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Climate Succession and Glacial History of the Southern Hemisphere Over the Past Five Million Years

Complied by P.G. Quilty

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CLIMATE SUCCESSION AND GLACIAL HISTORY OF THE SOUTHERN HEMISPHERE OVER THE PAST FIVE MILLION YEARS

Complied by

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PREFACE

There is much concern at present about the impact of human induced change in atmospheric composition and its possible consequences—the Enhanced Greenhouse Effect. There is even debate about whether or not the impact will be for good or ill.

It is essential that we document and get to understand what is natural so that we can identify and separate the human induced element. The papers of which this volume is an abstract will provide some of the basis for identifying the natural baseline dataset for the exercise.

Research into global change on various time scales has proceeded independently in the Southern Hemisphere countries, providing fascinating insights into the evolution of local environments and biota. Seldom, however, have these efforts been integrated into a hemispherical view of how the environment has changed, so that common influences can be identified and local effects differentiated.

Recent advances in emphasis to studies of global change, improvements in dating and other analytical techniques, and a larger pool of researchers, all have meant a vast increase in our knowledge. This with improved modern means of communication, has led to greatly enhanced appreciation of the topic.

Greatly enhanced knowledge of the Cenozoic glacial record in Tasmania, and development in Tasmania of a research focus into the evolution of the Late Neogene record in Antarctica through geological and glaciological research, stimulated the Tasmanian Division of the Australian and New Zealand Association for the Advancement of Science (ANZAAS) to convene a symposium to discuss the question of integrating this knowledge. In addition, it was decided to invite speakers with expertise in the history of other Southern Hemisphere countries, so that a Southern Hemisphere perspective could be obtained.

The abstracts contained in this volume are evidence of the success of ANZAAS in attracting expertise to the meeting. It is hoped that complete refereed papers will be published in the Papers and Proceedings of the Royal Society of Tasmania.

This meeting would not have been possible without support from various individuals, granting institutions and sponsors. The Antarctic Foundation provided funds for publication and travel of international participants; the Department of Industry, Science and Technology (DIST) assisted with support for international visitors. The Antarctic Division provided the venue and other facilities.

William Adams P/L, Croydon Travel, and P&O Polar gave grants which have helped the organisation of the meeting.

Pat Waddington, Jenny Cole and Claire Findlay gave willing and continuing support.

1. UPLIFT OF THE MACQUARIE RIDGE AT MACQUARIE ISLAND: PLEISTOCENE EVIDENCE FROM RAISED BEACHES AND TOPOGRAPHY

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Macquarie Island (54° 30'S 159°E) is the emergent part of the submarine Macquarie Ridge Complex. The Ridge is a submarine mountain range rising over 4000 m above the sea floor and extending south of New Zealand for over 2000 km along the boundary of the Pacific and Australian lithospheric plates. The island is generally thought to have emerged above sea level during the Pleistocene as a result of uplift of ocean-floor rocks that were formed at a spreading ridge during the Miocene. The formation of the ridges and troughs that form the seismically active Ridge Complex is thought to be associated with Pacific and Australian plate interaction of the present style, namely predominantly transcurrent movement and some convergence.

Macquarie Island is a steep-sided mountainous plateau 200 to 400 m high, rising either straight from the sea or from a gently sloping platform cut by the sea during the marine transgression following the last period when sea level was low world wide. This platform extends offshore to a depth of about 100 m on all sides of the island: on the west side it is about 2 to 4 km wide, on the eastern side it is narrower, but to the north and south it extends at least 30 km. The offshore small islands (Judge and Clerk to the north, Bishop and Clerk to the south) rise, like Macquarie Island itself, from this platform which is roughly 100 km long by 10 km wide. The Macquarie Ridge in the vicinity of Macquarie Island is planed off along its crest with the islands as marine trimmed remnants of higher land. To the west of Macquarie Island is a parallel but slightly lower ridge which we infer has not been exposed at the ocean surface even during the periods of low sea level during the successive world-wide glacial cycles of the Pleistocene. This ridge has a convex crest in contrast to the planed off top of the Macquarie Island ridge. We conclude that the western ridge is an analogue for the Macquarie Island ridge before it was lifted high enough to encounter marine erosion at the sea surface.

Above present sea level on Macquarie Island are a number of landforms which we interpret as having been formed or influenced by marine erosion at the sea surface when global sea levels have been high, i.e. during peaks of marine transgressions. Those associated with wave action include:

- raised marine beaches marked by concentrations of well rounded cobbles
- gently sloping and gently undulating benches at various altitudes from near sea level to over 300 m, and
- mountain peaks of concordant height.

To date their formation we have used two approaches:
- direct dating, and
- cross matching of the world sea level sequence with the altitude sequence of landforms on Macquarie Island.

Thermoluminescence (TL) dating of two of the best preserved marine beaches indicates their Pleistocene age, one at 100 m a.s.l. (172±40 Ka) and one at 263 m a.s.l (340±80 Ka). The dates obtained, however, only bracket widely the times of formation of the beaches.

An independent approach is to determine fairly accurately the altitudes of the beaches, benches and mountains of concordant height and to match the altitude sequence against the pattern of peaks of world-wide sea level determined from deep sea cores. A problem with this approach is to determine accurately the altitude of the relevant features. The existing topographic map is not able to give accurate heights for the features of interest with the possible exception of mountain tops. Global Positioning System (GPS) was used to overcome this difficulty in part.

Beaches at sea level today and those a few metres above present high sea level on the gently sloping marine-eroded terrace are definitely of mid to late Holocene age. Comparing the independently derived altitude and time scales, a good overall match is obtained when the extremely well developed beaches at 100 m a.s.l and at 263 m a.s.l. are assigned to marine transgressions at the beginning of oxygen isotope stages 5 (ca. 125-130 Ka) and 9 (ca. 330-340 Ka) respectively. This cross linking of the two scales conforms well with the TL date obtained for the 263 m beach on the high ridge between Hasselborough Bay and Scoble Lake (340±80 Ka). The TL date of the 100 m beach (172±40 Ka) on Wireless Hill, at the young limit of its uncertainty level, approaches the time of global high sea level at 125 to 130 Ka. The series of raised beaches of approximate altitudes of 50, 100, 170–190, 220, and 260 m, correlate well with high sea levels of various ages.

Concordant mountain peaks at 340–350 m (8 peaks) and 370–383 m (6 peaks) correlate with high sea levels of marine oxygen isotope stages 11 and 13 respectively. The three highest peaks on the island (Mts Hamilton, Fletcher and Waite) were probably planed off during stage 15, and Mt. Hamilton in particular may first have broken sea level some 700 Ka ago.

Uplift rates calculated by matching the altitudes of physiographic features with the age of global sea level peaks give an average rate of 0.8 mma^{-1} over some 600 Ka. This rate is about one half to one third the average rate determined from Holocene evidence, and about one twentieth of that previously estimated for the uplift of Wireless Hill. We now consider that the lower rate for Wireless Hill is the more reliable. We also now conclude that the whole island, including Wireless Hill, has emerged more or less as a coherent block since its appearance above sea level, although minor differential movement has occurred as shown by the numerous fault scarps with topographic expression. In addition, more or less coherent uplift at about 0.8mma^{-1} for some 600 Ka may have applied for the 100 km length of the Macquarie Ridge extending from at least Judge and Clerk in the north to at least Bishop and Clerk in the south. At this rate, 4000 m of ridge uplift in this 100 km long segment would have taken about 5 Ma. This estimate of the uplift time and hence the age of the Macquarie Ridge as a major mountain range in the vicinity of Macquarie Island is of a sensible order of magnitude and accords reasonably well with what is known of the past behaviour of the Pacific and Australian plates.

During the time Macquarie Island has been above sea level it has experienced about five complete glacial-interglacial cycles. We conclude that there is no compelling evidence on the island for landforms generated by flowing ice. However the walls of some modern gullies expose thick beds of angular cobbles that are younger than the raised beaches but are older than Holocene and terminal Pleistocene peats. One of these gully deposits overlies a bed of laminated lacustrine silts with a TL date of 92+20 Ka, and another overlies a diatomaceous peat whose age is beyond the range of radiocarbon dating. These beds of poorly sorted material are probable periglacial deposits of the last glacial cycle.

We conclude that the climate of the island during the Pleistocene was usually colder than at present but not glaciated, with intense periglacial activity at higher altitudes. At world-wide glacial times (with sea level some 100 m or more lower than during interglacials) the island would have been longer and wider than at interglacial times of high sea level, with substantial areas exposed close to sea level. Periglacial activity on a land surface with sparse plant cover would have dominated the uplands, but climatic conditions near sea level would have permitted the survival of those plants presently on the island. Past vegetation would therefore have had to migrate only relatively short distances horizontally and vertically in order to survive. We envisage that the island has been, for the last 600 Ka, a suitable habitat for those organisms presently there. The sequence of colonisation and the residence time of organisms were determined more by the accidents of arrival than by the severity of climatic oscillations.

