High latitude climates of the Pacific — past, present and future

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A brief review is given of the available historical record of instrumental observations at high latitudes of the Pacific, and selected examples are presented of proxy information sources particularly those for the late Quaternary over and bordering the high latitude ocean. The principal observed features of the present climate are described in terms of mean pressure, transient synoptic systems, wind, temperature, cloudiness, precipitation and sea-ice. Observed trends in the chemical composition of the global atmosphere are noted, and the characteristics of modelled climates at high latitudes resulting from extrapolated carbon dioxide trends are described. The limitations not only to knowledge of the past and the causes of interannual variability in the present climate but also to our ability to confidently predict future climates are emphasised.

Introduction

In common with many other features of the Pacific basin the climatic conditions of the high latitudes of both hemispheres were first experienced by the crew of James Cook's Resolution which, in 1773-74, traversed much of the South Pacific on the fringe of the pack ice, and which in 1778 explored the northwest coast of North America passing through Bering Strait to the ice of the Chukchi Sea. The environmental contrasts as well as the similarities of these summers at high Pacific latitudes would have been apparent to these men. For example, in December 1773 Resolution first encountered sea-ice at latitude 63° 40'S, 166° 41'W while, in the summer of 1778, at rather similar latitudes in the northern hemisphere the ship lay near the beautiful forested coastline of Prince William Sound and Cook Inlet in southern Alaska.

Since this first experience a fairly complete picture of at least the broad features of the climate has gradually evolved, but perhaps more slowly than that for most parts of the earth. The locations and dates of establishment of some of the earliest observing stations in the region are shown in Fig. 1 (it should be noted, however, that many of these have had irregular periods of operation since first established). Despite the very early meteorological observations at commercial centres (e.g. Unalaska in 1829 and Sitka and Hobart in the 1840s), the higher latitude stations often become established only during scientific expeditions, e.g. Barrow just prior to the First International Polar Year of 1883, Cape Adare by the Southern Cross expedition of 1898-1900 (the first meteorological observations from the Antarctic continent), McMurdo Sound by Scott's Discovery expedition of 1901-04 and Macquarie Island by Mawson's Australasian Antarctic Expedition of 1911-14.

In the northern hemisphere, western Canada, eastern Siberia, Alaska and the Aleutians have records dating generally from the last decade of the 19th century, and much information is available from the analysis of shipping observations on the active trade routes of the North Pacific. More recently, observations were obtained from ocean weather ships and buoys. In the southern hemisphere, continuing records began in the 1860s...
in New Zealand and the 1890s in southern Chile, but in the sub-Antarctic at Macquarie Island and Campbell Island and in the western Antarctic Peninsula at Deception Island and other Falkland Islands Dependency Survey (FIDS) bases, permanent observation stations were built only in the 1940s. The International Geophysical Year (IGY) of 1957-58 saw the first establishment of continuing bases on continental Antarctica. The high latitudes of the South Pacific were an active route for sailing ships bound from Australia and New Zealand to Drake Passage and North Atlantic ports during the 19th century, but since the turn of the century the region has been largely deserted. Apparently little of the data from these ships have been collected and analysed but more recent observations from whalers and expedition ships (notably, e.g. Discovery II in the 1930s and Eltanin in the 1960s and 70s) have been used in studies of the high latitudes. Only the advent of global satellite weather surveillance in 1966, and more recent advances in satellite technology, have enabled the first comparatively reliable weather charts to be produced for the South Pacific high latitudes. The absence of shipping and suitable island locations indicates clearly that the future of climate and weather studies in this area will be highly dependent on spacecraft-based remote sensing technology. The trial of new buoy and satellite data gathering systems during the First GARP (Global Atmospheric Research Programme) Experiment (FGGE) in 1978-79 showed the scope for detailed measurements over the oceans if it were economically possible to continue them on a regular basis.

In what follows, an attempt will initially be made to briefly outline some examples of recent work on the past climates of Pacific high latitudes; secondly to describe the principal characteristics of the present climate, and finally, to mention some of the hypotheses which have been advanced as an outlook for the future of global climates.

