 Loss-On-Ignition

Figure 9 displays the changes in organic content throughout the core profile, as determined by the Loss-On-Ignition method. Organic content is generally about 30% throughout the length of the stratigraphy, however there a number of depths where organic content dips significantly. Between 37.25 - 36.25cm, organic content is reduced to between 19-21% across these layers of the core. The organic content of LEA3 remains relatively stable until another decline between 22.25 - 20.75cm where the percentage of organic content is again drops to between 20-23% before returning values around 30%. At 10.75cm the organic content of this layer is reduced to 18% while the at 9.75cm – 9.25cm it also dips to around 22%. After a brief increase back to above 30%, organic content drops significantly to 16% at 5.25cm. The drop is accompanied by a secondary drop at 3.25cm where organic content is reduced 18%. Initial visual observations of the changes in the compiled radiograph images may suggest that layers which have darker appearances, due to coarser grained materials contained
in these layers, may correspond with the regions of reductions in organic content throughout the profile.

Figure 9: Stratigraphic plot of organic content (determined by % LOI) of LEA3
5.3 Dry Bulk Density

The trend in dry bulk density (DBD) throughout the core profile are displayed in Figure 10. After initial fluctuations in DBD at 38.25 - 36.25cm, between ~0.19$^3$ and 0.37g/cm$^3$ respectively, bulk density stabilises at approximately 0.21g/cm$^3$ until 24.75cm. After this a considerable spike occurs with maximum DBD of 0.44g/cm$^3$ at 20.75cm. Following this, DBD decreases to ~0.19g/cm$^3$ from 18.25cm to 11.75cm. From there DBD begins to again vary between each layer of the profile with a peak (~0.28g/cm$^3$) at 9.75cm shortly followed by a decrease to values around ~0.15g/cm$^3$. An additional peak in DBD values (~0.30g/cm$^3$) is also noted at 5.25cm before a slow decline the topmost layers of the profile towards the minimum DBD value of ~0.08g/cm$^3$ in the top sample at 1.25cm. It is important to note the darker regions in the radiographs contained considerable amounts of coarser grained materials, particularly between 3.25-5.75 and 19.25-21.75cm. These darker regions are believed to correspond with higher DBD values.

**Figure 10:** Stratigraphic plot of bulk density (g/cm$^3$) of LEA3
5.4 Grainsize Analysis

Figure 11 shows various grainsize parameters including mean grainsize, sorting, skewness, kurtosis and the distribution of clasts >1mm in size against depth and age/depth model of LEA3. The changes in composition from fine to coarse sands, fine to coarse silt and clay contents are also displayed. The composition of the LEA3 is generally dominated by silts and fine sands. The core is punctuated periodically by rapid transitions to larger grainsizes, these occur at 36.25-37.25cm (1820-1813 AD), 20.25-22.25cm (1922-1911 AD), 10.75cm (1970 AD) and 5.25cm (1992 AD). These changes are accompanied by reductions in organic content, increases in coarseness and percentage of sands, and a corresponding reduction in silts content. They are also marked by the appearance of clay in some cases.
Figure 11: Stratigraphic plot of organic content (%), Itrax XRF and grain size analysis results from LEA3.
5.5 Geochemistry

The Itrax XRF produced results for 29 variables including 28 elements and the inc/coh ratio. Seven elements (Ar, Ba, Cl, Cs, La, S, P) were excluded from further analysis as they had element counts <100 counts per second (CPS) and/or random distributions. Twenty-two variables remained for further analysis. These were: Al, Bi, Br, Ca, Ce, Cr, Cu, Fe, inc/coh, K, Mn, Ni, Pb, Rb, Se, Si, Sr, Ti, V, Y, Zn and Zr. Figure 12 shows the changes in selected element counts believed to represent a detrital erosion components and human activity, along with the inc/coh ratio throughout LEA3. Similar changes in counts occur among the detrital component elements (Al, Fe, Mn, Rb, Si, Ti). Most noticeable are the peaks in counts across all detrital elements at 37.25 - 36.25, 22.25 - 20.75cm, 10.75, 9.75 – 9.25, 5.25 and 3.25cm. The counts of Pb remain stable until abruptly increasing at 29.75cm, possibly signalling European arrival in the region. Counts remain relatively stable for the remainder of the core. The inc/coh ratio is also relatively stable apart from noticeable reductions at 36.75, 20.75 and 5.25cm, corresponding with some of the peaks in the detrital elements.
Figure 12: Stratigraphic plot of selected Itrax XRF analysis results from LEA3.
5.6 Multivariate Facies Analysis

