How Past Climate Change Can Help Reveal Australia's Future

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Summary

In Australia, high quality instrumental climate records only extend back to the late 19th century. They can therefore only provide us with a brief snapshot of our climate's natural state and its variability. It is possible to extend these records further back in time, however, using evidence derived from non-historical sources – that is from natural archives of past environmental conditions (called 'palaeo-records'). Such records provide a unique opportunity to test and improve our understanding of natural climate change and variability in Australia.

There are a large number of palaeo-records available for reconstructing climate in the Australian region, ranging from continuous records preserving annual to millennial scale change (such as those derived from tree rings, speleothems, corals, Antarctic ice cores, and lake and marine sediments) through to discontinuous records representing key periods in time (such as coastal deposits, palaeo-channels, glacial deposits and dunes). These records preserve indirect (also known as proxy) measurements of environmental conditions at the time they were formed. They provide a large body of evidence for past atmospheric, terrestrial and marine variability, which can in turn be used to limit the uncertainties in our understanding of climate change and its potential impact on Australia.

Palaeo-records have been used to extend Australian records of climatic parameters (e.g. precipitation, air temperature, evaporation and sea surface temperature) back hundreds of thousands of years. Annual and seasonal resolution records have been of particular use in extending back the instrumental records across many parts of Australia. At present, though, these high-resolution records only extend back hundreds to a few thousand years, limiting our ability to identify long-term climate trends and variability. Longer records are available to provide evidence of climatic change on millennial timescales, but generally these are of much coarser resolution.

We now have the geographical coverage of palaeo-records for key periods of time to begin to identify and understand long-term natural climatic variability that is not evident in the instrumental records. For instance, long continuous records provide evidence of successive cycles of cold periods (ice ages or glacials) and warm periods (interglacial) over the last two million years. Superimposed on these cycles are evidence of smaller scale cycles (millennial though to decadal) of climate change as well as long-term trends, such as increasing aridity in Australia over the last 350,000 years. Crucially, precise dating of these records allows changes in Australia to be placed in a global context. This not only allows us to assess the degree to which observed regional climate variations and change can be explained by natural processes, but can also improve our understanding of the relative effects of local and global climate drivers.

Evidence for changes in greenhouse gases over the last 500,000 years has been found in ancient air trapped in ice sheets across the world (in particular Antarctica and Greenland), as well as proxies recorded by tree rings, corals, speleothems and plant fossils. These records have been used to: establish the variability of greenhouse gases prior to the acquisition of direct atmospheric measurements; place the present growth rate changes of greenhouse gases in a longer time perspective; understand the biogeochemical cycles of greenhouse gases and how they might amplify or offset emissions in the future; identify evidence of abrupt events, such as responses to volcanic eruptions; identify causes of the recent warming observed at global and regional scales; synchronise climate records around the world; and as input to climate models. Similarly, palaeo-records have been used to identify the roles that aerosol concentrations, solar irradiance and land-cover change have had in climate forcing, both pre and post-industrial times (~1750 AD).

Palaeo-records are becoming increasingly recognised as playing an important role for modelling past, present and future climates. Palaeo-climatic data provides critical information on the behaviour of key climatic controls and allows their regional and global significance to be established. In addition, palaeo-data are necessary to establish the natural conditions for modelling past climates and to test the results of these simulations. The simulated models provide the length

of records necessary for testing climate models that instrumental records are simply too short to provide. These simulations in turn are extremely valuable for testing the global climate models that are used to predict future climate change.

Finally, palaeo-records provide valuable insights into how climate variation and change has and could affect our environment, both on land and in the sea. In particular, they allow us to identify how sensitive (and vulnerable) our ecosystems are to change. This information has great potential for planning for future climate change.

1. Background

In Australia, high quality instrumental climate records only extend back to the late 19th century and can therefore only provide us with a brief snapshot of our climate. Reconstructions of past climates from non-historical sources (which are commonly called 'palaeo-records'[1]), on the other hand, extend far into the past and have the potential to test and improve our understanding of the nature and impacts of climate change in Australia. As Oldfield and Alverson (2003) point out, the exploration of the past is central to the question of how to identify what fraction of global climate change we can assign to human activities, as well as what the severity, long-term effects, and possible consequence of such changes are likely to be.

Palaeo-records are derived from both direct and proxy evidence of past atmospheric, oceanic and terrestrial conditions. Direct evidence consists predominantly of measurements of atmospheric gases, for instance carbon dioxide (CO_2) and methane (CH_4), which are preserved in natural archives, such as ice cores. Proxy, or indirect evidence, constitutes the bulk of data of past climatic conditions and is derived primarily from natural archives such as tree rings, speleothems, terrestrial wetland sediments, geomorphic features, coastal sediments, glacial deposits, corals, ocean sediments and ice cores. The information most commonly preserved in these records are 'fossils' of plant and animal remains, chemical changes (including radioactive and stable isotopes) and physical features. All of the above improve the understanding of the nature, processes and forcings of past climate change and climate variability on a range of timescales, from annual to millennial. In addition, palaeo-data can provide us with information on the impacts of past climate change on both our terrestrial and marine environments. Palaeo-science, therefore, has the potential to deliver vital information about the ways in which our environment will respond to future changes in climate and atmospheric composition.

With this in mind, the Australian Greenhouse Office commissioned this report to investigate the key ways that palaeo-science can constrain uncertainties about climate change and its potential impacts in Australia. This report has been put together a multi-institutional and multi-disciplinary team of palaeo-scientists and climate modellers led by CSIRO experts.

2. Scope of the project

This review will provide a concise overview of the availability, relevance and best use of palaeo information in understanding climate change and its potential impacts in Australia. Specifically, this review will outline:

1. the current breadth of palaeo-research in Australia, the methods and approaches used, and the potential role of methods used overseas but not currently applied in Australia;
2. the extent to which palaeo-records can assist in the identification of how and why climate has changed in the 20th and 21st centuries, including

[1] The term *palaeo* is used in this study to encompass evidence from the past which is not derived from historic documents and/or instrumental records, i.e. evidence of environmental conditions prior to the period humans began collecting instrumental measurements. In Australia this is generally prior to the late 19th century, although for some records it is much later, such as atmospheric records (pre~1960) and solar records (pre~1980).

a. evidence of past variations in temperature, precipitation and other climatic parameters in Australia at regional and national scales,
b. the scope for palaeo-science to shed light on the extent to which natural climate variation has contributed to climate trends and discontinuities observed over the last few decades,
c. evidence for variation in greenhouse gases that help us understand recent changes and predict future climate drivers,
d. the scope for improved palaeo-data to contribute to better testing and verification of regional and global climate models;

3. the ways in which palaeo-science can enhance our understanding of the likely impacts of climate change in Australia, including
    a. evidence of the impacts of past climatic variation on flora and fauna, water resources and landscape processes such as erosion,
    b. evidence of the effects of historical climate variation on high impact events, such as fire, drought, floods and sea level rise,
    c. the scope for palaeo-data to contribute to an understanding of the future behaviour of terrestrial carbon sinks.

This report is designed to present an overview of the types of palaeo-records available for the reconstruction of past climates and climate change impacts, their key strengths and limitations, and the ways in which they can constrain uncertainties about climate change and its potential impacts in Australia. Rather than attempting an audit of the extensive body of Australian palaeo-research, we have selected a representative series of case studies to demonstrate the considerable potential of palaeo-records and provide a setting for discussion. These cases represent only a handful of the many examples being carried out by scientists on Australian palaeo-records.

3. The current breadth of palaeo-research in Australia

Australia is in a unique position to contribute to a regional and global understanding of how climate systems have operated in the past. The Australian states and territories span a range of climatic zones, including Antarctic, temperate, arid, subtropical, tropical, oceanic and continental. Australia is bracketed by several major oceanic and atmospheric controls which include the West Pacific Warm Pool, the Indian Ocean Dipole, the El Niño-Southern Oscillation (ENSO), tropical monsoonal flow, mid-latitude westerlies and Southern Ocean circulation. Australian sites provide data about global climate change and climate change impacts, including evidence from ice cores for greenhouse gas forcing, tree rings for exploring changes in the global carbon budget, and corals and microfossils in marine environments to reconstruct past sea level changes. The potential therefore exists to contribute significantly to the understanding of how shifts in global climate systems in the past have impacted on our regional climates.

This chapter provides an overview of the types of palaeo-research being carried out in Australia, the nature of their contribution to climate change research, their age range and resolution, and potential limitations.

3.1 The important question of scale

The nature of palaeo-records and the time resolution that they can be sampled at are key determining factors in understanding how they can contribute to climate change research. In general they fall into three broad groupings: seasonal scale records; decadal/sub-decadal scale

records; and millennial scale records. The palaeo-climate records that are currently available to us in the Australian region exhibit a range of scales and resolutions, both geographically and over time. Seasonal records have been developed from corals, tree rings and some coastal Antarctic ice cores. These natural archives have also produced sub-decadal/decadal and millennial scale records, as have some terrestrial sediment archives. Other sediment archives, both on land and in the ocean, can only provide longer-term records. This is in part due to inadequacies in the sampling of the sediment for proxies and the dating resolution, but in many cases is an artifact of the proxy itself. Underpinning all of these is precise dating control. Each of these scales of records has much to tell us about past climate change and climate variability and the climate drivers and processes.

3.2 The important role of chronology: strengths and limitations

Precise dating is a vital component of palaeo-science, providing the framework essential to understanding the timing and rates of past environmental change. Without this framework, our ability to utilise palaeo-records to understand the processes, forcings and cyclicity of climate change is severely hampered. For example, there is currently much debate about whether past climate changes have been synchronous across the Northern and Southern Hemispheres, which has implications for understanding global atmospheric and ocean responses to future climate change (Lynch-Stieglitz 2004). This debate has been significantly hampered by the lack of high-resolution, well-dated palaeo-records from the Southern Hemisphere, particularly in the Australian region.

Four classes of dating techniques have been used to date Australian palaeo-records: (1) those based on the decay of radioactive elements; (2) those based on the accumulation over time of trapped electrons; (3) those based on slow chemical reactions; and (4) those based on the counting of layers, such as tree and coral growth rings. In addition, age frameworks have been determined for palaeo-records through the correlation of events that are large and widespread e.g. volcanic eruptions, peaks in radioactive elements. The age range, precision and materials these methods can be applied are summarised in Table 1. It is important to realize that radiocarbon dating is the most common method of dating palaeo-records across the Australian region. This method is discussed further in section 3.2.1.

Table 1. Quaternary dating methods utilised in Australia (after Williams *et al.* 1998 pg 271).

Method	***Age range***	***Materials to which it is applied***
1. Radioactive decay		
Radiocarbon (^{14}C)	0-40 ka (possibly 60 ka under ideal conditions)	wood, resin, charcoal, peat, shell, coral, bone, organic sediments
Long-lived cosmogenic radioisotopes: beryllium-10 (^{10}Be), aluminium-26 (^{26}Al) and chlorine-36 (^{36}Cl)	10 ka to 10 Ma	exposure age dating of rocks
Uranium-thorium disequilibrium ($^{238}U/^{230}Th$)	0-250 ka	Coral, speleothems, eggshell, closed-system organic sediments (such as peats), bone
2. Trapped electrons		
Optically stimulated luminescence (OSL)	0 to 100-500 ka	quartz or feldspar sediments
Thermo-luminescence (TL)	0 to 100-500 ka	quartz or feldspar sediments, loess, pottery, hearths, tephras
Electron spin resonance (ESR)	0-1 Ma	Coral, teeth, calcite, gypsum

3. Slow Chemical reactions		
Amino-acid racemisation	0 to 100-500 ka	Eggshell, shells, forams, wood
4. Layer counting		Tree rings, coral growth rings, ice cores, laminated sediments (the latter is rare in Australia)

ka = thousand years ago, Ma = million years ago

3.2.1 Radiocarbon dating

Radioactive isotopes occur naturally in the environment, produced either from processes within the Earth or from the bombardment of elements in the atmosphere and on our planet's surface. Material such as sediments, bones, wood and rocks that contain these radioactive isotopes can be dated using the knowledge of the time taken for any given quantity of a particular radioisotope to be reduced by half (its *half-life*). The time range of each dating method depends on the half-life. The longer the half-life, the further back in time the method can extend.

Carbon-14 (also referred to as ^{14}C and radiocarbon) is the radioisotope most commonly used to date materials. It is a cosmogenic radioisotope that is formed in the upper atmosphere and is mixed throughout the atmosphere, biosphere and ocean at approximately the same concentration. There are inter-hemispheric and regional differences (the '^{14}C offset') in the concentration of ^{14}C attributed to oceanic upwelling (McCormac *et al.* 1998). Concentrations in all of the major carbon reservoirs have also changed since atmospheric thermonuclear bomb testing commenced in 1950. Radiocarbon is concentrated in the tissues, bones or shells of all living organisms, as well as in carbonate deposits, and has been used to date materials in three ways: (1) measuring the level of radioactive decay in samples; (2) 'wiggle' matching; and (3) identification of the atmospheric bomb-pulse.

Carbon-14 has a half-life of 5730 years and can be used to date materials back to around 40,000 years. It is possible to extend the range back to 60,000 years, although this requires the elimination of nearly all background contamination from laboratory equipment and chemicals, as well as a sample that has not been significantly contaminated. Contamination can occur in buried samples that adsorb dissolved organic compounds from the surrounding soil, shallow groundwater or, in the case of shells, from bicarbonate ions in percolating water. The possibility of modern carbon contamination increases with the age of a sample, limiting the ability to get an accurate date. The levels of ^{14}C are extremely small in samples at the age-limit of the technique (Chappell *et al.* 1996) and as a result, dates older than 30,000 years are often regarded as minimum ages.

Radiocarbon wiggle-match dating (WMD) uses past variations in the concentration of ^{14}C in the atmosphere that are caused by variations in the flux of cosmic rays entering the upper atmosphere, the Earth's magnetic field and the global carbon cycle. These atmospheric ^{14}C fluctuations (often referred to as 'wiggles') have been measured in tree-ring sequences, layered (also known as varved) marine sediments and corals of known ages to create calibration curves extending back 26,000 years (Hughen *et al.* 2004; Reimer *et al.* 2004). As a result, it is possible to provide a chronology for a palaeo-record by obtaining multiple ^{14}C dates through a record and matching its wiggles to those present in the ^{14}C calibration curve (Figure 1). The precision of this chronology depends on the shape of the relevant part of the calibration curve used, with there being periods up to 600 years in length where the ^{14}C calibration curve is almost flat (called 'radiocarbon plateaux'), thus making wiggle matching difficult (Blaauw *et al.* 2004). Radiocarbon ages obtained through these periods have a wide range of probable calendar ages. This is of particular concern during the end of the last ice age and beginning of the Holocene (Beck *et al.* 1992; Stuiver *et al.*

1995; Burr 1998; Bard *et al.* 2000; Hughen *et al.* 2004; Reimer *et al.* 2004). The chief limitation in the use of WMD is that the high number of ^{14}C dates required is expensive. In addition, not all records have the necessary sample resolution to allow this technique to be applied. This is particularly true for many Australian sediment records.

In the late 1950s and early 1960s, the concentration of ^{14}C in the atmosphere was dramatically increased by the creation of artificially-high levels of radiocarbon from atmospheric nuclear weapons testing (Enting 1982). These levels decreased again with banning of atmospheric nuclear testing in 1963. It is possible, therefore, to use this pulse of ^{14}C as a dating tool for samples. This approach has also been used as a tracer to improve our understanding of the exchanges between carbon reservoirs in the global carbon cycle, as well as atmospheric circulation (Levin and Hesshaimer 2000).

Past changes in the inter-hemispheric differences in the concentration of ^{14}C have also been used to trace changes in atmospheric circulation. Chapter 4 discusses this topic in more detail.

3.3 Terrestrial palaeo-records

Australia is fortunate in that it has not been affected by widespread glaciation, which in many regions in the northern hemisphere has destroyed most evidence of past environments. The variety, continuity and resolution of many Australian terrestrial records, however, have been affected by the arid nature of much of the continent as well as the slow rates of sediment deposition. Nevertheless, a wide range of evidence does exist which can provide us with valuable insights into past climates and climatic processes. Some of these key lines of evidence are outlined in the following sections.