The past

Long before the supposed earliest migrations of man into the Americas via the Bering land bridge and into Australia via Indonesia, and before the adventurous voyages of the Polynesians to settle Oceania, the earth, ocean and ice were recording in their own way the changing environmental conditions. Such records reflect to a greater or lesser degree some elements of the climate state. However, only in the past few decades has it been possible to systematically examine, date and interpret the climatic aspects of the earth's record prior to the period of instrumental measurement by man. The now general acceptance of the broad concept of continental drift has enabled many previously incomprehensible climatic inferences from the long-term geological record to be at least qualitatively understood. However, the time variations in the global disposition of continents, mountain ranges, oceans and ice caps and in the input to the earth of radiation from the sun, which is dependent on the characteristics of the earth's orbit, are extremely complex. Thus, an interpretation of geological evidence from a particular present site in terms of the climate of a past age is extraordinarily difficult, and the further back in time the larger the uncertainty. To review the climates of the Pacific high latitudes throughout geological time is clearly beyond the scope of this paper, and indeed, such a topic would be subject to much debate and conflicting evidence — the reader is referred to the most recent work on the evolution of global climates (Frakes 1979). We might note, however, the significant events in the development of the ocean configuration which profoundly affect the climatic states, e.g.

- The separation of South America, Africa and Antarctica and the formation of a circumpolar ocean in the southern hemisphere during the early Cretaceous, c. 120 x 10^6 years ago.
- The separation of Australia from Antarctica and the start of its drift to the north during the Palaeocene c. 55 x 10^6 years ago.
- The first Cenozoic glaciation of Antarctica for which definite evidence exists at c. 26 x 10^6 years ago — though earlier glaciations may have existed (Frakes 1982).
- The establishment of the present general configuration of the southern continents during the Miocene, c. 20 x 10^6 years ago.
- The joining of the two Americas at the Isthmus of Panama c. 3 x 10^6 years ago.
- The final inundation of the Bering land bridge c. 10 000 years ago.

The evolution of climate must be seen as grossly influenced by such changes and the attendant variations in ocean currents and mountain building, as well as by the cyclical changes in the characteristics of the earth's position relative to the sun which are now believed to be the most significant, though not the only features of long-term changes in global climate. The principal cycles are:

- that in the eccentricity of the earth's orbit of c. 93 000 years;
- that in the obliquity of the ecliptic of the earth of c. 41 000 years; and
- that in the precession of the equinoxes of c. 21 000 years.

Most field data to test these and other theories of climatic change and to describe broadscale patterns of climate over a substantial area of the earth are confined to the most recent geological time, viz. the late Quaternary, and in particular to significant events such as the last major glaciation (c. 18 000 years ago) and the generally warmer period of the Holocene (c. 5000-7000 years ago). The high latitudes are particularly important in providing evidence for these events because of the identifiable features of glacial and vegetation sequences which are often clearly major features of the landscapes and which can often be dated with some precision. Fig. 2 shows...
some selected sites at high latitudes of the Pacific coasts and islands from which evidence of late Quaternary climates has been obtained. The evidence obtained from these locations is generally of the following types:

- Deep sea cores in which sequences of deposited carbonates are analysed to determine the $\delta^{18}O$ isotope ratio which may be interpreted in terms of temperature of the surface waters in which the micro-fauna existed at the time of deposition. There are numerous complications and corrections to be applied in the use of this technique (see e.g. Lamb 1977 pages 89–96). However, systematic analyses of the cores have enabled an apparently consistent map of the global sea surface temperature to be produced initially for the maximum of the last glaciation (CLIMAP project members 1976). The difference between present and ice age sea surface temperature is shown in Fig. 2 (upper panel).

This constitutes a basic data set for attempts to intercorrelate other types of proxy data (e.g. Webster and Streten 1978) and to numerically model the global atmospheric circulation of the time (e.g. Manabe and Hahn 1977). High latitude cores from the Indian Ocean dating back some 450 000 years have also been used to provide evidence for the effect of the three astronomical cycles on climate (Hays et al. 1976).