2. ANTARCTIC SEA ICE: A PASSIVE VICTIM OF CLIMATE CHANGE OR A KEY PLAYER IN THE GAME

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The ocean sediment record indicates that the Antarctic sea ice extent was considerably greater during the Last Glacial Maximum than today. Compared to today's minimum ice area in February of 2.5×10^6 km^2, the LGM minimum was around 25×10^6 km^2. And the ill-defined LGM maximum extent was about 40×10^6 km^2 compared to the present day maximum of 20×10^6 km^2. The evidence for the past sea ice extent is very much less detailed than that for changes in the ice sheet and there is no clear evidence of how sea ice extent has changed with time during the Holocene. There is no evidence at all of past variations in the Antarctic sea ice thickness and concentration (the percentage of ocean covered by ice).

This is not all that different from the situation today. Modern observation systems, satellite passive microwave sensors in particular, provide a good picture of sea ice extent , and a reasonable one of ice concentration, but provide no information on ice thickness. Shipboard surveys are only now starting to provide a climatic picture of the sea ice thickness distribution in the Antarctic. And although some recent studies have suggested that there has been a change in sea ice extent over the very limited period (only about 20 years) that the passive microwave data have been available, the evidence, particularly in the Antarctic, remains contentious. Model predictions of the magnitude and timing of the response of Southern Hemisphere sea ice to any future CO_2 induced warming are similarly uncertain. Some studies provide evidence for polar amplification of warming and reduced sea ice extent, but others have suggested local sea-ice expansions.

Yet the sea ice around the Antarctic is an important component of the Southern Hemisphere cryosphere. The sea ice zone is not just a sensitive 'litmus' of climate change, but a critical component of the climate system. The extent, concentration, and thickness of sea ice strongly influence air-sea interaction, and in particular atmospheric and oceanic circulation, and regional precipitation. These of course also influence the ice sheet mass budget, and the overall climatic history of the Antarctic. In this paper I review some of the characteristics and processes of present day Antarctic sea ice (and their uncertainties) that demonstrate the complexity of the coupled system. These include the crucial role of sea ice dynamics in determining the ice extent and, through deformation, controlling the ice thickness distribution; the relative importance of different mechanisms of ice formation; air-sea exchanges in the sea ice zone; and water mass modification due to ice growth and melt processes.

3. GLOBAL AND LOCAL FORCING OF ANTARCTIC ICE AND CLIMATE CHANGES

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Throughout the pleistocene large changes in global climate and ice cover occurred primarily dominated by the ice sheet changes in the Northern Hemisphere. Nevertheless during the glacial periods apparently near synchronous cooling and increased extent of glaciers and ice sheets occurred around the world including the Antarctic. The changes of sea level forced by the Northern Hemisphere ice changes has been a primary factor in causing some global synchroneity in the Antarctic and Northern Hemisphere ice changes. The sea level lowering also contributes to some land surface cooling relative to the sea surface.

Other factors which contribute to the synchroneity of changes in both polar regions include the Earth's obliquity variations, which influence both polar summers together, the changes in atmospheric Greenhouse gases, and the global albedo feedback cooling resulting from the land ice sheet cover. Additional feedback also comes from the sea ice cover and snow on the land but these also respond to seasonal forcing factors as well as the global annual mean changes.

Modulations to the seasonal changes, which are out of phase in the two hemispheres, are caused by the variations in the timing of the Earth's perihelion particularly when the eccentricity is large. These variations in the seasonal changes are felt most strongly over land areas, because ocean storage smooths out the changes over the ocean, to a large degree. The slow response of the ice sheets to the radiation forcing, and the strong albedo feedback of the ice sheets on temperature, results in a large phase delay of around 5 to 10 thousand years for the feedback to the global mean temperature. This delay of almost one half of a perihelion cycle also contributes to the merging of the synchroneity of the annual mean changes of the two hemispheres.

The magnitude of the global changes and the response of the Antarctic ice sheet to the changes have been investigated using a hierarchy of models including an ice sheet model and a global energy balance model which includes sea ice. These models have been used to derive the changes caused by the different components in the climate system and the feedbacks and phase delays in the interactions.

4. THE SOUTHERN HEMISPHERE GLACIAL RECORD – NEW ZEALAND AND ANTARCTICA

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The New Zealand terrestrial glacial record commences in the Late Pliocene with Ross Glaciation till deposited in a topography of less relief than the present. Associated with, and overlying the Ross deposits are thoroughly weathered Pliocene conglomerates of the Old Man Group. In a separate area deeply weathered Moutere Gravels are also of Pliocene age. Both of these weathered gravel formations are attributed to an increase of glacial activity. Tills and gravels of the Porika Formation rest on the Moutere Gravel.

There is then a gap of well over a million years in the terrestrial glacial record, represented by marine sediments of the Wanganui Basin, a DSDP core from Site 594, and in part by uplifted coastal interglacial marine terraces together with cold climate aggradation terraces. Only over the last 0.35 Ma has a physiographic and stratigraphic record of glacial events been preserved on land. The surviving glacial evidence of this period was deposited in a topography similar to today's, and had generally similar magnitudes indicating climates similar to the last, Otiran Glaciation, when temperature depressions of between 4°C and 6°C have been estimated. Deposits of four glaciations commencing at oxygen isotope stage 10 have been identified. The last Pleistocene advance culminated at ca. 18 ka BP, followed by a rapid warming at ca. 14 ka BP which heralded the demise of the huge Pleistocene glaciers and the beginning of the present (Aranuian) interglacial. There followed several dated but poorly correlated 'late glacial' readvances between 12 ka and 8 ka BP before the Holocene climatic optimum.

Holocene glacier expansions to only a fraction of Pleistocene extents commenced ca. 5 ka BP with numerous well documented events continuing into the 'Little Ice Age' which terminated at 100 ka BP. These advances were of similar size, with nested moraines indicating a trend towards diminishing size of the advances towards the present.

The behaviour of Antarctic glaciers contrasts markedly with temperate latitude glaciers although both have responded to basically similar global climate changes. There are two basic reasons for the different behaviours:

1. Antarctic air and ice temperatures are normally well below 0°C rendering melt loss insignificant. The response of the glaciers to a temperature rise is to advance rather than retreat because increased temperature favours increased snowfalls.

2. Antarctic ice volumes are linked to sea levels by floating ice shelves. When sea levels fall during cool worldwide glacials, the ice shelves thicken from local precipitation and ground on the continental shelf, while ice levels of the continental interior lower as snowfalls diminish. During warmer interglacial periods, the ice shelves retreat while increased continental snowfalls cause the ice sheet to grow and local glaciers to expand.

In the McMurdo Sound area, the glacial history of Antarctica commences with the oldest glaciomarine sediments of late Oligocene age indicating the formation and growth of the ice sheet which attained volumes larger than the present by mid Miocene. The last expansion of the ice sheet to override the Transantarctic Mountains at 13.6 Ma, was followed by cold desert conditions until 5.5 Ma when the present small glaciers took their present form. Between 2.5 and 3.2 Ma there was a modest expansion followed by the greatest expansion in the last 3.5 Ma occurring between 2.7 and 3 Ma. Following the worldwide cooling at 1.8 to 2.5 Ma the glacial events began a repeated sequence of cold climate ice shelf thickening inter fingering with warmer interglacial thickening of the ice sheet. The present interglacial status is of expanded terrestrial glaciers and reduced, floating ice shelves.

The stability of the East Antarctic Ice Sheet has been under debate in recent years. One theory proposes that the ice has been stable for approximately 14 Ma, and that the continent has been subject to unbroken polar conditions since then. An alternative hypothesis involves the ice sheet melting in the Pliocene, then regrowing and overriding the Transantarctic Mountains in the late Pliocene. The latter theory accounts for Pliocene marine diatoms in Sirius Formation glacial deposits; the former theory assumes that the diatoms are surficial additions to the Formation.

5. PROBLEMS OF RELATING ROCK WEATHERING FEATURES IN THE EAST ANTARCTIC OASES WITH THE CONVENTIONAL THEORY OF THE EXTENT OF ICE ADVANCE AT THE LAST GLACIAL MAXIUMUM

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The view that the Bunger and Vestfold Hills oasis regions were covered by extension of the eastern Antarctic ice sheet at the Last Glacial Maximum some 18 000 to 20 000 years ago, and that thick ice extended to the edge of the continental shelf is questioned.

Minor weathering features on bedrock surfaces and on morainic boulders suggest that a long period of time has elapsed since the last expansion of ice covered the oases. The features of rock weathering include: development of tafoni cavities; case hardened iron crusts and iron stained rock surfaces; granular disintegration of large boulders; large volume reduction through weathering of glacial boulders; removal of the rock surface leaving basic dykes and protruding quartz veins marking the original surface; aeolian erosion of glacial deposits leaving lags of boulder gravel; and the development of ventifacts.

