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Past environmental analogues

P. De Deckker, A.P. Kershaw and M.A.J. Williams

Abstract - *Independent evidence from geology, biology and chemistry shows that Australia's climate has changed in the geologically recent past and strongly suggests that it is likely to continue to change in the future, regardless of any human presence. However, for the past 200 years we have ourselves become more and more active as agents of climatic change, particularly by increasing the concentration of atmospheric CO_2. Many workers warn that a world climate warmer and regionally wetter than today could result within the next 50 years. A careful scrutiny of possible former analogues of our likely environmental future is therefore timely.*

During the last 10 000 years Australia's climate has on occasions been slightly warmer and locally slightly wetter than it is today. In tropical northern Queensland temperatures were highest between about 5000 and 3600 years ago, and precipitation was also apparently higher at this time. In western Victoria, on the other hand, lake levels were very high from about 6500 to 5500 years ago, but were falling between 5000 and 4000 years ago.

Past environmental analogues are useful in showing rates of change, differential rates of response, and magnitudes of change. Quantitative estimates are now possible using bioclimatic indices derived from modern pollen studies, and salinity estimates obtained from the trace element and stable isotopic composition of fossil ostracod shells from carefully selected sites.

Antarctic ice-core data show high atmospheric CO_2 concentrations during prolonged intervals of warm climate (interglacials) and low CO_2 levels during glacial maxima. However, there is no obvious former counterpart to the present very high levels of atmospheric CO_2. Future climatic change may be gradual, but could equally be abrupt and rapid.

Key word Index: holocene climates, pollen analysis, Queensland vegetation history, Victorian lake fluctuations, ostracods, stable isotopes, palaeosalinity, Antarctic ice cores.

1. INTRODUCTION

What is the likely impact of the increasing concentration of atmospheric carbon dioxide (CO_2) and other greenhouse gases upon the future climate of our planet? In seeking to address this issue, atmospheric scientists have usually adopted three distinct approaches, one of which - the study of past climates - is the concern of this paper.

Perhaps the most common approach involves computer-assisted modelling, using a variety of more or less realistic atmospheric models (Hunt and Wells, 1979; Washington and Meekle, 1984). Many such models fail to include a suitably dynamic cloud cover, and suffer from the inability to specify realistic time-lags between coupled oceanic-atmospheric responses to changes in solar radiation.

A second approach is to consider extreme climatic events recorded historically under reasonably standardised conditions using conventional meteorological monitoring devices (Pittock, 1983). Problems here include large spatial gaps in the global observational network, especially over the southern oceans, as well as records of varying duration and quality.

A third approach, prompted by the realisation that climatic change is nothing new (Berger, 1981), is based on the premise that extrapolation of past climatic events, at varying scales in time and space, may be a useful guide to the probable magnitude and frequency of future climatic events.

Times in the geologically recent past when temperatures were higher than they are at present may be comparable, in certain ways, with an earth warmed by greenhouse gases, and may allow us to predict likely rates, directions and magnitudes of future environmental changes (Pittock and Salinger, 1982, 1983; Butzer, 1983). The most recent times of higher temperatures are the 'climatic optimum' or 'hypsithermal' of the present interglacial period (the Holocene) that began 10 000 years ago, and the height of the last interglacial estimated to have occured about 120 000 years ago. Although it is likely that the latter period experienced higher temperatures (Jouzel *et al.*, 1987), we will focus on the more recent period for which there is more information.

Our aim is to scrutinise some of the evidence for Holocene climatic change in Australia, and to plead for greater subtlety in using past climates as a possible guide to future change. In particular, we stress that much more attention needs to be paid to rates of change, especially rates of response by rivers, lakes and vegetation to changes in precipitation and temperature. Although the mid-Holocene may prove to be a useful analogue for Australia, we urge the need to refine and to quantify estimates of past climatic change.

The landscape of Australia is like a palimpsest, reflecting former erosional and depositional events, themselves triggered by ever-changing tectonic, volcanic and climatic regimes. Our soils were fashioned by physical, chemical and biological processes prevalent under climates and plant covers quite different from those of today. A substantial body of evidence from geology, biology, isotope geochemistry and prehistory indicates that Australia's climate has changed in the geologically recent past (Williams, 1984, 1985) for reasons that have nothing to do with human activities, so that it is highly likely that it will continue to change in the future, regardless of any human presence. Nevertheless, for the past 200 years we have ourselves become more and more active as agents of climatic change through our use of coal, oil and wood, evident in the increasing concentration of atmospheric CO_2 from about 260-280 ppmv some two centuries ago to about 345 ppmv by today. Many workers now warn that a world climate warmer and regionally wetter than today could result from this CO_2 increase over the next 50 years. A careful scrutiny of possible former analogues of our likely environmental future is therefore both timely and sensible. It is worth emphasising that it is not simply present and future climatic changes which are of concern here, but the impact of such changes upon our natural environment. We should not expect that every component of our physical and biological environment (for instance, rivers, lakes, groundwater, forests, grasslands, beaches) will react uniformly to a change in rainfall seasonality, for example, nor that regional climatic changes will be synchronous across the continent. Figure 1 serves to remind us that there may be significant time lags in the response of large lake systems and of regional groundwater tables to changes