- Deep ice cores from Antarctica by Byrd, Vostok, and Dome 'C' have been analysed in terms of the $O^{18}/O^{16}$ isotope ratio as a measure of the surface temperature at the time of the deposition of snow on the continent. The determination of climatic temperatures from such data is complicated by the establishment of the time scale, the effect of the elevation and flow characteristics of the ice sheet, the calculation of an appropriate transfer function from the isotope ratio to past temperature and other factors. However, these data are perhaps the most significant of the high latitude continental proxy information on the climatic history of the earth. Figure 3 shows data obtained from a 900 m ice core at Dome 'C' (lat. 74° 39'S, 124° 10'E) at an elevation of 3240 m in East Antarctica dating back some 30 000 years and clearly showing changes following the peak of the last glaciation in terms of isotope ratio (Lorius et al. 1979). A consistent chronology of microparticle concentration and carbon dioxide content of the ice have also been analysed from this core.

- Palynology of sub-polar bogs. Analysis of the relative abundance of pollens obtained from dated cores for many regions provides data on the change in vegetation pattern with time. The latter data may then be interpreted (not without some problems nor perhaps sometimes without imagination) into sequences which describe a climatic chronology. Such data require substantial cross-referencing with nearby sites but constitute a vast source of proxy climatic data for numerous key climatic locations. Examples include the present St Paul Island site at a location which constituted a hill on the southern coast of the Bering Sea land bridge during the last glaciation (Colinvaux 1981) and several southern Chilean sites notably that at Alerce (Heusser and Streeter 1980) from which evidence has been obtained and interpreted in terms of possible latitudinal
Fig. 3 δ record (i.e. a measure of the relative abundance of $^{18}$O isotope) in an ice core from Dome 'C' Antarctica. The record is plotted for about 4 m long increments and smoothed. The straight lines indicate mean values over the past 11 000 years and during the late part of the last ice age. Depths are expressed in metres of ice equivalent. Ages are estimated from a simple ice flow model assuming a variable or constant (numbers in brackets) rate of accumulation. Data from Lorius et al. 1970.


- Glacial sequences and glacial geomorphology. The major changes in the terrain and vegetation during glacial advance and retreat were among the earliest proxy evidence of climatic change. The Dry Valleys of Victoria Land in Antarctica reveal the major retreat from the last glaciation (see e.g. review by Nichols 1971) as do the glaciers of southern New Zealand (e.g. Chinn 1982), Chile (e.g. Porter 1981), Alaska (Péwé et al. 1965) and the terrain of the now totally deglaciated Tasmania (Derbyshire 1971). All glacial sequences, however, show complicated shorter-period advances and retreats within recent historical record and are frequently difficult to interpret in terms of climate as is shown by the often diverse behaviour of similarly located glaciers for which detailed modern records are available.

- Soil stratigraphy. Soils show past climatic effects in terms of amounts of material produced by weathering and of organic debris of plant and animal origin. Interpretation of the stratigraphy may provide a valuable source of climatic data sequences, but because of erosion and other local effects numerous sites are often required to give reliable information. An example of work at an important climatic site is the recent study of the peats of Macquarie Island (Selkirk and Selkirk 1982).

Other methods may also be utilised in studies of palaeoclimates. For example, dendrochronology or analysis of tree ring data may provide information on the past few thousand years. This work has been carried out in most of the Pacific fringe locations e.g. southwest Tasmania, New Zealand, southern Chile and Alaska, the Yukon, and British Columbia. A recent publication gives a review of these investigations (Hughes et al. 1982).

Studies of the climate variations of the period of instrumental record have been carried out for a number of sites. Streten (1977 a, b) investigated temperature and other climatic variables at high southern latitudes and Salinger (1979, 1982) has studied changing climatic features of New Zealand using the climatically sensitive characteristics of its terrain and glacier records to examine variations in circulation types over the southwest Pacific region.