These features will be illustrated from both Bunger and Vestfold Hills and suggestions will be made on how old the East Antarctic oasis regions may be.

6. THE LAST GLACIATION IN TASMANIA

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The importance of separating the ice limits of the Last Glaciation which attained their maximum extents at 18 000–20 000 years BP from older phases of glaciation when ice limits were more extensive is outlined. The methods that have been used to separate the most recent glacial drifts throughout Tasmania are discussed.

The distinctive landforms of glacial erosion and deposition that occur within and at the limits of the icecaps, outlet valley glaciers and local mountain cirque glaciers are discussed for the West Coast Range region, northern Central Plateau and Mersey and Forth Valleys, and the southern Central Plateau and upper Derwent and Franklin Valleys.

A map of the Last Glaciation ice limits is presented.

7. RECENT INCREASES IN TASMANIAN HUON PINE RING WIDTHS: CO_2 FERTILIZATION, NATURAL VARIABILITY OR GREENHOUSE WARMING?

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While only addressing a small part of the last 5 million years, recent tree-ring research in Tasmania coupled with high time-resolution ice cores from Antarctica provide an unusual opportunity to assess palaeoclimate reconstructions arising from the tree-ring work.

A summer temperature reconstruction using sub-alpine Tasmanian Huon pine from the extreme high altitude limit of the species distribution, now extends ~ 3 millennia before present to 800 BC. Compared to Huon pine from lower altitude sites, the ring-widths in the sub-alpine trees exhibit a straightforward strong sensitivity to current growth-season temperatures. The sub-alpine record indicates recent anomalous warming (0.330.006C over 1967–1991) that is consistent with both the regional and the overall hemispheric trends, based on instrumental records.

The reasons for the anomalous warming in the sub-alpine tree ring reconstruction are critically explored with particular reference to possible links to the enhanced greenhouse effect. The possibility that the trees are responding directly to CO_2 fertilization rather than temperature is not supported by the available evidence. We reviewed evidence that at least part of the anomalous warming is a consequence of 'natural variation' in the 2792 year record, rather than greenhouse forced warming.

Two millennia-long, tree-ring reconstruction of summer temperatures from South America do not exhibit the recent anomalous warming or other features in the Tasmanian record (though they do reflect regional records of temperature variations). It was demonstrated that part of the covariance between the Tasmanian ring widths and instrumental records can be attributed to climate influences of a distinctly regional character. The regional nature of climate variations in the Tasmanian region highlights the potential difficulty in extrapolating any regional decadal-to-century timescale records to global behaviour, even though the Tasmanian region appears to reflect hemispheric temperature behaviour over the period of available instrumental records.

8. HIGH RESOLUTION PALAEOCLIMATIC INFORMATION FROM RECENT SPELEOTHEMS

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Stable isotope and trace element analyses of speleothems have the potential to provide excellent sources of high resolution palaeoenvironmental information where caves and cave deposits occur. Speleothems are usually composed of calcium carbonate deposited when $C0_2$ degasses from percolation water upon entering a cave. The majority of palaeoclimatic research employing speleothems as an information source have concentrated on uniform diameter stalagmites and, to a lesser extent flowstones. Speleothems can be accurately and precisely dated for the past 500 ka by uranium series ($^{234}U/^{230}Th$) mass spectrometry dating. For ages of less than 200 years the ^{210}Pb technique can be utilised. This dating method has the potential to allow isotopic and trace element variations in recent stalactites to be compared directly with instrumental and historical climatic records and provide an opportunity for improved palaeoclimate interpretation of older speleothems.

Several minor elements have shown significant trends or periodic fluctuations that appear to be related to climate and or vegetation change. Significant statistical relationships have been found between variations in isotopic ratios and concentrations of magnesium, strontium and uranium. Other minor elements that offer promise as palaeoenvironmental indicators are bromine and chlorine.

The success of high resolution studies is very much dependent on the accuracy and precision of dating. There are two methods that can be employed to date recent stalactites: ^{210}Pb and counting annual cycles in minor element composition. In order to detect if seasonal variations in trace elements occur stalactites will be analysed using laser-ablation/microprobe mass spectrometry. The apparatus will permit extremely high resolution sampling and it is expected that seasonal patterns will be identified thus allowing a temporal scale to be defined. Comparison of recent records with instrumental and historic climatic records will allow us to interpret stable isotope and minor trace element variations in older speleothem material with much greater confidence.

9. MODERN SURFICIAL SEDIMENTS OF PRYDZ BAY, EASTERN ANTARCTICA: PROCESS AND DISTRIBUTION

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The modern surficial sediments of Prydz Bay are dominated by glaci-marine gravels, sands, and diamicts interspersed with biogenic siliceous muds and oozes (SMO), all of which overlie diamicts deposited during previous interglacials and compacted by a grounded ice sheet which probably extended to the current shelf break.

Primary Holocene sedimentary processes in Prydz Bay are dominated by ice-rafting of terrgenous material, mainly by icebergs from the coastal glaciers of the Ingrid Christensen Coast, but also by sea ice rafting of material from areas where coastal waters shoal to less than 2 m deep. Vertical accumulation of biogenic sediments is equally important, consisting mainly of the deposition of siliceous frustules of diatoms. *In situ* production of the siliceous spicules of glass sponges is also indicated.

The physical (glaci-marine) and biological processes operate throughout the area. Icebergs calve from the glaciers and icecliffs along the Ingrid Christensen Coast and slowly release their sediment load as they are carried around the bay by the Prydz Bay cyclonic gyre. Blooms of diatoms occur at the sea ice edge at the beginning of the summer and follow the ice edge as it retreats to the coastline. Over the summer, sea ice free period, diatom populations wax and wane in turn. Because these processes occur throughout the area, sediment supply is homogenous throughout the study area.

Secondary processes which rework the sediments include transport, winnowing, and sorting by bottom currents, and turbation by icebergs and benthic fauna. Iceberg turbation is the dominant secondary process. Icebergs are circulated through the bay by surface water currents and winds and are dragged across the seafloor, overturning sediments to depths of up to 10's of metres below the sediment/water interface. In Prydz Bay this effect is evident in water depths between 200 m and 700 m. The importance of bioturbation is not well known but benthic faunal abundances indicate that, while bioturbation is widespread in Prydz Bay, it is not important in comparison with iceberg turbation. The direct measurement of bottom currents in the study area is in its infancy, and grain size analysis of the sand fraction of Prydz Bay sediments provides evidence of some such reworking.

These processes result in two main sedimentary facies. Diamicts are the result of concurrent deposition of small amounts of terrigenous material supplied by icerafting and of vertically accumulated biogenic material which is subsequently admixed by iceberg- and bio-turbation. SMO is predominantly produced by accumulation of biogenic material but also contains minor amounts of icerafted-terrigenous material.

There is significant lateral variation with both of these facies found closely associated. On a larger scale, however, it is possible to identify areas in which one facies is dominant. SMO tends to be found in deeper water below 700 m, mainly in the southeast of Prydz Bay and on shallow banks in the northeast. Diamict is found in the rest of the Bay between the depths of 200 and 500 m, adjacent to the coast and to seawards of the shelf break.

10. MEROMICTIC ANTARCTIC LAKES AS INDICATORS OF LOCAL WATER BALANCE: STRUCTURAL CHANGES IN ORGANIC LAKE, VESTFOLD HILLS 1978-1994

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The lakes that occur in closed, rocky basins of the Vestfold Hills, East Antarctica, are sensitive indicators of local water balance. Water level in the lakes is controlled by a limited number of factors: meteoric input (direct and from catchment area snow melt), and the loss terms evaporation and sublimation. During periods of positive balance, lake levels rise and lake areas increase. Similarly, when net water input is negative, levels drop and lakes shrink.

The water levels of lakes in the Vestfold Hills, some of which have been measured regularly for the last 20 years, vary considerably from year to year (Burton, unpublished). Water balance trends for these years can be obtained from this data. Water level, however, provides no information on water balance outside this direct observational period. The data set can be extended back to the 1940s by incorporating information from lake areas, which can be obtained from aerial photographs. However, both these methods fail to yield information regarding earlier changes.

A further parameter strongly influenced by lake water balance is the physical structure of the permanently stratified (meromictic) lakes of Vestfold Hills. These lakes can be thought of simply as consisting for most of the year of a layer of ice covering a convectively mixed epilimnion (which, due to its contact with the ice, is maintained at its freezing point), which in turn sits on top of a stagnant monimolimnion. Stability is imparted by an increase in water density, which is essentially controlled by salinity, with depth to the bottom of the lake. The depth to which the epilimnion mixes is dependent on the salt concentration in this layer, which in turn is dependent on the water level: lower water level results in a saltier, denser epilimnion, which mixes more deeply into the monimolimnion (Figure 1). Increasing lake level, on the other hand, results in reduced penetration of the epilimnion, and leaves evidence of the previous depth of epilimnion mixing. Many lakes show multiple steps in their density profile recording maximum penetration of the epilimnion over a number of cycles of positive and negative water balance.