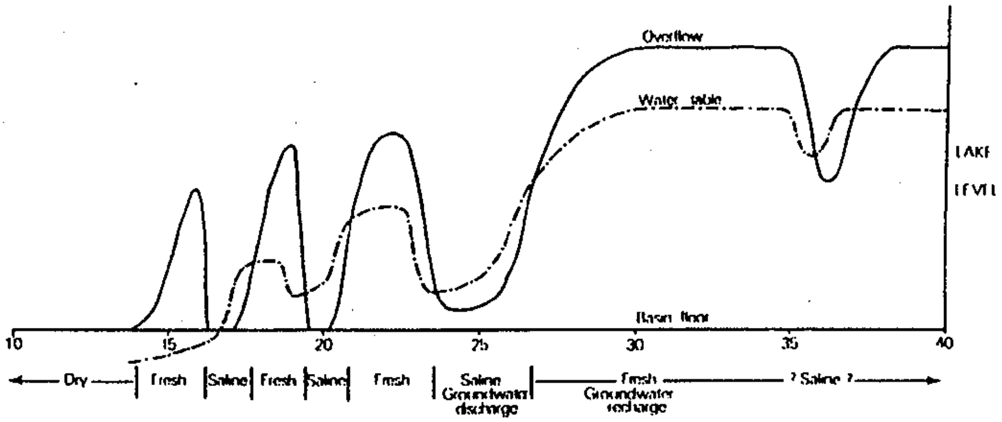


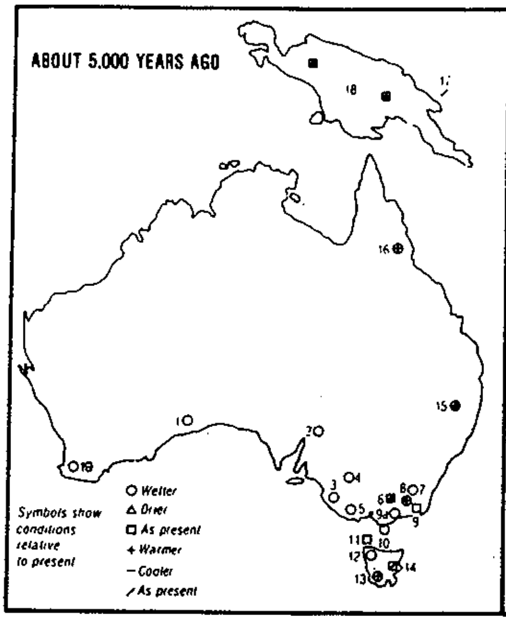
Figure 1. Differential response of lake levels and of regional groundwater tables to climatic change, with special reference to the late Quaternary Willandra lakes of western New South Wales. Horizontal scale in thousands of year. (After Bowler, 1983).

in rainfall, runoff and evaporation. It also offers a caution against uncritical use of lake levels as a synchronous proxy record of climate: a large groundwater-fed lake may be responding to climatic events which had already ceased hundreds (or even thousands) of years earlier.

2. THE HYPSITHERMAL IN AUSTRALIA

Previous workers thought that during the Holocene epoch Australia was at its warmest about 9000-7000 years ago (Pittock and Salinger, 1982, 1983; Williams 1984). This was partly based on available palaeoclimatic evidence brought together at the 1981 CLIMANZ symposium on the Late Quaternary history of Australia, New Zealand and surrounding seas (Chappell and Grindrod, 1983). However, recent evidence from new sites and reinterpretation of existing data suggest that at least for some parts of the continent maximum temperature levels may have been achieved somewhat later.

Figures 2 and 3 summarise the most reliable climatic evidence for roughly 8000 and 5000 years ago in Australia. Available evidence is mainly from pollen studies supported in some instances by microfaunal and sedimentary analyses. Symbols showing basic precipitation and temperature conditions relative to present represent single sites or groups of sites. Where there is conflicting evidence, the average or most common condition of a site group has been selected. It is clear from the maps that there is still very little relevant evidence for most of the continent and that sites for which we do have good evidence of past changes in temperature and rainfall are mainly concentrated in the southeast. There is no appropriate information from the arid centre although dry areas are represented by site locations 1, 2 and 4.



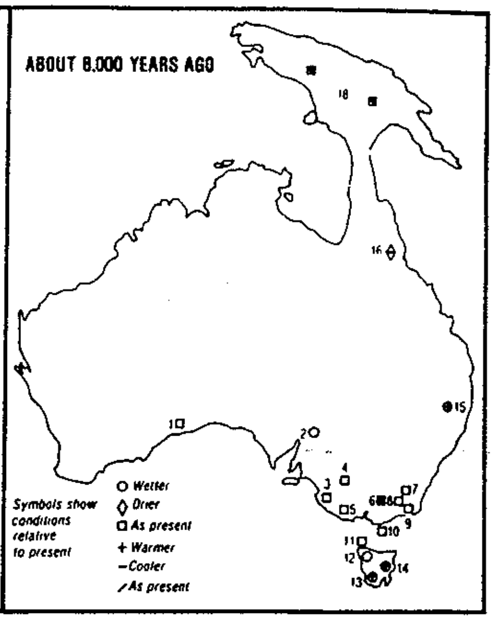


Figure 2. (Left) A partial reconstruction of Australia's climate 8000 years ago. For sources of data and numbered site locations see Figure 3.

