Building a future on knowledge from the past: what palaeo-science can reveal about climate change and its potential impacts in Australia

A research brief for the Australian Greenhouse Office prepared by CSIRO in association with scientific collaborators

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Executive summary

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, its mean state and its short-term variability. Palaeo-records enable these instrumental records of climate to be extended back in time, and thus provide us with the means of testing and improving our understanding of the nature and impacts of climate change and variability in Australia.

There is a vast body of palaeo-records available for the Australian region (including Antarctica), ranging from continuous records of sub-decadal up to millennial scale (such as those derived from tree rings, speleothems, corals, 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 provide a large array of evidence of past atmospheric, terrestrial and marine environments and their varying interactions through time. There are a number of key ways in which this evidence can, in turn, be used to constrain uncertainties about climate change and its potential impacts in 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 sub-annual resolution records obtained have been of particular use in regard to extending back the instrumental records in southern, western and northeastern Australia. To date, these high-resolution records only extend back hundreds to a few thousand years, restricting our ability to identify long term climate trends and variation at an annual scale. Longer records are available, providing evidence of climatic parameters on millennial scales. However, these are generally of much coarser resolution, although there is potential for higher resolution to be obtained with additional research.

We now have the spatial and temporal coverage from these records to begin to identify and understand cycles of climate variation which are not evident in the instrumental records. Long, continuous records provide evidence of millennial scale cycles of climate change (such as 100,000 year glacial-interglacial cycles and 1,500 year Dansgaard-Oescher cycles). The latter has been observed to affect ENSO cycles, with phases of “warm” and “cool” ENSO events. Long records also provide evidence of long-term climate change, such as the trend of increasing aridity apparent for Australia within the last 350,000 years. Higher resolution, continuous records give evidence of decadal and sub-decadal scale climate variation, such as that associated with the Indian Dipole. In addition, by comparing records from different regions it is possible to identify spatial variation and/or synchroneity in climate cycles. This not only allows us to assess the degree to which observed regional climate variation 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.

Evidence for variation in greenhouse gases over the last 500,000 years has been derived from direct measurement from air enclosed in ice sheets (Antarctica, Greenland, the Arctic, and high altitude temperate and tropical glaciers), as well as proxy evidence from 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).

Sound, well constrained palaeo-records are playing an increasing role in climate modelling. Palaeo-climatic data can potentially provide important additional information on the behaviour of key processes in the global climate system of regional to global significance. This information is essential for climatic modelling. In addition, palaeo-data are necessary to both initialise past climate simulations and to validate results of the simulations. These simulations in turn are essential for testing the global climate models that are used to forecast future climate change. They provide the length of records necessary for testing climate models that instrumental records are simply too short to provide.

Finally, palaeo-records provide valuable insights into how climate variation and change has and could affect our terrestrial and marine environments. In particular, they allow the identification of sensitivities and vulnerabilities. This information has great potential to be utilised in our 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, its mean state and its short-term variability. 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 (e.g. carbon dioxide ($CO_{2)}$ and methane(CH_4)) 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. Micro and macrofossils, cosmogenic nuclides, stable isotopes, geochemical measurements and physical features form the basis of palaeo-records. 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 has commissioned a report to investigate the key ways that palaeo-science can constrain uncertainties about climate change and its potential impacts in Australia. This proposal seeks to carry out such an investigation using a high level multi-institutional and multi-disciplinary team of palaeo-scientists and climate modellers led by CSIRO experts.

2. Scope of the project

The project 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, the study will assess:

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
    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,

[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 (pre ~1960) and solar (pre~1980) records.

c. the scope for palaeo data to contribute to an understanding of the future behaviour of terrestrial carbon sinks.

This project 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 significant body of Australian palaeo-research, it uses case studies of palaeoclimates and environmental responses to past climate change and variability to demonstrate potential and provide a setting for discussion. These cases represent only a few of the many examples of exceptional work being carried out by Australian and international palaeo-scientists.

3. The current breadth of palaeo-research in Australia

Australia is in a unique position to contribute to our 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 dominant oceanic features - such as the Pacific Warm Pool, the Indian Ocean Dipole, ENSO and the Southern Ocean circulation - that couple with terrestrial climate processes. Australian sites provide data about global climate change and climate change impacts, including evidence from ice cores for greenhouse gas forcing, from tree rings of movement of atmospheric carbon, and from corals and sea surface temperatures and microfossils in marine sediments of 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 been translated to 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 chronologic range and resolution, and their main limitations.

3.1 The important question of scale

The chronological resolution and nature of palaeo-records 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 temporally and spatially. Seasonal records have been derived 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 terrestrial and marine, can only provide longer term, millennial scale records. This is in part due to inadequacies in the sediment sampling and dating resolution; however, in many cases it is an artefact of the proxy itself. Underpinning all of these is chronological 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

Chronological control 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 atmospheric and ocean circulation (Lynch-Stieglitz 2004). This debate has been significantly hampered by the lack of high resolution, well dated palaeo-records from the Southern Hemisphere.

Four classes of chronological techniques have been used for Australian palaeo-records: those based on the decay of a radioactive element; those based on the accumulation over time of trapped electrons; those based on slow chemical reactions; and those based on the counting of layers, such as tree and coral growth rings, or the expected growth rate/accumulation rate of material (corals, trees, sediments, ice). There are also relative techniques, such as cross dating with events that are large and widespread (e.g. Volcanic eruptions, glacial-interglacial signals, the 14C “bomb-pulse”). The age range, precision and materials to which these methods can be applied are summarised in Table 1. It is worth making further note of the applications of radiocarbon analysis as it has important applications in palaeo-climate research which extends beyond dating. This is outlined 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 at the Earth's surface. Material (e.g. sediments, bones, wood, rocks) containing 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 (^{14}C, 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 in varying concentrations. There are also inter-hemispheric and regional differences (^{14}C offset) in the concentration of ^{14}C attributed to oceanic upwelling (McCormac *et al.* 1998). Levels in all of the major carbon reservoirs have 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: measuring the level of radioactive decay in samples; 'wiggle' matching; and 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. However, this requires the elimination of nearly all background contamination from laboratory equipment and chemicals, as well as a sample that has not been contaminated. Contamination can occur in buried samples which 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, as does the effect of such contamination on the ability to acquire an accurate date, the levels of ^{14}C being extremely small in samples at the age-limit of the technique (Chappell *et al.* 1996). Because of this, dates older than 30,000 years are frequently regarded as minimum ages.

Radiocarbon wiggle-match dating (WMD) uses past variations in the concentration of ^{14}C in the atmosphere due to the changes in the flux of cosmic rays entering the upper atmosphere. These ^{14}C fluctuations (wiggles) have been measured in tree-ring sequences, varved marine sediments and corals of known ages to create calibration curves extending back 26,000 years in the Northern Hemisphere (Hughen *et al.* 2004; Reimer *et al.* 2004) and 11,000 years in the Southern Hemisphere (McCormac *et al.* 2004). It is possible to provide a chronology for a palaeo-record by obtaining a high resolution sequence of ^{14}C dates from the record and matching its wiggles to those present in a ^{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 (radiocarbon plateaux), thus making wiggle matching difficult (Blaauw *et al.* 2004). Radiocarbon ages obtained from these periods have a wide range of probable calendar ages. This is of particular concern during the late Last Glacial and beginning of the Holocene (Beck *et al.* 1992; Stuiver *et al.* 1995; Burr 1998; Bard *et al.* 2000; Hughen *et al.* 2004; McCormac *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 terrestrial sediment records.