A cluster analysis was performed to identify the major facies units within LEA3. This was performed with the use of Itrax, Grainsize and Organic content data. The cluster analysis was performed with the software “PAST” (Hammer et al., 2001) using Ward’s method, (that is, the Euclidean (dis)similarity measure), and was unconstrained. The results of the analysis and the sedimentary facies in LEA3 are displayed in Figure 13. Cluster analysis identified seven major facies units within LEA3. Facies units 1-3 consist of considerably coarser material when compared to other facies groups. The remaining facies 4-7 display smaller mean grainsizes. Facies units 1 and 3 are exclusively occur between 30cm to 40cm in LEA3, that is at the base of the core. Facies unit 2 is associated with layers of the core at 20.75-20.25, 10.75 and 5.25cm. Facies units 4-6 alternate throughout various layers of LEA3 above 30cm while facies unit 7 occurs only at 29.25-27.25, 6.75 and 2.25-1.25cm. The distribution of the layers contained in each facies throughout the stratigraphy show the coarser facies units (1-3) match to the darker regions of the x-radiographs which contain large clasts. Conversely, layers contained in the facies groups considered less coarse (4-7), correlate with the identified regions of finer grainsize in the x-radiographs.
Figure 13: A. Cluster analysis results with seven identified facies units. B. X-radiograph of LEA3 alongside the results of the cluster analysis showing the distribution of each facies unit throughout the core. C. Grainsize distributions for <1mm fraction for each facies unit.
A Principle Component Analysis (PCA) was performed using the Itrax, Grainsize and Organic content data. The results from the PCA show that the variation in element counts and grainsize distribution can be mostly described by four independent axis (Figure 14; Table 3). The components of the analysis fitted to PCA Axis 1 (consisting of Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Zn, Rb, Sr, Zr, Ce, VCSilt LOI and Kurt) accounted for the greatest percentage in variance (36.2%), while components aligned with PCA Axis 2 (consisting of Se, Br, Pb, Bi, .1mm, Skew, Sort, Msand, Fsand, Csand, VFSand, VCSand, Mean, Clay, Cu, Y, VFSilt, Fsilt, Msilt and Csilt) explained 21.1% of the variance among the components. Both Axis 3 and 4 accounted for 11.0% and 8.2% of the variance respectively. PCA Axis 1 is primarily representative of organic content with the elemental components and VCSilt assigned positive axis scores and LOI and Kurt allocated negative axis scores. This implies that changes in geochemistry and VCSilt compositions would result in opposing changes to organic content and kurtosis. Therefore, units of the core with lower organic content will be displayed on the right of the ordination while layers with higher organic content will be displayed on the left of PCA Axis 1. PCA Axis 2 is illustrative of the variance in grainsize components and abundance of Pb, Bi and Se. These elements with the inclusion of Bi and the various components of the grainsize analysis (>1mm, Skew, Sort, Mean, VFSand, Fsand, Msand, Csand, VCSand and Clay) all have positive scores on this axis while the remaining variables (Cu, Y, VFSilt, Fsilt, Msilt and Csilt) received negative axis scores.

From this, the variation in facies units can be identified in LEA3 is visualised through ordination. Facies units 1 and 2 are separated from the remaining units due to their low organic content. However, they vary considerably in grainsize composition. Facies 1 contains very coarse silt material while 2 consists of coarser sand materials. Facies 3 and 4 vary from each other due to coarseness of materials with the mean grainsize of unit 3 higher than 4; but are similar in terms of organic content. Finally, facies 5-7 are more organic, with a transition into finer grainsized materials from unit 5 through to 7.
5.7 Tropical Cyclone Occurrence Analysis

Seventy-seven tropical cyclones were identified as having passed the identified region of possible influence of Lake Eacham between 26/01/1910 and 2/02/2011. During this period of below, there are observable periods of both increased and decreased tropical cyclone occurrences within the region of influence for Lake Eacham (Figure 15). There is a prolonged absence in tropical cyclone occurrences between 1913-1929 with only 6 events occurring in the defined region of influence over this period (16 years). This contrasts with the period between 1930-1936 where there were 7 recorded tropical cyclones events over only 6 years. Following this, another lull in tropical cyclone activity with only 2 tropical cyclones in the region around Lake Eacham during the 7 years between 1937-1944, before 9 tropical cyclones pass through the region over the next 5 years (1945-1950). There is again, a brief lull (1951-1954) in the activity of tropical cyclones in the region of influence before a staggered series of 6 events between in the period after (1955-1959). Over the next 13-year period (1960-1973), 6 tropical cyclone events have been identified to have affected Lake Eacham. Tropical Cyclone occurrences then increase significantly with 11 events occurring over 5 consecutive years (1974-1979) with an additional
8 then passing through in the following six (1980-1986). An absence in tropical cyclones again occurred between 1987-1995 with 3 systems within the region of Lake Eacham. In the most recent years relevant to this study, tropical cyclone activity can be considered relatively consistent with 14 systems active in the region over 15 years (1996-2011).