3.3.1 Tree rings

One of the most valuable types of sub-decadal terrestrial palaeo-records are sequences of tree rings produced by long-lived tree species (usually gymnosperms). Those trees that grow in regions that experience a strong seasonality lay down annual rings of growth. Examination of variations in the thickness of these rings, the density of the wood and the ratios of stable carbon, hydrogen and oxygen isotopes provides evidence of environmental and climatic conditions at annual and sub-annual resolution. Tree ring records can be extended back many thousands of years by focusing on long-lived species and cross-matching records from living and dead trees within a species population. It is important when establishing long tree ring records that a link is made to a tree of known calendar age. Where such a link cannot be made the tree ring record is regarded as ‘floating’, and an approximate age is established through radiocarbon dating. Such sequences, however, still provide evidence at annual resolution of past environmental change, although these changes are difficult to tie down to a specific period of time. In some cases it is possible to provide a calendar age for floating tree ring records by wiggle matching the ^{14}C concentrations to the international radiocarbon calibration curve (Barbetti *et al.* 2004).

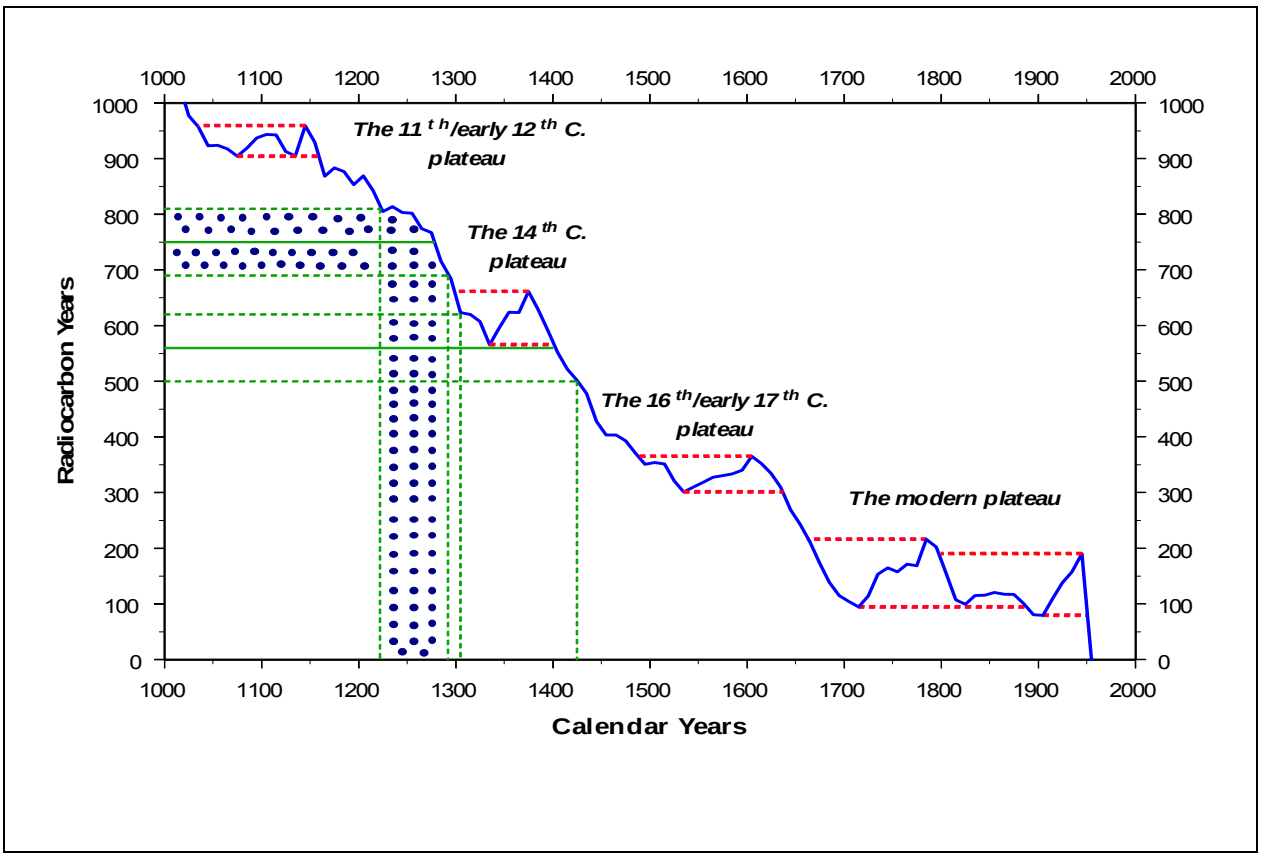


Figure 1. A 1000 year radiocarbon calibration curve for the Southern Hemisphere. The international calibration curve showing the relationship between radiocarbon dates and calendar years AD (based on the INTCAL98 curve of Stuiver *et al.* 1998). There is a general increase in radiocarbon age further back in time, but for certain periods the trend is reversed. These periods are indicated by dashed horizontal lines and are generally referred to as plateaux. The calibration of two high-precision radiocarbon dates is illustrated. An older radiocarbon age of 750 years before present (yrs BP) with two-sigma uncertainty of ±60 years (stippled region) is shown. The age intercepts a steep part of the calibration curve - the vertical lines indicate the corresponding calendar age range at 95% confidence. A younger radiocarbon age of 560 yrs BP with two-sigma uncertainty of ±60 years is also shown. This age falls partly within a plateau region of the calibration curve, the effect of which is to markedly broaden the calendar age range (Quan in Grave and Barbetti 2001).

The main limitation of tree ring studies (commonly referred to as dendrochronology) is that not all tree species are suitable, with the best specimens generally being found in ecologically marginal areas where tree growth is slower and longevity is higher (Briffa 2000). There are restrictions, therefore, to the spatial coverage of tree-ring records. There is also a limitation to how far back in time tree records can extend, with the current range of continuous records being in the order of 7000 to 10,000 years (Grudd *et al.* 2002). Nevertheless, there are a number of sequences that extend back over at least the last 2000 years from around the globe that enable both regional reconstructions of past climates and regional inter-comparison. From this, factors such as late Holocene climate variability and the inter-hemispheric offset in ^{14}C concentrations can be examined (Hua *et al.* 2003; Barbetti *et al.* 2004).

Only a few species of trees in Australia are suitable for tree ring studies. Most do not produce consistent annual rings. Taxa that have either provided or shown the potential to provide palaeoclimate records include *Lagarostrobos franklinii* (Huon pine), *Phyllocladus asplenifolius* (celery top pine), *Athrotaxis selaginoides* (King Billy pine), *Eucalyptus pauciflora* (snow gums), *Eucalyptus oreades* (Blue Mountains ash), *Toona ciliata* (Australian red cedar), *Pinus radiata* (for very recent records) and northern rainforest gymnosperms (such as *Araucaria*) (Cook *et al.* 2000;

Allen 2001; Allen *et al.* 2001; Hua *et al.* 2003; Heinrich and Banks 2005). Eucalypt species other than those at high-altitudes have also been investigated, however due to significant variation in their growth patterns, have proved too problematic thus far to interpret (Argent *et al.* 2004). The longest and most comprehensive records have been developed using populations of *Lagarostrobos franklinii*, a long-lived species endemic to Tasmania. To date, published tree ring records from this species extend back continuously to 572 BC from low altitude sites and 3,700 years from a high elevation site (Buckley *et al.* 1997; Cook et al., 2000). In addition, there are several floating records: a 4,000 year linked record extending back from around 3520 cal BP (Barbetti 1999); an overlapping record from 7,500 to 8,800 cal BP; another spanning from 9,000 to 9,500 cal BP; an overlapping record from 9,600 to 10,400 cal BP; and several pre-Holocene (>10,000 cal BP) records, including logs dated as greater than 38,000 years old (Barbetti 1999). There is a potentially continuous 10,000 year record from Mt Read (Buckley *et al.* 1997; Anker *et al.* 2001). The Huon pine tree ring sequences obtained from high elevation sites (>700 metres above sea level or masl) record strong responses to temperature for most growing season months, providing reliable records of past temperatures between November and April (Buckley *et al.* 1997). Sequences from lower altitude sites exhibit a more complex relationship, with a weak response to growing-season temperature and a strong inverse relationship with temperature of the previous season of growth (Buckley *et al.* 1997). Indeed, the response parameters of the lowland tree records appear to vary through time, with temperature, sunlight and atmospheric CO_2 concentrations all having different effects at different times.

Australian dendrochronological records have been used to investigate climate change and variability over the last 10,000 years (Buckley *et al.* 1997; Cook *et al.* 2000; Allen *et al.* 2001), past fluctuations in atmospheric CO_2 levels (Hua *et al.* 2003; Hua and Barbetti 2004), radiocarbon offsets between the northern and southern hemispheres through time (Barbetti *et al.* 2004), and the relationships between climatic variables and atmospheric and land surface processes (Cook *et al.* 2000). These will be presented in more detail throughout chapter 4.

3.3.2. Speleothems

Measurement of stable isotopes, fluorescence banding and trace element content of carbonate speleothems (stalagmites and stalactites) have provided proxy evidence of past climates (e.g. Goede 1994; Shopov *et al.* 1994; Roberts *et al.* 1998; Desmarchelier *et al.* 2000). Speleothem research in Australia has concentrated on stable isotope analysis, largely from cave sites in southern Australia. The ratio of stable oxygen isotopes ^{18}O and ^{16}O (often referred to as $\delta^{18}O$) in speleothems have been used to provide both a signal of rainfall and a combined signal of rainfall and temperature. For example, seasonal and inter-annual variations of $\delta^{18}O$ in a well-dated stalagmite from a cave in southwestern Australia have been used to reconstruct seasonal variation in rainfall and identifies a historical shift in the frequency of intense winter rainfall events in the region (Treble *et al.* 2005). Another speleothem $\delta^{18}O$ record, from eastern Australia, has provided a good record of past El Niño Southern Oscillation (ENSO) variation (McDonald *et al.* 2004). The ratio of ^{12}C and ^{13}C (often referred to as $\delta^{13}C$) in speleothems have also provided combined records of past climate and environmental conditions, including: changes in the relative abundance of C3 and C4 plants in the cave area, which in turn can be related to climate (Pate *et al.* 1998); fluctuations in the concentration of soil CO_2 as a function of the level of vegetation activity; limestone dissolution under open or closed system conditions; the rate of CO_2 degassing from drip waters over a speleothem surface; and changes in the atmospheric CO_2 through time (Desmarchelier *et al.* 2000; Treble *et al.* 2005).

Depending on the sampling and analysis techniques used, Australian speleothems have provided records of annual to seasonal resolution for periods throughout the last two hundred thousand years (e.g. Desmarchelier *et al.* 2000; Xia *et al.* 2001; McDonald *et al.* 2004; Treble *et al.* 2005). However, as yet, no continuous records spanning the entire time frame have been obtained. Furthermore, unlike tree rings, no records have been correlated together to create a continuous history. Like tree rings, speleothems records are geographically limited; in this case to those areas containing suitable cave deposits. This can be problematic for calibrating the speleothem records

against climate, frequently because cave deposits do not have nearby instrumental climate records. Where instrumental records are nearby, research has been initiated to verify climatic interpretations of the speleothem stable isotope records, although it is in its early stages (e.g. Treble *et al.* 2005). Unlike other proxy climate sequences, climate change proxies contained in speleothems are not affected by post-depositional process, thus reducing some of the complications associated with interpreting other proxy records (Desmarchelier *et al.* 2000). Unfortunately, the relationship between the stable isotope signatures and climate can often be complex to interpret (e.g. Treble *et al.* 2005). Nevertheless, much progress has been made in Australia in this field of palaeo-research.

3.3.3. Lakes, bog and swamp sediments

Lakes, bogs and swamps are depositional environments, made up of sediments that have been laid down over time. Preserved in these sediments is often a range of proxy evidence for past environments, including micro and macrofossils, trace elements, stable isotopes, and the physical properties of the sediments themselves. Analysis of sediment cores extracted from these environments can therefore provide proxy records of past climates and climate impacts on the landscape on millennial to sub-decadal time scales.

The key advantage of sediment sequences developed from wetlands is that they can provide continuous records of past changes in terrestrial environments, potentially extending back over several ice ages. These sequences contain a variety of evidence of the impacts of past climate change, including those on vegetation, fire regimes and lake hydrology. Wetlands can also provide valuable information about the main drivers of climate change and climate variability through time (e.g. Kershaw *et al.* 2003).

The principle disadvantage of wetland sediment records is that they are spatially biased towards the moister climates of Australia, principally in the temperate and sub-tropic regions of southern and eastern Australia. There can also be problems in acquiring sub-decadal records from these sites as sedimentation rates in Australia are generally low. Sub-sampling to the resolution required to obtain sub-decadal records has been problematic in the past. However, in recent years it has been possible to obtain such records with the development of new coring equipment that can collect sub-centimetre samples, coupled with the availability of Accelerator Mass Spectrometry (AMS) dating technology that enables small radioactive samples to be dated. Although resolution on a seasonal scale is generally unattainable from Australian terrestrial sediment records, some preliminary investigations have been carried out into the potential for reconstructing past seasonal variation in climate by analysing the chemistry of ostracod shells (Ito *et al.* 2003).

Interpretation of the climatic signals provided by proxies from wetland sediment records can also be complicated, with multiple climate and environmental factors often playing a role. For example, pollen representation in sediments can often be the product of the interaction of precipitation, temperature and local environmental disturbance factors, including fire. In addition, there can also be lags between changes in climate and the vegetation response. This is less of a problem with short-lived microfauna that respond relatively quickly to changes in local water temperatures and salinities (the latter being an indicator of changes in effective precipitation). However, the response of these organisms to climate change can also be complex, requiring a sound knowledge of environmental drivers if they are to be useful in interpreting past climates.

An overview of the key ways in which proxies found in lake, swamp and bog sediments have been used in Australia is given below.

<u>Micro and macro fossils</u>

The low oxygen and moist environments in which lake, swamp and bog sediments are deposited are ideal for the preservation of a range of micro and macro fossils, including pollen, charcoal, diatoms and faunal remains, such as ostracod and beetle carapaces. Pollen records have been used to reconstruct past changes in local and regional vegetation across Australia (e.g. Kershaw *et*

al. 1991; Colhoun 2000; Dodson and Lu 2000). For the most part, pollen records provide evidence of changes in effective precipitation, which is the main climatic factor governing the distribution of vegetation over much of Australia. Pollen reconstructions can provide indications of past temperature shifts in alpine and subalpine areas, but these signals are complicated by the influence of precipitation. Although most of the climate reconstructions derived from Australian pollen records have been qualitative, in recent years progress has been made in providing quantitative reconstructions (e.g. McKenzie and Kershaw 1997; Harle *et al.* submitted 2005).

Micro and macro charcoal studies are frequently combined with pollen studies to reconstruct past fire regimes, and in turn the climatic conditions and processes (such as El Niño - Southern Oscillation variability) conducive to fire promotion and suppression (Haberle in press). Unfortunately, charcoal records are frequently complicated by depositional processes as well as human activity which impact on fire regimes. Nevertheless, carefully selected and prepared records have much to offer for understanding the past interaction between vegetation, fire and climate in our landscape.

Local aquatic pollen records can provide proxy evidence of shifts in the water balance, particularly in lakes. This is also true of microfossils such as diatoms and ostracods, which are dependent on environmental conditions within the local aquatic environment for their survival and, where present in the records, provide information on lake level fluctuations in response to changes in effective precipitation. Ostracods can also provide evidence of changes in water temperature (see the sections below on Geochemistry and Stable isotopes).

Geochemistry

Geochemical analysis of lake, bog and swamp sediments and of fossils found within these sediments can also contribute to our understanding of past climate change. For example, analysis of the magnesium and calcium ratio of ostracod shells found in lake sediment cores from southern Australia has been used to reconstruct past changes in temperature (Chivas *et al.* 1986). Another study focusing on the trace element concentrations within the sediments themselves coupled with a comparison to instrumental climate records from the region, identified that past patterns of sedimentation into Lake Burragorang (NSW) were strongly associated with high rainfall events. This not only provided evidence of the impact of climate variability on lake catchments in the region but also provided a tool for extending records of rainfall intensity further back into the past (Harrison *et al.* 2003).