Figure 3. (Right) A partial reconstruction of Australia's climate 5000 years ago. Numbered sites are: 1 Nullarbor Plain; 2 Lake Frome; 3 SE of South Australia; 4 Lake Tyrrell (Luly, 1986); 5 Western Plains of Victoria; 6 SE Highlands; 7 Breadalbane, NSW (Dodson, 1986); 8 Snowy Mts (Raine, 1974; Martin, 1986); 9 Delegate River; 9a Sperm Whale Head; 10 Wilson's Promontory; 11 Hunter Island; 12 NW Tasmania, 13 SW Tasmania; 14 Lake Tiberias; 15 Barrington Tops (Dodson et al., 1986); 16 Atherton Tableland; 17 Huon Peninsula; 18 New Guinea highlands; 19 SW Australia. Unless specified the data sources are from Chappell and Grindrod (1983) and present text.

The majority of sites record changes in precipitation. Only for highland areas, where there is evidence of altitudinal changes in vegetation, is information available on temperature. However, it is often assumed that there has been a close relationship between temperature and precipitation in Australia with higher rainfall coinciding with higher temperatures. This assumption needs testing.

Data from about 8000 years ago show that temperatures in the highlands of southeastern Australia and New Guinea were at or above present levels but were lower than today in northeastern Queensland. Sea-surface temperatures off the Huon Peninsula in New Guinea, deduced from oxygen isotope analysis of giant clam shells, were also lower than present (Aharon, 1983). At this time most sites providing evidence of precipitation show conditions similar to those of today. A major exception is Lake Frome where proposed higher summer rainfall has been explained by invoking southward expansion of the summer/winter rainfall boundary (Singh, 1981).

Evidence from almost all sites shown on Figure 3 points to higher temperatures and precipitation 5000 years ago but this time is very much towards the end of the climatic optimum that lasted from about 8000 or 7000 to 5000 years ago at almost all sites. However, 5000 years ago marks the beginning of the period of highest temperatures in northeastern Queensland, so that it is not possible to define a single short 'hypsithermal' interval valid for the whole of Australia. However, 5000 years ago is a significant time in that it is embraced by the period of highest temperatures at all sites. It is also preferable to the period centred on 8000 years ago as an analogue for the greenhouse climate in that one major boundary condition, sea level, was similar to today but was some 20 m below present 8000 years ago (Chappell, 1983). Bathymetric charts suggest that New Guinea would still have been joined to Australia by a land-bridge when the sea level was 20 m lower, thereby preventing flow of warm water through Torres Strait.

3. QUANTITATIVE RECONSTRUCTION OF CLIMATIC CHANGE

Very few palynological studies in Australia have so far attempted to provide quantitative palaeoclimatic estimates. A recently devised method now allows quantitative estimates to be made of temperature and a variety of other bioclimatic parameters from certain environments (Kershaw and Nix, in press). The method applies the CSIRO bioclimatic prediction system developed by Nix *et al.* (unpublished manuscript) to the extensive rainforest data set compiled by Webb *et al.* (1984). This allows the determination of present-day climatic ranges for rainforest species and species groups (Nix, 1984). Palaeoclimatic conditions for fossil assemblages can then be estimated from the overlapping climatic ranges of recorded taxa (see Figure 4).

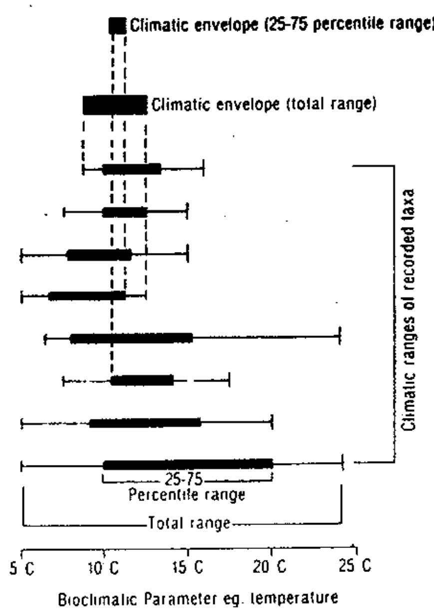


Figure 4. Method used to construct climatic envelopes for a given taxon assemblage (after Kershaw and Nix, in press).