In the late 1950s and early 1960s, the concentration of ^{14}C in the atmosphere was dramatically increased by the injection of artificial 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. It has also been used as a tracer to improve our understanding of the exchanges between carbon reservoirs and 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 evidence of previous environments. The variety, continuity and resolution of many of our terrestrial records, however, have been affected by the arid nature of much of the Australian 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 derived from long-lived tree species (usually gymnosperms) occurring in seasonal climates that induce annual periods of growth. Examination of variations in the thickness of these rings, the density of the wood and concentrations of carbon and oxygen isotopes provides evidence of environmental and climatic conditions at annual resolution. Tree ring records can be extended back many thousands of years by focussing on long-lived species and cross-matching records from living and dead trees within a species population. It is important, in the establishment of such composite tree ring records, that a link is established with a tree of known calendar age – usually a living tree. Where such a link cannot be established the tree ring sequence is regarded as floating, with only a general age, rather than a calendar age, being 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 specific calendar years. In some cases it is possible to provide a calendar chronology for floating tree ring records by wiggle matching the ^{14}C concentrations with ^{14}C curves obtained from trees outside of the region (Barbetti *et al.* 2004).

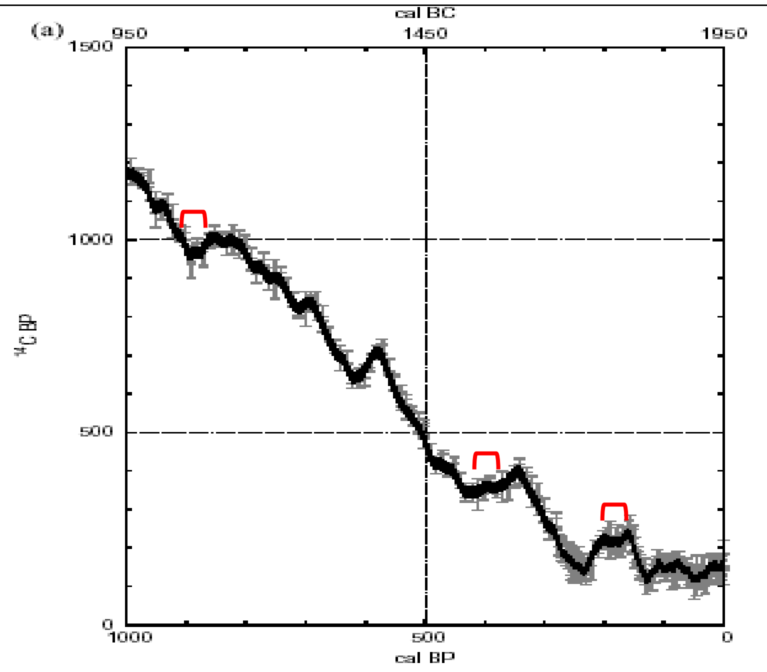

Figure 1. A 1000 year radiocarbon calibration curve for the Southern Hemisphere.

The curve represents a plot of the measured radiocarbon age (^{14}C BP) against the calibrated age (0 cal BP = 1950 AD) derived from tree-ring measurements. Individual measurements are shown with 1-standard deviation error bars in ^{14}C age. Red brackets show examples of radiocarbon plateaux – see text (after: McCormac *et al.* 2004).

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, the majority not producing consistent annual rings. Taxa that have either provided or shown the potential to provide palaeoclimate records include *Lagarostrobos franklinii* (Huon pine), *Phyllocladus aspleniifolius* (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 pursue (Argent *et al.* 2004). The longest and most comprehensive records have been derived from populations of *Lagarostrobos franklinii*, which is 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). 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 m asl[2]) record strong responses to temperature for most growing season months, thus providing reliable records of past temperatures between November and April (Buckley *et al.* 1997). Sequences from lower altitude sites

[2] above sea level

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), ^{14}C 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. Speleothem $\delta^{18}O$ records have been used to provide both a signal of rainfall and a composite 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 possibly shifts 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 ENSO variation (McDonald *et al.* 2004). The $\delta^{13}C$ contents of speleothems have also elicited composite signals 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 this time frame have been obtained, nor have records been correlated to piece together a continuous history, as has been done for tree rings. Like tree rings, speleothems records are spatially limited; in this case to those areas containing suitable cave deposits. This can be problematic for calibrating the speleothem sequences, in that areas with cave deposits frequently do not have instrumental climate records. Where such an overlap does occur, research has been initiated to verify interpretations of the speleothem stable isotope records, although it is in its early stages (e.g.Treble *et al.* 2005). Unlike tree ring records and 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 and therefore not straight forward 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, with sediments being laid down each year. Preserved in these sediments is 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 thus 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 derived from wetlands is that they can provide continuous records of past changes in terrestrial environments extending back several glacial-interglacial cycles, depending on the nature of the site. They contain a variety of evidence of the impacts of past climate change, including impacts on vegetation, fire regimes and lake hydrology. They 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 AMS dating technology, enabling these smaller samples to be dated. Although resolution on a seasonal scale is generally unattainable from Australian terrestrial sediment records, some preliminary investigation has been carried out into the potential for reconstructing past seasonal variation in climate by analysing the chemistry of ostracods[3] 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, such as fire. In addition, there can be lags between changes in climate and the vegetation response. This is less of a problem with short lived microfauna which can exhibit relatively quick responses to changes in local water temperatures and salinities (the latter being an indicator in 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 conducive 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 in northeastern, eastern, southeastern and western Australia (e.g. Kershaw *et al.* 1991; Colhoun 2000; Dodson and Lu 2000). For the most part, these records provide evidence of changes in effective precipitation[4], which is the main climatic factor governing the distribution of vegetation over much of Australia. They 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 the anthropogenic influence, such as aboriginal burning, on fire regimes. Nevertheless, carefully selected records 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).

<u>Geochemistry</u>
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, this time 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

[3] micro-crustacean with a calcareous carapace[4] effective precipitation is defined as the product of the interaction of precipitation, temperature and evaporation

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 well into the past (Harrison *et al.* 2003).

Stable isotopes

As with geochemical analyses, the stable isotope content of lake, bog and swamp sediments and of fossils contained in these sediments 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 palaeohydrology, with climatic inferences, and palaeotemperatures (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[5] dropped in response to falling sea levels (Williams *et al.* 1998). They 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 sedimentary 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 proxy evidence of 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 and in turn phases of high and low moisture availability (Nanson *et al.* 1991; Page *et al.* 1996; Nott *et al.* 2002). Fluvial facies 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[6] and source-bordering dunes (Harrison 1993). Microfossil, geochemical and physical evidence contained in lake sediments also provide evidence of past lake level fluctuations, however 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), 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 palaeo lake, riverine and dune geomorphological records are chronological control and resolution. These records tend to be, by their very nature, intermittent and of coarse resolution. The latter is exacerbated by the wide uncertainty ranges associated with the methods used to date the deposits. Dating uncertainties have also contributed to debates about the ages and interpretations of the geomorphic evidence (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 it is not always 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

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[5] 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.