Stable isotopes

As with geochemical analyses, the stable isotope content of lake, bog and swamp sediments and their fossils has been used to reconstruct past climatic environments. Stable carbon isotopes have been used to reconstruct changes in vegetation type (C3 and C4 plants) and, in turn, moisture availability (Pack *et al.* 2003). Oxygen isotopes have been used to reconstruct past changes in hydrology and temperature (Lister 1988; Dutkiewicz *et al.* 2000). Strontium isotopes have been used to identify periods of marine incursion into a glacial lake setting in the Gulf of Carpentaria, thus giving evidence of past sea level fluctuation in response to global climate change (McCulloch *et al.* 1989).

3.3.4. River, lake and dune geomorphology

Geomorphic evidence of the past extent and nature of lakes, rivers and dunes in Australia can provide valuable information about past changes in the water balance of catchments. In particular, they can provide information about past moisture availability (which in the Australian landscape is the product of the interaction of precipitation, temperature and evaporation), wind strength and wind direction.

Palaeochannels, river terraces and alluvial plains give evidence of past river flows under different climatic regimes. River terraces, for example, can provide evidence of river incision during periods

where base levels[2] dropped in response to falling sea levels (Williams *et al.* 1998). These features can also provide evidence of increased aggradation of coarse grained sediments during periods of heightened fluvial activity (Nott *et al.* 2002). The shape, size and sediment composition of palaeochannels and alluvial plains, such as those evident on the Riverine Plain of NSW, have been used to provide data on the rates and volume of flow and in turn reconstruct changes in effective precipitation (e.g. Nanson *et al.* 1991; Fried 1993; Page *et al.* 1996). Age determination has played an important role in interpreting these palaeo-records, with techniques such as uranium-thorium and thermoluminescence being used to date the evidence for past fluvial activity in Australia (Nanson *et al.* 1991; Page *et al.* 1996; Nott *et al.* 2002). River sediments have also been used to reconstruct past shifts in atmospheric circulation, in particular the Australian monsoon (Croke *et al.* 1996; Croke *et al.* 1999).

Similarly, dating geomorphic evidence for past lake level fluctuations has contributed to our understanding of the timing and nature of past climate variability. The geomorphic evidence of periods where lake levels have been high includes wave-cut terraces, beach ridges and marginal sediment exposures. Evidence for past low lake levels include the presence of lunettes[3] and source-bordering dunes (Harrison 1993). Microfossil, geochemical and physical evidence contained in lake sediments also provide evidence of past lake level fluctuations. These are discussed in section 3.3.3. Geomorphic evidence of past lake levels have been used to reconstruct the timing of major wet phases in arid and temperate Australia (Harrison 1993; Bowler *et al*., 2003), past variability in the precipitation/evaporation balance (Jones *et al.* 2001) and past shifts in the sub-tropical anti-cyclonic belt (STA), the westerlies and intensity of the Australian monsoon (Croke *et al.* 1999; DeVogel *et al.* 2004).

Evidence for past mobilisation of the dune fields spanning much of inland Australia acts as a proxy record of past periods of aridity and can provide valuable information about past changes in wind direction and speed (Bowler 1986; Nanson *et al.* 1995). In some cases, dune deposits are interspersed with lake and fluvial deposits, providing a complex record of wet and dry phases (e.g. Page *et al.* 2001).

Two of the most significant limitations of fully exploiting palaeo lake, riverine and dune geomorphological records for climatic reconstructions are dating control and sampling resolution. These records tend to be, by their very nature, intermittent and of coarse resolution. The latter is exacerbated by the wide uncertainties associated with the methods used to date the deposits (Kershaw and Nanson 1993; Shulmeister *et al.* 2004). In addition, the morphological response of rivers, lakes and dunes to changes in climate is complex and is not easy to interpret. For example, evidence of greater river flows can be a simple response to increased precipitation or a complex interaction between depositional processes, precipitation, evaporation and vegetation cover, with the last influencing the stability of catchments and amount of sediment available for deposition (Fried 1993). A further limitation to the value of palaeo-geomorphological records from dunes, lakes and rivers is their geographical bias. The lake sites, for example, tend to be clustered in the southern and eastern regions of Australia (see Figure 2), whilst the dune evidence has a clear arid-zone bias. Nevertheless, these records can provide a powerful hydrologic record of past climates in Australia, particularly when taken in combination. Correlation of lake records, for example, has enabled the examination of the synchronicity (or lack of it) of past climate changes across Australia and in turn investigation of past changes in atmospheric circulation (e.g. Harrison 1993; Shulmeister *et al.* 2004).

[2] The base level of a stream is the level below which a stream cannot erode its channel, which in the case for water courses entering the oceans, is sea level.

[3] A crescent shaped dune formed on the leeward edge of a lake. See glossary for more details.

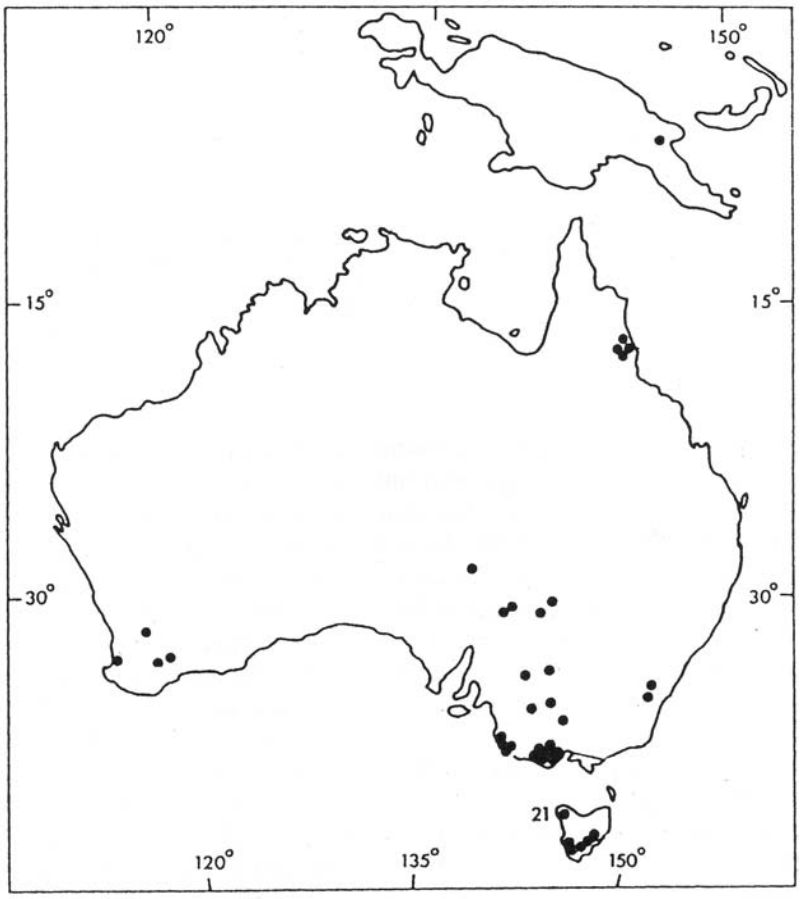


Figure 2: Selected Australian lake sites from which palaeo-records of past climates have been obtained.

Although not all of the Australian palaeo-lake sites are shown, this map does indicate the geographic bias of the sites (after Harrison 1993).

3.3.5. Coastal sediments

As the interface between oceans and land, Australian coastal sediments have much to tell us about the nature and impacts of past climate processes and change in areas currently highly populated. Of particular importance are beach ridges and coastal dunes.

Beach ridges form on accreting coasts where waves and onshore winds concentrate sediment in ridges parallel to the shore. Ancient beach-ridge successions, therefore, can provide useful records of the character and rate of beach sediment accumulation, shoreline extension and the past configuration of the coast. Where relict intertidal sediments can be identified in these deposits they provide a record of past sea level (Otvis 2000; Orford *et al.* 2003). Numerous studies of beach ridge successions have been able to reconstruct coastal environments of the Last Interglacial and Holocene using radiometric (e.g. radiocarbon; uranium-thorium) and luminescence dating methods (Mason and Jordan 1993; Kennedy and Woodroffe 2000; Murray-Wallace *et al.* 2002; Brückner and Schellmann 2003; Goy *et al.* 2003; Orford *et al.* 2003). The rate at which modern and historical beach ridges and beach-ridge successions develop has also been measured using aerial photographs and survey markers (Carter 1986; Sanderson *et al.* 1998).

Developing chronologies for beach ridges that are older than the historical period but too young to

be accurately dated by the radiocarbon method is now possible using the optically stimulated luminescence (OSL) method (e.g. Murray-Wallace *et al.* 2002; Ballarini *et al.* 2003). The great advantage of examining sandy beach ridges that sit immediately behind modern beaches, therefore, is that these deposits can provide relatively detailed records of coastal environmental change over a time scale that can range from tens to thousands of years. For instance, beach ridges composed of relatively coarse sediment, such as pebbles and boulders, can form on coasts during storm events. Dating successions of these type of ridges can therefore provide a relatively detailed record of past storm events such as the passage of cyclones on the central coast of Queensland (Hayne and Chappell 2001). These types of deposits can also be used to assess the magnitude as well as the frequency of ancient and historical cyclones (Nott and Hayne 2001; Nott 2004).

Coastal dunes record the delivery of sand to beach systems and its reworking landward by onshore winds. These deposits can provide records of episodes of shoreline deposition and coastal landscape instability during the historical period. When dune deposits have their original depositional morphology preserved or exhibit exposures of internal sedimentary structures, as a result of stabilisation by vegetation or the cementation of the sediment, they can provide records of historical and ancient wind regimes (e.g. Brooke *et al.* 2003). Successions of dune deposits, such as those on the Coorong coastal plain of South Australia, can provide long term (over several hundred thousand years) records of dune mobility and long quiescent periods when soil horizons were formed (Murray-Wallace *et al.* 2001).

3.3.6. Glacial deposits

Quaternary glacial and periglacial landforms present in the highland regions of mainland southeastern Australia and Tasmania provide evidence of climates during past ice ages when glacial and periglacial activity was much more widespread than today. Mapping and dating evidence for past glaciers in these regions, in particular moraines, has allowed scientists to reconstruct the extent and timing of past glaciations (Colhoun and Fitzsimmons 1990; Barrows *et al.* 2001). Recent advances in dating techniques have been of particular significance, enabling scientists to identify the previously unrecognised complexity of ice advances during the last ice age (Barrows *et al.* 2001; 2002). This work has enhanced regional comparisons as well as comparisons with other proxy evidence from Australia and surrounding regions (such as marine sediment records of sea surface temperature). Such correlations have in turn contributed to the understanding of past processes and drivers of climate change.

Periglacial landforms are features such as block streams, block slopes and solifluction deposits are more widespread than glacial deposits. These landforms are thought to be less sensitive to changes in precipitation and are therefore considered to be more reliable indicators of past temperatures (Galloway 1965; Barrows *et al.* 2004). Recent advances have been made in dating periglacial features in the Australian landscape, thus improving our understanding of the timing and extent of past cold phases (Barrows *et al.* 2004).

Estimates of past temperatures during glacial periods, particularly the last ice age, have been developed from the analysis of glacial and interglacial deposits (Galloway 1965; Colhoun 1985). These estimates are currently being revised on the basis of improved chronologies. Correlation of these records of cold landform deposits with other proxy evidence in Australia, such as fluvial and lacustrine records, are also being used to improve our understanding of the regional hydrology of southeastern Australia during ice ages (Barrows *et al.* 2001).

The most significant weakness of Australian glacial and periglacial deposits is that they do not give continuous records of past temperature change. The uncertainties associated with dating can also complicate the interpretation of the evidence, as can the combined role of precipitation and temperature in glacier formation. The strength of these landscape features is that they are one of the few proxy indicators of a significant temperature control in a landscape dominated by the

effects of changes in moisture.

3.4 Marine palaeo-records

3.4.1 Corals

Massive corals growing in shallow tropical and sub-tropical oceans have microlaminations (referred to as 'density banding') that contain physical, isotopic and geochemical evidence of past environments at annual and sub-annual resolution (Gagan *et al.* 2000; Lough 2004). Corals are widely distributed in tropical regions (Figure 3) and can be accurately dated (using annual banding and radiometric dating techniques), potentially providing continuous records that span centuries (Gagan *et al.* 2000). In addition, fossil corals can provide evidence of atmospheric and oceanic conditions well into the past, such as during the last ice age. Overlapping records can be linked to provide records extending back thousands of years, such as in the southwestern Pacific (Gagan *et al.* 2000). Physical characteristics of coral bands (such as skeletal density, linear extension rate, tissue thickness and calcification rate) provide time-series information about the environmental conditions that controlled coral growth at the time of formation, such as sea surface temperature (SST; Lough and Barnes 2000).

Measurement of stable oxygen isotope ratios ($\delta^{18}O$) in corals can provide information about sea surface temperature, sea surface salinity and the hydrological balance of oceans. Oxygen isotope records obtained from corals growing in regions where the $\delta^{18}O$ composition of seawater is constant provide good evidence of sea surface temperature variability. Where the $\delta^{18}O$ composition of seawater is controlled by the interaction of precipitation, evaporation and water advection, the coral records provide a record of changes in the hydrologic balance. In regions where the $\delta^{18}O$ composition of seawater correlates with precipitation, coral records can be used to reconstruct precipitation (see Gagan *et al.* 2000 for a review). Geochemical analysis of coral bands have also been used to reconstruct past sea surface temperatures, with most research focused on strontium-calcium ratios (Sr/Ca e.g. Beck *et al.* 1992; Alibert and McCulloch 1997; Gagan *et al.* 1998). Other geochemical proxies for temperature that have been explored include magnesium-calcium (Mg/Ca), uranium-calcium (U/Ca), boron (B) and fluorine (F) (Min *et al.* 1995; Hart and Cohen 1996; Mitsuguchi *et al.* 1996). Luminescent banding found in corals have been used to improve dating control of coral records as well as provide a proxy for precipitation and river runoff from nearby land masses (e.g. Hendy *et al.* 2003). In addition to providing age control for the corals, radiocarbon analyses of coral bands have been used in the calibration of the ^{14}C timescale and identification of the movement of ocean surface waters (Hua *et al.* 2004; Hughen *et al.,* 2004; Fairbanks *et al.* 2005).

Australian scientists have been at the forefront of coral research, utilising high quality records gathered from around Australia (including the Great Barrier Reef; Figure 3) to reconstruct past sea surface temperatures, precipitation, evaporation, movement of ocean waters, ocean-atmospheric interactions from seasonal through to millennial scales (including variations in ENSO and the Indo-Pacific Warm Pool), atmospheric forcing of abrupt climate change and the impact of climate change on Australian river systems (e.g. Gagan *et al.* 2001; Hendy *et al.* 2003; Correge *et al.* 2004; Gagan *et al.* 2004; Hua *et al.* 2004; McGregor and Gagan 2004). These applications will be presented in more detail in Chapter 4.

As with all other proxy records of climate change, coral records can contain bias and errors unrelated to climate. For example, the upward growth of a coral can lead to the exposure of its surface to shallower water depths, affecting temperature, salinity and light intensity levels. This has potential ramifications for the isotopic and geochemical records obtained (Gagan *et al.* 2000). One way to identify and adequately take into account such effects is to cross match coral records. Some studies have done this, attempting to quantify the reliability of climate proxies contained within coral records through local, regional and global cross matching as well as comparison with instrumental records (e.g. Guilderson and Schrag 1999; Evans *et al.* 2002; Hendy *et al.* 2002).

However, many studies rely on the implicit assumption that variations identified in a single coral record are attributable to one or more climatic variables (Lough 2004). Some caution needs to be applied, therefore, in utilising coral records. If the various potential influences on proxies contained within corals are well understood, and the coral records obtained are well calibrated and validated, they provide an extremely powerful tool for understanding climate change and variability from seasonal through to millennial time scales. This is particularly true when multi-proxy analyses are carried out.