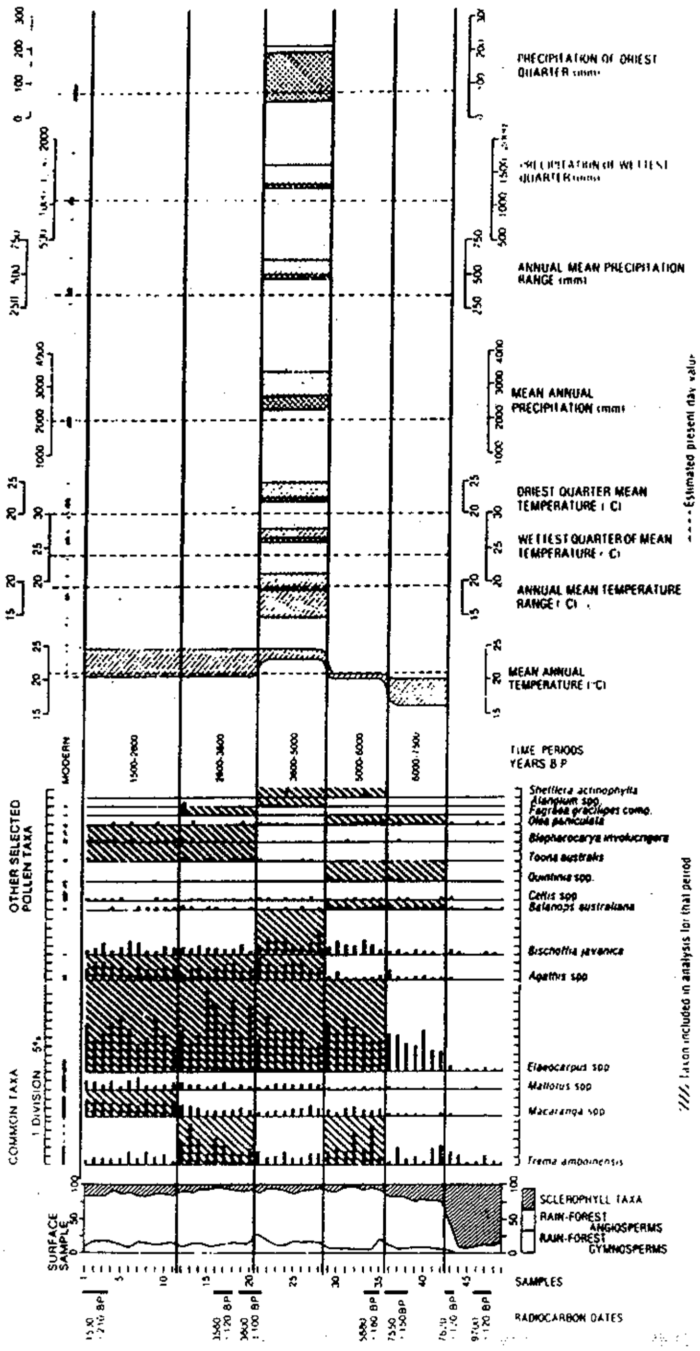


Figure 5. Palaeoclimatic envelopes deduced for Lake Euramoo (see text).

Using the upper and lower climatic limits (which indicate the total range), each climatic estimate is the envelope of values that can accommodate those climatic conditions required to support all taxa. Percentile values, such as the 25 and 75 percentiles, can provide a tighter climatic envelope which can be useful where taxa have very broad distributions. In some instances, particularly with percentiles, ranges fail to overlap. Here, the best estimate of climatic range is considered to be the gap between the taxon with the lowest maximum value and that with the highest maximum.

Figure 5 illustrates the application of the method to a pollen diagram from Lake Euramoo on the Atherton Tableland. Climatic estimates based on total taxon ranges and 25-75 percentiles (where appropriate) are shown for the present and for selected intervals during the time in which rainforest was dominant in the region. Only those taxa considered to have been growing locally are used in envelope construction, and for each time interval these are indicated by shading.

A test of the accuracy of the method is provided by comparison between envelopes constructed from the modern assemblages or surface samples and climatic conditions predicted from site locations. For all climatic parameters the predicted values fall within the envelope of total range. Furthermore, for the precipitation-related parameters, the predicted value also falls within (or very close to) the much narrower 25-75 percentile range. These results allow confidence in the palaeoclimatic estimates.

It is clear from these results that maximum Holocene temperatures were not achieved in this area until 5000 years ago and that the most likely period of highest temperatures was 5000 to 3600 years ago. At this time, a tight envelope of total range indicates that mean annual temperatures were at least 2°C and possibly as much as 3.5°C higher than those of today. For northeast Queensland, some good indication of climatic conditions associated with higher temperature levels can be gained by examination of results for other climatic parameters from the Lake Euramoo analyses (Figure 5). Of the temperature-related measures, temperatures were higher in both the wettest (equivalent also to the warmest) and driest (equivalent also to the coolest) quarters. Consequently the annual mean temperature range remained the same. Mean annual precipitation was also higher than at present by at least 300 mm and most probably 500-800 mm. There may have been little difference in dry-season precipitation, but wet-season rainfall was clearly higher. In support of these estimates, the annual mean precipitation range is also higher. It is interesting to note that these precipitation estimates are very similar to those proposed by Pittock and Nix (1986) in their CO_2 warmed earth scenario for this part of the world.

4. LAKES AS INDICATORS OF CLIMATIC CHANGE

Certain types of lakes are highly sensitive indicators of changes in precipitation and evaporation over their catchments. Perhaps the best evidence to date, and certainly the easiest to interpret, comes from a series of volcanic lakes in western Victoria. These lakes occupy volcanic craters ("maars") which formed as a result of explosions which took place when hot lava came into contact with ground water. Owing to their impervious bases, nearly conical shape and clearly defined crater rims which act as distinct drainage boundaries, these crater lakes have operated as gigantic rain-gauges. In contrast to lakes which are fed by rivers or from ground water (and for which it is difficult to establish an accurate water budget) crater lakes will normally act as natural recorders of precipitation and evaporation over the lake basins.

Judicious investigation is necessary to show whether or not a maar lake is connected to the groundwater-table. If it is not, then changes in lake level in the maar will be a direct reflection of the precipitation to evaporation ratio (P/E) over the lake. A fall in lake level will result from a change in P/E, and will also be registered as a change in lake water salinity. Any lake will contain a certain amount of dissolved salts, so that a rise or fall in level of a maar lake will also be reflected in a decrease or increase in water salinity. Several techniques have already been used to determine changes in lake level and water salinity in order to document former changes in P/E over a number of crater lakes in western Victoria. These techniques all rely on the recovery of cores taken through lake floors. The cores comprise sediments laid down at the bottom of the lakes and thus represent a history of lake sedimentation. Fossilized organisms recovered from the cores (such as the pollen of aquatic plants discussed earlier, algae and the calcareous shells of various organisms, including ostracods and molluscs), can also yield information about past conditions in the lakes during their lifetime, particularly since different species have different ecological requirements. A thorough ecological knowledge of present-day species is a prerequisite for analysing past aquatic conditons.