These processes are exemplified by changes observed in the structure of Organic Lake over the period 1978-1995. This lake is a small, shallow meromictic water body for which numerous temperature, salinity and density profiles have been recorded. The minimum winter epilimnion temperature recorded for various years (i.e. recorded at the time of maximum epilimnion mixing depth) is given in Table 1. From these temperatures it can be seen that water salinity was initially high (reflected in the lower water temperature), decreased to a minimum in 1989, before increasing in the 1990s. Figure 2 showed that, as predicted, the depth of mixing of the epilimnion increased dramatically between 1989 and 1994 as the water density also increased. The distinct step in the 1989 density profile, which probably reflects the maximum depth of epilimnetic mixing in 1978, has been wiped out by this deepening of mixing.

The interpretation of the Organic Lake temperature and density data is supported by limited accurately determined lake heights (Table 2). As would be predicted from the temperature data, lake height rose between 1978 and 1984-87, and then dropped by 1994-95.

Organic Lake is but one of approximately 30 meromictic lakes in the Vestfold Hills. By understanding the effect of water level on the structure of this lake, the processes that have lead to the observed profiles in other lakes can be better understood. By analysing the profiles it is possible that more information on water balance in the region prior to modern scientific investigation can be obtained.

Table 1. Minimum epilimnion water temperatures, Organic Lake, 1978-1994.

Date	Minimum Temperature
22/08/78	-14.1
24/10/84	-10.0
25/10/87	-10.1
27/09/89	-10.0
12/10/90	-10.4
7/10/91	-10.8
19/09/92	-12.5
23/11/93	-14.1
16/09/94	-13.5

Table 2. Water Level (metres above sea level), Organic Lake 1978-1994. (1978 figure approximate).

Date	Minimum Temperature
22/08/78	~1.75
26/12/84	2.75
9/01/89	2.75
16/09/94	1.91
16/09/94	1.85

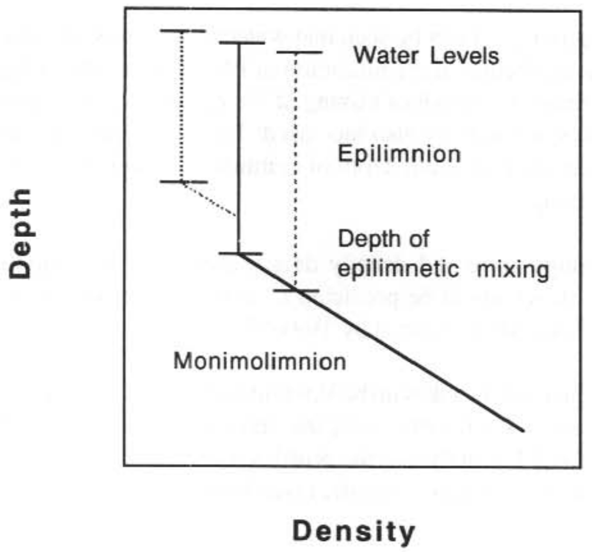

Figure 1. Changes in epilimnion mixing depth with water level change.

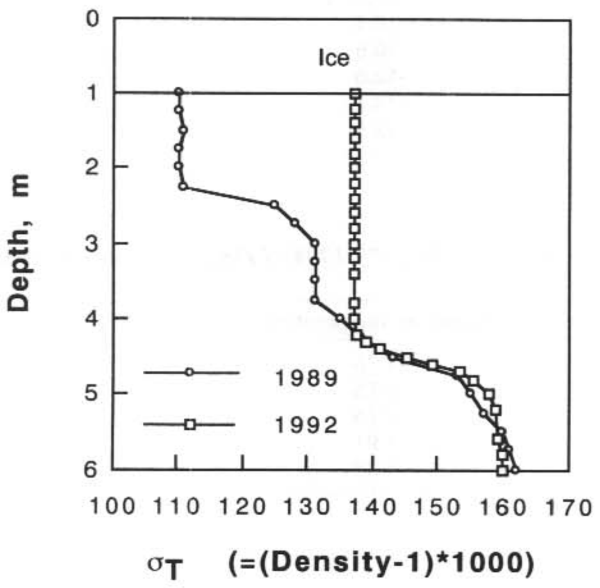

Figure 2. Density profiles of Organic Lake: September 1989 and December 1992. Profiles for 1987 were similar to the former, and after 1992 to the latter.

11. ON THE RESPONSE OF LAW DOME, EAST ANTARCTICA TO CLIMATE FLUCTUATIONS DURING THE HOLOCENE

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Glacial geological studies on the Windmill Islands and along the margin of the Law Dome, East Antactica indicate that the glacial extent of Law Dome has fluctuated during the Holocene. The Post-Glacial retreat of the Law Dome ice margin during the Early to Mid Holocene is reconstructed from the evolution of coastal features, the glacio-isostatic emergence of palaeo-shorelines, the establishment and abandonment of Adélie penguin rookeries and the evolution and ^{14}C radiocarbon chronostratigraphy of lake sediments on the Windmill Islands. The morphology and structural geology of the present ice margin indicate that Law Dome has re-advanced over part of the Windmill Islands since the culmination of the Post-Glacial retreat. Glacial geological studies of the proglacial and ice marginal environments, and the emergent basal ice exposures and Loken Moraines confirm that the Law Dome has re-advanced across marine embayments and inland islands, incorporating marine ice, nearshore and beach sediments into the basal zone, during the Late Holocene. A chronology of the re-advance is produced from relative lichenometry of the Loken Moraines and coastal nunataks in conjunction with the ^{14}C radiocarbon dates from the proglacial and coastal zones.

Contraction of the Vanderford Glacier was established before 8 000 years B.P. with the adjacent outer Windmill Islands, ice free at this time. Contraction of the grounded Law Dome ice margins lagged the Vanderford Glacier with the inner Windmill Islands deglaciated by 5 500 years B.P. Subsequently, the ice margin continued to retreat to a position further inland than the present until 4 500 years B.P., whilst the Windmill Islands emerged from the sea, forming raised marine shorelines, as a result of glacio-isostatic uplift. Between 4 000 to 1 000 years B.P. it is concluded that the Law Dome grounded ice margins thickened and expanded seawards across part of the Windmill Islands, followed by a partial contraction and thinning, between 500 years B.P. to the present.

A glaciological sensitivity analysis of the response of Law Dome to climate fluctuations suggests that primarily, fluctuations in ice sheet snow accumulation rates during the Late Plesitocene/ Holocene Transition and during the Holocene, played a major role in the interpreted Mid to Late Holocene re-advance. Relative sea-level changes may have contributed to the initiation of the re-advance, whilst the interior of the Law Dome was thickening with a cumulative increase in snow accumulation. It is suggested that accumulation rates on Law Dome during the Holocene may have varied by up to 25% from the present values, in response to temperature fluctuations which have been interpreted in the deep ice cores from the East Antarctic interior, together with changes in atmospheric circulation and sea ice extent.

12. SEDIMENTARY RECORD OF POST-18 KYR BP ICE SHEET RETREAT FROM THE EAST ANTARCTIC CONTINENTAL SHELF: RECENT RESULTS FROM THE MAC.ROBERTSON SHELF

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During the last Northern Hemisphere glaciation, the Antarctic ice sheet expanded across the continental shelf reaching the shelf break, eroding away sediments deposited on the shelf during previous episodes of contracted ice sheet conditions. Sediments deposited during the subsequent retreat of the ice sheet in the Late Pleistocene and early Holocene preserve a record of this event. Furthermore, dating of the facies boundary representing the onset of the present, open-marine conditions, provides a means by which the timing and rate of ice sheet retreat may be constrained. In this paper, facies are described based on recently obtained gravity cores from the Mac.Robertson Shelf. Facies successions are interpreted in the context of a glacier retreating along the axis of a fiord, that is now a shelf valley. Application of this model to the rest of the East Antarctic shelf will be discussed.

13. PLANT MACROFOSSILS AS BIOCLIMATIC INDICATORS DURING THE PLIO-PLEISTOCENE

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Both the floristics of plant macrofossils (that is, estimating climates from the modern range of the nearest living relatives to fossils), and aspects of the morphology and anatomy of fossils which are correlated to modern climates, can be used to estimate past climates. These estimates may be more accurate than pollen based records because macrofossils are less likely to have been transported long distances, reworking is very uncommon, they may be more accurately identified and their morphology reflects the conditions under which they were growing. Two types of organ provide the best evidence: leaves and wood. In general, we consider that the best palaeobotanical estimates of climate are those which synthesise evidence from as many different sources as possible.