In concluding this very brief discussion of the study of past climates it is important to note that periodical critical review and comparison of the results of all proxy evidence of climate on a global or large regional basis is essential to build up a coherent picture of conditions at a particular time. One might cite the substantial global catalogue of data for the period of the last glaciation (Peterson et al. 1979) and the attempt by the so-called CLIMANZ group in Australia and New Zealand to examine the evidence for the late Quaternary climates of the region at specific time 'spikes' in sequences between c. 37 000 and c. 5000 years before the present (CLIMANZ Proceedings 1982). With the increasing field activity and the development of better dating techniques, such review and comparison of data from different sources is assuming considerable importance.

The present climate

We turn now to a brief survey of the principal features of the high latitude Pacific climates in the present era. No attempt will be made here to provide a detailed climatology or an historical account of such studies. The reader is referred to recent analyses given in the appropriate chapters of a forthcoming publication (van Loon 1982) for such information on the oceans and to other volumes of the World Survey of Climatology series for the bordering continental areas. These publications and a recent review of Polar climatology (Polar Group 1980) give comprehensive lists of references on specific topics.

Pressure and wind

The broadscale mean pressure pattern at sea level
over the Pacific is shown in Fig. 4 for January and July. The most notable feature of the high latitude distribution over the oceans is the intense pressure gradient and associated westerly circulation over mid-latitudes in the southern hemisphere throughout the year, which is unmatched in strength in the northern hemisphere. Figure 5 shows the annual variation of the strength of this westerly current in terms of the gradient of pressure between 40°S and 60°S at Pacific longitudes. The diagram displays one of the well known half-yearly cycles in southern hemisphere circulation features which have been studied by van Loon (1967) and van Loon and Rogers (1981). The cause of such oscillations is not fully established, though van Loon has explained them in terms of differences in the annual course of seasonal heating and cooling trends between middle and higher latitudes which are ultimately related to different responses in the two regions to the earth's heat budget. The interannual fluctuation in these half-yearly cycles is important in studies of the year to year seasonal conditions over the southern hemisphere continents. So too, is the pattern of change in the strength of the westerlies in particular longitude sectors, the mean seasonal patterns of which are shown in Fig. 6 emphasising the much stronger flow in the western sector south of Australia. Figure 4 also shows part of the ring of low pressure surrounding Antarctica — the so-called Antarctic trough which persists throughout the year though also exhibiting half-yearly oscillations in latitude (Fig. 5). By comparison, the Aleutian Low of the North Pacific so dominant in winter is much less in evidence in mid-summer.

The mean pressure field is but a time average of all the individual pressure systems which appear in a sequence of weather charts or which may be inferred from their cloud signatures in satellite pictures. Such weather systems, in particular the travelling depressions of the westerlies, have been studied by satellite and other means. The weather conditions associated with these are the prime factors influencing the climate of the middle and high latitudes. Particular regions whose positions are determined by the longwave pattern of the atmosphere, by thermal contrasts in the ocean and atmosphere and sometimes by coastlines occur where development of such depressions is a maximum. A generalised picture of these so-called ‘climatic fronts’ is shown in Fig. 7. The mid-latitude polar fronts of both hemispheres are similar in orientation though in the southern hemisphere a branch into the lower latitudes is an active region of cyclogenesis. This is located between regions of higher pressure and is
Fig. 7  Climatic fronts of the Pacific region. SPF — summer polar front; WPF — winter polar front; SAF — summer Arctic front; WAF — winter Antarctic front (based on data of Reed 1959, and Taljaard 1968).

Fig. 8  Generalised pattern of principal tracks of cyclones and anticyclones for the Pacific Ocean (modified from USSR Ministry of Defence 1974).

flow patterns in the lower atmosphere. These phenomena, which are often of complex structure, are known generally as ‘blocking’ and are often accompanied by major seasonal anomalies in weather conditions, particularly precipitation. A very recent example has been the persistence of blocking pattern conditions which resulted in a major drought situation during the winter of 1982 over much of eastern Australia.