A technique recently pioneered at the Australian National University and Monash University by A.R. Chivas, P. De Deckker and J.M.G. Shelley has as its aim the accurate reconstruction of past changes in lake temperature and salinity. The concept behind this technique is to calculate the uptake of trace elements (magnesium and strontium) in the calcareous shells of ostracods (small aquatic organisms common in rivers and lakes), and to relate this uptake to conditions of the aquatic environment in which the organism lives. Using field collections and laboratory experiments, this work has so far shown that the uptake of magnesium (Mg) in ostracod shells is controlled by water temperature as well as by the ratio of magnesium to calcium (Mg/Ca) in the host water. The uptake of strontium (Sr), on the other hand, is not affected by water temperature but is controlled by the Sr/Ca ratio of the host water. Therefore the analysis of both Sr and Mg in ostracod shells should enable the influence of temperature upon the uptake of Mg to be determined. This temperature signal should also be detectable in the stable oxygen isotope ratios of the shells since fractionation of the oxygen isotopes is controlled by water temperature and salinity (see Chivas *et al.*, 1983, 1985, 1986). At present, we lack reliable Holocene temperature estimates for Australian lakes, but calculation of the temperature-dependence of various ostracod species will allow us to remedy this deficiency in the near future.

The best studied maar lake in Victoria is Lake Keilambete situated north of the township of Terang. Reconstruction of the last 10 000 years of Lake Keilambete's history is based on a number of quite independent lines of enquiry (Figure 6). These include sediment analysis to reconstruct water level fluctuations and associated changes in lake salinity (Bowler, 1970, 1981); aquatic pollen and algal remains to reconstruct water salinities (Dodson, 1974); invertebrate fossil remains to obtain past conditions of lake water, such as water depth and water chemistry (De Deckker, 1982); as well as the trace element composition of calcareous shells of small invertebrate crustaceans such as ostracods to reconstruct water temperature and salinity (Chivas *et al.*, 1985, 1986). Figure 6 summarises the major changes in water level and salinity at Lake Keilambete during the last 10 000 years deduced from these independent methods of analysis. Since there are numerous maar lakes in the volcanic district of western Victoria, a study of the fluctuations in other lakes makes it possible to decide whether the changes in Lake Keilambete reflect regional climatic events rather than very localized influences. Here, too, the selection of appropriately informative maar lakes is critical. The freshwater Lake Purrumbete, for instance, was not suitable. It is connected to a river, and may also be influenced by ground water (De Deckker, 1982). Lakes Bullenmerri and Gnotuk near Camperdown were ultimately chosen.

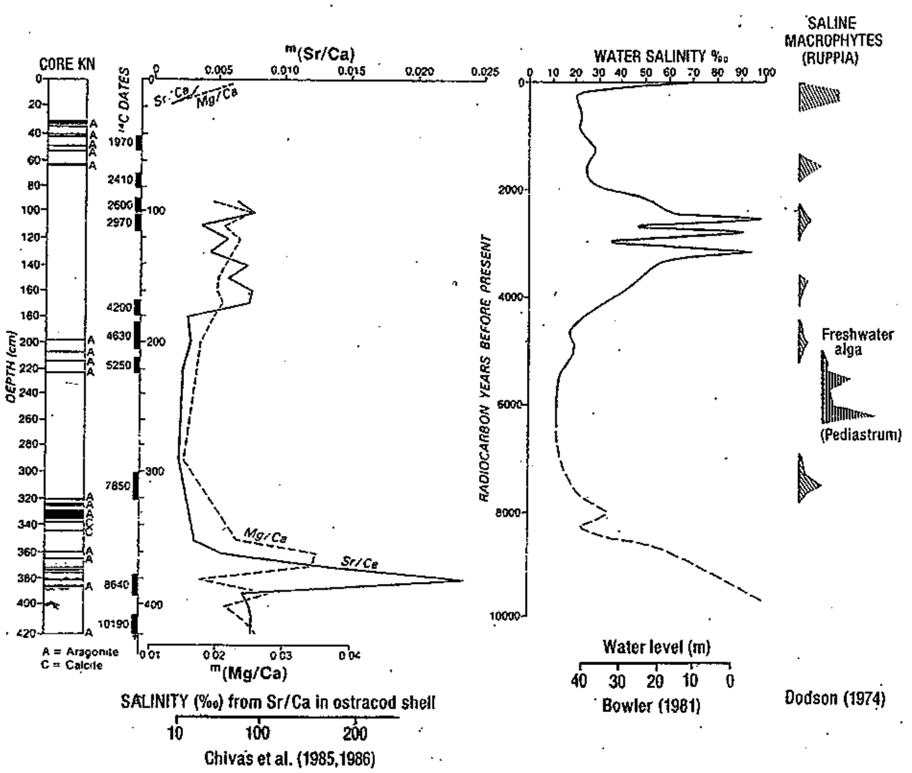


Figure 6. Holocene water level and salinity fluctuations in Lake Keilambete, Victoria. The salinity curve of Chivas et al. (1985) is based on trace element analyses (particularly of strontium) of individual ostracod shells. Bowler's (1981) salinity curve was deduced from grain size analyses which in turn relate to lake levels. Dodson's (1974) pollen evidence provides broad independent confirmation of the salinity curves. Bowler's core K4 probably did not recover material as old as that in core KN of Chivas et al. (1985), hence the discrepancy in salinity valued obtained by the two techniques for the start of the Holocene when the lake was very shallow. In addition, the sharp change in salinity interpreted from the analyses of strontium/calcium in ostracods at 180 cm depth in core KN results from a change in lake chemistry at that time reflected in a dramatic change in authigenic mineral precipitation in the lake from dolomite to aragonite. More closely spaced samples analysed for grain size near the level would no doubt also confirm the sudden drop in lake level.