[6] A crescent shaped dune formed on the leeward edge of a lake. See glossary for more details. [7] Millennial-scale warm events in the North Atlantic palaeo-climate record

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 spatial 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 an obvious 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).

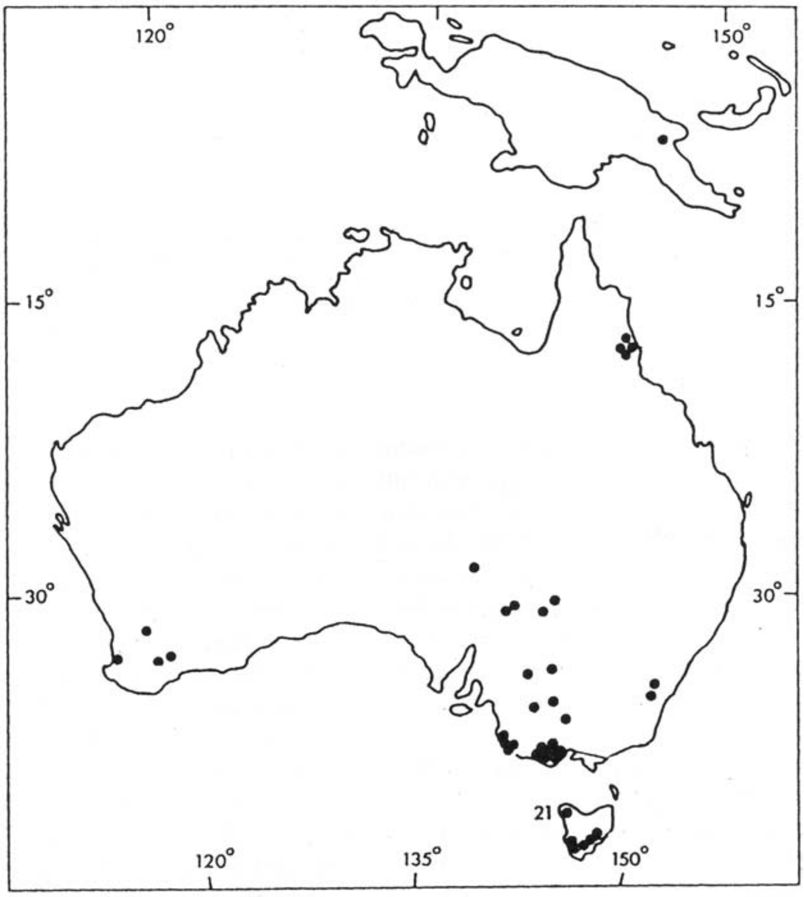


Figure 2. Selected Australian lake sites from which palaeo-records of past climates have been obtained.

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 change and climate processes. Of particular importance are beach ridges and coastal dunes.

Beach ridges form on accreting coasts where waves and onshore winds emplace sediment in shore-parallel ridges. Relict 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 can 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). Obtaining 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 now provide relatively detailed records of coastal environmental change over a temporal scale that can range from a few tens of years to thousands of years. Beach ridges composed of relatively coarse sediment, such as pebbles and boulders, can form on coasts during storm events. Successions of these type of ridges, when dated, 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 landwards 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 to 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 (several hundred thousand yrs) 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 the glacial phases when glaciers advanced and snow and the effects of periglacial 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 glaciation (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 Glacial period (Barrows *et al.* 2001; 2002). This has enhanced the 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 (such as block streams, block slopes and solifluction deposits) are more widespread than glacial deposits and are thought to be less sensitive to changes in precipitation than glacial landforms and therefore more reliable indicators of past temperatures than glacial landforms (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 of past cold phases and the extent of their effect (Barrows *et al.* 2004).

Estimates of past temperatures during glacial periods, particularly the Last Glacial, have been derived from 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 glacial periods (Barrows *et al.* 2001).

The most significant weakness of Australian glacial and periglacial deposits is that they do not provide continuous records of past temperature change. The uncertainties associated with dating can also complicate the interpretation of the evidence, as can the interaction of precipitation with temperature in glacier formation. Their strength is that they are one of the few proxy indicators of terrestrial palaeo-temperatures in a landscape dominated by the effects of changes in effective precipitation.

3.4 Marine palaeo-records

3.4.1. Corals

Massive corals growing in shallow tropical and sub-tropical oceans have microlaminations (density banding) that contain physical, isotopic and geochemical evidence of past environments at annual and sub-annual resolution (Gagan *et al.* 2000; Lough 2004). They are widely distributed (Figure 3) and can be accurately dated (using annual banding and radio-isotopic techniques), with many corals providing continuous records spanning 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 Glacial period. Overlapping records can be linked to provide records extending back thousands of years. This has been done for the southwestern Pacific (Gagan *et al.* 2000). Physical characteristics of coral bands, such as their skeletal density, linear extension rate, tissue thickness and calcification rate provide time-series data about the environmental conditions controlling coral growth, 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 SST, 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 SST variability. Where the $\delta^{18}O$ composition of seawater is governed by the interaction of precipitation, evaporation and water advection, the coral records provide evidence 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 SSTs, with most attention being focussed on strontium-calcium ratios (Sr/Ca; e.g. Beck *et al.* 1992; Alibert and McCulloch 1997; Gagan *et al.* 1998). Other coralline geochemical proxies for temperature that have been explored include magnesium-calcium ratios (Mg/Ca), uranium-calcium ratios (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 adjacent 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).

Australian scientists have been at the forefront of coral research, utilising high quality records gathered from around Australia (Great Barrier Reef, northern and western Australia; Figure 3) as well as the Indian and Pacific Oceans to reconstruct past SSTs, 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 palaeoclimates, 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, and in turn slightly different 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.