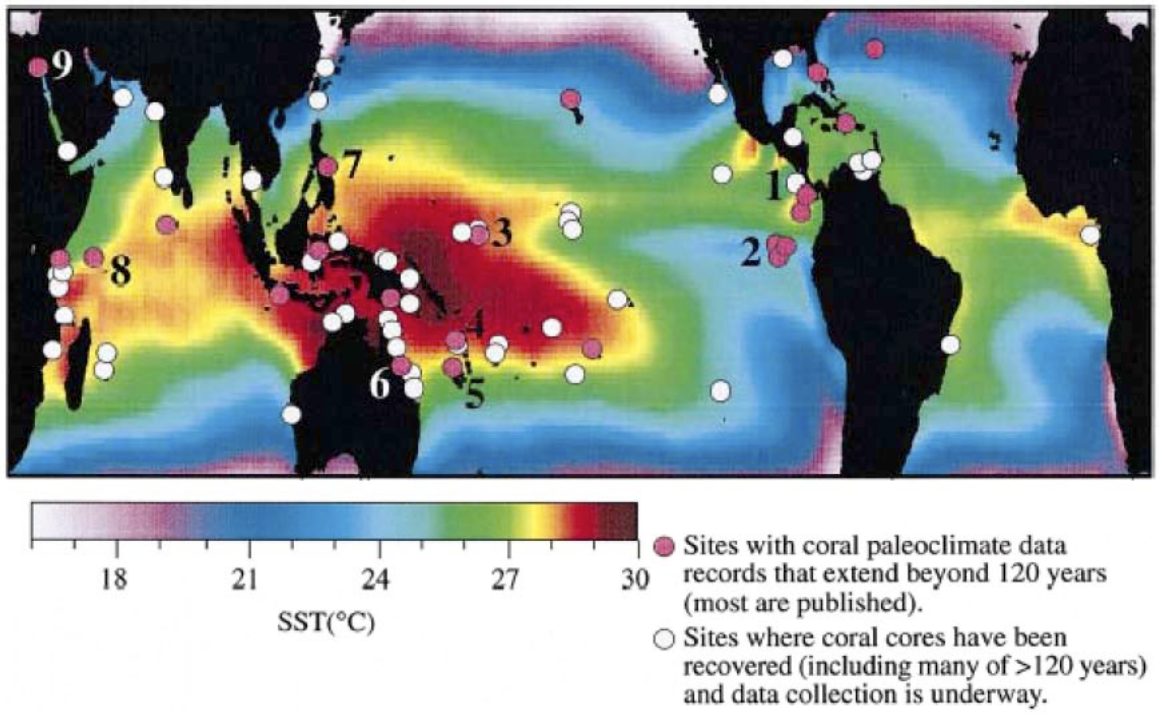


Figure 3. **Approximate locations of key coral palaeoclimate research sites mapped against annual mean tropical sea surface temperatures (SST).**
SST data are from the National Meteorological Centre and are available at: http://www.ingrid.ldgo.columbia.edu. *1. Panama, 2. Galapagos, 3. Tarawa, 4. Vanuatu, 5. New Caledonia, 6. Great Barrier Reef, 7.Philippines, 8. Seychelles, 9. Red Sea* (after Gagan *et al.* 2000).

3.4.2. Ocean sediments

Deep-sea sediment cores are particularly valuable in that they are widely distributed, can be correlated across large distances, and provide some of the longest, most continuous records we have of past climates. They can therefore be used to piece together past global and regional changes in oceanic and climatic conditions. Evidence of changes in past ocean circulation, sea surface temperatures, sea surface salinity, sea level and global ice volume have been obtained from microfossil, geochemical and isotopic evidence contained within deep-sea cores. Much of this information has been developed from the species abundance, geochemical and isotope analyses of microfossils (such as foraminifera, ostracods and diatoms). Modern analogue analysis of species abundance of carbonate foraminifera preserved in the sediments, together with their geochemical (e.g. Mg/Ca) and oxygen isotope content have provided records of past fluctuations in ocean temperature and global ice volume (e.g. Barrows and Juggins 2005). Palaeo-records of ocean circulation, ocean primary productivity, nutrient levels, and ocean upwelling and ventilation (which controls CO_2 release into the atmosphere) have been developed from the analysis of

carbon and nitrogen isotopes ($\delta^{13}C$, $\delta^{15}N$), cadmium/calcium ratios (Cd/Ca) and barium in foraminifera (e.g. Boyle 1992; Williams *et al.* 1998; Martínez *et al.* 1999; Pedersen *et al.* 2003).

In recent years, significant advances have been made in understanding the temporal and geographic variation of sea surface temperatures in the Australian region through isotopic, modern analogue and geochemical analyses of surface-dwelling foraminifera (known as *planktonic* foraminifera). This in turn has led to an enhanced knowledge of past variability in important drivers of climatic change in the Australian region, such as the Indo-Pacific Warm Pool and the ENSO (Martínez *et al.* 1999; Gagan *et al.* 2004; Barrows and Juggins 2005).

In addition to providing information about ocean conditions, marine cores can also capture information from adjacent terrestrial environments. For example, the pollen and charcoal contained within marine cores from around Australia have provided evidence of shifts in vegetation and fire regimes in response to climatic fluctuations (Harle 1997). Variations in the dust content of cores from the Tasman Sea have also been used to reconstruct past changes in aridity, wind direction and velocity over the Australian continent (Hesse and McTainsh 1999).

Although marine records provide a powerful palaeo-tool for reconstructing past climate change, they do have some drawbacks. Chief amongst these is that generally the sedimentation rate is low, limiting high resolution analyses, with samples typically representing 100-1000 years. Additionally, as with many other palaeo-records records, interpreting the proxy data can be complicated. For example, interpretation of the $\delta^{18}O$ signal from foraminifera requires a knowledge of the relationships between sea surface temperature and ice volume at any given site over time.

3.5 Antarctic records

There is increasing evidence that the climate of the southern high latitudes, and Antarctica in particular, is coupled to the global climate system in ways that have not previously been recognised (van Ommen 2005). Palaeo-records from Antarctica, therefore, are vitally important in understanding the mechanisms of global climate change, including the influence of human activities. Additionally, in recent years, Antarctic palaeo-records have provided proxy evidence of past climate change in Australia. This section outlines the key ways that Antarctic palaeo-records have contributed to our reconstruction of past climates and in turn significantly contributed to our understanding of the global climate system.

3.5.1. Ice cores

Ice cores collected from polar and low-latitude mountain glaciers and ice caps have provided sensitive records of past climatic conditions and processes. Depending on where they are collected from, ice records can cover recent decades in great detail or extend back hundreds of thousands of years. Several long sequences have been obtained from Antarctica, including a 420,000 year old record from Vostok (Petit *et al.* 1999) and a recently obtained 740,000 year record from Dome C (EPICA 2004). The age control on these longer cores tends to be fairly coarse, with sample resolutions of the order of tens of years or more, largely due to compaction of ice at great depth. Shorter ice cores extracted from the coastal areas of Antarctica are capable of providing much higher sampling resolution. In some cases sample resolution of two weeks is possible. The trade off, however, is that such cores tend to span much shorter time periods, generally in the order of 400 years. The longer, lower resolution records are therefore more suitable for investigating long term millennial scale climate change and processes, whilst the shorter cores provide excellent, high resolution records of sub-decadal to recent millennial scale changes.

Ice cores from Antarctica contain a range of proxy evidence for palaeoclimates. Analyses of fluctuations in $\delta^{18}O$ and deuterium (δD) in ice cores have been used to reconstruct changes in

surface air temperatures over Antarctica and surrounding oceans through time, as well as variations in ice volume (Petit *et al.* 1999; Vimeux *et al.* 1999). In addition, stable isotope records have been compared with solar variation indices (Bard *et al.* 2000) to explore the long-term relationship between energy emitted from the Sun and Earth's climate (van Ommen 2005). The aerosol content of Antarctic ice cores has also been a valuable source of past climate change and impacts. Changes in sodium concentrations, largely produced by sea-salt from the oceans surrounding Antarctica, have provided proxy evidence of changes in the extent of sea ice, conditions in the surrounding ocean, atmospheric circulation and precipitation over Antarctica and in Australia (see Box 1 and section 4.2; Goodwin *et al.* 2004). Analysis of the dust content has yielded evidence of continental aridity, wind strength and trajectories, and indirectly precipitation (Petit *et al.* 1999). Estimates of past ice accumulation rates obtained from well-dated Antarctic cores provide proxy evidence of precipitation changes as well as an understanding of past changes in the ice sheet mass-balance, which in turn improves our ability to reconstruct past sea-level variations (van Ommen 2005). Biogenic sulphur tracers have given proxy evidence of primary biological productivity through time, which can be related to past climatic changes (van Ommen 2005) and sea ice extent (Curran *et al.* 2003).

In addition to providing proxy evidence of past climate systems, ice records from Antarctica have yielded direct evidence of past atmospheric composition through the analysis of greenhouse gases, such as concentrations and isotopic ratios of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), trapped in air bubbles in the cores (Etheridge *et al.* 1996; Etheridge *et al.* 1998; Francey *et al.* 1999; Petit *et al.* 1999; EPICA 2004; Flückiger *et al.* 2004). Indeed, Antarctic records are thought to provide the most reliable evidence of changes in global atmospheric CO_2 (Raynaud *et al.* 1994). Law Dome, in the Australian Antarctic Territory, provides unparalleled air age resolution and has already significantly contributed to our understanding of the role of human activity on changes in atmospheric methane content over the past 2000 years (Ferretti et al., 2005). Such records have not only enabled an improvement in our understanding of the relationships between atmospheric gases and climate (Petit *et al.* 1999; Crowley 2000; van Ommen 2005) but have also provided us with the means of placing recent changes in atmospheric gas composition and climate change in the context of natural variability (see section 4.3).

A key strength of Antarctic ice cores is that they provide multi-proxy evidence of Southern Hemisphere climates, atmospheric and oceanic conditions over long time scales and at high resolution (annual to seasonal). In particular, they provide records of past environments where other records, such as tree rings, cannot be gathered. The principle weakness of ice core data is that interpretation of some proxies can often be complex and subject to bias. For example, the relationship between snow chemistry and atmospheric concentrations has not yet been fully elucidated for aerosols and reactive gases (Raynaud *et al.* 2003).

3.6 Summary

This chapter has provided a brief taste of the vast array of palaeo-records available in Australia. With recent technological developments in sample collection, dating and analysis, it is now possible to produce high resolution, high quality records capable of extending our climate records considerably beyond the instrumental records of the 19th century. Although some geographical gaps exist for key periods, the range of proxies available mean that we are now in a position to carry out cross-regional analyses to better understand the natural climate system. This theme is explored in the following chapters. A summary of the palaeo-techniques employed in the Australian region (including the Australian Antarctic Territory) is provided in Table 2 and Figure 4.

Table 2. Summary of palaeo-records utilised in palaeoclimate research in the Australian region, their applications and limitations.

	Palaeo-record	*Environmental parameter*	*Chronologic classification*	*Highest resolution*	*Spatial resolution*	*Key potential uses*	*Key limitations*
Terrestrial	Tree rings - *Ring width/density* - *Radioactive isotopes (^{14}C)* - *Stable isotopes ($\delta^{13}C$, $\delta^{18}O$)*	• temperature • precipitation • evaporation • sunlight hours (cloudiness) • SST • atmospheric ^{14}C and CO_2 levels	seasonal to millennial • continuous* • discontinuous* (floating records)	annual	Predominantly Tasmania, some potential in NSW and Qld wet forests	• climate change and variability • climate systems • biosphere-atmosphere interactions • ocean-atmosphere interactions • atmospheric CO_2 and ^{14}C • climate impacts on trees, atmosphere, SST	• only limited number of tree species suitable • confined geographic range • limitation in how far back continuous records extend • lowland tree rings provide complex signals that can be difficult to interpret
	Speleothems - *Stable isotopes ($\delta^{13}C$, $\delta^{18}O$)* - *Radioactive isotopes (^{14}C)*	• temperature • precipitation • evaporation • groundwater movement and volume	seasonal to millennial •continuous •discontinuous (floating records)	annual	Where cave systems occur. Most work to date in southern and eastern Australia	• climate change and variability • climate systems • climate impact on groundwater and cave systems •	• confined geographic range • can be problems in calibrating due to lack of nearby instrumental records • can be difficulties in interpreting complex proxies

*continuous records are regarded as those which provide a continuous sequence extending back from the present, discontinuous records are isolated splices of time of varying length – annual to millennial; SST = sea surface temperature, SSS = sea surface salinity

Table 2 *continued*

	Palaeo-record	*Environmental parameter*	*Chronologic classification*	*Highest resolution*	*Spatial resolution*	*Key potential uses*	*Key limitations*
Terrestrial (cont.)	Lake, bog and swamp sediments - *Microfossils (e.g. pollen, charcoal, fauna)* - *Macrofossils (e.g. charcoal, leaves, faunal remains)* - *Geochemistry* - *Stable isotopes ($\delta^{13}C$, $\delta^{18}O$)* - *Radioactive isotopes (^{14}C, U/Th, 210Pb etc.)* - *Physical properties (e.g. moisture and organic content)*	• temperature • precipitation • evaporation • vegetation • fire • lake/bog/swamp water levels • water quality • erosion • atmospheric ^{14}C?	sub-decadal to millennial • continuous	sub-decadal (2-4 years, depending on site)	Where lakes, swamps and bogs occur - mainly in southern and eastern Australia	• climate change and variability • climate systems • biosphere-atmosphere interactions • climate impact on vegetation, aquatic fauna, erosion, wetland hydrology	• spatially biased to moister regions • sedimentation rates often low – reduced resolution • few quantitative analyses (this is changing) • lags between proxy and climate change (e.g. vegetation) • can be difficulties in interpreting complex proxies • some proxies also affected by non-climatic factors • chronological control can be difficult, especially for older records
	River, lake and desert dune geomorphology - *palaeo river channels (shape, composition, course)* - *alluvial deposits* - *palaeo-lakes* - *lake shoreline features* - *dune shape, composition, alignment*	• temperature • precipitation • evaporation • wind strength and direction • lake levels • river flow volume • vegetation cover (indirect from dunes)	millennial • discontinuous • continuous (less common)	millennial	Rivers – Australia wide Lakes – regions where lakes have occurred, mainly in south and east Desert dunes - western, central and some southeastern regions	• climate change and climate variability • climate systems • climate impact on landscape and river, lake and groundwater hydrology	• chronological control can be difficult (although improving with new techniques) • coarse time resolution • some spatial bias

*continuous records are regarded as those which provide a continuous sequence extending back from the present, discontinuous records are isolated splices of time of varying length – annual to millennial; SST = sea surface temperature, SSS = sea surface salinity

Table 2 *continued*

Terrestrial (cont.)	Coastal sediments (non-wetland) - *coastal dunes (shape, composition, alignment)* - *beach ridges* - *palaeosols* - *fossils, e.g. shells, roots*	• sea level change • sediment budget – catchment and marine sediment loads • wind strength and direction	decadal-millennial • discontinuous	decadal	Coastal regions	• climate change and climate variability • climate systems • climate impacts -coastal • ocean-atmosphere interactions	• chronological control can be difficult (although improving with new techniques) • coarse time resolution • records only found on coasts that have or have had positive sediment budget (i.e. depositional) • most records are discontinuous
	Glacial deposits - *periglacial features (e.g. blocky fields, solifluction deposits)* - *glacial tarns, cirques, moraines, ice scratching*	• temperature • precipitation • ice volume • periglacial conditions	millennial • discontinuous	millennial	Tasmania and Snowy Mountains (esp. Kosciusko area)	• climate change • climate systems • cryosphere-atmosphere interactions • climate impacts – Tasmania and alpine SE Australia	• coarse time resolution • records are discontinuous
Marine	Corals - *coral band width* - *coral luminescence* - *stable isotopes ($\delta^{13}C$, $\delta^{18}O$)* - *geochemistry*	• SST • SSS • precipitation • atmospheric ^{14}C and CO_2 levels • climate impact on shallow marine and adjacent terrestrial environments	decadal-millennial • continuous	bi-weekly	Subtropical and tropical shallow oceans around Australia Tasmania Adjacent terrestrial regions	• climate change and variability • climate systems • ocean-atmosphere interactions • atmospheric ^{14}C • past oceanic currents?	• spatially limited and biased to warm, shallow waters • can be difficulties in interpreting complex proxies

*continuous records are regarded as those which provide a continuous sequence extending back from the present, discontinuous records are isolated splices of time of varying length – annual to millennial; SST = sea surface temperature, SSS = sea surface salinity