These lakes lie adjacent to one another, but differ in morphology, shape and water salinity (for details see De Deckker, 1982). Two other juxtaposed lakes called the Basin Lakes (East Basin and West Basin), situated between Camperdown and Colac, were selected for their differing limnological characteristics (see Timms and Brand, 1973; Last and De Deckker, 1987) and were also cored. Lake Keilambete lies about 50 km from the Basin Lakes. Figure 7 summarises the changes in levels of these five lakes over the past 5000-10 000 years, and show that broadly similar fluctuations have been characteristic of all five lakes within time slots of 1000 years. The highest levels ever attained during the last 10 000 years were within the interval 7000 to 5000 years ago, when the lakes must have been overflowing. Also noteworthy is the dramatic fall in lake levels over the past 100 years, possibly to levels as low as those evident at the start of the Holocene. We can at present offer no convincing explanation of this most recent hydrological event. It may reflect a change in the P/E ratio, but could equally reflect pumping of water from the lake catchments.

a. P/E ESTIMATES FOR 5 VICTORIAN MAAR LAKES FOR THE HOLOCENE

x1000 years before present	KEILAMBETE	GNOTUK	BULLENMERRI	WEST BASIN	EAST BASIN
0–1	MEDIUM AND BECOMING LOW	BECOMING LOW -MEDIUM	BECOMING LOW -MEDIUM	LOW	LOW ?
1–2	MEDIUM	MEDIUM	MEDIUM	?	MEDIUM ?
2–3	LOW AND CHANGING	LOW	LOW	LOW	LOW
3–4	LOW	MEDIUM	MEDIUM -- LOW	LOW -- MEDIUM	MEDIUM
4–5	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM
5–6	HIGH	HIGH	HIGH	HIGH	HIGH
6–7	HIGH	HIGH	HIGH -- MEDIUM	HIGH	NO RECORD
7–8	MEDIUM	LOW	MEDIUM -- LOW	LOW	
8–9	LOW	LOWEST	MEDIUM	LOWEST	
9–10	LOWEST	LOWEST			

b. TECHNIQUES USED TO OBTAIN EVIDENCE OF CHANGES IN LAKES

KEILAMBETE	GNOTUK	BULLENMERRI	WEST BASIN	EAST BASIN	
X					SEDIMENT-SIZE
X			X	X	SEDIMENT MINERALOGY
X	SOME	SOME	SOME	SOME	BIOLOGICAL REMAINS-FLORA (pollen, algae and spores)
X	X	X	X	X	BIOLOGICAL REMAINS- FAUNA (many components)
X					OSTRACOD SHELL CHEMISTRY

Figure 7(a). Precipitation/evaporation estimates for five Victorian maar lakes for the past 10 000 years averaged in 1000 year time-slots. Today this part of western Victoria has a precipitation/evaporation (P/E) ratio of about 0.5. When lake levels were much higher than today and especially when lakes were overflowing the P/E ratios are considered to be >1 and are labelled here as high.

7(b). The type of work carried out to obtain the data on changes in lake level.

5. COMPLEX RESPONSE OF VEGETATION TO CLIMATIC CHANGE

Figure 8a provides a summary of major environmental changes deduced from pollen analysis of the organic sediments which were laid down at a number of localities in the Atherton Tableland of northeastern Australia during the past 10 000 years and more.

Organic sediments were accumulating in Lynch's Crater well prior to 10 000 years ago, but deposition began progressively later at Bromfield Swamp, Lake Euramoo and Quincan Crater. The onset of sedimention at these sites is related to their location relative to the present-day precipitation gradient. We might therefore envisage that deposition began with the establishment of permanent lakes at each site, with precipitation gradually increasing from some time before 11 000 to at least 7000 years ago. An alternative explanation is that local site conditions caused a progressively delayed response to a single major increase in precipitation. Quincan Crater has a porous scoria substrate and so might be expected to be slow in filling with water; it may be no coincidence that it was the last to develop a permanent lake.

The expansion of rainforest in the area was no doubt a response to the increase in precipitation, but as the time of arrival of rainforest occurs some time after precipitation increase and does not occur at the highest rainfall site first, there is obviously a delayed response to this event. Ash (1983) has proposed that the time of arrival of rainforest around the various Atherton Tableland sites can best be explained by the time needed for the forest to migrate from the most likely refuge areas occupied during the previously dry glacial period (Figure 8b). A synchronous response to a subsequent reduction in precipitation is suggested by the end of the maximum rain-forest expansion phase towards 3000 years ago at all sites.

6. DISCUSSION

We noted earlier in this paper that the earth was slightly warmer than it is today during the height of the last interglacial period some 120 000-130 000 years ago. At that time the level of the sea was also about 5 to 8 m higher than it is at present, reflecting the smaller volume of the world's ice caps and glaciers and the fact that sea-surface temperatures were a few degrees warmer relative to present. Locked up in these same ice caps is a very informative record of former surface air temperature and also - highly pertinent to greenhouse discussions - a record of former atmospheric composition, including CO_2 concentration. In this context the recently published analyses of a 2083 m long ice core collected from Vostok station in East Antarctica are extremely interesting.