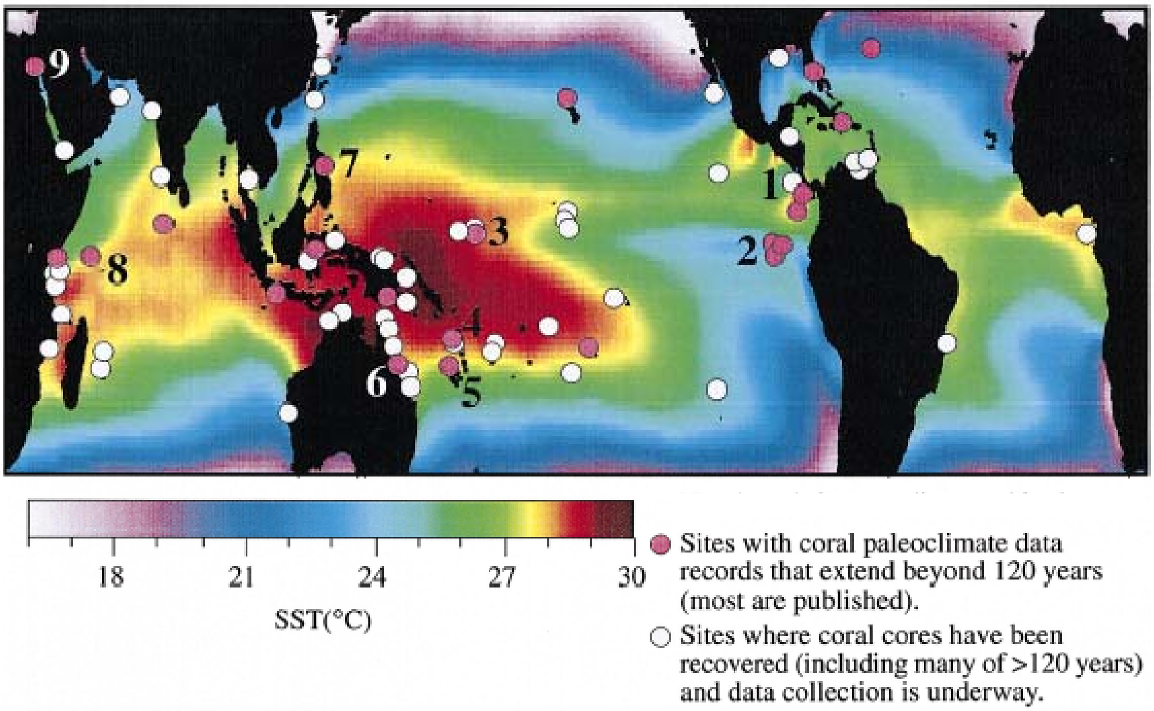


Figure 3. Approximate locations of key coral palaeoclimate research sites mapped against annual mean tropical sea surface temperatures (SST).
SST data are from the National Meteorological Centre and are available at: http://www.ingrid.ldgo.columbia.edu. *1. Panama, 2. Galapagos, 3. Tarawa, 4. Vanuatu, 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 readily correlated across large distances, and provide some of the longest, most continuous records we have of Quaternary climates. They can therefore be used to piece together spatial (global and regional) and temporal pictures of past oceanic and climate 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 derived from the species abundance, geochemical and isotope analyses of microfossils (such as foraminifera, ostracods and diatoms). Modern analogue analysis of species abundance of carbonate fossils, in particular foraminifera, together with their geochemical (e.g. Mg/Ca) and oxygen isotope content have provided long, continuous 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 derived 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 spatial variation of SST's in the Australian region through the isotopic, modern analogue and geochemical analysis of 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 nature of 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 fluctuation (Harle 1997). Fluctuations in the dust content of cores from the Tasman Sea have been used to reconstruct past aridity, wind direction and wind velocity over the Australian continent (Hesse and McTainsh 1999).

Although marine records provide a powerful palaeo-tool for reconstructing past climate change, variability and drivers, they do have some drawbacks. Chief amongst these is that, in general, the resolution of the records is course, with samples typically representing 100-1000 years. Additionally, as with many other palaeo-records records, interpreting the proxy data can be complicated and open to debate. For example, interpretation of the $\delta^{18}O$ signal from foraminifera requires a sound knowledge of the relationships between SST and ice volume at any given site through 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 only recently been recognised (van Ommen 2005). Palaeo-records from Antarctica, therefore, are vitally important in understanding the processes and forces influencing the global climate as well as the potential consequence of anthropogenically induced atmospheric changes. Additionally, in recent years, Antarctic palaeo-records have provided proxy evidence of past climate change in Australia and the processes that have influenced such changes. This section outlines the key ways that Antarctic palaeo-records have contributed to our reconstruction of past climates and in turn contributed to our comprehension of how the global climate system operates.

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, variability, processes and forcing. Depending on where they are collected from, ice records can cover recent decades in great detail or extend back thousands to 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 chronological resolution on these longer cores tends to be fairly coarse, with sample resolutions in the order of tens of years or more. This is principally because of the properties of the ice from which it is possible to take such long cores. Shorter ice cores extracted from the coastal areas of Antarctica are capable of providing much higher temporal resolution, down to two-weekly resolution in some cases. 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 the $\delta^{18}O$ ratio and deuterium (δD) in ice cores have been used to provide evidence of changes in surface air temperatures over Antarctica and surrounding oceans through time, as well as the changes in ice volume (Petit *et al.* 1999; Vimeux *et al.* 1999). In addition, the stable isotope records have been compared with solar variation indices (derived from analysis of cosmogenic nuclides; (Bard *et al.* 2000) to explore the long-term solar-climate connection (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, predominantly representing sea-salt aerosol entrainment 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 fluctuations in Antarctic mass-balance, which in turn improves our ability to constrain and quantify past sea-level rise (van Ommen 2005). Biogenic sulphur tracers have given proxy evidence of primary biological productivity through time, which in turn 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) and Law Dome, in the Australian Antarctic Territory, provides unequalled air age resolution. Such records have not only enabled an improvement of our understanding of the relationships (leads, lags and interactions) between atmospheric gases, climate and other climate forcings (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 past, natural changes. 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 biases. For example, the relationship between snow chemistry and atmospheric concentrations (transfer functions) 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 well back in time. There are some spatial and temporal gaps that need to be addressed, if possible. However, the range of proxies available mean that we are now in a position to carry out cross-regional analysis. This in turn will allow us to improve our understanding of our climate systems. This 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 1.

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 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

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 both spatial and temporal 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. Regional 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 provide the information necessary to determine to what degree twentieth century climate change is natural rather than anthropogenically induced. Palaeo-records do have this capacity, providing evidence not only of the nature of past climate change and variability, but also the processes driving climate change. Evidence from before the past 2 centuries is often necessary 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 testing and verification of regional and global climate models.

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

Australian palaeo-records have both provided and have the potential to provide 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 assemble the growing number and variety of palaeo-records into palaeo-databases in order to carry out cross-regional, national scale analyses. This type of work is in its infancy, but with appropriate direction and funding it will allow us to approach the levels of understanding that have already been obtained for the data-rich areas of the northern hemisphere, which have been assembled to the point where broader regional and national scale assessments can be made at a range of temporal and spatial scales. 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 chronological 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 climate variation.

4.1.1. Sub-decadal/decadal

Sub-decadal/decadal records of past variations in climatic parameters have been derived for northern and western Australia from coral and terrestrial sediment records, for Tasmania from tree rings, and for Antarctica and southwestern Australia from ice cores. There is some potential for these records to be extended to other areas of Australia, although this is limited by geography. For example, ice core records obtained from around coastal Antarctica have the potential to provide data about precipitation change for different regions of southern Australia, however, are less likely to provide information about northern Australia other than in general terms of changes to atmospheric and oceanic circulation patterns (see Box 1). At this stage, these records do not extend continuously back more than 4,000 years (at this resolution), although there is potential for longer records as research advances.

Annual records of sea surface temperature for regions around northern and western Australia have been derived from coral records (Figure 4). Current integration of these records suggests that, in contrast to the Northern Hemisphere temperature reconstructions (Mann and Jones 2003), SST in the tropical southwest Pacific during the latter part of the Little Ice Age (17th-19th centuries) were as warm as the early 1980s (Gagan *et al.* 2004). A conflicting SST coral record has been derived from New Caledonia, suggesting a 1.4°C cooling around AD 1730. It has been postulated that the apparent regional differences in the temperature records for the Little Ice Age is 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 variation in precipitation, sunlight hours and CO_2 can also be inferred from Tasmanian tree ring records, although the interpretation is far more complicated (see section 3.3.1).