Table 2 *continued*

	Marine sediments - *microfaunal content (e.g. foraminifera)* - *stable isotopes ($\delta^{13}C$, $\delta^{18}O$, $\delta^{15}N$)* - *geochemistry* - *aerosols (e.g. pollen, dust)*	• SST, deep sea temperature • SSS • ocean nutrients and biological activity • precipitation • wind strength, direction • vegetation of adjacent landmass • river flow of adjacent landmass • atmospheric ^{14}C and CO_2 levels • ocean circulation • global ice volume	Decadal to millennial • continuous	Decadal	Deep ocean Adjacent terrestrial near-coast regions	• climate change and variability • climate processes (ocean-atmosphere interactions) • climate systems • atmospheric ^{14}C • past ocean circulation • climate impact on marine and adjacent terrestrial environments	• coarse resolution • can be difficulties in interpreting complex proxies
Antarctic	Antarctic ice cores - *atmospheric gases in air bubbles* - *stable isotopes (δD, $\delta^{18}O$)* - *geochemistry* - *aerosols (e.g. dust)*	• temperature • precipitation • greenhouse gases • aerosols • solar irradiance • wind strength, direction • ice volume • SST • SSS • Sea level • mean sea level pressure • atmospheric greenhouse gases • ocean circulation • atmospheric circulation	Sub-decadal to millennial	Interior sites – millennial Coastal sites – seasonal, several years or more for enclosed gases	Antarctica Southern Ocean Southern Australia	• climate change and variability • climate processes (ocean-atmosphere interactions) • past oceanic currents?	• can be difficulties in interpreting complex proxies • longer records have coarse resolution

*continuous records are regarded as those which provide a continuous sequence extending back from the present, discontinuous records are isolated splices of time of varying length – annual to millennial; SST = sea surface temperature, SSS = sea surface salinity

Table 2 continued

	Marine sediments - *microfaunal content (e.g. foraminifera)* - *stable isotopes ($\delta^{13}C$, $\delta^{18}O$, $\delta^{15}N$)* - *geochemistry* - *aerosols (e.g. pollen, dust)*	• SST, deep sea temperature • SSS • ocean nutrients and biological activity • precipitation • wind strength, direction • vegetation of adjacent landmass • river flow of adjacent landmass • atmospheric ^{14}C and CO_2 levels • ocean circulation • global ice volume	Decadal to millennial • continuous	Decadal	Deep ocean Adjacent terrestrial near-coast regions	• climate change and variability • climate processes (ocean-atmosphere interactions) • climate systems • atmospheric ^{14}C • past ocean circulation • climate impact on marine and adjacent terrestrial environments	• coarse resolution • can be difficulties in interpreting complex proxies
Antarctic	Antarctic ice cores - *atmospheric gases in air bubbles* - *stable isotopes (δD, $\delta^{18}O$)* - *geochemistry* - *aerosols (e.g. dust)*	• temperature • precipitation • greenhouse gases • aerosols • solar irradiance • wind strength, direction • ice volume • SST • SSS • Sea level • mean sea level pressure • atmospheric greenhouse gases • ocean circulation • atmospheric circulation	Sub-decadal to millennial	Interior sites – millennial Coastal sites – seasonal, several years or more for enclosed gases	Antarctica Southern Ocean Southern Australia	• climate change and variability • climate processes (ocean-atmosphere interactions) • past oceanic currents?	• can be difficulties in interpreting complex proxies • longer records have coarse resolution

*continuous records are regarded as those which provide a continuous sequence extending back from the present, discontinuous records are isolated splices of time of varying length – annual to millennial; SST = sea surface temperature, SSS = sea surface salinity

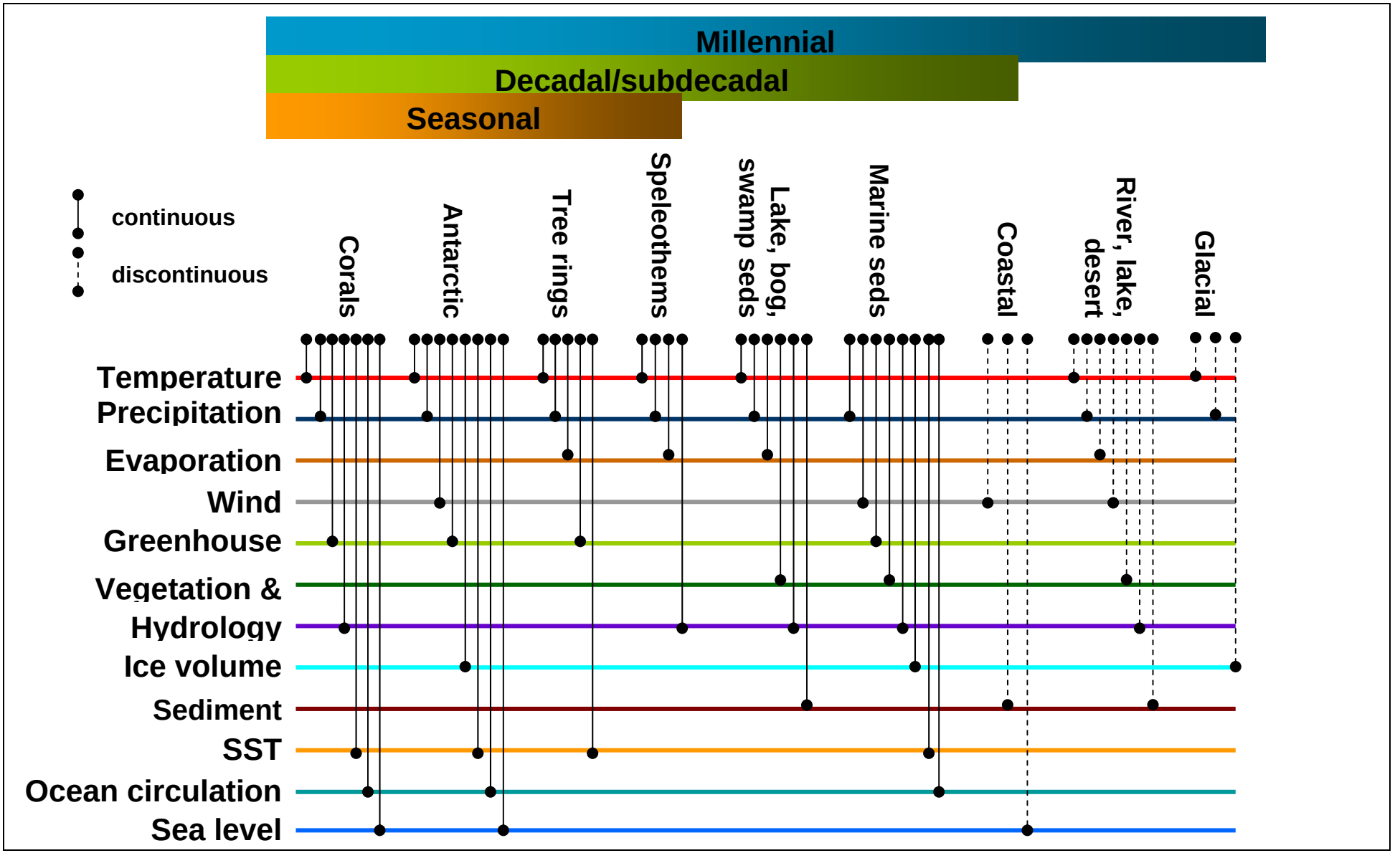


Figure 4. Summary of the main parameters for which information can be provided by key palaeo-archives.
It should be noted that this summary is not an exhaustive list.

4. The extent to which palaeo-records can assist in the identification of how and why climate has changed in the 20th and 21st centuries

Australian instrumental climate records, which generally extend back to 1900 AD, exhibit some geographic variability. However, most records give evidence of an Australia wide warming trend since the 1950s, with an across the board mean annual maximum temperature increase of 0.06°C/decade and mean minimum temperature increase of 0.12°C/decade over the period 1910 to 2004. Shifts in rainfall have been less spatially consistent, although there is a general trend for droughts to be hotter. Climate model simulations indicate that the warming is likely to have been caused by both natural variability and the enhanced greenhouse effect (Nicholls and Collins, in press). Because climate instrumental records do not extend back beyond the late 19th century, they are unable to quantify the level of natural variability. Palaeo-records do have this capacity, providing evidence not only of the nature of past climatic change and variability, but also the processes driving climate change in the Australian region. Evidence from before the past two centuries is critical for this purpose.

This chapter examines the extent to which palaeo-records can assist in the identification of how and why climate has changed over the last two centuries. It does this by focusing on four lines of evidence provided by palaeo-records: (1) evidence of past variations in temperature, precipitation and other climatic parameters in Australia at regional and national scales; (2) the scope for palaeo-science to shed light on the extent to which natural climate variation has contributed to climate trends and discontinuities observed over the last few decades; (3) evidence for variation in greenhouse gases that help us understand recent changes and predict future climate drivers; and (4) the scope for improved palaeo-data to contribute to better evaluation of climate models at global and regional scales.

4.1 Evidence of past variations in temperature, precipitation and other climatic parameters in Australia at regional and national scales

Australian palaeo-records have provided considerable evidence of past variations in climatic parameters, such as temperature and precipitation. For the most part, these records have been used to reconstruct climates at regional scales. However, in recent years, there has been a push to bring together the growing number of palaeo-records in order to carry out cross-regional, national scale analyses. This type of work is in its infancy, but with appropriate direction and funding, will allow the exploitation of Australian datasets to rival that of the northern hemisphere, where broader regional and national scale assessments are routinely made. Examples are given in the following sections of how palaeo-records have provided evidence of past variations in climatic parameters in the Australian region at two time scales - sub-decadal/decadal and millennial. This distinction is important, as the temporal scale of the record dictates the nature of the information that can be provided about past climatic variations.

4.1.1. Sub-decadal/decadal

Sub-decadal/decadal records of past variations in Australian climatic parameters have been derived from corals, terrestrial sediments, tree rings and Antarctic ice cores. There is considerable potential for these records to be extended to other areas of Australia, although this is limited to some extent by geographic constraints on the availability and coverage of various different types of palaeo-records. For example, ice core records obtained from coastal Antarctica have the potential to provide data about precipitation change for different regions of southern Australia. However, they are less likely to provide information about northern Australia other than in general terms of changes relating to atmospheric and oceanic circulation patterns (see Box 1). At this stage, the ice core records do not extend continuously back more than 4,000 years at this resolution, although longer records may be developed in the future.

Annual records of sea surface temperature for regions around northern and western Australia have been derived from coral records (Figure 5). Current integration of these records suggests that, in

contrast to the Northern Hemisphere temperature reconstructions (Mann and Jones 2003), sea surface temperature in the tropical southwest Pacific during the latter part of the Little Ice Age (17th to the 19th centuries) were as warm as the early 1980s (Gagan *et al.* 2004). A conflicting sea surface temperature coral record has been derived from New Caledonia, suggesting a 1.4°C cooling around AD 1730. It has been suggested that the apparent regional differences in the temperature records for the Little Ice Age were the result of significant shifts in the ocean-atmosphere system during this period, with temperature gradients between tropical low latitudes and mid-to-high latitudes being greater during the Little Ice Age (Hendy *et al.* 2002). Tree ring records from Tasmania, however, do suggest cooling during the Little Ice Age (Briffa 2000; Cook *et al.* 2000), supporting the concept of regional variation. Past variations in precipitation, sunlight hours and atmospheric CO_2 levels can also be inferred from Tasmanian tree ring records, although the interpretation is more problematic (see section 3.3.1).

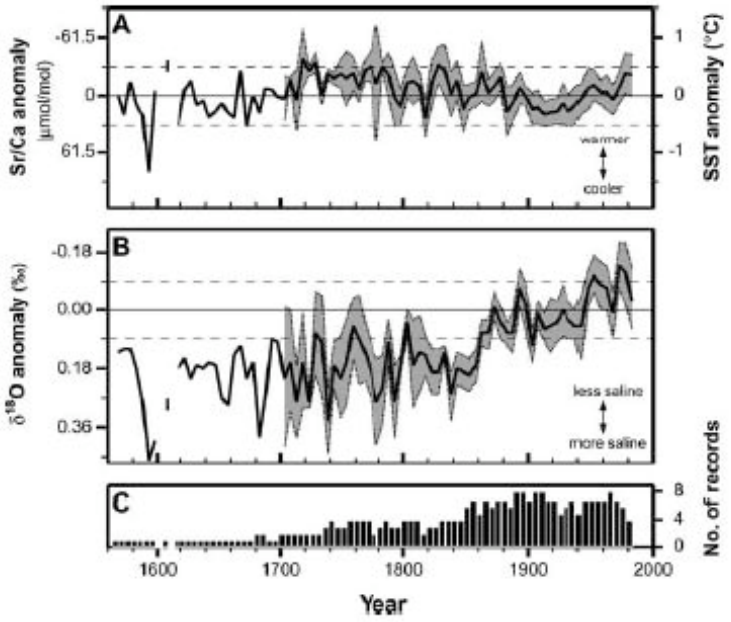


Figure 5. Composite records of (A) coral Sr/Ca and (B) coral $\delta^{18}O$ for AD 1565–1985 based on eight cores from massive *Porites* colonies from the central GBR, Australia (after Hendy *et al.* 2002).

Solid lines are reconstructions, at pent-annual resolution, normalized to the period 1860–1985 with 95% confidence intervals shaded. The Sr/Ca-SST reconstruction is plotted as ratios (left axis) and SST anomalies (right axis) using the calibration slope of 61.5 mmol/mol per °C (Alibert and McCulloch 1997; Gagan *et al.* 1998). Horizontal dashed lines define the 70.5 °C relative to 1860–1985 period. The number of records averaged at each pent-annual interval for the $\delta^{18}O$ reconstruction is given in (C). (source: Gagan *et al.* 2004)

4.1.2. Millennial scale records

There is a much larger number of millennial-scale palaeo-climate records available in Australia in comparison to sub-decadal/decadal records. In addition to tree ring, coral and ice core records, millennial-scale datasets have been produced from long continuous sequences from terrestrial wetland sediments and marine sediments, and more discontinuous records from speleothems, coastal sediments, glacial deposits, and rivers, lakes and dunes. The strength of millennial scale records is that they enable the identification of long-term patterns of climate variability that can overlay decadal variability. For example, long continuous records obtained from ice cores, marine

sediments and lake sediments give evidence of the interaction of climate cycles at various different scales, ranging from 100,000 year to 1,500 year climatic cycles. Quantitative reconstructions of past climatic variations, such as in temperature and precipitation, have been carried out for some of the records, particularly the marine, ice core, tree ring and coral records. However, there is a dearth of quantitative reconstructions from long continuous terrestrial records, such as those provided by pollen records from southeastern and northeastern Australia. In recent years, some attempts have been made to use modelling (see Box 2) and modern analogue analysis to quantify past changes. For example, a quantitative reconstruction of past temperature and precipitation over the last 200,000 years has been derived from a long pollen record from Western Victoria using a modern analogue analysis. This reconstruction explores changes in both mean and seasonal temperature and precipitation change, including rainfall seasonality (Harle *et al.* submitted 2005).

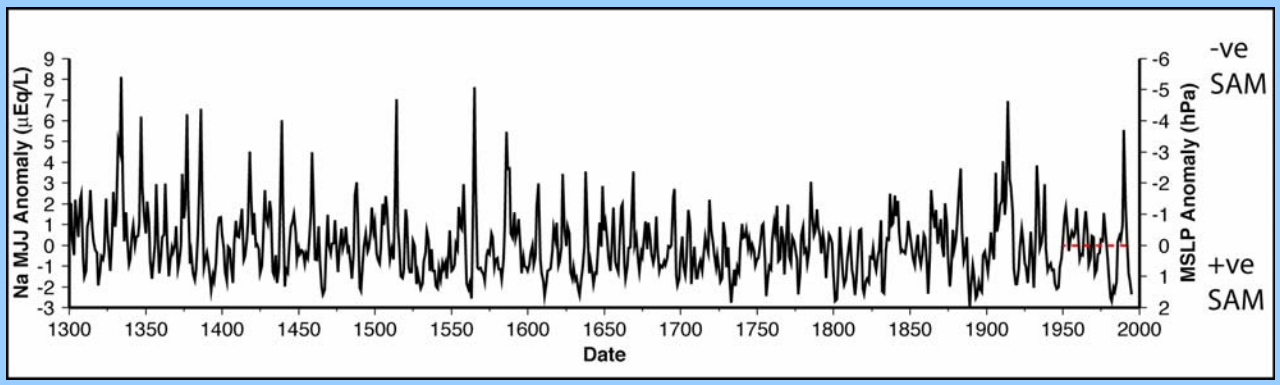
In addition, simulations of palaeoclimates for key periods, such as the Last Glacial Maximum (LGM), have been developed using palaeoclimate modelling. These efforts have been largely driven by international research groups, with some input from Australian scientists. These models tend to be Northern Hemisphere orientated and frequently provide unrealistic estimates for the Southern Hemisphere, which is of major concern (Pinot *et al.* 1999).