The best Pliocene example of the value of plant macrofossils in estimating palaeoclimate are *Nothofagus* leaves and wood from the Sirius Group in the Transantarctic Mountains. These fossils are abundant, well preserved, clearly *in situ* and are probably in the range of 2.5–4.3 million years old. The leaves are from a deciduous species, and using frost resistance measurements on nearest living relatives, the minimum winter temperatures has been predicted to have been $\geq$ -22°C, with summer temperatures clearly above 0°C for a relatively long period, to allow the species to leaf out and reproduce in the presence of liquid water.

The fossil wood has extremely small growth rings, suggesting very slow growth rates, and was from small diameter stems that were growing more or less horizontally along the ground, much as the Arctic willow (*Salix arctica*) does today in high northern latitudes. Some fossil branches contain evidence of traumatic events and scarring. Such damage occurs commonly today in high northern latitudes amongst Arctic willows and is the result of catastrophic flooding and erosion in a glacial environment. The northern hemispheric model for this fossil wood suggests mean summer temperatures of 4°C, with growth occurring within only a few months. A combination of available evidence is compatible with mean annual temperatures well below freezing, and probably in the order of -16°C. If this is accurate, it suggests that the minimum temperature that could be withstood by this species was substantially below that of any extant relative.

Western and Central Tasmania have Australasia's best record of Pleistocene leaf macrofossils. These record a wide range of climates, from full glacial conditions to those apparently warmer than today's. Early Pleistocene macrofossils occur at Regatta Point and the Huskisson/Marionoak Divide. The fossil floras at Regatta Point contain taxa which no longer occur in Tasmania, and which indicate warmer and probably wetter conditions than at present. These taxa include Lauraceae, a species of *Rubus* with subtropical affinities, *Quintinia*, a warm temperate species of *Oxylobium* and a species of Myrtaceae subfamily Myrtoideae. The diversity of these fossil floras is also consistent with warmer than modern climates. The leaf morphology of these fossils and the presence of cold climate indicators, however, suggest that the temperatures may have been lower than implied by the floristics, but still higher than at present. This suggests that the geographic distributions of the nearest living relatives of fossils older than Middle Pleistocene do not always reflect the climatic preferences of their extinct antecedents accurately. These sediments are about 10 m above modern sea level, but are clastic and may have been transported a short distance. They show no indicators of marine environments.

Thus, even though temperatures were higher than now, it is unlikely that sea levels were more than about 20 m above modem sea level. Macrofossils in the Huskisson/Marionoak Divide sediments clearly indicate the presence of cooler climates (about 4°C below present) than those implied by the pollen record alone. These sediments occur in a lens among glacial sediments. Other sediments from Regatta Point indicate a period during the Early-Middle Pleistocene with lowland temperatures at least 3.8°C cooler than now, and at least as wet. This indicates that some, if not all, stadial/glacial periods in westem Tasmania were wet. Thus, macrofossils confirm the occurrence of relatively strong climatic cycles in the Early Pleistocene. However, the Early Pleistocene record in Tasmania is compatible with evidence from the Sirius Group, and suggests that warmer conditions extended beyond the Late Pliocene. Many species survived one or more early glaciations in the Pleistocene, but later became extinct. The macrofossil evidence is also compatible with a relatively limited sea level increase at this time.

There are a number of Middle Pleistocene records of plant macrofossils. The leaves in the Regency Formation record a warming from late glacial to full interglacial conditions, although the macrofossils show no indication of conditions any warmer than at present. The Langdon River sediments show a transition from interglacial/interstadial conditions to cooler conditions. Sediments near Cathedral Mountain indicate conditions perhaps 3-4 °C colder than now, and are associated with glacial sediments. In each of these cases, both the floristics and leaf morphology support these estimates. Macrofossils from the Late Pleistocene have been less well studied. One record of climatic interest is a cushion plant from 17 000 BP at low altitude that has been interpreted as indicating temperatures about 7°C below current temperatures at the Last Glacial maximum.

There have been no significant climatic studies of Pleistocene wood as yet, although there is considerable potential in this field.

14. SEASONALITY IN LATE HOLOCENE CLIMATE VARIATIONS FROM ICE CORE RECORDS

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The exceptionally high accumulation and relatively low temperatures at the summit of Law Dome in East Antarctica means an ice core drilled there has sufficiently well defined seasonal accumulation layers to permit separation of long term temperature trends on a seasonal basis. Temperature data is obtained by oxygen isotope ratio ($\delta^{18}O$) analysis in which 12-15 samples per annual accumulation layer are used to define the seasonal temperature cycle. The large amount of noise observed in the short term records is reduced by smoothing the intra-annual values over about 50 years. Although noise due to the vagaries of weather systems and snow accumulation is still large, averaging the seasonal signal over many years produces a mean annual profile that closely matches the measured temperature cycle. Both direct measurements (automatic weather station data) and the isotope record show the characteristic 'coreless winter' seen in the annual temperature cycle of polar regions. The conformance of the isotope ratio/temperature record to the auto station temperature record is taken to show that any systematic bias in accumulation throughout the year is small.

The data consist of 700 years of $\delta^{18}O$ measurements along the core with 12-15 measurements per year. Precision dating is obtained simply by counting years down from the surface. In a few places where the isotope ratio record is unclear peroxide and electrical conductivity data have been use to clarify the timing. It is estimated that the dating by annual layer counting is within 1% i.e. ± 1 year at 1890 and ± 6 years at 1300. The dating is further controlled by detection of fallout from several known volcanic eruptions.

The summer maximum for each year is located by fitting a quadratic to the points around the $\delta^{18}O$ maximum and using the curve maximum as the beginning of the year. This is preferable to simply using the maximum point as it avoids artificially concentrating data points at the beginning of the year. The data were resampled onto a uniform time grid using spline interpolants and finally, in order to look at small variations, the mean $\delta^{18}O$ curve was subtracted from each year's data and a residual obtained. The smoothed residuals were then mapped by year and season.

The principal features of the residuals data are:

- most of the variation is in the winter temperatures except for a period in the last 100 years centered around 1900 when there were cool summers
- there is a period of warm winters between 1400 and 1500 AD (medieval optimum)
- there is a period of cold winters between 1750 and 1850 (Little Ice Age—LIA)

Despite the better accuracy of the more recent proxy records, and even the availability of instrumental data from the last few hundred years, there is considerable uncertainty in the timing and size of climatic changes over the last millennium. Part of this is due to the apparently unprecedented stability of climate over the last 10 000 years—small changes are harder to detect—but changes did occur and these had a significant effect on human activities. Most records show a warm period somewhere between 800 and 1400 (the medieval optimum) followed by a cooling to a minimum around 1850 (LIA) but there is also contradictory evidence and some researchers have suggested that global changes were minimal and the observed effects were mainly due to movement of weather systems leading to cooling in some places and warming in others. The concentrating of evidence in particular locations (mainly Europe) in the Northern Hemisphere does not help the interpretation. There is now however, sufficient proxy evidence to show that both the warming around 1000 AD and the cooling corresponding to the LIA also occurred in the Southern Hemisphere. The data from the Law Dome ice core suggest that in Antarctica anyway most of the change occurred in the winter period. If indeed the LIA was predominantly a winter phenomenon the fact that most proxy data applies to only one season accounts for its presence in some proxy records and absence in others.

15. PATTERNS OF GLACIAL EROSION AND DEPOSITION IN PRYDZ BAY AND THE PAST BEHAVIOUR OF THE LAMBERT GLACIER

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Marine seismic, echo sounder and sea bed sampling data can be used to infer the distribution of subglacial erosion and deposition beneath the Lambert Glacier when it advances across Prydz Bay. This pattern of erosion and deposition is largely responsible for the geomorphology of the bay. It is mostly occupied by a broad topographic basin, the Amery Depression. Depressions up to 1000 m are found in the south-western corner of the Bay (the Lambert and Nanok Deeps) and running parallel to the Ingrid Christensen Coast is an elongate trough up to 1000 m deep called the Svenner Channel. Another elongate deep, the Prydz Channel, runs along the western edge of the Amery Depression, extending to the Continental Shelf edge. Offshore from the Amery Depression, the shelf shallows to be less than 200 m deep along the shelf edge, forming the Four Ladies Bank, on the eastern side of the Prydz Channel and Framm Bank on the western side. The topography of Prydz Bay is rugged along its southeastern flanks between the edge of the Svenner Channel and the present coast. Large U-shaped valleys extend northwest from the termini of the Sørsdal, Ranvick and Polar Record Glaciers. Sea floor close to the present position of the Amery Ice Shelf front features valleys tens of kilometres wide and separated by narrow ridges. The continental slope beyond Prydz Bay consists of two areas of different morphology. The western side features a large smooth-surfaced fan offshore from the Prydz Channel. The fan lacks submarine canyons. The eastern side is steep with dendritic tributaries of the Philippi Canyon starting on the upper slope.