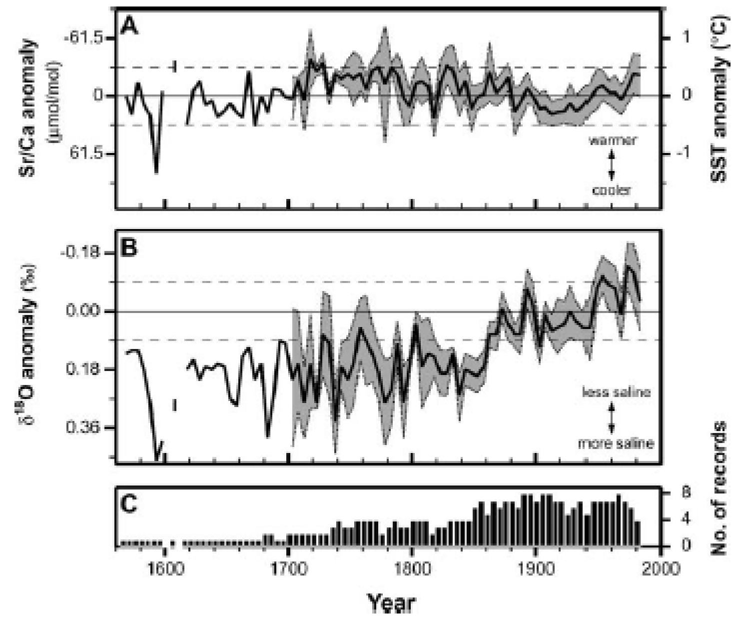


Figure 4. Composite records of (A) coral Sr/Ca and (B) coral δ^{18}O for AD 1565–1985 based on eight cores from massive *Porites* colonies from the central GBR, Australia (after Hendy *et al.* 2002).
Solid lines are reconstructions, at pent-annual resolution, normalized to the period 1860–1985 with 95% 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 δ^{18}O reconstruction is given in (C). (source: Gagan *et al.* 2004)

4.1.2. Millennial scale records

There is a much broader range of millennial (century) scale palaeo-climate records available in Australia in comparison to sub-decadal/decadal. These records include tree ring, coral and ice core records, as described in section 4.1.1 and sections 3.3.1, 3.4.1 and 3.5.1, as well as long continuous records from terrestrial wetland sediments (3.3.3)and marine sediments (section 3.4.2), and more discontinuous records from speleothems (section 3.3.2), coastal sediments (section 3.3.5), relict glacial deposits (section 3.3.6), rivers, lakes and dunes (section 3.3.4). The strength of millennial scale records is that they enable the identification of long term patterns of climate variability that can overlay decadal variability, such as ENSO. 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 glacial-interglacial cycles to 1,500 year Dansgaard-Oescher cycles[7]. Quantitative reconstruction of past climate variables, such as temperature and precipitation, has 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, there have been some attempts to provide these quantitative records using modelling (see Box 2) and modern analogue analysis. 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 changes in rainfall seasonality (Harle *et al.* submitted 2005).

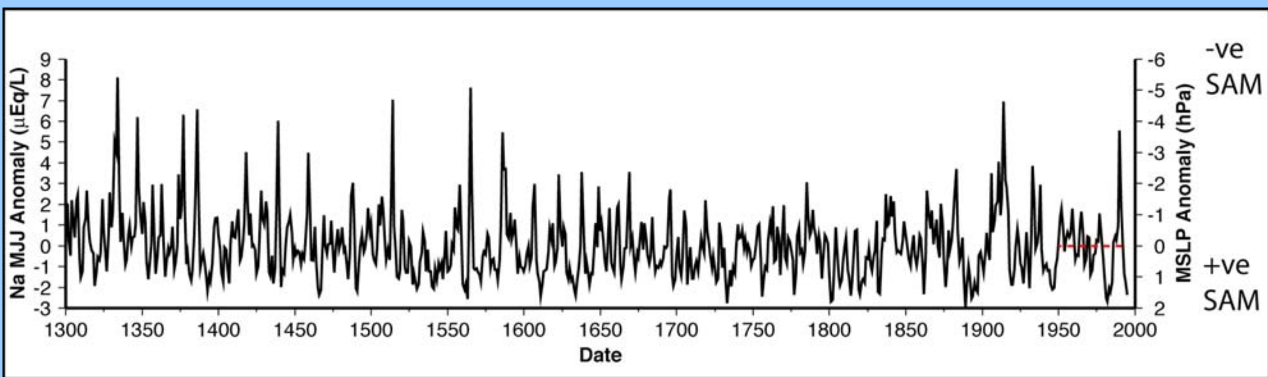
In addition, simulations of palaeoclimates for key periods, such as the Last Glacial Maximum (LGM), have been derived using palaeoclimate modelling. These efforts have been largely driven by international research groups, with some input from Australian scientists. These models tend to be Northern Hemisphere orientated and frequently provide unrealistic estimates for the Southern Hemisphere. This is a field of palaeo-science that would benefit from investment (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 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 record indicates pronounced decadal-scale variability (10.5 year cyclicity) throughout this period. The period post 1500 AD is characterized by slower climate variations (23 year cyclicity) and a poleward AAO or positive SAM index (enhanced westerlies in the 50° to 65°S zone) compared to the early part of the record (10.5 year cyclicity, an equatorward AAO or negative SAM index, and enhanced westerlies in the mid-latitudes). The 700 year proxy MSLP and AAO record is shown in the figure below. Climate forecasts 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 AAO, with the mean passage of low pressure and frontal systems traveling further south of the Australian continent. Research in progress 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. Present progress, has shown that south Western Australian winter rainfall is significantly correlated to the behaviour of the AAO, and that 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, that is similar to the past 50 years (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

Palaeoclimatic information on rainfall is one of the most difficult areas from which to extract a clear climatic signal. This is because of the effect that other factors, such as land-use feedbacks, have on those proxies. For example, stable isotope information extracted from speleothems can yield records of environmental wetness, but this record will be affected by groundwater and soil moisture which are affected by land cover and other aspects of the water cycle in that vicinity, some of which may be very local effects. Furthermore, the past 200 years of land-use change following the European occupation of Australia has introduced a signal in very many proxy records, which makes it very 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 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 using a 130 year long record of instrumental climate as constructed for these three lakes and calibrated using historical lake levels from the same period (Jones et al., 2001). This water balance model was then used to simulate climatic conditions to reproduce 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 record of atmospheric moisture balance for the region over the past 16,000 years.

The climate before 10,500 BP was drier than today, with P/E_L ratio ranging between 0.70–0.75. Although both warming and wetting can be observed following the glacial maximum, P/E_L ratio remained fairly constant, except when warming increased faster than precipitation between 14,000–12,000 BP. Most of the Holocene was wetter than today, but revealed a surprisingly wide variation in P/E_L ratio, ranging from 0.79, the modern instrumental average, to >1.2. The main features 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 extending 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 as part of the industrial revolution. Therefore, this last change is also interpreted as being natural.