Temperature

The general distribution of mean temperature over the Pacific is shown in Fig. 9. Notable is the great extent of cold air throughout the year over the Southern Ocean and the absence of any marked warm period in midsummer. This is of course related to the dominant oceanic environment and to the absence of ice free land masses at high southern latitudes. However, the proximity to the North Pacific of the vast Asiatic and North American land masses extending from lower latitudes ensures much greater seasonal extremes over these regions. Figure 10 reveals the inter-hemispheric differences quite clearly in showing mean monthly temperatures at a number of coastal and island station pairs similarly located as to latitude in both hemispheres. Their relative geographical positions are indicated in Fig. 11 and their co-ordinates in Table 1.

The extreme conditions of a northern hemisphere east coast in winter are apparent at Ust Kamchatsk.
Fig. 10 Mean monthly temperature (°C) at selected Pacific high latitude stations (see Fig. 11 and Table 1 for locations). Bracketed figures are the respective mean annual temperatures. Upper panel — mid-latitude stations; lower panel — higher latitude stations.

whose thermal climate reflects seasonal changes in the characteristics of the air mass over coastal Siberia. The lower layers of such air masses of continental origin are gradually modified by passage over the water; however, island locations such as Cold Bay still retain substantial seasonal contrasts in marked contrast with the mild purely oceanic climates of the southern hemisphere westerlies at similar latitudes (e.g. Macquarie Island or Evangelistas). Lying between such extremes are the climates of the northwest coast of North America (e.g. Prince Rupert) where the climate is essentially maritime, and because of topography and circulation features not subject to such extremes as the Siberian coast. The inter-hemispheric thermal contrasts continue at the polar coasts but are less evident than at mid-latitudes (cf. Dumont D'Urville and Anadyr or Barrow and Hallett).

Cloudiness
The great extent of cloudiness over the higher latitude westerlies particularly in the southern hemisphere is well known (Fig. 12). This feature, resulting also in a low percentage of possible sunshine hours, characterises more than any other the climate of these regions. The cloud type is dominated by lower-level stratocumulus and stratus forming under inversions as warm air masses originating in lower latitudes are stabilised by movement over cooler water. Such cloud is interspersed with substantial zones of active weather-producing cloud extending to higher levels in the atmosphere and associated with the frontal bands of cyclones. Outbreaks of colder polar air from higher latitudes to the rear of such cyclones result in large convective cloud fields. Close to the Antarctic coast in the zone of the easterlies, mean cloudiness is frequently reduced due primarily to
Table 1. Co-ordinates of selected northern and southern hemisphere high latitude stations in the Pacific region.

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<tr>
<th>Northern hemisphere</th>
<th>Southern hemisphere</th>
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<tr>
<td>Adak</td>
<td>Campbell Island</td>
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<tr>
<td>51°53'N</td>
<td>52°33'S</td>
</tr>
<tr>
<td>Prince Rupert BC</td>
<td>Evangelistas</td>
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<tr>
<td>54°17'N</td>
<td>54°24'S</td>
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<tr>
<td>Cold Bay</td>
<td>Macquarie Island</td>
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<tr>
<td>55°12'N</td>
<td>54°30'S</td>
</tr>
<tr>
<td>Ust Kamchatk</td>
<td>Deception Island</td>
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<tr>
<td>56°14'N</td>
<td>62°59'S</td>
</tr>
<tr>
<td>Sitka</td>
<td>Dumont D'Urville</td>
</tr>
<tr>
<td>57°03'N</td>
<td>66°41'S</td>
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<tr>
<td>St Paul</td>
<td>Hallett</td>
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<tr>
<td>57°09'N</td>
<td>72°18'S</td>
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<tr>
<td>Nome</td>
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<tr>
<td>64°30'N</td>
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<td>Anadyr</td>
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<tr>
<td>64°47'N</td>
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<tr>
<td>Kotzebue</td>
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<td>66°51'N</td>
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<tr>
<td>Barrow</td>
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<td>71°18'N</td>
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Fig. 12 Mean cloudiness (tenths of the sky covered) for the Pacific Ocean. Regions with cloud amount greater than eight tenths shaded (adapted from USSR Ministry of Defence 1974).

suppression by offshore and downslope winds from the continent. This process is also apparent but less so off the Arctic coasts.