The inner, deeper parts of the Amery Depression is a zone in which glacial erosion has predominated since the onset of Cenozoic glaciation. Seismic lines indicate substantial downcutting to pre-glacial rocks. Further offshore and downstream of this erosional zone, the amount of glacial deposition increases relative to erosion. The outer Amery Depression is floored with clayey diamicton and pebbly clays which were moulded into megaflutes or drumlins. Such bedforms indicate excavational deformation of the bed just prior to ice retreat. Still further from the current ice margin, the sediments thicken. The Four Ladies Bank is underlain by horizontal, overcompacted diamicton deposited as subglacial till overlying seaward-dipping beds deposited by progradation of the continental shelf. The Prydz Channel is floored by thinner, less compact sandy clays and diamictons which contain some evidence of shear deformation. This channel was probably formed by a fast-flowing ice stream moving on a rapidly-deforming bed. The rapid bed deformation meant that this ice stream deposited less subglacial till than ice on Four Ladies Bank; rather it delivered more sediment to the shelf edge, producing the large trough mouth fan. The progression from erosion in inner Prydz Bay to subglacial deposition on the Four Ladies Bank can be interpreted in terms of declining shear stress at the bed down glacier. This longitudinal decline on shear stress was less along the Prydz Channel ice stream, resulting in less till deposition.

Ice retreat produced a blanket of glaciomarine clay across Prydz Bay and a series of grounding line moraines. The most extensive moraine are approximately parallel to ice motion, suggesting they formed at grounding line positions separating the western ice stream, which floated first, and the eastern part of the Lambert Glacier, which retreated more slowly. Similar moraines are present around the Lambert Deep in southwestern Prydz Bay and offshore from the Publication Ice Shelf, suggesting minor readvance of grounding lines since the last retreat from the shelf edge.

High resolution seismic data shot along the axis of Prydz Channel indicate that the style of glacial deposition on the shelf has evolved through time. Pre-Miocene sequences accumulated mostly by vertical aggradation. This was replaced by shelf-edge progradation and aggradation, punctuated by episodes of upper slope erosion until an episode of significant slope erosion during the Pliocene, but less than 4 Ma ago. After that, the previously-deposited topsets were eroded and the shelf edge prograded, but with seaward dipping topset beds. Advance of the ice to the shelf edge is marked by shelf progradation and periods of reduced ice extent by erosion surfaces on the upper slope, although none show as much relief as the Pliocene surface. Another episode of significant upper slope erosion took place in the late Pliocene to early Pleistocene. Since then, the shelf edge as prograded with thin, horizontal topset. Unprocessed high resolution seismic data display 16 erosion surfaces sediments deposited since the late Miocene. This number will probably be revised after processing and systematic mapping of the data.

The marked erosion surface in the Pliocene represent:
1. A prolonged ice-free period with accompanying sediment starvation.
2. An catastrophic failure of the shelf edge.
3. Enhanced erosion of the slope by ocean currents during an ice-free period.

Further mapping of the surface and sequence geometries is required to understand this erosion event. The change in depositional style after this time probably results from the development of the western ice stream in Prydz Bay.

Dating of the various events recognised on seismic data and in cores is still in its early stages. Pre-Pliocene to early Pleistocene date require seismic ties to Ocean Drilling Program Leg 119 holes in eastern Prydz Bay. Control will improve with better diatom biostratigraphy and additional tie lines. Later events require dating of shallow core material. At present, C14 dates from ODP 740 (Domack *et al.* 1991) indicate the onset of open marine conditions at 10 700 years B.P., with a readvance of the Amery Ice Shelf between 7300 years B.P. to 3800 years B.P. Biostratigraphy has been unsuccessful so far with core material containing a variety of reworked diatom, foraminifera and palynomorphs.

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16. CLIMATIC HISTORY OF SOUTHERN AFRICA SINCE THE LATE NEOGENE

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Africa south of the 20°S parallel is noteworthy on account of its pronounced east-west climatic gradient. This is of considerable antiquity: following its temporary appearance in the Palaeogene, it became established as a more-or-less permanent feature by the Upper Miocene.

The post-Miocene climatic history of southern Africa, although dominated throughout by the meridional disposition of climatic belts, owed much to globally important influences, such as the major extension of high latitude ice-sheets after 2.8 myr and the resulting intensification of cold upwelling along the west coast of the subcontinent. Of fundamental significance has been the influence of late uplift movements on a regional scale. Like those associated with rifting and volcanism in East Africa, these movements were concentrated in the eastern hinterland, where uplifts within the Pliocene may have reached 900 m in some localities. The effects on regional palaeoclimates were profound, resulting in the focussing of precipitation along the eastern limb of the great escarpment and the accentuation of aridity in the west. Concurrent subsidence within the Bushveld Basin contributed further to the rearrangement and Fragmentation of climatic zones.

Several key sites have vouchsafed important evidence of these events Langebaanweg on the Western Cape coast documents the transition from Miocene palm forests to mosaics of woodland and shrubland in the early Pliocene, containing elements of the local Fynbos (macchia) vegetation of today. The latter appears to have become firmly established as a globally important biome only after the cooling which accompanied the growth of the high latitude ice-sheets between 2.8 and 2.5 myr. Documentation of the shift to more seasonal patterns of rainfall which followed this event is forthcoming from aeolian deposits of the Kalahari, palaeodrainage features of the Northern Cape and the unique records encapsulated in the hominid-bearing cave deposits of Cauteng and the Northern Transvaal.

During the latter part of the Pliocene and the Pleistocene, repetitive climatic shifts driven by orbital cycles can be documented at a number of sites. Among the more important of those which have yielded long sequences spanning the last one or two glacial cycles are the Pretoria Saltpan, whose 200 000 year record clearly indicates the dominant influence of precessional changes in receipts of solar insolation on rainfall over the interior plateau of southern Africa.

Patterns of change across the subcontinent were, however, far from simple. For example, a dry early Holocene was characterisitic of most part of southern Africa, but the first onset of Holocene wetness is evident earliest in the north and latest in the south. Likewise, the progression from a predominantly winter rainfall regime in the southern Cape during isotope Stage 2 to one with a significant component of summer rainfall in the later Holocene, appears to have begun earliest in core of the winter rainfall area, from where it spread northwards. This diachronism argues for the involvement of factors other than isolation alone in the patterning of changes in precipitation across southern Africa.

17. ICE-CORE RECORDS OF LATE HOLOCENE CLIMATE IN THE ANTARCTIC PENINSULA REGION

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The climate of the Antarctic Peninsula region is dominated by a complex interplay between the zonal tmospheric circulation and the extent of the marginal ice zone. Therefore, recent climate exhibits greater interannual variability and also larger trends than observed elsewhere in the southern hemisphere, including the interior of Antarctica.

Ice cores are the principal means to extend the instrumental records of climate both temporally and spatially in this region. The high accumulation rates of the region enable precision dating of high resolution records and provide a basis for calibrating the records against neighbouring weather stations. Existing ice core records reach back about 500 years although there is the potential to extend this for up to several thousand years in future deeper cores in the central plateau region, and in the larger ice islands adjacent to the Weddell Sea.

Oxygen isotope data from several cores from sites exposed to conditions over the Weddell Sea, appear to show that the warmest conditions of the past 250 years occurred in the mid- to late 19th Century. Our analysis, based on examination of the behaviour of constituents in the ice that are affected by ocean-atmosphere exchanges in the sea ice zone (MSA and deuterium excess) suggests that this feature probably reflects the influence of a greater abundance in precipitation of moisture drawn from within or adjacent to the pack ice zone. Conditions at that time, which we believe to be reflected more faithfully in the records drawn from higher altitudes, were probably fairly cool.

The coldest period of the past 300 years seems to have occurred around 1760–1780 AD, apparently associated with strongly disturbed atmospheric circulation. This interpretation accords with evidence on the ice margin at Signy Island, which indicates that local glaciers were at advanced positions at that time, and may be linked to a more sustained cooling apparent in ice cores from East and central Antarctica, including Law Dome.

Whilst time series of the annual snow accumulation rate can be determined unambiguously using multi-parameter identification of individual annual layers, there is a substantial spatial variability. Nevertheless, with only 3 years averaging the longest available record from Dyer plateau (~500 years) shows a significant correlation with the stable isotope ratio. The derived gradient of accumulation rate with temperature of 7.8%/=B0C is similar to the saturation mixing ratio/ temperature gradient and supports the idea that at least for the high elevation, cold parts of the Antarctic Peninsula region reasonable estimates of future changes in accumulation rate may assume that these are regulated by the Clausius Clapeyron equation.

The recent strong warming observed throughout the region is also reflected in increasing accumulation rates; and at Dyer Plateau both parameters now exceed levels reached in the previous 500 years. Other changes currently observed in the Antarctic Peninsula also indicate that the recent warming is unusual, at least on a time scale of several centuries; these include:

- the rapid disintegration of ice shelves on both the eastern and western coasts
- the observation of the highest dust levels for at least 500 years in ice cores from Siple Station and Dyer Plateau–most probably reflecting increasing exposure of rock in the Peninsula region
- the observed thickening of the ice sheet at two cold, high elevation sites

Future work must extend the time perspective to obtain a more complete characterisation of Holocene climate variability outside the limits of the 'European Little Ice Age'.