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 circulation having large impacts on rainfall and regional hydrology must be considered as reasonable 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 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.

Jones, R.N., Bowler, J.M. and MacMahon, T.A. (1998) A high resolution Holocene record of P/E ratio from closed lakes in Western Victoria. *Palaeoclimates*, **3**, 51–82.

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 variation 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 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 derived from marine sediments, ice cores and terrestrial lakes – enable us to identify millennial scale cycles of climate change, such as 100,000 year glacial-interglacial cycles and 1,500 year Dansgaard-Oescher cycles (e.g. Petit *et al.* 1999; Turney *et al.* 2004). They also provide evidence of long-term climate trends, such as the trend of increasing aridity apparent for Australia within the last 350,000 years (Kershaw *et al.* 2003). Higher resolution, continuous palaeo-records – such as those derived from corals, tree rings, speleothems, lake sediments and ice cores – give evidence of decadal and sub-decadal scale climate variation, such as ENSO. In addition, by comparing records from different regions it is possible to identify spatial variation and/or synchroneity in climate cycles. This not only allows us to assess the degree to which observed regional climate variation 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. 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 (Cook *et al.* 2000). In another study, on SST 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 give 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 (giving evidence of rainfall in southwest WA; 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 fluctuation 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

Variations in greenhouse gases have modulated climate from geological timescales to the glacial interglacial changes of the past several hundred thousand years, and more recently, the “Anthropocene” (the human influenced period of the late Holocene). Unlike the variations in solar irradiance caused by orbital factors (Milankovitch cycles), changes in the concentrations of most greenhouse gases are largely unpredictable. An understanding of the causes of past observed greenhouse gas changes and their links with climate is helping to narrow the range of future likely concentrations and their climate forcing.

Precise systematic measurements of CO_2 in the atmosphere began only in 1957 with the International Geophysical Year. Records of the other gases began even more recently, in some cases (such as some halogenated compounds such as PFCs and isotopes of N_2O) only in the past decade. Compared to the duration of the anthropogenic perturbation or the processes controlling many of the greenhouse gas sources and sinks and hence their atmospheric concentrations, these observational records are very short and require extension into the past with indirect or proxy information. The “palaeo” period for atmospheric composition thus needs to extend to much more recent times than for many other climate 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. More spatial information is required to help understand the sources and sinks of the gases. Accurate, and importantly, highly time-resolved dating is necessary to reveal variations on periods relevant to the gas budgets and to correlate with 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 0.5 million years (Raynaud *et al.* 2000). Ice contains whole air in bubbles (accessed via coring) or in open pores in the overlying firn layer (containing younger air, but more readily sampled). Most greenhouse gases are preserved in selected ice core sites for hundred's of thousands of years allowing reconstructions at precisions of a few per cent or better. The main limitation is due to the air enclosure process (diffusion to depths where bubbles are slowly formed), which spreads the air age of any one sample 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 useful mainly for times before the oldest ice as they are much less precise than the ice core method (even relative to the much larger likely CO_2 variations in the geological past i.e. millions of years ago). They also are limited to estimates of CO_2 only.

Australian research in long-term greenhouse gas changes has benefited from the use of an important site, 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 CSIRO and partner groups such as ANSTO, NIWA (NZ), CNRS (France) 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 beforehand (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 anthropogenic climate change (e.g. Crowley 2000; Mann and Jones 2003). These records await extension into the earlier Holocene to find, for example, the impact of the climatic anomaly of the 8200 yr BP event, when it is suggested that a surge of ice sheet melt water slowed North Atlantic circulation. There is also scope for the precise and highly age-resolved gas measurements in Law Dome ice to clarify the sequence of events during the warming phases of the well known variations during the past 400,000 years in the 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 for initiating both the warming and the 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 1800 AD is accompanied by a decrease in the relative abundance of the minor isotope $^{13}CO_2$ as measured from ice and in the radioisotope $^{14}CO_2$, found from both ice and tree ring measurements (Francey *et al.* 1999). These confirm that the CO_2 growth is both organic and fossil in origin. 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 the glaciations, the mid Holocene and the Little Ice Age and CO_2 stabilisation in 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.* submitted) and will benefit from emerging measurement technologies suitable for the ~micromole sample size limit 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 anthropogenic 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.* submitted);
- 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 carbon monoxide and CH_4 which affect the abundance of the hydroxy radical (OH), the atmospheric "detergent" which removes CH_4 and other greenhouse gases from the atmosphere, and tropospheric ozone, a significant greenhouse gas in the troposphere. This is largely because ozone is a very reactive gas and has few long-term atmospheric measurements and little prospect of ice core measurements, and because 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 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 with 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. 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 for future projections. Aerosol sources include continental dust, emissions from volcanic eruptions (mainly sulphate), anthropogenic sulphate and soot from biomass burning. Removal processes can be quite 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 derived from a range of locations. Aerosol forcing must also take into account the albedo of the particles which can vary greatly between highly absorbing soot aerosols and reflective mineral dust. Ice cores incorporate aerosols with advantages of good preservation and dating. They have produced records of increased continental dust levels during glacial periods, peaks in acid aerosols from major volcanic eruptions, and anthropogenic increases in nitrate and sulphate. Regional dust accumulations are also available for larger changes, such as during glacial times (see dust evidence section). 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 a good example of a climate feedback in the biogeochemical system. The main sources for this dust include South America and Australia.

Solar forcing includes changes in the energy output (total solar irradiance) of the sun and the geometry of 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, rotation rate) have acted as proxies. To examine the period before telescopes allowed observations (in the 1600s), measurements of isotopes ^{10}Be and ^{14}C, the atmospheric production rates of which are modulated by the solar wind, are used as palaeo indicators (Bard *et al.* 2000). These isotopes are well recorded in ice and in tree rings. The reconstructions of irradiance can vary significantly depending on the methods and proxies used.

Land cover changes have received less attention in forcing climate. Land cover influences albedo, moisture exchange and surface roughness, and is likely to have changed significantly. The changes and the impacts are regional. For example, Bauer et al.(2003) produced more accurate global climate simulations when the effects of deforestation were included.

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

Sound knowledge of palaeoclimate (through improved palaeoclimatic information) can enhance our ability to verify the capacity of global climate models (GCMs) to simulate current climate and future climate change. This can be achieved in a range 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 both globally and regionally, and is also required for the application of climate results to detection and attribution of climate change. The instrumental record can be used to assess the realism of natural fluctuations in climate on inter-annual 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 global to regional. Indeed, it is possible to focus on collecting relevant palaeo-data for specific variables and regions where there are current trends of concern (such as rainfall in southwest Western Australia).

Palaeoclimatic data can also be used to validate the ability of climate models to simulate past climate where the mean state is different to the current mean state (i.e. such as simulating the details of the climate applied during the last glacial). Ability to accurately simulate a climate different to the present would enhance our confidence in simulating future (greenhouse-related) climate changes. Good palaeoclimatic data are required, both to initialise the past climate simulation (such as ice-extent, surface vegetation and sea surface temperature –if not running an interactive ocean), and to validate the results of the simulation (such as terrestrial rainfall and temperature patterns). However, such validation exercises do present some difficulties. There may not be full knowledge of the relevant climate forcing to apply in the past climate simulation (changes in the pattern of solar radiation, and CO_2 levels may be known, but some other factors may not be). The role of the ocean may not be well represented if fixed sea-surface temperature is used, but if a full ocean model is used uncertainty in ocean initialisation may have a significant impact on the 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 in narrowing the range of future projections in global warming.