Box 1: Antarctic ice core records of the Antarctic Annular Oscillation and the hindcasting of south Western Australian rainfall over the past 700 years

Australian palaeo-scientists have derived a 700 year proxy record (at monthly resolution) for winter - May, June, July (MJJ) - mean sea-level pressure (MSLP) variability over the Southern Ocean, by analysing sea-salt (sodium) aerosol concentrations in an ice core from Law Dome in East Antarctica. The relationship between modern patterns of mid-latitude and sub-Antarctic atmospheric circulation and variations in sodium (Na) delivery to Law Dome ice was identified by analysing co-variations between Na concentrations, MSLP and wind field data. The observed relationship was then used to hindcast (model back in time) a proxy record of early winter MSLP anomalies and the Antarctic Annular Oscillation (AAO), also known as the Southern Annular Mode (SAM) of climate variability. The hindcast MSLP and AAO was completed for the South Indian and southwest Pacific Ocean regions over the period 1300–1995 AD. The 700 year proxy MSLP and AAO record is shown in the figure below. The record indicates pronounced decadal-scale variability (10.5 year cyclicity) throughout this period. The early part of the record (pre 1500 AD) is characterized by 10.5 year climate cycles, an equatorward AAO (or negative SAM index) and enhanced westerlies in the mid-latitudes. The period post 1500 AD is characterized by slower climate variations (23 year cyclicity), a poleward shift in the AAO (positive SAM index), and enhanced westerlies in the 50° to 65°S zone. Climate projections, produced using Global Circulation Models (GCM), indicate that southern Australia will receive less winter rainfall in the future due to the shift towards the positive index state of the SAM, with the mean passage of low pressure and frontal systems traveling further south of the Australian continent. Research by Australian palaeo-scientists is focusing on the application of the 700 year proxy record of the mid-latitude MSLP and the AAO to hindcast southern Australian rainfall variability. Recent results have shown that southern West Australian winter rainfall is significantly correlated to the behaviour of the AAO. Periods of higher mean winter rainfall, with high interdecadal variability occurred during 1300 to 1600 AD, followed by lower mean but less variable winter rainfall from 1600 to 1900 AD. The early 20th century appears to be charcterised by more variable rainfall. However, the record indicates that in the last 50 years rainfall has assumed a similar pattern to the 1600 to 1900 AD period (Goodwin, in prep, 2005).

Further reading

Goodwin *et al.,* 2004. Mid latitude winter climate variability in the South Indian and southwest Pacific regions since 1300 AD. *Climate Dynamics* 22, 783-794.



Box 2: Understanding past rainfall changes

Rainfall is one of the most difficult climatic parameters to reconstruct, partially because of the effect of factors such land-use feedbacks on proxies of moisture. For example, stable isotope information extracted from speleothems can yield records of environmental wetness, but will be affected by groundwater and soil moisture which are in turn affected by land cover and other local controls on the water cycle. Furthermore, the past 200 years of land-use change, following the European occupation of Australia, has introduced a bias in many proxy records, making it difficult to create a baseline from which to measure past changes. Lakes and other wetlands are the most common source of such information, but many do not have continuous records because they are commonly dry in Australia's variable climate, or else will not contain highly stratified sediments which are essential to obtaining a record of short-term climate variability. Therefore, proxies that can yield an unambiguous climate signal are very rare.

Three closed lakes in western Victoria - Lakes Keilambete, Gnotuk and Bullenmerri - have yielded detailed information on lake level and salinity: two for the Holocene, and the third extending back to 16,000 before present (BP). Long-term water level movements in these lakes filter out small variations in climate, reflecting significant changes in both rainfall and potential evaporation over time. If the climate changes, the lakes will move towards a new climate-lake equilibrium, only deviating from that course if the climate changes again.

A water balance model for these three lakes was developed using a 130-year long instrumental record of climate, and was calibrated using historical lake levels from the same period (Jones et al., 2001). This water balance model was used to simulate climatic conditions to reproduce lake-level movement for the past 16,000 years (Jones et al., 1998). The resultant record, expressed as a precipitation/lake evaporation (P/E_L) ratio, provides a detailed reconstruction of atmospheric moisture balance for the region over the past 16,000 years.

The climate before 10,500 BP was drier than today, with a P/E_L ratio ranging from 0.70 to 0.75. Although both warming and wetting can be observed in the record after 10,500 BP, the P/E_L ratio remained fairly constant, except when warming increased faster than precipitation between 14,000–12,000 BP. Most of the last 10,000 years was wetter than today, but had a surprisingly wide variation in P/E_L ratio, ranging from 0.79 (modern instrumental average) to >1.2. The main features of the record are a dry period 10,500–9,000 BP, a gradual wetting to 7,500 BP, very moist conditions occasioning overflow in all three lakes between 7,000–5,500 BP, a gradual drying to 3,000 BP, followed by dry but unstable conditions. A reasonably moist period ensued from about 2,000 BP to AD 1840, when the dry conditions of the instrumental period, comparable to the early Holocene, were established. This last change saw the P/E_L ratio change from about 0.95 to 0.79 and preceded the large increase in greenhouse gases that occurred since the industrial revolution.

The past 10,000 years has seen at least eleven changes in P/E_L ratio that can be considered as abrupt. The scale of these changes would have been regional, affecting much of south-eastern Australia. Changes in regional atmospheric circulation that drive variations in rainfall and regional hydrology must be considered as frequent within the recent palaeoclimatic record, and an ongoing feature of long-term climate dynamics. The idea of a changing climate as a gradual trend is not always supported by past evidence. The reconstruction of Holocene P/E_L ratio in southern Australia shows both abrupt changes and long-term secular trends, including brief periods of instability when climate switched from dry to wet several times at century-long intervals. Whether such changes may be exacerbated by greenhouse-induced radiative forcing, or may be contemporaneous with greenhouse-induced climate change is an important question that should be explored.

Further reading

Jones, R.N., McMahon, T.A. and Bowler, J.M. (2001) Modelling historical lake levels and recent climate change at three closed lakes, Western Victoria, Australia (c.1840-1990), *Journal of Hydrology*, **246**, 158-179.

4.2 The scope for palaeo-science to shed light on the extent to which natural climate variation has contributed to climate trends and discontinuities observed over the last few decades

Australian instrumental records exhibit what appear to be cyclical variations in both temperature and precipitation over the past 100 years, with an overall trend of warming (Nicholls and Collins in press). The extent to which these variations and trends can be attributed to natural climate variation can best be determined by using the long-term records provided by palaeo-science.

We now have the spatial and temporal coverage with palaeo-records to be able to identify and understand past climate variability and trends on decadal to millennial scales, as well as across regions. Long, continuous palaeo-records - such as those developed from marine sediments, ice cores and terrestrial lakes - enable us to identify millennial scale cycles of climate change (e.g. Petit *et al.* 1999; Turney *et al.* 2004). They also provide evidence of long-term climate trends, such as the trend to increasing aridity in Australia over the last 350,000 years (Kershaw *et al.* 2003). Higher resolution, continuous palaeo-records - such as those developed from corals, tree rings, speleothems, lake sediments and ice cores - give evidence of decadal and sub-decadal scale climatic changes. By comparing records from different regions it is possible to identify spatial variation and test whether these changes were synchronous across Australia. This not only allows us to assess the degree to which observed regional climate variations and change across Australia can be explained by natural processes, but can also improve our understanding of the relative effects of local and global climate drivers.

An example of this research in Australia is the analysis of tree rings from Tasmania to determine if post-1960 warming is part of a cycle of natural climate variability (Cook *et al*., 2000). This study demonstrated that there have been significant shifts in the intensity of climate variability over the last 3,000 years, with a recent shift occurring around AD 1900. The study also concluded that only around 51% of post-1960 warming could be explained by natural cycles of climate variability. In another study, using sea surface temperature records obtained from coral records, it was suggested that modern ENSO periodicities switched on around 5,000 years ago, with an abrupt increase in ENSO magnitude approximately 3,000 years ago (Gagan *et al.* 2004). This corresponds well with pollen and charcoal records from northern Australia, which provide evidence for an intensification of burning and frequency of drought from around 4,000 years ago, which has been linked to the intensification of ENSO (Turney *et al.* 2004; Haberle in press). At much higher resolution, palaeo-records from both Antarctica (Goodwin *et al.* 2004) and Queensland (Haberle in press) suggest possible 300 year cycles of ENSO intensity, with a period of increased variation from 1300 to 1600 AD, followed by a period of reduced variability from 1600 AD to 1900 AD, then a reversion to high variability post-1900 AD.

4.3 Evidence for variation in greenhouse gases that help us understand recent changes and predict future climate drivers

4.3.1. Radiative forcing by greenhouse gases

Unlike variations in solar activity caused by changes in the Earth's orbit around the Sun (often referred to as 'Milankovitch cycles'), variations in the concentration of most greenhouse gases appear to be largely unpredictable. An understanding of the causes of past greenhouse gas changes and their relationship with climate is crucial to narrow the range of future likely concentrations and their climatic forcing.

Precise systematic measurements of atmospheric CO_2 only began in 1957 (the International Geophysical Year). Records of other gases began even more recently, with levels of some halogenated compounds (such as PFCs) and isotopes of N_2O only being recorded over the past decade. Compared to the timescale of natural cycles, these observational records are far too short and require extension into the past using indirect or proxy information. The "palaeo" period for

atmospheric composition thus needs to extend to more recent times than for many other climatic parameters.

Because the main greenhouse gases have atmospheric lifetimes longer than the mixing time of the atmosphere (~1 year), a record from one "baseline" location (remote from local influences) may be sufficient to provide an estimate of the radiative forcing for the globe, including the Australian region. However, more geographic information is required to help understand the sources and sinks of these gases. Accurate and highly time-resolved sampling is necessary to reveal variations in concentrations and their relationship to rapid events, such as ENSO, volcanoes, warmings during glacial-period terminations, methane hydrate bursts.

The measurement of air enclosed in ice sheets (Antarctica, Greenland, the Arctic, high altitude temperate and tropical glaciers) is the best and most direct way of reconstructing atmospheric gas composition over the past 500,000 years (Raynaud *et al.* 2000). Ice contains trapped air in the form of bubbles that can be accessed via coring. Most greenhouse gases are preserved in ice core sequences for hundred's of thousands of years allowing direct reconstructions. The main limitation is the time lag for the air to be fully enclosed by the compacting snow as it forms ice, which spreads the air bubble age and modifies the gas isotopic composition. These effects can be largely corrected for in numerical models.

Other proxies of CO_2 concentration can be found in the carbon isotopic ratios of tree rings and corals (Bohm et al., 2002), fossil leaf stomata (Retallack 2001; Kouwenberg *et al.* 2005), and geochemical measurements and models (Berner 1994; Pearson and Palmer 2000). These become particularly useful for periods that predate the oldest ice as they are less precise than direct measurements obtained from ice cores (even relative to the much larger likely CO_2 variations in the geological past (i.e. millions of years ago). These alternative approaches are also are limited to estimates of CO_2 only.

Australian research in long-term greenhouse gas changes has greatly benefited from the Law Dome ice sheet, which is accessed and sampled through the Australian Antarctic Program and its Glaciology team. Law Dome provides outstanding ice quality and unique age resolution that, combined with leading air measurement techniques at the Commonwealth Science and Industrial Research Organisation (CSIRO) and partner groups such as the Australian Nuclear Science and Technology Organisaton (ANSTO), the New Zealand National Institute for water and Atmospheric Research, the French National Centre for Scientific Research, and the University of Colorado (USA), have produced the most precise and detailed greenhouse gas records of the past 1000 years. These document the increases during the industrial period and the natural variations prior to this time (Etheridge *et al.* 1996; Etheridge *et al.* 1998; Sturrock *et al.* 2002). The records cover a period that is being intensely studied for evidence of human-induced climate change (e.g. Crowley 2000; Mann and Jones 2003). These records await extension into the early Holocene to find, for example, the impact of the climatic cold event centred on 8200 years BP, when a final collapse of the North American ice sheet impacted on North Atlantic ocean circulation. There is also scope for precise and highly age-resolved gas measurements in Law Dome to clarify the sequence of events during the warming phases of the well known variations over the past 400,000 years recognised in the Antarctic Vostok, Dome C and Dome F records (Petit *et al.* 1999; Flückiger *et al.* 2004). New evidence suggests a greater role for the Southern Ocean in initiating both the warming and CO_2 increase during the last deglaciation (Morgan *et al.* 2002).

Model interpretation of the measured isotopic changes of the greenhouse gases helps determine the causes of the observed concentration changes. For example, the CO_2 increase since AD 1800 is accompanied by a decrease in the relative abundance of the minor isotope $^{13}CO_2$ and in the radioactive isotope $^{14}CO_2$, found in both ice and tree ring records (Francey *et al.* 1999). These confirm that the CO_2 growth is from fossil organic sources, consistent with combustion of fossil fuels. However, the measurement and interpretation of isotopes of trace gases in ice is still in its infancy and improved data are needed to explain changes such as the CO_2 decreases during glacial periods, the mid Holocene, the Little Ice Age and CO_2 stabilisation of the 1940s (Broecker and Clark 2003; Trudinger 2005). Isotopic measurements of other gases show promise in exposing

their sources (Rockmann *et al.* 2003; Ferretti *et al.* 2005) and will benefit from emerging measurement technologies suitable for the extremely small sample size limit (micromole) imposed by the lower concentrations of gases such as CH_4 and N_2O (see Box 3).

The greenhouse gas concentration records are used in several ways:

- to quantify the human-induced perturbation and to establish the variability of greenhouse gases before direct atmospheric records began (e.g. Etheridge *et al.* 1996; Raynaud *et al.* 2000);
- to place the present growth rate changes, such as the CH_4 stabilisation, the CO_2 growth maxima, and responses of CFC concentrations to the Montreal Protocol, in a longer time perspective (Etheridge *et al.* 1998; Sturrock *et al.* 2002);
- to understand the biogeochemical cycles of greenhouse gases and how they might amplify or offset emissions in the future (climate feedbacks) (Cox *et al.* 2000; Trudinger 2005);
- to search for evidence of abrupt events, such as responses to major volcanic eruptions, the rapid changes during the last deglaciation, and methane hydrate releases;
- as input to climate model simulations to test the climate sensitivity to greenhouse gases (and, as a result, the sensitivity to other climate forcing agents);
- to identify the causes of the recent warming observed at global and regional scales (Crowley 2000; Mann and Jones 2003);
- as climate proxies, using the sensitivity of CO_2 and CH_4 concentrations to temperature and precipitation;
- to detect changes in other environmental change, for example, biomass burning (from $^{13}CH_4$), the oxidising potential of the atmosphere (from CO), and nuclear emissions (from radioisotopes of CO_2, CH_4 and chlorine) (Levchenko *et al.* 1997; Wang and Jacob 1998; Ferretti *et al.* 2005);
- to synchronise climate records around the globe, by using measurements of well mixed tracers such as CH_4 (e.g. Morgan *et al.* 2002).

A significant knowledge gap exists in the understanding of atmospheric chemical processes involving CO and CH_4 which affect the abundance of the hydroxy radical (OH), the atmospheric "detergent" that removes CH_4 and other greenhouse gases from the atmosphere. This is also true of ozone which is a significant greenhouse gas in the troposphere but which is a very reactive gas and has few long-term atmospheric measurements and little prospect of ice core measurements. Furthermore, the few existing ice core carbon monoxide records are uncertain (Haan and Raynaud 1998; Wang and Jacob 1998). Until measurements and modelling improve in this area, prediction of the concentrations of these direct and indirect greenhouse gases will be difficult.

Even for greenhouse gases for which past concentrations are well known, predicted future concentrations remain uncertain, due to insufficient understanding of natural variations, climate feedbacks and technological and economic influences. The palaeo record, supplemented by isotopic measurements and interpreted using models, can provide constraints on the effects of first two of these processes.