Fog
Maps of the frequency of fog over the oceans are most reliable for the northern hemisphere. In midsummer the frequency of marine observations reporting fog reaches a maximum of over 35 per cent in the region extending from Bering Strait to the area southeast of Kamchatha (USSR, Ministry of Defence 1974). At this season, this area experiences the contrast of warmer and moister air moving northward on the flank of the North Pacific high (see Fig. 4) and over the Kuro Shio, encountering the cold waters of the Bering Sea with resulting condensation and high occurrence of fog. The frequency falls progressively eastward to less than 10 per cent in the region of the Canadian coast. In winter, the fog frequency is much lower (c. 5 per cent) over the high latitude North Pacific. Over the South Pacific, the data are poor particularly in winter, but the seasonal contrasts in fog frequency appear to be less marked; e.g. Macquarie Island experiences an annual average of 64 days of fog fairly evenly distributed throughout the year, though less evident in spring. The ocean data suggest that fog frequencies over the high southern latitudes may be generally 5 to 15 per cent throughout the year. The contrast between the hemispheres might be expected in view of the more uniform and stronger atmospheric circulation over the southern oceans.

Precipitation
The frequency and amount of precipitation over the oceans is not well known particularly at high latitudes. Observational estimates from ship reports are of limited value, and data from island and coastal stations may be substantially affected by site and exposure. Thus, only broad generalisations are possible in describing ocean precipitation; Fig. 13 shows average annual precipitation over the Pacific and illustrates the general decrease poleward over the middle and high latitudes. Figure 13 also depicts average annual precipitation as a function of latitude for selected stations (Fig. 11; Table 1) at the higher latitudes of both hemispheres. The general and fairly regular decrease with latitude is indicated for the ocean-island and higher latitude locations. At mid-latitude stations on exposed west coasts having a substantial topographic barrier across the westerly flow, much higher precipitation is experienced (e.g. Evangelistas, Sitka and Prince Rupert). It is well known of course that annual precipitation may range widely in the same climatic region depending on exposure and topographical effects. Accurate measurement of precipitation at Antarctic stations is extremely difficult owing to the difficulty of distinguishing between blowing and drifting snow in strong winds and because the precipitation is known to be very low. Estimates of snow accumulation made by snow stratigraphy studies (e.g. Schwerdtfeger 1971) are the most useful.

Some indication of the monthly distribution of precipitation at high latitude stations is shown in Fig. 14. The low interseasonal variability in the southern hemisphere westerly regime is apparent compared with the high latitude north Pacific stations which, in general, have precipitation maxima occurring at distinct seasons dependent on latitude, exposure and proximity to active depression tracks. A further discussion of the seasonal and interannual climate variability at high southern latitudes is given elsewhere (Streten 1977b).

Sea-ice
The climate of the high latitude oceans is profoundly
Fig. 13 Upper panel: General representation of average annual precipitation (mm) over the Pacific Ocean with regions having greater than 1000 mm shaded (USSR Ministry of Defence 1974). Lower panel: Average annual precipitation at indicated stations (see Fig. 11 and Table 1) as a function of latitude. Dashed line is one of approximate trend for island and higher latitude sites (see text).

Fig. 14 Histograms of average monthly precipitation at indicated stations (see Fig. 11 and Table 1).

affected by the annual cycle of sea-ice growth and decay, and its variability from year to year may also have substantial influence on broadscale circulation patterns and seasonal conditions at lower latitudes (see e.g. Fletcher 1969). However, only with the advent of satellite technology has it been possible to consistently monitor its extent and more recently some of its physical characteristics. An example of such satellite imagery is given in Fig. 15 which shows a satellite view of the sea-ice at the time of its spring retreat from the north Pacific through Bering Strait.