![Figure 15: Tropical cyclone event frequency per year within the region of possible influence for Lake Eacham](image)

From these identified tropical cyclone events, 71 occurred within the period where 24-hour total rainfall data is available at the Malanda Post Office Weather Record Station (17.35°S, 145.59°E 762m.a.s.l.) (from 1920). Figure 16 shows the distribution of rainfall totals for the 71 tropical cyclones. There is considerable variation in the amounts of rainfall with the daily totals ranging from a minimum of 0mm in 24-hours to a maximum recorded total of 439.6mm in 24-hours. The Mean 24-hour rainfall total associated with tropical cyclones within the region of Lake Eacham is 95.55mm while the standard deviation for the recorded rainfall amounts was 84.37. This indicates that the rainfall delivered to Lake Eacham by tropical cyclones can vary significantly. This variability is likely to be a function of how close the tropical cyclone passed to the climate station at Malanda.
Figure 16: Cumulative 24-hour Rainfall Totals (mm) associated with known tropical cyclone events within the region of possible influence for Lake Eacham, QLD. The coloured bars represent multiple tropical cyclones occurring for that year.
6 Discussion

The hypothesis that Lake Eacham may be suitable for reconstructing a record of tropical cyclones is based on the assumption that lakes can be ideal for investigations of past climatic conditions. This due to the continuous accumulation of sediments from their surrounding catchment, including biological remains and sediments from their catchment or the atmosphere (Bigler, 2007). The sections which follow are centred on discussing whether the results demonstrate that a tropical cyclone ‘signature’ can be identified within the sediments of Lake Eacham.

6.1 Reliability of the Age Model

When undertaking inquiries of climate-related information obtained from the analysis of lake sediments, accurate dating is essential to provide a reliable chronology to base any further findings upon (Bigler, 2007). The application of the most appropriate age model was determined through the comparison of both the constant initial supply (CIC) and constant rate of supply (CRS) models which are commonly used when creating sediment chronologies from $^{210}\text{Pb}$ dating (Appleby, 2001). The CRS model was chosen as the most appropriate method to produce an age model as this model is better suited to account for the fact that the unsupported $^{210}\text{Pb}$ decay curve was non-monotonic (Binford, 1990) as the key assumptions of this model assume that initial concentrations of $^{210}\text{Pb}$ in the sediment can be variable and rates of sediment influx can also be change (Appleby and Oldfield, 1978). There are some situations where neither the CRS or CIC models available are entirely valid. This can occur in environmental setting where surficial sediment can be mixed by either physical or biological processes or there is change in the supply of $^{210}\text{Pb}$ due to alterations in the patterns of sediment focussing within the lake. There is a possibility that physical mixing of material within both the lake and/or catchment has occurred; as highlighted in variations of supported $^{210}\text{Pb}$ and non-monotonic nature of the unsupported $^{210}\text{Pb}$ depth-profiles (Figure 6). This is may also be demonstrated by the $^{14}\text{C}$ dates, with mixing of material before deposition in the lake a likely explanation for the reversal in ages (Table 2). Hence, it is important to attempt to validate $^{210}\text{Pb}$ dates by utilising addition independent chronological evidence (Appleby, 2001). This is particularly important in this study, when attempting to match the geochemical and sedimentary evidence with known dates of tropical cyclone occurrences.

A widely used independent technique used to validate $^{210}\text{Pb}$ dates in such models is to identify the activity of artificial radionuclides such as Caesium-137 ($^{137}\text{Cs}$). There are no natural sources of $^{137}\text{Cs}$, it is only produced during nuclear fission and has been present in the environment since early nuclear testing began in 1945 (Carter & Moghissi, 1977). This dispersal of $^{137}\text{Cs}$ became widespread globally with major periods of global fallout in 1958 and 1963, as testing of high-yield thermonuclear weapons...
intensified (Ritchie & McHenry, 1990). Fallout amounts peaked in 1963, coinciding with the test-ban treaty (Appleby, 2001). Where there are good qualitative records of atmospheric fallout in sediment records, these events throughout the history of nuclear testing can be identified and thus, be utilised as accurate dates to validate $^{210}$Pb age models. However, due to time constraints and limitations in the amounts of subsamples available, such validation of the age model presented in this study was unable to occur.

There is a significant increase in lead (Pb) counts within the stratigraphy of Lake Eacham, as indicated by the (Pb/Ti) ratio, where an increase in the ratio signifies anthropogenic geochemical perturbation (Figure 17). A probable cause of this is the commencement of both Ag and Pb mining in the district around Chillagoe ($17^\circ09'S, 144^\circ31'E$), 120 km west of Lake Eacham. The comparison of the timing of the increase in the Pb/Ti ratio and the historical timeline of mining in the region of Chillagoe may provide an accurate time marker to validate the age model with. The presence of mineral deposits and the commencement of mining in the region began in 1888 AD, as documented in the Annual Report of the Department of Mines (Queensland) for that year (De Keyser & Wolff, 1964). At first production was limited due to insufficient transport links due to rough country to the east of the mineral deposits. To assist in this situation, a series of small smelters were constructed to begin to treat ores locally in 1891 and 1894 the construction of a railway line between Mareeba and Chillagoe begun in 1897 and was completed in 1901. Industries such as these have been associated with the perturbation of metals into the atmosphere as they are typically released in gas phase or as fine particulate matter, allowing transport for large distances (Pacyna & Pacyna, 2001; Marx et al., 2008). Due to the proximity of these mining activities to Lake Eacham, and the recorded dates associated with the onset of both mining and settlement of the region, it is possible assess the reliability of the dates given by the CRS age model to the lower region of the stratigraphy of LEA3.