4.3.2. Forcing by aerosols, solar irradiance and land use

Although greenhouse gas increases have caused the largest climate forcing since pre-industrial times (~1750 AD), forcings by changes in aerosols, solar irradiance and land cover have also occurred. When taken together, they improve the climate model simulations of temperature over the past hundreds of years (Crowley 2000; Bauer *et al.* 2003). The direct radiative and indirect radiative effects of aerosols in the atmosphere remain uncertain for the past and are a source of uncertainty in future projections. Aerosol sources include continental dust, emissions from volcanic eruptions (mainly as sulphate), and human-created sulphate and soot from biomass burning.

Removal processes from the atmosphere can be relatively rapid. As a result, atmospheric aerosol loading, and thus the aerosol climate forcing, can be highly variable in time and space and palaeo-records must be developed in a number of locations. Aerosol forcing must also take into account the reflectivity of the particles (often referred to as 'albedo') which can vary greatly between highly absorbing soot aerosols and reflective mineral dust. Ice cores contain aerosols, thus providing well dated long-term records of changes in the aerosol content of our atmosphere. From ice core records it can be seen that there were increased continental dust levels during glacial periods (ice ages), peaks in acid aerosols after major volcanic eruptions, and in recent times human-induced increases in nitrate and sulphate. Regional dust accumulations are also available for larger changes, such as during glacial times (see section 3.4.2). An intriguing connection between the mineral dust record and CO_2 concentration records in ice cores during glacial times has been used to estimate the iron "fertilisation" effect on ocean CO_2 uptake (Mahowald *et al.* 1999; Claquin *et al.* 2003). This is an excellent example of climate feedback in the global system. The main sources for iron-rich dust include South America and Australia.

Solar forcing includes changes in the energy output (total solar irradiance) of the sun and the geometry of the Earth's orbit. Both vary in time, though the orbital variations are both slower and entirely predictable (Berger 1978). Irradiance has been measured only for the past two solar cycles (about 22 years). Beforehand, solar physical observations (such as sunspot numbers) have acted as proxies. To examine the period before direct observations (in the AD 1600s), measurements of the atmospheric production rates of isotopes ^{10}Be and ^{14}C (which are modulated by solar activity) are used as palaeo indicators (Bard *et al.* 2000; Turney *et al*., 2005). These isotopes are preserved in ice and tree ring records. The reconstructions of irradiance can vary significantly depending on the methods and proxies used.

Land cover changes have received less attention in forcing climate. Humans' have significantly impacted large areas of the Earth's surface. Vitousek et al. (1997) estimate that over 45% of the Earth's surface is currently affected by human-induced land cover changes. Over the last few last centuries, the intensity and scale of these modifications has increased significantly (Williams, 2003). Land cover modification is believed to impact on the global climate (Chase et al., 2000; Pitman and Zhao, 2000; Zhao et al., 2001), but is probably insignificant compared to changes in greenhouse gases. There is, however, strong evidence that LCC can influence local to regional scale climate (Pielke et al., 1998) at levels equivalent to a doubling of atmospheric CO_2 (Pitman and Zhao, 2000). Land cover affects regional climate via a change in albedo, moisture exchange and surface roughness. These factors affect the regional temperature, moisture convergence and atmospheric boundary layer structure. A major advance was reported by researchers who explored the role of vegetation-climate interactions on long time scales and demonstrated that these feedbacks have to be included for climate models to capture observed changes in the palaeo-record (Claussen *et al*., 1998; Claussen *et al.*, 2001). Other evidence from Harvey (1989), Berger et al. (1993) and de Noblet et al. (1996) show that the vegetation-snow-albedo feedback contributed significantly to Northern Hemisphere cooling during the last interglacial (which occurred around 125,000 years ago). Evidence that North Africa was much greener than today in the mid-Holocene can be explained in part via a positive feedback between vegetation and precipitation in this region i.e. more vegetation encourages greater precipitation (Kutzbach et al.,1996; Texier et al.,1997; Claussen and Gayler, 1997; Broström et al., 1998). Overall, these analyses, developed from palaeo-observations of the Earth system, have substantially enhanced our understanding of the role of the biosphere in explaining long term climatic changes.

4.4 The scope for improved palaeo-data to contribute to better testing and verification of regional and global climate models

A greater understanding of palaeoclimates can significantly improve our ability to evaluate the capacity of global climate models (GCMs) to simulate current and future climatic change. This can be achieved in a number of ways, which are discussed below.

Having an accurate representation of natural climatic fluctuations in climate models (including

abrupt changes) is necessary for accurately projecting the full range of future climates at both regional and global scales. These fluctuations need to be simulated reliably on timescales relevant to likely future change. Simulating natural climate variability is also important when climate models are used in detection and attribution studies. The ability to simulate natural climate variability over timescales of millennia is not a requirement for confidence in the ability of a climate model to simulate 50-100 years into the future. However, demonstrating that a climate model can simulate climate variability over longer timescales builds confidence in the models for future climate projection.

The instrumental record can be used to assess the degree of natural climatic variability on interannual to interdecadal time scales. The palaeoclimate record allows scope to validate model-simulations variations at longer time scales (multidecadal to century scale and longer). This can apply at spatial scales ranging from regional to global. Indeed, palaeo-science can be focused towards collecting specific variables in regions where trends in climatic parameters are of significant concern, such as rainfall in southwest Western Australia (e.g. Treble *et al*., 2003).

Palaeoclimatic data can also be used to validate the ability of climate models to simulate past climate where boundary conditions were different to today, such as simulating climate during the last ice age. The demonstration that models can accurately simulate past climates different to the present is one reason why there is such confidence in future predictions. Good palaeoclimatic data are required, both to setup past climate simulations (such as ice-extent, surface vegetation and sea surface temperature) and to validate the results of the simulation (such as rainfall and temperature patterns). However, such exercises do present some difficulties. There may not be the complete knowledge of the relevant climate forcing to apply in the past simulation. Also, the role of the ocean may not be well represented if a fixed sea-surface temperature is used. If a full ocean model is used uncertainty in the setup conditions of the ocean may have a significant impact on the final results. Knowledge of past variations in global temperature, CO_2 concentrations and climate forcing (such as solar radiation changes) can be used with climate models to constrain the range of global climate sensitivity. In this way palaeoclimate information can be used to narrow the range of future climate change scenarios.

Palaeoclimatic data can potentially provide important additional information on the behaviour of key processes in the global climate system of regional to global significance. For example, the past behaviour of systems such as the El Niño-Southern Oscillation under different climate states (see section 4.2) can reveal variations that can be used to test global climate model simulations, and help identify improvements.

As climate modelling starts to utilise a range of Earth System processes (including vegetation, land use, atmospheric chemistry, hydrology, ocean and land dynamic features and ice sheet dynamics) a broader range of palaeo data will be needed as constraints and to test simulations.

Earth Systems Models of Intermediate Complexity (EMICs) are being developed to include all the essential components of the Earth System, in a more simplified form than in global climate models. EMICs are designed to allow multiple simulations of known components of the Earth's climate and physical, chemical and biological processes over long periods, without the computational costs of a full GCM. A major disadvantage of EMICs is that they gain the computational efficiency via a very major reduction in spatial resolution implying that they may be useful tools for global-scale analyses but are unlikely to provide useful information at a regional scales. Examples of EMICS include the Potsdam Climber (Climate and Biosphere) model (Claussen *et al.* 1999), and the MIT Integrated Global System Model (Wang *et al.* 1998bb) which have strong biological and atmospheric chemistry representations, respectively.
A number of GCM and EMIC runs of deglaciations and warmings through the industrial period, forced by palaeo data, have provided simulations that can be tested against palaeo observations of the global climate (Petit *et al.* 1999; Crowley 2000; Bauer *et al.* 2003). These have provided tests of the model climate sensitivities and of the relative effects of the forcings, suggesting that

greenhouse gas changes were responsible for about half of the glacial-interglacial temperature changes, and most of the warming of the past 50 years.

Models can also be tested and constrained over smaller geographical areas and timescales. For example, Bromwich *et al*. (2004) used a meso-scale model over North America to simulate the LGM annual cycle at high spatial resolution with an emphasis on the winter atmospheric circulation. The mesoscale model produced a substantially different atmospheric response to the parent GCM and other similar runs. The results were generally consistent with proxy climate estimates in North America and may help resolve some long-standing discrepancies between proxy data and previous simulations.

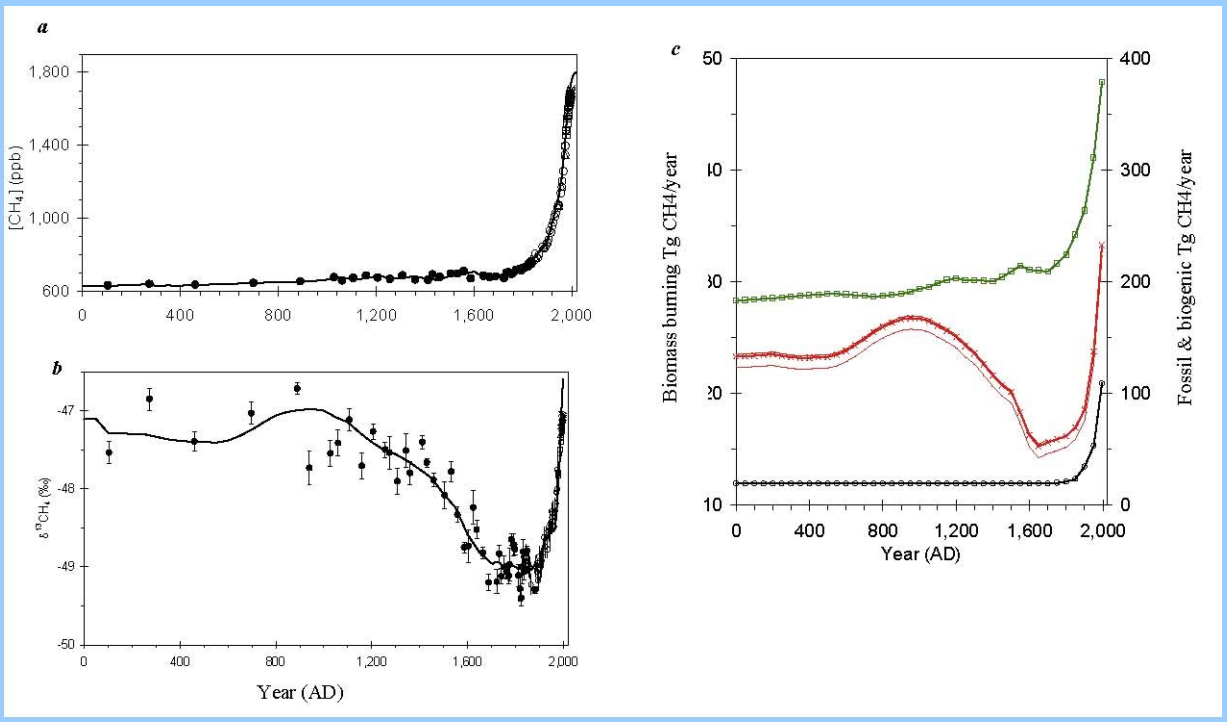
Box 3: Greenhouse gas changes - finding new evidence of causes

The changing concentrations of the main greenhouse gases CO_2, CH_4 and N_2O are highly correlated with temperature over hundreds of thousands of years. Ice core records have revealed the full range of natural variability and the more recent human signals in atmospheric composition with their effects on climate.

Recent analytical advances are now allowing the isotopic changes of these trace gases to be measured precisely enough to identify the causes of the concentration changes. Emissions of trace gases from different sources and removal from the atmosphere by sink processes can cause characteristic isotopic imprints. For example, methane released from biomass burning carries a smaller amount of carbon-13 than atmospheric methane and decreases the ratio of $^{13}CH_4$ to $^{12}CH_4$ in the atmosphere. Methane released from fossil fuels and from hydrated formations in the deep ocean (sometimes referred to as 'clathrates') contains no carbon-14 isotope and lowers the atmospheric $^{14}CH_4$ to $^{12}CH_4$ ratio. Technical challenges in measuring these rare isotopes (for example, only about 5 kilograms of $^{14}CH_4$ are present in the entire atmosphere) are now being overcome so that changes in time can be found from the small amounts of air available in ice samples.

Model interpretation of these isotopic signals provides a constraint on greenhouse gas budgets. This improved understanding can be used to help predict future emissions and atmospheric concentrations and therefore climate forcing. The research may also shed light on whether changes in recent years, such as the unexpectedly rapid growth of CO_2 and the apparent stabilisation of CH_4, have happened in the past.

Australian research groups such as CSIRO Atmospheric Research, the Australian Nuclear Science and Technology Organisation and the Antarctic Division have combined their sampling, measurement and interpretation skills to lead in this area, resulting in requests to join overseas projects.



Legend: The causes of 150% increase in the concentration of methane in the atmosphere (a) can be found from model interpretation of isotopic changes such as $^{13}CH_4$ (b), and in (c) showing how fossil (black) and biogenic (green) sources have increased from nearly stable pre-industrial/agricultural backgrounds, whereas biomass burning sources (red) had significant changes throughout the past 2000 years. From Ferretti et al., 2005.

5. The ways in which palaeo-science can enhance our understanding of the likely impacts of climate change in Australia.

5.1 Evidence of the impacts of past climatic variation on flora and fauna, water resources and landscape processes such as erosion.

The majority of palaeo-records are proxy records, and therefore, provide direct information about the impacts of past climatic variation on flora, fauna, water resources and landscape processes. Pollen and charcoal records provide data about the flora, which in turn can be used to infer the effects on fauna (although this is rarely done in Australia). Australian tree ring records give direct evidence of the response of trees to shifts in temperature and in some cases precipitation, although at present the evidence is confined largely to Tasmania. Microfossil records from lakes and the oceans provide us with information on how aquatic fauna (freshwater and marine) respond to shifts in environmental conditions associated with climate change. Coral records give evidence of how corals have responded to climate induced changes in sea surface temperature, sea surface salinity and river runoff. In turn, river and lake records provide evidence of past hydrological responses to climate change and give an insight into how water resources are affected by climate. Although they tend to be discontinuous, macrofossils of leaves and animals provide information about how plants and animals have responded to past climate variability. For instance, recent work has suggested a role for climate in affecting extinct Australian megafauna (e.g. Trueman *et al.,* 2005). Some examples of how these records have and could be applied in Australia are given below.

As mentioned above, palaeo-lake and river records can provide evidence of the impacts of past climatic variation on water sources, providing information about the combined effects of changes in precipitation, temperature and evaporation. For example, there has been extensive palaeo-proxy and palaeo-modelling work carried out on lakes throughout southeastern Australia to determine how they have responded to past climate variability (Harrison 1993; Jones *et al.* 2001). One of the interesting facets that came out of this research was the discovery that lake systems have not responded at the same time across the landscape to past climatic shifts. For example, the lakes of the inland arid/semi-arid regions, such as Lake Eyre, exhibited high levels during the last ice age whilst lakes from more temperate regions, such as in western Victoria, exhibited low levels (Harrison 1993). This information has contributed to an improved understanding of how shifts in atmospheric circulation affect regional climates, and in turn flora, fauna and water resources (Shulmeister *et al.* 2004). Palaeo-river records not only provide information about the past response of water resources to climatic variations, but also give evidence of erosion. Indeed, palaeo-river sequences are by their very nature erosional records, with evidence for high sediment loads frequently being interpreted as erosion events associated with increased rainfall and possibly the interaction of aridity, rainfall and vegetation (Fried 1993; Nott *et al.* 2002). See section 3.3.4 for further details.

Dust records can also provide valuable information about the influence of climate on erosion. Dust contained in marine records in the Tasman see, for instance, has been used to reconstruct the scale of wind erosion from the Australian continent under different climate regimes (Hesse and McTainsh 1999).

Pollen, charcoal and sediment from peat bogs in the Southern Tablelands and Alps of New South Wales indicate that drier climatic conditions over the last 5,000 years have caused some bogs to cease growth, whilst others experienced a major growth phase over the last 2-3000 years (Hope 2002). Although a climatic cause is suspected for these growth patterns, it is not yet fully understood. These bogs play an important role as faunal and floral reserves and in the hydrology of southeast Australia, slowly releasing stored water through the drier months. Palaeo-records from these sites, therefore, have the potential to provide valuable information about the impacts of climate variability on fauna, flora and water resources.