The overall variability of the Pacific sea-ice is depicted in Fig. 16 emphasising the vast extent of the sea-ice zone, particularly that of the Antarctic, in relation to the ocean area. The interannual range of the Antarctic sea-ice edge throughout an investigation period of five years has been observed to average about 3 degrees of latitude over all Pacific longitudes in each month (Streten and Zillman 1982). However, the variability is greater (c. 5 to 8 degrees)

Fig. 15 Very High Resolution Radiometer (VHRR) satellite view of the sea-ice in the region of the Bering Strait, 29 April 1973.
in the longitudes of the Ross Sea embayment, particularly in summer, suggesting that ocean circulation and atmospheric conditions in this region are important in affecting ice distribution. A further region of considerable variation lies in the extreme southeastern Pacific at the approaches to Drake Passage, where, according to Lamb (1967), ships also observed excessive ice around the turn of the 19th century.

Our knowledge of sea-ice processes and their possible effects on climate via atmosphere-ocean-ice feedbacks is only at an early stage of development (see e.g. review by Ackley 1981). Numerical modelling studies (e.g. Parkinson and Washington 1979) offer the best hope of understanding the mechanisms at work but these must be supported by an extensive observational program. Still less is known about the distribution frequency and characteristics of Antarctic icebergs which may prove to be an important resource of Antarctic waters (Schwerdtfeger 1979).

The unknown future

Although we can describe the present climate in some detail, our understanding of its variability is most incomplete. In understanding even the relative importance of the processes at work in any given time or region, the interplay of (interalia) incoming and outgoing radiation, cloud distribution, varying albedo of the earth, geographical distribution of the continents, topography, ocean temperatures, currents and sea-ice constitute an extremely difficult scientific problem. Numerical modelling is a tool which can be used to elucidate some of these problems of climate in the same way as it has proved invaluable in weather forecasting out to four or five days (see e.g. a review by Hunt 1980). However, fully reliable, integrated models of the atmosphere, ocean and ice for climatic research are only at early stages of development, and many do not yet well replicate many of the important observed features of the present climate which we have described, e.g. the Antarctic trough is very poorly reproduced in many general circulation models.

Climatic features of all types are observed to be subject to a natural variability with irregular fluctuations of different time scales. Trends or regular periodicities persisting for long periods are only rarely found. Notably, indices of the broadscale circulation such as those of the southern oscillation generally display low persistence from month to month and change markedly at irregular time intervals. Similarly, certain dispositions and sequences of anticyclonic and cyclonic patterns are observed such as those studied by Trenberth (1976) over the southwest Pacific, and those related to regional climatic trends or changes lasting over periods even up to some decades (e.g. the New Zealand observations reported by Salinger 1979). Such fluctuations, while of considerable interest in displaying modes of atmospheric behaviour, have so far not been fully understood physically; nor have they proved generally useful in forecasting future seasonal conditions. Indeed, a recent review of all known methods of seasonal forecasting (Nicholls 1980) concluded that none of the methods so far employed displays a useful degree of skill in a general sense, though some methods may have at least some value in certain regions and for particular seasons of the year.

During the past decade there has been an increasing pre-occupation in climatology and in the media with various types of imminent hypothetical ‘climate change’ where this expression must be interpreted in terms of a general and long lasting trend. These ‘changes’ have only one thing in common — all are deemed to represent at least a threat to mankind if not a global disaster. In the early part of the decade an apparently increasing trend was suggested by the short observational record of global (but primarily northern hemisphere) cover of winter snow and this led to some predictions of an onset of colder global conditions. This trend was not continued, and, as with most geophysical quantities, it reversed and has since fluctuated.

By the early 1970s it was possible also to regularly observe the Antarctic ice extent. This has been found to show a downward trend from about 1973 until around 1977 (Streten and Pike 1980) but the trend has since reversed and the record shows patterns of fluctuations from year to year at particular longitudes. Ice and snow data indicate the danger that may exist when observations are available for only a part of a fluctuation, and a persisting trend.
is predicted from insufficiently long records, particularly if some plausible physical reason can be advanced for the trend in the observations.