According to the age model, the enrichment of Pb and in Lake Eacham occurred from 1865 AD (29.75cm), considerably earlier than the written historical accounts of both the settlement and the commencement of mining. However, the range of dates that this layer can be dated to, determined by the error of the CRS model, is $\pm 20.61$; giving a possible age range of 1845-1885 AD. Consequently, the later date is more likely to be correct when compared to the historical records, highlighting the need for further validation of the chronology of the sediments by other methods in future studies of this nature, such as determining the $^{137}$Cs activity throughout the stratigraphy to increase the validity and confidence of the model chosen. This will reduce the possibilities of the mis-identification tropical cyclone occurrences when the stratigraphy is compared to climatic record. Overall, the Pb enrichment result implies that the mean CRS age model may be too young by up to 20 years i.e. there may have
been some downcore movement of $^{210}\text{Pb}$ in the core profile, however other processes could also have independently affected Pb enrichment in the core.

![Figure 17: Stratigraphic plot of Lead (Pb) to Titanium (Ti) ratio of LEA3. Highlighted section indicates the possible age range at 29.75cm as determined by error in the CRS age model](image)

6.2 Identification of the Tropical cyclone ‘signature’

Through analysis of various environmental proxies throughout core from Lake Eacham, several defined changes can be observed throughout the length of the sedimentary record. These changes occur at particular depths and may be caused by disturbance events, i.e., tropical (Figure 18). This is discussed further in the sections that follow.

Tropical cyclones are closely associated with periods of heavy rainfall, which in turn can result in increased potential for erosional events and subsequent sediment transport in the catchments effected (de Scally, 2014; Chagué-Goff et al., 2016). Events such as this are known to occur relatively frequently in tropical North-eastern Queensland and there is a relatively extensive climatic record of tropical cyclones for the Lake Eacham region as previously analysed above. Terrestrial inputs of sediment from the volcanic-basalt rich catchment of Lake Eacham during periods of increased erosion...
would be expected to manifest to peaks in elements such as Iron (Fe), Titanium (Ti), Silicon (Si) and Rubidium (Rb), as previously discussed by Chagué-Goff et al., (2016). There a number of examples of peaks in these elements at various depths of the Lake Eacham core; particularly at depths of 5.25cm, 10.75, and between 20.25-21.25cm (Facies Group 2) and 35.75-37.25cm (Facies Group 1) (Figure 18).

The increases in detrital elements also correspond with a reduction in organic content at each of these points, implying increased mineral matter at these points of the core. Additionally, the plotted titanium-calcium ratio (Ti/Ca) also concurs with the signals associated with increased input of detrital materials (Figure 18), as it is a proxy for terrigenous inputs (Kuechler et al., 2013). Spikes in the abundance of these elements, high Ti/Ca ratios and reduced organic content are largely associated within Facies Units 1 and 2. This implies these Facies Units are the result of significant erosional events/periods, triggered by regular intense rainfall. Therefore, Facies Units 1 and 2 may represent ‘signatures’ of tropical cyclones.

The analysis of changes in grainsize throughout the reconstructed core shows clearly defined zones of higher grain sizes. These are associated with Facies Unit 2 (Figure 18). The increase in coarse sands in these zones is accompanied by a reduction silts (Figure 11). This can be partly due to the hydrodynamic relationships were increases in flow velocity can enable the transportation of larger sized materials. This relationship between discharge energy and particle size should enable the identification of large magnitude influx events as they are expected to appear as distinct layers of coarse material within sedimentary records of lake basins (Schillereff et al., 2014). Considering this, there is potential for the heavy rainfall events associated with tropical cyclones to deposit plumes of coarser sediments from the catchment. This sediment-flux signature observed in Lake Eacham can be refined down to a group of key indicators including; reductions in organic content, increases in mean grainsize and a corresponding peak in elements associated with terrestrial sediment inputs such as Titanium (Ti). Therefore, the coarse layers associated with Facies Unit 2 may be indications of erosional events caused by high intensity rainfall and may form the basis for the identification of a tropical cyclone ‘signature’.
Figure 18: Stratigraphic Plot of Itrax XRF, organic content (%), Ti/Ca ratio and grainsize analysis results of LEA3. Note the variations in terrestrial sediment input signals across both Facies Groups 1 and 2 as highlighted.
6.2.1 Comparison of the sedimentary record of Lake Eacham with historic tropical cyclones