The core data span the last 160 000 years and confirm that CO_2 concentrations were high during times of high world temperature such as the last interglacial and the Holocene and low when world temperatures were low. For example, times of maximum glaciation coincided with CO_2 concentrations of 190-200 ppmv and interglacials were characterised by CO_2 concentrations of 260-280 ppmv which also represent the historic levels prior to the widespread burning of coal and oil associated with the last 200 years of the Industrial Revolution (Jouzel *et al.*, 1987; Barnola *et al.*, 1987).

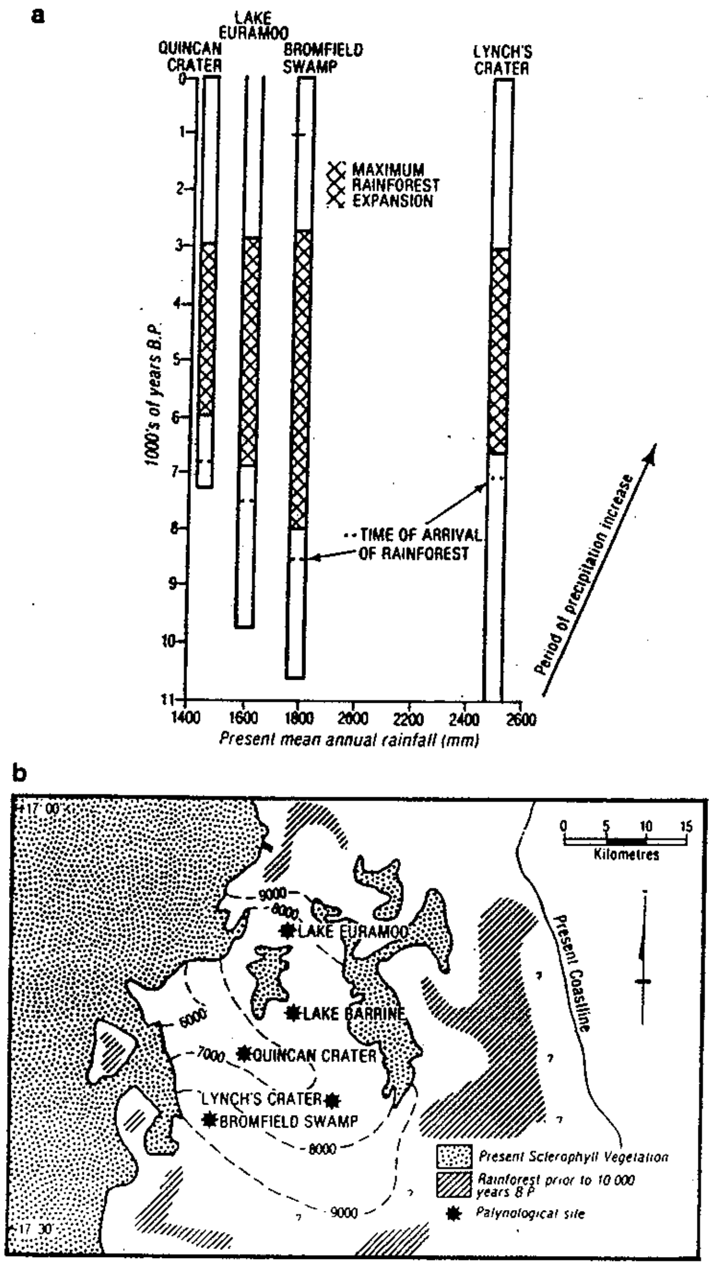


Figure 8. Vegetation and environmental changes in northeastern Queensland deduced from analysis of crater lake sediments. (a) Gradual increase in rainfall as judged from beginning of sedimentation at different sites and migration of rainforest determined from pollen evidence (modified from Kershaw, 1983). (b) Preferred migration of rainforest from 'glacial' retreats. Isolines show likely approximate location of advancing front at 1000 year intervals (adapted from Ash, 1983).

Present-day concentrations of 345 ppmv have no counterpart either during the last interglacial or during the last 10 000 years of Holocene time. It seems that we are presently creating what Broecker (1987) has called a superinterglacial which, in terms of its atmospheric CO_2 concentration, appears to have had no equivalent during previous interglacials.

The causes of these naturally occurring cyclical changes in atmospheric CO_2 concentration (low during glacial maxima, high during interglacials) are not yet understood. We can surmise that they must be related to changes in ocean biomass productivity (and so to changes in photosynthesis and respiration), to changes in terrestrial biomass productivity, and to changes in carbon storage in soils, organisms and marine carbonates. But it remains remarkably difficult in this context to distinguish between cause and effect.

We therefore concur with Genthon *et al.* (1987) that caution is needed in extrapolating from past times of warmer climate and high atmospheric CO_2 concentration to predicting the future climatic impact of the modern dramatically increasing CO_2 levels. Nevertheless, if high CO_2 concentrations have indeed helped to amplify past changes in solar radiation, as seems highly plausible (Genthon *et al.*, 1987), then any future increase in CO_2 may also play a similar role in amplifying what would otherwise be quite minor temperature fluctuations.

Broecker (1987) has sounded a further note of caution on the topic of future climatic change. On the basis of changes in the stable oxygen isotopic composition of the calcareous tests of marine foraminifera, many workers believed that past climatic changes were relatively gradual when set against the scale of a human life-span. However, these isotopic changes are primarily a measure of changes in global ice volume. Since ice caps respond slowly to even quite major changes in world climate, the impression gained from the isotopic analyses of slow rates of climatic change is in fact misleading.