For example, it is known that 90% of the last million years have been cooler than the last 1000 years; that past interglacials such as that in which we now live have lasted some 8000 to 12 000 years and that the present interglacial has lasted some 10 800 years (Bryson and Murray 1981). Further, there is some evidence that quite sudden changes to glacial conditions have occurred in the past, so it is not unreasonable to expect that evidence might be found to suggest the onset of colder conditions. Similarly, as we will presently discuss, there are good reasons for believing that increasing carbon dioxide may lead to a global warming and that evidence (so far not forthcoming) may be found to show this effect. If changes are occurring in the trend of global temperature then the observations of the southern hemisphere sea-ice should provide a sensitive long-term index. However, rather than attempted prediction the appropriate activity for scientists at this time would appear to be careful and consistent monitoring with attempts to understand the variability pattern (see e.g. Kukla and Gavin 1981).

Other atmospheric parameters, notably the relative proportions of the gaseous constituents — ozone, the oxides of nitrogen and carbon dioxide have become accurately measurable only in recent years. These have been shown to be important in terms of changes in atmospheric behaviour, and the trends may be ‘real’ and continuing in that the changes in these constituents are believed to be due to the increased activities of man, i.e. for the first time man may now be a significant global climatic agent.

Of the constituents mentioned above, carbon dioxide has been subjected to the greatest study (see e.g. Pearman 1980) and its well-known effects in absorbing outgoing longwave radiation from the earth permit a prediction of increasing temperature with increasing carbon dioxide. Observations of the global CO₂ concentration show an increasing trend since the earliest observations and as the CO₂ content is assumed, on apparently reasonable evidence, to result from man’s increasing industrial and perhaps also his agricultural activity, projections of future levels have been made. On the assumption that CO₂ content could well double by the middle of the next century, numerical predictions with general circulation models (Manabe and Wetherald 1980; Manabe and Stouffer 1980) have shown a warming of the atmosphere averaging c. 2°C with much higher rises occurring in the polar regions (Fig. 17). From these results have followed predictions of reduction in sea-ice extent and thickness (Fig. 18) increased melting of continental ice sheets, global sea level rise, break up of the West Antarctic ice sheet and other phenomena. Scenarios based on analogies with present extreme seasons, on evidence from the Holocene warm period and from numerical models, have been produced (e.g. Pittock 1980; Pittock and Salinger 1982; Wigley et al. 1980).

It is now apparently generally believed that the upward trend of CO₂ is a continuing and irreversible process (at least without some enforcement of policies requiring a drastic reorganisation of global commerce, industry and society). However, we must note that the history of the measurement of CO₂ levels is a relatively short one; that the budget of the CO₂ sinks, particularly the polar oceans, is not at all well known and the mechanisms of the hypothetical secondary effects resulting from the increase are also not presently predictable with any certainty of accuracy. Thus, although the observed increases in CO₂ must be such as to arouse scientific study and to require a continuing program of
monitoring of sensitive climatic factors backed up with studies of historical analogies and increasingly realistic numerical modelling, a great degree of caution should be adopted towards our ability to predict future climates resulting from a CO₂ increase or indeed, any other change.

Concluding remarks

In this brief review of climates of the high latitude Pacific we have considered three time periods wherein our knowledge and our research methods vary considerably.

(i) The distant past, where field evidence, its interpretation and intercomparison are paramount. As yet the data are in general inadequate to define climatic parameters except in broad outline.

(ii) The present and recent past, for which we can describe average climates, and more importantly study the variability of the climatic record and the relationships between events at one location and their teleconnections. For this period, much data exist to test theoretical concepts and mathematical models of the way in which the atmosphere, ocean and ice interact to produce climate.

(iii) The future, where theoretical considerations and modelling are most important. Such concepts can be tested for the near future but for the distant future only remote prospects of observation of trend are now possible. The predictions are only as good as the theories and what is included and not included in models.

Thus a spectrum of uncertainty exists about climate. For the past we are gaining evidence, the present we only partly understand, the future despite our vital interest in it remains unknown, though we may note with some caution the predictions of the soothsayers.

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