The sediment-influx ‘signature’ observed in the layers associated with Facies Unit 2 were compared to the climatic data and tropical cyclone record to determine whether these erosional events are the result of tropical cyclone activity and thus, determine whether Lake Eacham does contain a record of tropical cyclones. The ‘signature’ observed can be characterised by a group of key indicators including a reduction in organic content, increase in mean grain size and a corresponding peak in elements associated with terrestrial sediment input such as Titanium (Ti), believed to be a response to regular intense rainfall events i.e. tropical cyclones. Periods of increased cyclone activity within the boundary of Lake Eacham occurred between 1930-1936 AD (7 events), 1945-1950 AD (9 events), 1974-1979 AD (11 events) and 1980-1986 AD (8 events). There were also periods of reduced tropical cyclone occurrences, particularly between 1913-1929 AD (6 events), 1937-1944 AD (2 events), 1960-1973 (6 events) and 1987-1995 (3 events). Tropical cyclone activity was relatively consistent between 1955-1959 (6 events) and 1996-2011 (14 events) (Figure 15, 19).

The topmost layer of Facies Unit 2 (5.25cm, 1992 AD) displays an association with two tropical cyclone events that are known to have occurred within the age range for that section of the stratigraphy (Table 4). Two tropical cyclone events which occurred in 1990, totalling 308mm in rainfall, may have contributed to the sediment-influx ‘signature’ present in this layer (Figure 19). The significant rainfall associated with consecutive events may have had the potential facilitate the input of detrital material into Lake Eacham, constituting a possible example of the response of the catchment to tropical cyclone activity and the high rainfall associated these events. These two tropical cyclones are also isolated events as they occurred within the lull of activity between 1987-1995, making it possible that ‘signature’ at 5.25cm can be linked specifically to this pair of events. A second sediment-influx ‘signature’ is observed at 10.75cm (1970 AD). This section of the core may also be representative erosional inputs resulting from tropical cyclones as three events (1967, 1971, 1971), which amounted to 392mm of rainfall, occurred during the possible age range of this layer. Similar to the layer at 5.25, the erosional ‘signature’ occurred during a lull in tropical cyclone activity, making these events also quite isolated. The gap between the 1967 event and the pair of events in 1971 make it unlikely that the erosional ‘signature’ is the culmination of the impacts experienced by the catchment from these events, while the range of possible ages for this section of the core and similarities in rainfall make it difficult to determine which event the ‘signature’ is related to.

Despite the varying associations of these layers and the sediment-influx ‘signature’ to the tropical cyclone record, there are other sections of the stratigraphy which have been subject to events increased intensity and frequency but lack the sediment-influx signal associated with Facies Unit 2.
Periods of both frequent and intense cyclone events are visible in the climatic record including clusters of events which occurred between 1930-1936, 1945-1950, 1974-1979, 1980-1986AD (Figure 19). These periods result in significantly more rainfall and consecutive tropical cyclone occurrence but lack any evidence of an erosional event comparable with the ‘signature’ occurring in those sections of the stratigraphy associated with Facies Unit 2. In fact, these clusters appear to occur in tandem with sections of stratigraphy classified under Facies Units 4-7 which are characterised by finer grain size compositions and increased organic content. This proposes that the Lake Eacham catchment is certainly not responding to every major tropical cyclone occurring in the region, however there is still evidence of disturbance events which could be related to the occurrence of tropical cyclones.

Table 4: Comparison of possible ‘signature’ layers to periods of known tropical cyclone events and associated rainfall.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Age(s) (AD)</th>
<th>Age Error</th>
<th>Age Range</th>
<th>Recorded Tropical Cyclone Events</th>
<th>Total Rainfall During Tropical Cyclone(s) (mm)</th>
</tr>
</thead>
</table>
There appears that there may be an offset between the between the erosional response displayed within the stratigraphy of the core, and the tropical cyclone record (Figure 19) and as discussed previously, there is also uncertainty in the age model (Figure 17). Considering this, both the minimum and maximum ages (based on analysis uncertainty) were plotted against the stratigraphy and tropical cyclone in order to facilitate the better alignment of the erosional ‘signature’ with periods of increased tropical cyclone activity and intensity (Figure 20). As a result, the topmost unit identified to contain an erosional ‘signature’ (5.25cm) now corresponds to the two tropical cyclone events which occurred in 1990, while also corresponding to a smaller tropical cyclone that occurred in 1989. At 10.75cm, the potential tropical cyclone signal now corresponds with additional cyclone events in 1964, 1965 and
1967. By plotting the maximum ages in the error range of the age model, the layer at 5.25cm is only slightly influenced by the small 1989 tropical cyclone event while at 10.75cm, it now corresponds with tropical cyclone events in 1974, 1975 and 1976. The most notable change when plotting the maximum ages to the climatic data is the cluster of cyclone events which are now associated the facies group at 20.25cm-21.25cm. This previously corresponded with one tropical cyclone event when plotted with the median ages and no events with the minimum ages. The cluster tropical cyclone events of 1927, 1929, 1930, 1931 and 1932 which correspond with these layers are quite substantial as the combined rainfall associated with these events is quite considerable at 873.5mm. This again proposes that catchment of Lake Eacham does not respond exclusively to every major tropical cyclone event or cluster of events which are occurring in the region.