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 past behaviour of systems such as El Niño Southern Oscillation under different climate states (see section 4.2) can reveal important aspects of these systems that one could test in global climate model simulations, and in that way identify potential improvements to process representation in these models.

As climate modelling develops into earth systems modelling, incorporating biogeochemical cycles, vegetation, land use, atmospheric chemistry, hydrology, ocean dynamic features such as ENSO and ice sheet dynamics (among a growing list of features), 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 the essential processes of GCMs in a more simplified form. They are designed to allow multiple simulations of more of the known components of the earth's climate and physical, chemical and biological processes over long periods, without the computational overheads of a full GCM. 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 of the warming of the industrial period, forced by palaeo data of ice cover, orbital changes, solar irradiance, aerosols and greenhouse gases, 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, leading to the influential findings that the 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 on smaller spatial 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

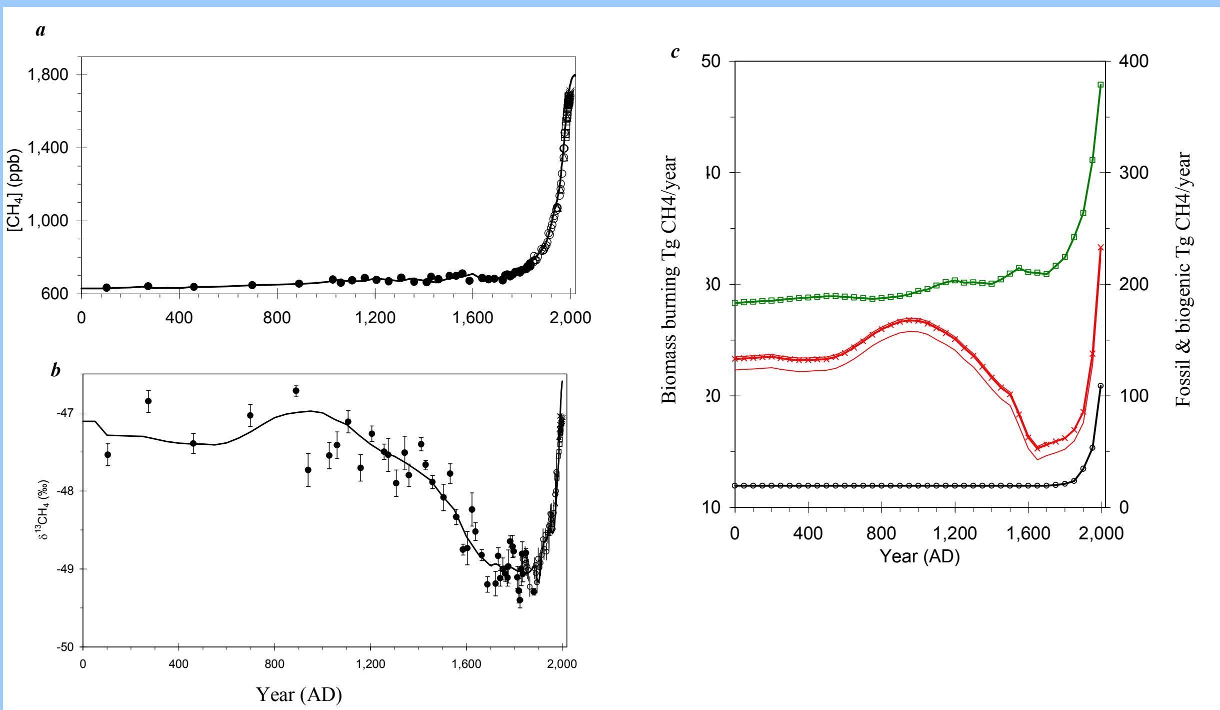
Box 3: Greenhouse gas changes - finding new evidence of causes.

The changing concentrations of the main greenhouse gases CO_2, CH_4 and N_2O, highly correlated with temperature over hundreds of thousands of years, are familiar palaeoclimatic results from ice cores. These records have revealed the ranges of natural variation and the more recent anthropogenic signals in atmospheric composition and its feedbacks on climate, over a range of timescales. Continued growth throughout the next century is presently assumed in all IPCC scenarios for CO_2 and N_2O and in many scenarios for CH_4.

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 (clathrates) contains no carbon-14 isotope and lowers the atmospheric $^{14}CH_4$ to $^{12}CH4$ 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. Isotopes can similarly provide information on CO_2 and N_2O sources.

Model interpretation of these isotopic signals provides a constraint on greenhouse gas budgets. The 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 CO2 and the apparent stabilisation of CH4, are new states or temporary variations in emission from a particular type of source.

Australian research groups such as CSIRO Atmospheric Research, ANSTO 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., submitted.

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.

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 our flora, fauna, water resources and landscape processes such as erosion. Pollen and charcoal records provide data about the flora, which in turn can be used to imply conditions for our fauna (although this is rarely done in Australia). Australian tree ring records give direct evidence of the response of our forests to shifts in temperature and in some cases precipitation, although at this stage this evidence is confined largely to Tasmania. Microfaunal records from lakes and the oceans provide us with information on how our aquatic fauna (freshwater and marine) respond to shifts in environmental conditions associated with climate change. Coral records give evidence of how they have responded to climate induced changes in SST, sea surface salinity and river runoff. In turn, river and lake records provide us with evidence of past hydrological responses to climate change and thus provide us with an insight into how our water resources are affected by climate. Although they tend to be discontinuous, macrofossil records, such as leaves and faunal remains can provide us with some information about how fauna has responded to past climate variability. For instance, recent work has demonstrated a strong link between the extinction of the Australian megafauna and other faunal communities in response to past climate change (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 our water source, 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 synchronously across our 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 glacial whilst lakes from more temperate regions, such as in western Victoria, exhibited low levels (Harrison 1993). This information has contributed to our understanding of how shifts in atmospheric circulation may have affected our regional climates, and in turn our flora, fauna and water resources (Shulmeister *et al.* 2004). Palaeo-river records not only provide us with information about the past response of water resources to climatic variation, but also give evidence of erosion. Indeed, they 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.

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 our 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 spatial coverage, temporal resolution and sophistication of palaeo-climate records have been improved, it has become possible to identify the effects of past climate variation on high impact events such as fire, drought, storms, floods and sea-level rise. Sub-decadal palaeo-records, such as those derived 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 enable us to identify long term variation, ranging from hundreds of years 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 occasionally near-coastal marine cores (e.g. Moss and Kershaw 2000). Although charcoal records in Australia are frequently complicated by the anthropogenic influences (the advent of aboriginal burning 40-60,000 years ago 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 variation. For example, a high-resolution charcoal record from the Atherton Tablelands in Queensland has provided evidence of a fluctuation 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 (drought) thought to be caused by changes in precipitation associated with 1,490 year ENSO intensity cycles. These cycles have been correlated with evidence for northern hemisphere climatic variation - Dansgaard-Oeschger[8] events. 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 'warm' ENSO events centred on 40, 25 and 15 ka, and 'cold' ENSO events centred on 30 and 21 ka (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 with fluctuations in the intensity of runoff from the Burdekin River in Queensland, providing evidence of flooding and of 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 suggested that storm frequency in this region has remained statistically 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 derived from ice cores, deep sea sediments and from some terrestrial sites. The latter, for instance, in Australia provides evidence of variations in vegetation communities and fire regimes associated with orbital-scale climate variation (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 derived 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 curves 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).