More recent work on marine cores collected from the North Atlantic has revealed that the surface temperature of the North Atlantic increased by nearly 8°C between about 15 600 and 13 500 years ago, but plummeted by a similar amount towards 10 800 years ago, before rising again to present values by about 10 000 years ago, remaining steady thereafter (see Broecker, 1987, for a very clear summary).

The Vostok ice-core data also shed light on rates of temperature change. The deuterium content of the ice is a good measure of local air temperature. At Vostok the warmest part of the Holocene was towards 9000 years ago when temperatures were at least 9°C warmer than during the glacial maximum of 18 000 years ago (Jouzel *et al.*, 1987). Between 18 000 and 9000 years ago the CO_2 concentration rose from about 190-200 ppmv to 260-270 ppmv (Barnola *et al.*, 1987), equivalent to a 36% increase in concentration. The corresponding surface temperature increase at Vostok was from about -65.5°C to -52°C (Jouzel *et al.*, 1987) or roughly equivalent to a 20% increase.

Broecker's (1987) warning about the possibility of rapid climatic changes needs to be taken seriously. Hence, there is a very clear need to document recent climatic fluctuations as accurately as possible. This we have tried to do in our deliberately very bald maps of Australia's climate 8000 and 5000 years ago, and in our discussion of methods of refining palaeoclimatic analysis, illustrated with examples from northern Queensland and western Victoria. The former is broadly representative of our tropical summer rainfall region, the latter of the temperate winter rainfall area of southeastern Australia.

Two final points deserve mention. Pittock and Nix (1986) have suggested that Australia's future "greenhouse" climate will be characterised by higher summer rainfall in the tropics and by lower winter rainfall in the southwest and southeast of the continent. It is interesting to note that the lake levels of west-central Victoria were dropping between 5000 and 4000 years ago (see Figure 7) but that precipitation in the far north of Queensland was at its apparent maximum between 5000 and 3600 years ago (Figure 8).

Possible explanations for the comparatively late Holocene peaks in temperature and precipitation in northeastern Australia must at present remain speculative. The precipitation peak may be directly related to higher sea-surface temperatures, to more frequent tropical cyclones, to a stronger monsoonal incursion during the summer, to a change in the seasonal frequency of the southeast trade winds, or to some combination of these factors.

Although there is no sound reason why Australia's future climate should change everywhere at the same time and in the same direction (past analogues suggest that the opposite may be more likely), there is one important exception which is linked to the Southern Oscillation. The strong correlation between very positive values of the Southern Oscillation Index and synchronous extreme floods in the Nile, Darling and Krishna/Godavari basins of Africa, Australia and India during the last hundred years (Adamson *et al.*, 1987) demonstrate the reality of a globally synchronous response to climatic events (Figure 9). What the impact of future warming may be upon the Southern Oscillation is not yet clear, but we offer a very tentative guess that a positive regime is more likely than a negative (El Nino) one, with fewer intertropical droughts and more frequent floods in rivers now controlled by the Southern Oscillation, including the Nile and the major rivers in southeastern Australia

7. CONCLUSIONS

Past environmental analogues are useful in showing rates of change, differential rates of response, and magnitudes of change. Quantitative estimates are now possible using bioclimatic indices derived from modern pollen studies, and salinity estimates obtained from the trace element and stable isotopic composition of fossil ostracod shells.

In tropical northern Queensland, temperatures were highest between 5000 and 3600 years ago; and rainfall was also apparently higher at this time. In western Victoria lakes were very high or overflowing between 6600 and 5000 years ago, but levels were falling between 5000 and 4000 years ago.

The available evidence from mid-Holocene Australia is entirely consistent with a climate that was warmer overall, but with rainfall increasing in the tropical north and decreasing in the temperate south, possibly denoting a trend towards higher summer and lower winter rainfall, very much as predicted by Pittock and Nix (1986) for Australia's forthcoming climate.

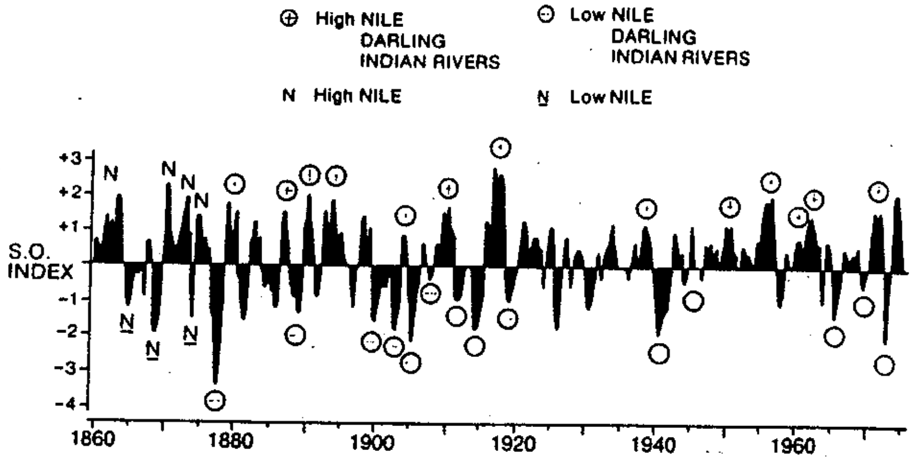


Figure 9. Relationship between the Southern Oscillation Index and river flow in the Nile, Darling, Krishna and Godavari rivers from 1860 until 1975 (after Adamson et al., 1987).

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