5.2 Evidence of the effects of past climate variation on high impact events, such as fire, drought, floods and sea level rise.

As the geographic coverage, time resolution and detail of palaeo-climate records have been improved, it has become possible to identify the effects of past climate variations on high impact events such as fire, drought, storms, floods and sea-level rise. Sub-decadal palaeo-records, such as those developed from tree rings and corals, have been of particular use for identifying impacts associate with short-term climate variation, such as ENSO. Longer, millennial scale records allow the identification of long-term variations, ranging from hundreds to thousands of years.

Evidence of past fire regimes have been derived predominantly from charcoal records extracted from terrestrial wetland sites (e.g. Turney *et al.* 2004) and near-coastal marine cores (e.g. Moss and Kershaw 2000). Although charcoal records in Australia are frequently complicated by human influences (the advent of aboriginal burning 60,000 to 40,000 years ago was followed by post-European settlement fire patterns), they do have the potential to provide sensitive records of changes in fire regimes in response to climatic variations. For example, a high-resolution charcoal record from the Atherton Tablelands in Queensland has provided evidence of fluctuations in the fire regime which has a strong correlation with ENSO (Haberle in press). Similarly, a high-resolution record of surface moisture obtained from another Atherton Tablelands site, Lynch's Crater (Turney *et al.* 2004), has provided a 45,000 year record of millennial-scale dry periods thought to be caused by changes in precipitation associated with 1,490 year ENSO intensity cycles. These cycles have been correlated to major northern hemisphere climatic variations of similar periodicity. In addition, drying phases related to climate variability cycles at a semi-precessional timescale (~11,900 years) have also been identified. These have been interpreted as evidence for increasingly frequent and sustained 'warm' ENSO events centred on 40, 25 and 15,000 years ago, and 'cold' ENSO events centred on 30 and 21,000 years ago (Turney *et al.* 2004).

Both drought and flood events associated with ENSO variability have been inferred from coral records obtained from the Great Barrier Reef. Evidence for growth discontinuities and patterns in luminescent banding in corals from the

Great Barrier Reef has been linked to fluctuations in the intensity of runoff from the Burdekin River in Queensland, providing evidence of flooding and drought (Hendy *et al.* 2003). As with the terrestrial records, the coral sequences indicate cyclical variability in the strength of ENSO through time.

Work conducted by Hayne and Chappell (2001) on storm deposits at Curacoa Island in north Queensland has provided a palaeo-record of tropical cyclone frequency over the last 5000 years. Their results suggest that storm frequency in this region has remained broadly constant over this period and has remained unaffected by variation in sea surface temperatures, such as that associated with ENSO.

The influence of climate variability on high impact events can be deduced from long, millennial-scale palaeo-records, such as those developed from ice cores, deep sea sediments and from some terrestrial sites. The latter in Australia provides evidence of variations in vegetation communities and fire regimes associated with orbital-scale climate variations (i.e. glacial-interglacial cycles), and with the expansion of drought-tolerant vegetation coupled with an increase in burning during the drier, glacial phases (Kershaw *et al.* 1991; Harle *et al.* 2004). Also on orbital to millennial time scales, evidence for changes in sea level have been developed from Antarctic ice cores, coral terraces and beach deposits (Petit *et al.* 1999; Chappell 2002; Brooke *et al.* 2003). For example, palaeo-records have been used to reconstruct sea-level changes from around the globe, with evidence for a mid-Holocene sea-level high stand, followed by a fall of 1-2 m during the late Holocene. Various palaeo-records have been investigated to explain the causes of these sea level changes, including Antarctic ice cores (Goodwin 1998).

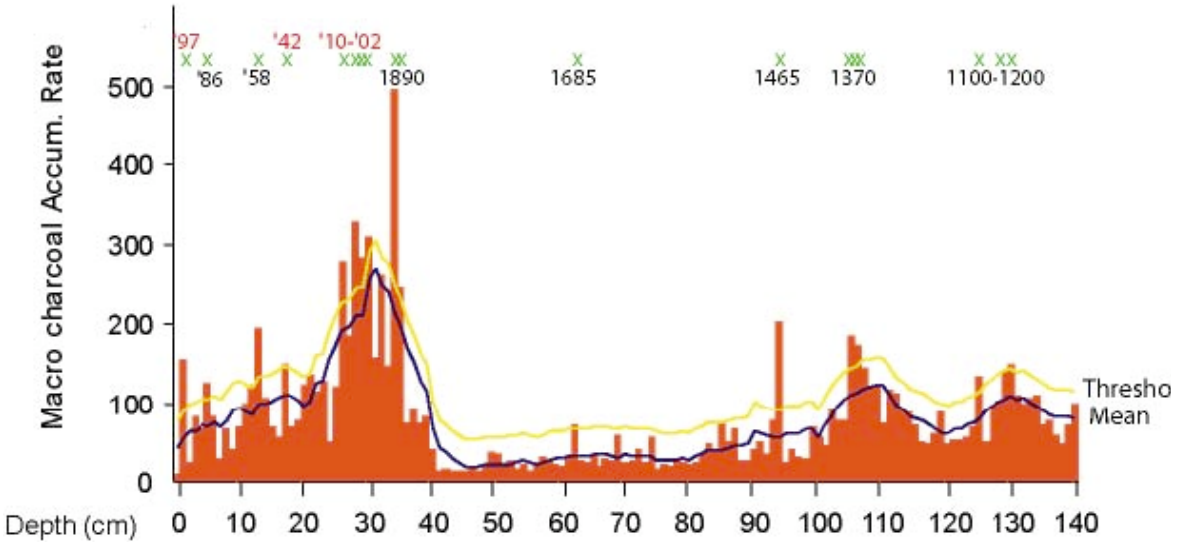


Figure 6. The macro charcoal record from Lake Euramoo (Atherton Tableland, QLD).

El Niño years are signified by the green crosses. Dates given in red indicate major El Niño years as recorded in meteorological records. The blue line is a 400 year moving mean. The yellow line is a statistical derived threshold above which charcoal peaks are deemed to indicate significant fire events. The diagram shows a clear correlation between significant charcoal peaks and El Niño events, thus demonstrating the capacity for palaeo-charcoal records to record both the occurrence and impacts of past climate variability (source: Haberle 2005, unpublished data).

5.3 The scope for palaeo-data to contribute to an understanding of the future behaviour of carbon sinks.

An understanding of how carbon sinks are likely to behave in the future can be found from evidence of how they have operated in the past under different climatic conditions. Palaeo-records provide us with a range of essential knowledge to be able to acquire such an understanding. They provide us with evidence of changes in the physical characteristics of carbon sinks (terrestrial and oceanic), they can tell us about past fluctuations in atmospheric carbon under different climate regimes (see section **Error! Reference source not found.**), and importantly, allow us to investigate the interaction in the past between the carbon sinks and the atmosphere.

The evidence from ice cores, such as Vostok (Petit *et al.* 1999; EPICA 2004), is that that there has been significant fluctuation in atmospheric CO_2 levels in response to the onset of glacial and interglacial periods. For example, values typically rose between 80 and 100 ppm as climates became warmer in the transitions from glacial to interglacial periods (Raynaud *et al.* 2003). The question of why this happens has much to tell us

about the behaviour of carbon sinks. To answer this, palaeo-records of the transition from the height of the last Ice Age (Last Glacial Maximum) to the current warm phase (the Holocene) have been examined. Of the potential sources of CO_2, the oceans and the terrestrial biosphere have been identified as the most important. Pollen records from around the globe indicate vegetation, in particular forests (a major sink), expanded as glaciers retreated and climatic conditions became more amenable with the onset of the Holocene. In addition, both pollen and sedimentary records give evidence of the development of peatlands (another major terrestrial carbon sink), particularly during the mid to late Holocene (Franzen 1994; Whinam and Hope in press). The terrestrial biosphere therefore acted as sink rather than a source during this warming phase, with palaeo-database estimating uptake of between 430 and 1500 GtC (Adams and Faure 1998; Peng *et al.* 1998) and model-based estimates between 50 and 700 GtC (Peng *et al.* 1998). However, there is still debate and uncertainty over the exact degree of exchange between the atmosphere and terrestrial carbon reservoirs. Much of this uncertainty centres on gaps in our knowledge over the varying degree to which C4 plants expanded during the Last Glacial Maximum as well as with the different response of C3 and C4 plants to changes in atmospheric CO_2 (Street-Perrot 1994; Peng *et al.* 1998). While some initial efforts to explore how the Australian terrestrial carbon sinks has and will respond in the future to increasing CO_2 (Narisma and Pitman, 2004, 2005) these are preliminary studies. Nevertheless, these studies point to a new area of uncertainty in future Australian climate change scenarios.

It is widely accepted that the main control on shifts in atmospheric CO_2 are processes operating within the oceans, which includes changes in sea surface temperature and salinity (the solubility pump), the supply and removal of total CO_2 (the biological pump) and alkalinity in surface waters (the alkalinity pump), surface winds, and variations in sea ice cover (Bentaleb and Fontugne 1998; Pedersen *et al.* 2003). Palaeo-records enable the reconstruction of how these various drivers of oceanic-atmospheric of CO_2 exchange have operated in the past. For example, analysis of the carbon isotopic composition of sedimentary organic matter in marine cores has been used to reconstruct the operation of the biological pump in the Southern Ocean during the Last Glacial Maximum and the transition from this cold phase to the Holocene. This knowledge has then been used to explore the implications of changes in the biological pump for CO_2 flux into the atmosphere (Bentaleb and Fontugne 1998). At much higher resolution, recent research investigating the ways in which radiocarbon analysis of tree rings can contribute to an understanding of atmospheric circulation and air-sea exchange of CO_2 has identified an apparent shut-down of the flux of CO_2 from the ocean into the atmosphere during El Niño events (Barbetti *et al.* 2004; Hua and Barbetti 2004).

Evidence of carbon cycling over the last few hundred years using modelling of ice core CO_2 and $\delta^{13}CO_2$ shows how the terrestrial biosphere has changed from a carbon source to a sink in more recent decades. Natural climatic variations, often connected with ENSO, have also influenced terrestrial CO_2 uptake with the ocean being a sink of CO_2 throughout most of the past 200 years. Methane isotopic records also show the variability of biomass burning which is an important source of carbon emissions (see Box 3).

6. Where to from here?

In recent years there has been significant progress in exploiting Australian palaeo-records, with advances in sample collection, dating, and analyses enabling the development of more sophisticated and higher resolution palaeo-climate records. These developments are opening up exciting opportunities to extend climate records back beyond historical records from the 19th century and thereby improve our understanding of climatic variability as well as identify how climate change affects terrestrial and marine environments. This information can, in turn, provide valuable input to public policy on how to plan for the impacts of future climate change. There are still many important gaps in our knowledge of past climates, however, both in terms of geographical and chronological representation. This is particularly true for records with subdecadal resolution, which are vital for understanding decadal and other short-term climate variations. The majority of records do not extend beyond a few thousand years, although in some cases (such as with ice core and lake sediment records) there is potential for extension considerably further back in time. Whilst records of a few thousand years can provide valuable information about climatic variability, they do not extend back sufficiently far enough in time to encompass the full natural range.

There is also a distinct spatial bias in palaeo-records within the Australian region which needs to be overcome. This is largely a factor of site suitability, but is also due to the relatively small number of researchers working in the Australian region (relative to efforts in the Northern Hemisphere). There are many sites and avenues of palaeoscience yet to be explored. For example, more spatial information is required to help understand the sources and sinks of greenhouse gases, whilst accurate, high-resolution dating is necessary to reveal the mechanisms of past climatic change. In addition, revisiting key palaeo-records that were obtained prior to the availability of high-resolution sampling and dating techniques could greatly improve the spatial and temporal coverage of past climates. In particular, many earlier reported records are qualitative, and need to have quantitative techniques applied to them. There is also considerable need to identify uncertainties in datasets if we are to utilise palaeo-records for testing climate models.

At present, much of the research effort of the Australian palaeo-science community and its collaborators has been focused on the acquisition of records, with only limited comparisons being undertaken. In essence, only now is there sufficient spatial and temporal coverage to carry out multi-proxy, cross regional comparisons and correlations. Australia is well placed to make major contributions to the use of palaeo-science for understanding climate change, being located in a region of immense importance to the global earth-ocean-atmosphere system. The integration of data across the region, therefore, is of vital importance. Some efforts are being made in this area, but further coordination between researchers is needed.

There is also a need for palaeo-scientists to improve the communication with policy makers and natural resource managers. There is significant potential for palaeo-records to provide insights into how our environment will respond to future climate change through the identification of past mechanisms of change.

Finally, one of the key ways that palaeo-science can contribute to understanding and

constraining uncertainties about climate change and its potential impacts in Australia is to use the data obtained from palaeo-records to test climate models. So far, such efforts have largely been driven by researchers in the Northern Hemisphere, using Northern Hemisphere data. In many cases, the Southern Hemisphere data is inadequately represented and/or the simulations are inadequate for the region. Australia is the only country with the research capacity and infrastructure to lead efforts in testing climate models of the Southern Hemisphere

7. Glossary

BP	-	before present (AD 1950)
^{14}C	-	carbon-14, radiocarbon
C3 plants	-	plants that have the most common pathway of carbon fixation in photosynthesis. This process converts carbon dioxide and ribulose bisphosphate (RuBP, a 6-carbon sugar) into phosphoglycerate. C3 plants include more than 95 percent of the plant species on earth.
C4 plants	-	Plants with the second most common pathway of carbon fixation in photosynthesis, in which carbon dioxide is drawn out of malate and into the reaction rather than directly from the air. C4 plants are common in tropical climates.
cal BP	-	calendar years before present (0 cal BP = 1950 AD)
CO_2	-	carbon dioxide
chronology	-	time frame
cosmogenic	-	produced by cosmic rays
dendrochronology	-	A term commonly applied to the study of annual tree rings
ENSO		El Niño-Southern Oscillation
glacial	-	the cold stage of a fixed cycle of warm and cool periods during a major ice age (such as the Quaternary), during which glaciers advance across much of the globe.
Holocene	-	the name commonly applied to the most recent epoch in the Quaternary period, that is the current interglacial, which commenced around 10,000 years ago.
interglacial	-	the warm stage of a fixed cycle of warm and cool periods during a major ice age (such as the Quaternary), during which climates ameliorates to similar levels to those of today (see Holocene).
Last Glacial	-	a term frequently applied to the last glacial period, which spanned the period 117,000 to 10,000 yrs ago.

LGM	-	Last Glacial Maximum – the period within the Last Glacial period during which maximum ice development and coverage occurred. Commonly recognised as occurring between 21,000 and 17,000 years ago (although there is ongoing debate about the exact timing).
lunettes	-	a crescent shaped dune formed on the leeward edge of a lake. They are thought to be formed by the wind-blown dust gathered from the shores of seasonally exposed lake floor.
macrofossil	-	a fossil that is visible to the naked eye
microfauna	-	tiny animals only visible using a microscope
microfossil	-	a fossil that are only visible using a microscope (e.g. pollen)
ostracod	-	a micro-crustacean with a calcareous carapace
palaeo	-	from Greek *palaios* meaning old, ancient or prehistoric. Commonly used to denote evidence of past environments not contained in instrumental or documented records (commonly known as historic records)
palaeosol	-	ancient, buried soil
radioactive isotope		a radionuclide is an atom with an unstable nucleus. The radionuclide undergoes radioactive decay by emitting a gamma ray(s) and/or subatomic particles.
speleothem	-	a mineral deposit of calcium carbonate that precipitates from solution in a cave. The two most common forms are stalagmites (which extend up from a cave floor) and stalactites (which extend down from a cave roof).
stable isotope	-	an isotope of a chemical element which is not spontaneously radioactive
$\delta^{13}C$		the ratio between two isotopes of carbon (carbon-12 and carbon-13)
$\delta^{18}O$	-	the ratio between two isotopes of oxygen (oxygen-18 and oxygen-16)
varve	-	A layer or series of layers of sediment deposited in a body of still water in one year.
WMD	-	wiggle match dating – a dating technique whereby a curve of ^{14}C concentrations obtained from a natural archive, such as tree rings, is compared to a similarly constructed ^{14}C calibration curve from an archive of known age (usually wood).

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