![Figure 20: Minimum ages (left) and Maximum ages (right) plotted against facies layers and distribution of 24-hour rainfall (mm) totals associated with identified tropical cyclone events. The yellow bars also represent the possible age ranges represented by these sedimentary units.](image)

While the potential tropical cyclone signals highlighted in Facies Unit 2 appear to occur in tandem with multiple tropical cyclone events over the Lake Eacham region across the various possible ages of the sediments, further investigation is needed to fully understand the occurrence of the tropical cyclone ‘signature’ in the core, as the tropical cyclone activity corresponding with these periods still appear to not be as substantial in comparison with other clusters events with increased event frequency and significant amounts of rainfall. To do this, each tropical cyclone was ranked from smallest to largest based on cumulative rainfall while the tropical cyclone was within the Lake Eacham region. The largest event was assigned the largest rank (65, equal to the number of tropical cyclones with rainfall data influencing Lake Eacham from the historical record up to 2005) and the smallest rank of 1. Following
this, an intensity score was calculated for every 5-year period (1916-1920, 1921-1925, etc.) within the core using the sum of all the intensity rank scores for eventual tropical cyclone cycles occurring within that 5-year window (Figure 21). The 5-year clusters with the most intense and consistent regular tropical cyclone activity where 1976-1980, 1986-1990 and 1926-1930. The potential tropical cyclone ‘signature’ at 5.25cm does to match directly to any tropical cyclone activity in the period of 1991-1995. The Facies Unit 2 present at 10.75cm matches best with the 1966-1970 5-year period. The erosional ‘signature’ present at 5.25cm may possibly be a delayed response to the 1986-1990 period of cyclone activity including the two largest events of this period which occurred 1990 (Table 3). The ‘signature’ at 10.75cm does occur during cyclone activity, but as observed before, appears to be in period of reduced cyclone intensity and frequency.

![Figure 21: Facies layers plotted against 5-year total tropical cyclone intensity ranking scores](image)

While there is some evidence of a positive relationship between the sediment-influx signature and tropical cyclone occurrences, the response of the Lake Eacham catchment to these events specifically is incredibly variable. Regardless of which variation of the age model is applied, there are still major periods of tropical cyclone activity that are not present in the core, however, further investigations to validate the age model may further refine the model and be better fitted to the climatic record.
A possible explanation of this could be a discrepancy between the amounts of precipitation which have been recorded to have fallen at the weather station site and Lake Eacham. The spatial variability associated with the impacts and rainfall of tropical cyclones could account for the variation in catchment response between each event and the rainfall amounts that are perceived to be correspond with that event. The influence of antecedent rainfall conditions and other severe rainfall events such as thunderstorms and monsoonal rain events may also be a point of consideration. Perhaps the influence of these events occurring in tandem with tropical cyclone activity may result in an erosional and subsequently produce a sediment-influx ‘signature’.

6.3 Variable Responses to Disturbance Events

As noted above, while both Facies Units 1 and 2 display evidence of terrestrial erosion signals in their respective geochemical properties, there is a discrepancy between these groups whereby layers associated with Facies Unit 1 displaying and erosional signal without a major change in grainsize. This suggests that the response of Lake Eacham’s catchment to disturbance events can vary greatly. It must also be considered that not every tropical cyclone that has been deemed to pass within the defined region around Eacham would have resulted in the homogenous impacts due to the spatial variability of the systems and their associated rainfall (Yu et al., 2015). Not every tropical cyclone necessarily has the amounts of precipitation or intensity to induce erosional events on the crater rim. Therefore, it is likely that the tropical cyclone ‘signature’ that is deemed to be present within Lake Eacham’s stratigraphy will mostly represent only the most severe tropical cyclones or periods of consistent activity impacting on Lake Eacham (Chagué-Goff et al., 2016).