18. THE PLIOCENE ENVIRONMENT OF ANTARCTICA

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Antarctica is often referred to as 'pristine', meaning 'This is the way it always has been; let's leave it that way'. This, and sentiments like it, are aphorisms that gain credibility, justified or otherwise, with repetition. Geologically, Antarctica has not always been the way it is now, and there is a case for saying that it is not pristine in its current glacial guise. Perhaps there is no such thing as 'pristine Antarctica' and the debate can get bogged down in semantics, losing sight of the important issues. Change, and its rate and amplitude, has taken on a new importance in recent years because of the debate over potential global change induced by humanity's influence on the composition of the atmosphere—the Greenhouse effect.

Antarctica has loomed large in the question of global change for several reasons including the potential impact of global change on the Antarctic (reduction in ice volume, vegetation invasion), the impact of changes in the Antarctic on other parts of the world (changed Southern Hemisphere weather patterns, sea level rise, human migration) and the role of Antarctica as a source of records on past global change (global ice volume, past atmosphere composition).

One issue that has led to a very heated and unpleasant debate in the Antarctic context has been the matter of the Pliocene environment of the continent. It is the purpose of this paper to review the evidence for that environment.

The Pliocene globally has become an issue in itself because there is a school of thought that suggests that the environment of the Pliocene may be the palaeoanalogue of the human induced global change. There is a general recognition that the world was warmer during parts of the Pliocene and Australian research has contributed significantly to the story. It is thus important to reconstruct the global Pliocene palaeoenvironment, to examine how different it was and whether or not humanity would be content to live in such a world.

THE DEBATE

In its oversimplified form, the debate centres on whether Antarctica during the Pliocene was much the way it is now (the static ice sheet model) or very different with a reduced icesheet and vegetation in places (the dynamic model). It is oversimplified this way because the Pliocene was about 3.3 million years long and much can happen in that time.

The static icesheet school has held a symposium and published the results to support its case.

Many have reviewed the debate. The issue has advanced significantly with the conduct by National Science Foundation of a workshop in Woods Hole in April 1995 to determine a way forward in resolving the debate.

The paper will review the evidence for each of the models and the role of Australian research in the debate, now and into the future.

19. OXYGEN AND CARBON ISOTOPE COMPOSITION OF MODERN POLAR CARBONATES AND THEIR IMPLICATIONS ON THE ORIGIN OF EARLY PERMIAN POLAR CARBONATES, TASMANIA, AUSTRALIA

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Modern polar biogenic carbonates are forming at about -1.5°C seawater temperatures and contain glacial dropstones. They are mainly composed of low-Mg calcite. The amount of melt-water varies in polar regions: it is small in the southern hemisphere and large in the northern hemisphere due to differences in atmospheric temperatures and residence time of glaciers.

The $\delta^{18}O$ and $\delta^{13}C$ isotope fields of polar skeletons from Antarctica are clearly separated from temperate ones due to differences in seawater temperatures, $\delta^{13}C$ in seawater and circulation of seawater masses (Rao *et al.* 1995). $\delta^{18}O$ values of bryozoa, benthic foraminifera and bivalve molluscs give near equilibrium seawater temperatures of around -1.8°C. Melt-water effects are small in the polar sea around Antarctica.

The $\delta^{18}O$ and $\delta^{13}C$ fields of bivalves from Greenland (Israelson *et al.* 1994), from the northern hemisphere, are appreciably lighter than those of Antarctica due to strong melt-water dilution that reduces the salinity in shallow seawater (<30m) to about 25‰. Though actual seawater temperatures around Greenland are about -1.5°C, the seawater temperatures calculated from measured $\delta^{18}O$ values, without correcting for salinity, correspond to 10 to 22°C. Consideration of change of $\delta^{18}O$ values due to salinity decrease in shallow seawater around Greenland in the $\delta^{18}O$ thermometry give normal temperatures of around -1.5°C.

The Early Permian Tasmanian carbonates formed at a paleolatitude of 80°S and contain glacial dropstones. Since icebergs in the southern hemisphere are confined to latitudes of >60°S where surface seawater temperatures are <3°C, the dropstone bearing Tasmanian Permian polar carbonates also probably formed at temperatures <3°C. The original mineralogy of Tasmanian Permian carbonates was low-Mg calcite (Rao, 1981), similar to that which now occurs in modern polar shallow seas due to cold temperatures of <3°C. Staining and cathodoluminescence of these Permian carbonates reflect strong changes in composition of seawater during deposition and early diagenesis as a result of melt-water dilution. Light $\delta^{18}O$ values up to -26‰ PDB in these limestones are similar to those in fresh water cements in Permian tillites in Gondwanaland because these limestones are strongly affected by melt-water dilution (Rao and Green, 1982; Rao, 1988, 1991). If it is assumed that -6‰ $\delta^{18}O$ of Permian Tasmanian shallow seawater affected by melt-water dilution, similar to those around Greenland today, the Permian seawater temperatures calculated from $\delta^{18}O$ thermometry will be around -2°C.

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20. GRAIN SIZE, BIOTA, MINERALOGY AND OXYGEN AND CARBON ISOTOPES OF SEDIMENTS, DAVIS STATION AND PRYDZ BAY, ANTARCTICA: EVIDENCE FOR OCCURRENCE AND RECESSION OF SHELF ICE

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Grain size variation of sediments up to about 1000 m water depth, near Davis station and Prydz Bay, ranges from gravel, sand, silt, mud to siliceous ooze. Sediments are poorly sorted and texturally immature because they contain mud from 15 to 100%. Samples contain up to 50% of biogenic carbonates. Diamict facies extend up to 800 m present water depth due to occurrence of Last Glacial shelf ice.

Biota content varies with grain size: high in gravel (mean 51%) and low in coarse sand (25%) and sand (28%). The type of biota varies with grain size of sediments due to growth size of biota and subsequent reworking. Gravel fractions contain sponges (relative percent; mean 77%), bryozoa (34%), bivalves (21%), worm tubes (9%) and echinoderms (5%). Coarse sand fractions contain sponges (relative per cent; mean 65%), diatoms (55%), foraminifera (44%), bryozoa (30%), bivalves (8%), echinoderms (7%) and worm tubes (2%). Sand fractions contain sponges (relative per cent; mean 61%), foraminifera (33%), diatoms (32%), bryozoa (23%), worm tubes (18%), echinoderms (11%), bivalves (7%) and ostracods (7%). The variation of these fauna, in different grain size fractions, is unrelated to water depth because these fauna are aphotic organisms and are living or lived in a few meters to about 900 m water depths. The ^{14}C dates of fauna, corrected to reservoir effect, indicate that the fauna grew during the Late Holocene.

The mineralogy of bryozoans, from water depths up to 900 m, is mainly low-Mg calcite and minor high-Mg calcite. This calcite mineralogy corresponds to <3°C seawater temperatures in laboratory experiments. Thus bryozoan mineralogy is sensitive to seawater temperatures.

The $\delta^{18}O$ values of bryozoans, benthic foraminifera and bivalves from shallow seawater (<200 m) are in equilibrium with seawater temperatures of -1.8°C. The $\delta^{18}O$ values of similar fauna from deep seawater (200 m to 900 m) are lighter than those from shallow water because they are in equilibrium with relatively warmer temperatures of about 0°C in deep sea. Thus these fauna are living or lived in water depths up to 900 m.

Some fauna from deep water (>200 m) are very light in $\delta^{18}O$ (up to -16.3‰ PDB) and $\delta^{13}C$ (up to -6.3‰ PDB) due to melt-water dilution from slow recession of Last Glacial shelf ice that extended up to present water depths of about 800 m. Reworking of diamicts provided terrigenous sediment, particularly mud. Animals colonised on these reworked surfaces and some equilibrated with melt-water during the recession of Last Glacial shelf ice.

21. THE MODERN CLIMATE RECORD

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This study presents observed trends and variability in the modern climate record for the Southern Hemisphere. High-resolution of past climate from dendroclimatic studies, which are limited to a few areas, are also presented for the last few centuries.

Enough land and marine surface temperature observations exist to enable reconstruction of surface temperature trends since 1860. These results are derived from high quality, long-term climate datasets. These data show that annual surface air temperatures have warmed by 0.6°C over the period 1860 to 1994. Trends are similar for all four seasons. The coolest periods occur in the early 1860s and during the 1870s, when temperature departures are 0.4°C below the 1961–1990 normal. Other cooler periods occurred in the early 1890s and 1900s. A period of warming occurred in the 1930s, then Southern Hemisphere temperatures fluctuated. A period of strong warming occurred after 1975, and the last decade up to 1991 was the warmest in the entire record. Temperature departures of 0.3°C above the 1961–90 normal occurred in the late 1980s. The impact of volcanic aerosols from the winter 1991 eruptions is seen in the record for 1992 and 1993.