[8] Millennial-scale warm events in the North Atlantic palaeo-climate record

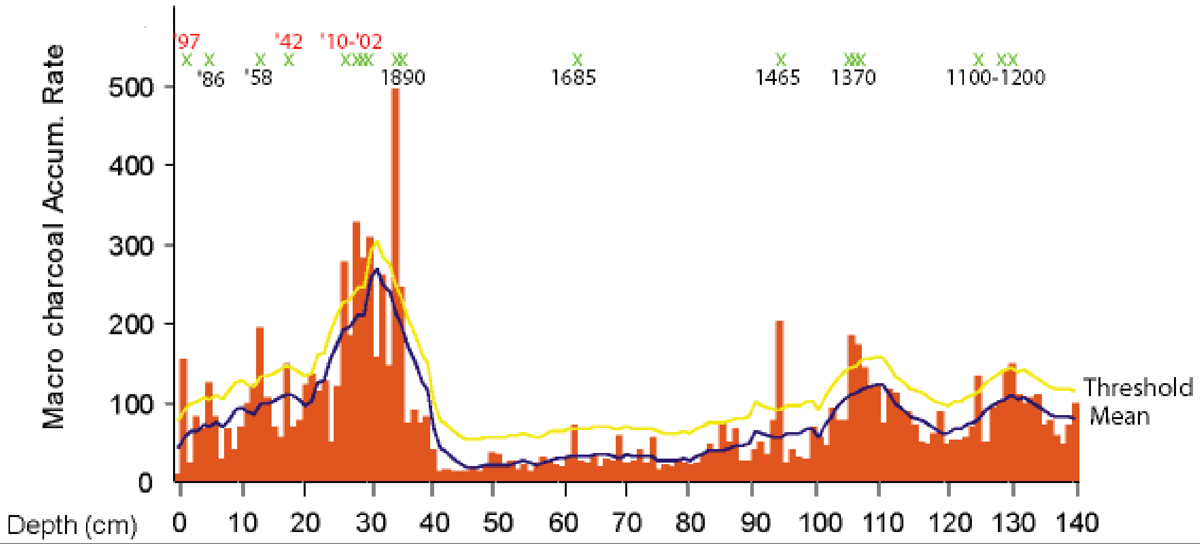


Figure 5. The macro charcoal record from Lake Euramoo (Atherton Tableland, QLD). El Nino years are signified by the green crosses. Dates given in red indicate major El Nino years as recorded in meteorological records. The blue line is a 400 year moving mean. The yellow line is a statistical derived threshold above which charcoal peaks are deemed to indicate significant fire events. The diagram shows a clear correlation between significant charcoal peaks and El Nino 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 3.5.1), 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 Last Glacial maximum (LGM) to Holocene transition 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 was therefore acting as sink rather than a source during this warming phase, with palaeo-database estimates of uptake 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 around gaps in our knowledge over the varying degree to which C4 plants expanded during the LGM as well as with the different response of C3 and C4 plants to changes in atmospheric CO_2, in particular low CO_2 (Street-Perrot 1994; Peng *et al.* 1998).

It is widely accepted that the main control on shifts in atmospheric CO_2 is processes operating within the oceans, with changes in SST 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 all being important (Bentaleb and Fontugne 1998; Pedersen *et al.* 2003). Palaeo-records enable us to reconstruct, and in turn, understand 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 LGM and LGM-Holocene transition and the implications for CO_2 flux into the atmosphere (Bentaleb and Fontugne 1998). At a 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 in past 100s of years from modelling of ice core CO_2 and $\delta^{13}CO_2$ shows how the terrestrial biosphere has changed from a carbon source in the early anthropogenic period to a sink in more recent decades. Natural climatic variations, often connected with ENSO, also influenced terrestrial CO_2 uptake. The ocean has been a sink of CO_2 throughout most of the past 200 years. Methane isotopic records also show the variability of biomass burning, an important source of carbon emissions (see Box 3).

6. Where to from here?

In recent years there has been significant progress in palaeo-science in the Australian region, with advances in sample collection, dating, and analysis enabling the development of more sophisticated and higher resolution palaeo-climate records. This is opening up exciting opportunities to extend our climate records back in time, identify cycles of climate variation, improve our understanding of the drivers of climate change, identify how climate change can affect our terrestrial and marine environments and, in turn, inform public policy on how to plan for the impacts of future climate change. There are still many important gaps, however, both in terms of spatial and chronological representation. This is particularly true for records with subdecadal resolution, which are vital for understanding decadal and short-term millennial scale cyclical changes in climate variation, such as that described for ENSO in this report. The majority of these records do not extend beyond a few hundred to few thousand years, although in some cases (such as with ice core and lake sediment records) there is potential for extension much further back in time. Whilst records of a few thousand years can provide us with valuable information about climate variation, they do not extend back far enough to understand the effect of longer term variation in our climate systems.

There is also a distinct spatial bias in palaeo-records from our region which needs to be overcome. This is largely a factor of site suitability, but is also due to the small number of people working in this region (relative to the effort applied in the Northern Hemisphere). There are many sites and avenues of science yet to be explored. For example, more spatial information is required to help understand the sources and sinks of the gases, whilst accurate, high-resolution dating is necessary to reveal variations on periods relevant to the gas budgets and to correlate with rapid events such as ENSO, the effect of volcanic eruptions, and methane hydrate bursts. 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 our past climates. In particular, many of these records are subjective, and need to have quantitative techniques applied to them. There also needs to be a greater analysis and reporting of uncertainty if we are to utilise palaeo-data for testing climate models.

To date, much of the research effort of the Australian palaeo-science community and its collaborators has been focussed on the acquisition of records, with only limited comparisons being undertaken. In essence, we are only just at the stage whereby we have the 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. We are located in a region of immense interest to those researching climate-atmosphere interactions, specifically the Southern Ocean, the Asian and Australian monsoons, the Western Pacific Warm Pool and the Indian Dipole. 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 great potential for palaeo-records to provide us with insights into how our environment will respond to future climate change through identification of processes, drivers and sensitivities. For example, palaeo-records can tell us much about the effect of climate variation on our water resources.

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 in a good position to lead efforts in testing climate models of the Southern Hemisphere

A more detailed discussion of the way forward for palaeo-science in regard to contributing to future climate change research will arise from a meeting[9] to be held at the Australian Academy of Science in Canberra on June 27th and 28th 2005.

[9] 'Reconstructing past climates for future prediction: Integrating high-resolution palaeo data for meaningful prediction in the Australasian region'

7. Glossary

BP	-	before present
^{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 (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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