During the wet season of the tropics (December to March), the most significant weather events are not restricted to only tropical cyclones but also thunderstorms systems and tropical rain depressions which can deliver up to 80% of the annual mean precipitation totals for some regions (Lee & Neal, 1984; Bureau of Meteorology, 1988a). Like tropical cyclones, some thunderstorms can also produce significant rainfall and runoff in short, high-intensity rainfall events, while tropical rain depressions and monsoonal activity vary with the Southern Oscillation Index and El Niño effect. The rainfall associated with the occurrence of these events all have the potential to facilitate erosional events in catchment of Lake Eacham, with the variations in the timing, intensity and amounts of precipitation delivered by these events possibly contributing to the variable responses of the catchment displayed throughout LEA3. Such events may coincide with tropical cyclone events with the possibility that antecedent rainfall may be a possible mechanism attributing the variances in response of the catchment to tropical cyclones.
There is research to suggest that antecedent conditions within a catchment, particularly in terms of soil moisture content, can be a major contributing factor in the amounts of sediment available for transport following consistent rain rainfall events (Woo, 2012). When the soil and sediments of a catchment are subject to consistent rainfall events, resulting in wet or saturated conditions, the amounts of moisture able to infiltrate into the material decreases and hydraulic conductivity increases, leading to higher runoff ratios. At saturation point, significant rainfall can result in sediment to be entrained and mobilised as water flows off the surface as saturated overland flow (Woo, 2012). With this, the responses of a small catchment to precipitation should be greatly dependant on the moisture conditions within the catchment at any point in time (Seeger et al., 2004). The interactions between antecedent rainfall, soil and sediment moisture contents of the catchment and the occurrence of tropical cyclones may result in varied catchment responses.

A situation of total catchment saturation followed by a tropical cyclone event would most likely enhance the erosional potential and possibly be more evident in the change of both the geochemical and grainsize signals. It is possible that the erosional potential of tropical cyclone may have been increased as they occurred in tandem with possible antecedent rainfall event, or alternatively that erosional events may be generated by rainfall events not associated with tropical cyclones. Major rainfall events >100mm not associated with tropical cyclone events can occur frequently in the region, with some years receiving multiple storm events which can deliver up to 4 (1921, 1945, 1967, 1977, 1979 AD) consecutive >100mm rainfall totals (Figure 22). Of the three Facies 2 units in the Lake Eacham, the uppermost Facies 2 Unit at 5.25cm does not match large non-tropical cyclone rainfall events, therefore it is more likely to reflect a ‘signature’ of the occurrence of a tropical cyclone. At 10.75cm, there is a substantial rainfall within the time range (1967, 880.8mm) with the only tropical cyclone before the erosional ‘signature’ occurring in the same year. A major rainfall event that was not associated with the cyclone event of that year produced 379mm on the 12/03/1967. Following this, Tropical Cyclone Elaine passed through the Lake Eacham boundary during the 14/03/1967 resulting in an additional 178mm received by the catchment. The timings of these events are likely to have resulted in the saturation of the Lake Eacham catchment followed by a tropical cyclone event making it very reasonable to confidently suggest the erosional signal present at 10.75cm is very likely to be tropical cyclone ‘signature’. The timing of the storms and tropical cyclone event associated with the Facies Unit 2 between 20.25-21.25cm is reversed from the previous ‘signature’ facies. The tropical cyclone events both occur before the major storm events of 1921, making it likely this erosional ‘signature’ may not be exclusively the result of tropical cyclone occurrences.
Figure 22: Identified possible ‘signature’ erosional layers in the Lake Eacham core (yellow bars) plotted against cumulative events of 24-hour rainfall (mm) totals >100 mm and tropical cyclone occurrence frequency. The yellow bars also represent the possible age ranges represented by these sedimentary units (Table 4).
Another point of discussion on the variable responses to disturbance events, particularly the response of layers associated with Facies Unit 1 (35.75-37.25cm), as it displays a strong erosional signal with peaks in the geochemistry but lack evidence of an influx of coarser sands associated with this (Figure 11, 18). The variation in the erosional response observed here may reflect the differences in the responses of the Lake Eacham catchment before and after European settlement. The absence of coarser materials before settlement of the area and their prominence in the layers following suggest that catchment response has varied due to possible changes in both land cover and land use within the catchment Page et al., (1994) allowing coarser material to be transported more readily into the lake. While disturbance in the form of the construction recreational facilities on small portion of Eacham’s foreshore has been documented to occur in 1943 (DNPSR, 2012–2018), it is possible that other changes of land use, that may have been undocumented during the early settlement of the region, in the catchment may have resulted changes to landcover of the catchment. Change particularly in the riparian vegetation along sections of the lakes shoreline which may have led to the destabilisation of sediment and allowed coarser materials to be transported into the lake more readily during disturbance events (Shafroth et al., 2002). This may be comparable to the sedimentation patterns observed in Lake Tutira, as the appearance of larger sediment influxes composed of coarser sands reflected the response of the catchment to changes in vegetation and land-use, while the layers preceding settlement were associated with lower sedimentation and reduced frequencies of graded bedding within the lake (Page et al., 1994).