The pattern of annual land-only surface temperature trends reflect these broad trends, but are somewhat different. Over the entire period the warming amounts to 0.4°C, however, the coolest period in the land-only record occurs in the 1890s, with temperatures 0.5°C below the 1961–90 normal. This period was one of particularly cool autumn's and winter's. The warming since 1975 has been less marked as well over land areas. The trends are different in each of the four continents. Australian trends show that the period 1860 to the mid 1880s was relatively warm, with temperature anomalies of 0.4°C above the 1961–90 normal. Temperatures then cooled to average 0.2°C less than the 196–90 normal from the 1900s through until the 1950s. Subsequently Australian temperatures warmed to 0.3°C above the 1961–90 normals by 1990. Trends in Southern Africa more closely resemble the hemispheric trends. The coolest periods occurred around 1860 and 1880, with temperatures 0.7 and 1.0°C below the reference period. Temperatures warmed in the 1910s, and remained close to normal from 1920 to 1975. Subsequently they have wormed to 0.5°C above normal. South American trends show coo conditions throughout the 1860s, and around 1890, when temperatures were 0.5 and 1.0°C less than normal. Subsequently temperatures warmed to slightly below the reference period from 1900 to 1940, then have been close to normal since. In Antarctica the record only commenced in 1957. Land surface air temperatures warmed by 1.1°C by 1991. They subsequently have cooled.

A more recent detailed study of Oceania (Australia, New Zealand and the south Pacific) finds that annual surface air temperatures have warmed between 0.4 and 0.8°C throughout most of the region in the period 1951–1994. The fewer longer term records from parts of Oceania show warming of 0.7 ± 0.2°C of land air temperatures and that of the surrounding sea surface from the beginning of the century, consistent with hemispheric trends. Concurrent with warming over the past four decades, a significant decrease in diurnal temperature range (DTR) has occurred over significant parts of Australia, and in the central south west Pacific, particularly in areas where cloud cover has increased.

The entire Oceania region shows a significant changes in climate commencing in the mid 1970s. At the same time that marked warming in temperatures commenced, increases in summer precipitation occurred over eastern Australia. At the same time increases in precipitation occurred in the south-west Pacific to the north-east of the South Pacific Convergence Zone (SPCZ), whilst decreases occurred to the south-west of the SPCZ. The Southern Oscillation is an important driver of interannual variability in temperature and precipitation throughout this region, and Southern Africa. More prevalent El Nino episodes since the mid 1970s have influenced the longer term trends in precipitation.

Finally, there are very limited number of potential high-resolution proxy records to extend the climate record prior to the mid 19th century. Tree-ring studies from similar regions in temperate South America show few similarities. Tree-ring width records from Tasmania show summer temperatures over the last 500 years was warmer than most of the twentieth century. Only the 1890–1920 period is unusually cold. This contrasts with the New Zealand tree-ring record, where warm season reconstructions show cooler periods in the 18th and 19th centuries, with strong warming in the 20th century.

The observed instrumental climate record of change in the Southern Hemisphere show some definite trends this century. The observations are not inconsistent with climate forcing expected from anthropogenic and natural sources. These include the enhanced greenhouse effect, cloud cover changes and the effects of anthropogenic and volcanic aerosols in the atmosphere. High-resolution climate information on climate before 1860 is sparse.

22. TIMESCALE DEPENDENCE IN THE RELATIONSHIP BETWEEN ANTARCTIC PACK ICE COVER AND CYCLONES

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A major role of the atmosphere (and to a lesser extent, the ocean) is to redress the latitudinal imbalance of the net radiation by transporting energy (in the form of latent, sensible and potential components) from the tropics to high latitudes. Virtually all of this transport in the middle and high latitudes is effected by largescale wave activity. An important difference between this process in the two hemispheres is that in the north a significant proportion of this is accomplished by the 'stationary' waves. By contrast, in the Southern Hemisphere (SH) virtually all of the poleward flux of energy is associated with the activity of 'transient' disturbances. These can be thought of as the mobile highs, lows and frontal systems which are ubiquitous features of the southern extratropics.

Given this, it is clear that changes or variations in the characteristics (e.g. frequency, intensity) of SH extratropical cyclones may influence not only 'weather' along the 'storm tracks' but also climates both to the north (say, the subtropics) and the south (Antarctica and its environs). Recent studies have shown that, in particular, the meridional energy and moisture fluxes in Antarctic latitudes exhibit considerable variability, and this has important implications for the mass balance of the continent.

The atmosphere behaves in many respects as a turbulent fluid and exhibits variability (e.g. interannual variability) in the absence of 'boundary values' changes. Hence the numbers and tracks of lows can change from year to year (and from epoch to epoch) purely as a results of the chaotic nature of the system. The lows obviously also respond to changes in the, for example, alterations in the conditions at the surface. One important characteristic of the surface at high southern latitudes is the condition of the sea ice coverage. With what has been said above, it seems reasonable that variations in extratropical cyclone behaviour could influence the sea ice (through heat and moisture transport from the north and through mechanical action on the pack). On the other hand, it could be thought that the condition of sea ice could influence cyclones and their developments through modification of the surface fluxes of heat, moisture, momentum and of the location of the baroclinic regime. Hence there is the potential for sea ice to influence, and be influenced by, the transient systems in the SH and all the implications this has for climate on the larger scale. Our purpose in this paper is to explore the relationship between Antarctic sea ice condition and characteristics of extratropical cyclones.

The idea of sea ice condition influencing cyclone behaviour, through the modulating effect sea ice has on latent and sensible heat fluxes and the position and strength of the baroclinicity, is one with strong intuitive appeal. Any of these factors have the potential to alter cyclone characteristics. It should be pointed out, however, that this appeal may be limited to the specific timescales inherent to these processes and may not be applicable on other frequencies of variation. Work which seeks to quantify associations between sea ice and cyclone behaviour on interannual and longer timescales in a statistically rigorous manner is reported.

Use has been made of long series of seasonal sea ice extent and extratropical cyclone statistics. Results indicate that on the interannual timescale, there appears to be little connection between regional ice edge and a variety of measures of cyclone status (except in certain sectors). Notwithstanding this, there appears to be weak connections between these parameters when considered over a larger spatial scale. The evidence also suggests that cyclonic conditions impact more on ice edge position than conversely.

The trends in the nature of cyclones over the past two decades are also examined with a view to determining whether these could be thought of as associated with sea ice variability. The role played by the quasi-regular variations of the 'semi-annual oscillation' in the high southern latitudes over the 50 years are also be addressed.

Our findings caution against the application of specific chains of reasoning to *all* timescales, while the particular physical processes invoked (e.g. baroclinicity) may operate on a specific temporal window. The conclusions also have implications for climate associations on the scales of millions of years.

23. MODELLING THE SENSITIVITY OF THE ANTARCTIC ICE SHEET TO CLIMATE CHANGE

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The primary effects of global warming on the Antarctic Ice Sheet involve increases in surface melt (confined mainly to lower elevations), increases in net accumulation (further inland) and increased basal melting under floating ice. With global warming, resulting in ocean temperature increases of several degrees celsius, the large increase in basal melting becomes the dominant factor in the long term response of the ice sheet. The increased basal melt rates lead to a reduction of the ice shelves, increased strain rates and flow at the grounding lines, then further thinning from increased sliding and floating of the marine ice sheets, with consequential further basal melting.

The mass loss from melting is counteracted to some extent by increased accumulation, but in the long term the area of ice cover decreases, particularly in West Antarctica, and the mass loss dominates. A further developed version of the ice sheet—ice shelf model of Budd *et al.* (1994) has been used to carry out a large number of sensitivity studies of the long term response of the Antarctic ice sheet to prescribed amounts of global warming. The changes in the ice sheet are computed out to equilibrium over 50 000 years although most of the changes take place within the first 10 000 years. The model is used to study the sensitivity of the response of the ice sheet to the different factors in the warming (surface accumulation, ablation and basal melt) separately and in combination. The consequential changes in floating and grounded ice, above and below sea level, are computed to derive impacts on sea level change.

In the past, sea level changes, primarily forced by northern hemisphere ice changes, have been a dominant factor in Antarctic margin advances and retreats. With low northern hemisphere ice volume additional sea level rise resulting from further warming comes primarily from loss from the Antarctic ice sheet. The feedback of sea level change as well as bedrock isostatic response are also examined with the model.

Finally over long time periods tectonic changes can cause bedrock elevation change which you can effect the ice sheet and through feedback the climate. Sensitivity studies are also carried out on the possible impacts of large tectonic bedrock elevation changes.

The results of the model provide insight into the possible long term impact of warming on the Antarctic Ice Sheet and sea level and also into the magnitude of the changes required for the removal of the bulk of the West Antarctic Ice Sheet under possibly warmer climatic regimes of the past.

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