Further research utilising other indicators of land changes/use at Lake Eacham will be required to fully determine the processes contributing to the differences in erosional response from disturbance events from both pre and post European settlement at Lake Eacham. Records of pollen assemblages are another common proxy that can used to detect the onset and impacts associated with human activities on landscapes (Li et al., 2008). The appearances of exotic and/or anthropogenically introduced pollens such as Lantana, Mimosa and Pinus/Plantago in lake sediments can provide clear stratigraphic markers for the onset of European occupation and land use as described at nearby Lake Euramoo by Haberle, (2005). Timber harvesting was prominent during the early 19th Century in the region and the impacts of this are also highlighted within the pollen assemblage records with key taxa found within the rainforests of the region including Agathis and Podocarpus severely reduced due to exploitation over the last 120 years (Birtles, 1988). Although land changes and uses such as this is understood to have not occurred and may allow for greater amounts of coarse material to be transported during disturbance events within the Lake Eacham catchment since the time of settlement, it cannot be discounted and may be a contributing to factor in explaining the variable catchment responses observed in the layers of stratigraphy classified under Facies Group 1. This may
also be supplemented by the analysis of Carbon/Nitrogen (C/N) ratios as it can provide a proxy which highlights changes in the sources of organic matter for sediments which can be vary greatly under the influences of catchment disturbance (Lamb et al., 2007). Despite this, there is only one example of a disturbance and subsequent sediment influx event observed that greatly differs from the other key facies layers which occur towards the top of the core, further discussion and future investigations surrounding the catchment history, response and sedimentary archive of Lake Eacham will be beneficial in determining the processes which dictate the response of the catchment to such disturbance events.
7 Conclusion and Recommendations

The primary aim of this study was to develop a record of past tropical cyclones from Lake Eacham and in doing so provide a long-term record of tropical cyclone activity in Northeast Queensland. This was achieved through the analysis of various sedimentary, geochemical and biological proxies extracted from a core (LEA3) collected from Lake Eacham, a maar lake located on Atherton Tablelands, alongside historical climatic data to identify a tropical cyclone ‘signature’. From this, a decision on the suitability of the use of Lake Eacham as a site to reconstruct tropical cyclone records and the potential for further investigations of this nature was made. Considering this, the following conclusions about the reconstruction of a tropical cyclone records in Lake Eacham have been made;

- There is an observable tropical cyclone ‘signature’ within the stratigraphy of Lake Eacham, however further investigations will allow for greater understanding into the non-homogenous response of the catchment to such events.

- The ability to extract a definitive tropical cyclone record from the core is difficult due the frequency in which other major storm events occur within climatic record for the Lake Eacham region. It is apparent that antecedent conditions play a more important role in influencing catchment response than first assumed, due the storm prone climate of the Northeastern Australia. Better understandings through modelling of the moisture status of the Lake Eacham catchment over the period of the historical climate record may assist in understanding what conditions leave the catchment vulnerable to disturbance events such as the occurrence of tropical cyclones.

- Inquiries of climate-related information obtained from lake sediments demand reliable a reliable chronology to base any findings upon. Further refinement of the age model through additional independent validation methods, such as $^{137}$Cs activity analysis would greatly increase the accuracy of the comparisons between the ‘signature’ facies units of LEA3 to the periods of both tropical cyclone occurrences and antecedent conditions within the climatic record.

With these findings, it can be concluded that there is indeed a tropical cyclone ‘signature’ present within the sediments of Lake Eacham, however the relationship between the catchment response and the occurrence of these events is still poorly understood. As a result of this, there is potential for further research to be undertaken at Lake Eacham in order to improve on these initial findings,
increase accuracy in the identification tropical cyclone occurrences in the core and extend the event record further.

7.1 Recommendations for Future Work

The evidence of a ‘signature’ of tropical cyclone events within Lake Eacham is incredibly encouraging and could be greatly important in directing future research in the reconstruction of a cyclone records in suitable lakes. However, to do this in further detail and with better accuracy, more comprehensive work is needed to gain a more complete view of Lake Eacham and the interactions of its catchment to the disturbance events.

A major part in the identification of a tropical cyclone ‘signature’ is the ability to match the relevant facies containing the signal with the historical climate record. Further enhancement of the age model is required to increase confidence when aligning facies units to periods of tropical cyclone activity. It is recommended that additional independent validation of the age model should occur, perhaps through $^{137}$Cs analysis or even through additional $^{210}$Pb and $^{14}$C dates, to increase accuracy and confidence when attempting to compare tropical cyclone ‘signatures’ with the historical climate record. Additional cores would also be beneficial during these comparisons.

This study only presents a generalised assumption of the catchment response to disturbance events such as tropical cyclones. Further investigation into the catchment response and timings and patterns of sediment deposition into the lake through the installation of sediment traps may also assist with comparison of ‘signature’ facies units to the climatic record in future studies. This may also be assisted through analysis of additional proxies such as the C/N ratio and stable isotopes.
8 References


changes and human activities recorded in the sediments of Lake Estanya (NE Spain) during the Medieval Warm Period and Little Ice Age. *Journal of Paleolimnology, 46*, (3), 423-452.


