, Ann Arbor, Michigan, May 10–12, 1977."

A. and Edgington, D. N. (1972). The use of
d fallout radionuclides to measure recent
tion rates in southern Lake Michigan. *In*
gical and Environmental Research Division
eport Part III," pp. 31–53. Jan–Dec 1972.
National Laboratory, ANL-7960.

A., and Edgington, D. N. (1975). Deter-
of recent sedimentation rates in Lake
using lead-210 and cesium-137. *Geo-*
Cosmochimica Acta **39**, 285–304.

A., Edgington, D. N., Gustinis, J., and
, J. O. (1975). Geochronology of Lake
sediments: anomalies in lead-210 distribu-
Radiological and Environmental Research
Annual Report, Ecology, III, pp. 40–50.
1974, Argonne National Laboratory, Ar-

A., Krezoski, J. R., and Mozley, S. C.
adioactivity in sediments of the Great
st-depositional redistribution by deposit-
ganisms. *Earth and Planetary Science Let-*
25–333.

., Turekian, K. K., and McCaffrey, J.
e accumulation of metals in and release
nents of Long Island Sound. *In* "Estuarine
" (L. E. Cronin, Ed.), pp. 28–43.
Press, New York.

er Service, "Climatological data, Michigan
mmary, 1914–Present." National Weather
National Oceanographic and Atmospheric
ation, Dept. of Commerce, Washington,

I. A., and Nelson, D. M. (1973). Residence
plutonium-239 and cesium-137 in Lake
water. *In* "Radiological and Environ-
search Division Annual Report, Ecology,"
9. Jan–Dec 1973, Argonne National La-
Argonne, Ill., ANL-3060, Part III.

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Late Quaternary Ice Age Climates of Tropical Australasia: Interpretations and Reconstructions

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Paleoecological and paleogeographical evidence is used to mold a framework from which the basic parameters of the late Quaternary glacial-age climate of tropical Australasia can be inferred. The theory of physical circulations, a knowledge of present tropical circulation patterns, and a study of anomalous and extreme events in the present era are used to reemphasize the view of a less pluvial tropical and subtropical zone at that time. Cooler sea-surface temperature, cooler trades, and the effect of the then exposed land areas are indicated as instrumental in producing drier conditions. Tropical areas west of Cape York Peninsula and Torres Strait were subject to fewer tropical disturbances and were similar to the present tropical savannah of the northern interior of Australia. Such effects would exist even without shifts in major climatic zones, although they are shown to be consistent with an equatorward shift of the westerlies brought about by the increased pole to equator temperature gradient. Paleoenvironmental evidence from the New Guinea Highlands and southeastern Australia suggests that their climates were anomalous. Substantial data of the glacial period in New Guinea show snow lines to be 1000 to 1500 m lower than at present which matches a 6 to 8°C lowering of temperature in highland New Guinea. The deep-sea cores of the CLIMAP Project suggest a mere 2°C cooling of the surrounding tropical oceans. It is shown that it is highly unlikely that an upper-level decrease in temperature of 6 to 8°C could be maintained while the surface cools by only 2°C. It is suggested that either the temperature of the tropical oceans of the western Pacific were overestimated by CLIMAP or that cold air incursions from higher latitudes (for which some analogs exist today) were sufficiently frequent to allow the maintenance of a snow line well below the freezing level of the ancient ambient tropical atmosphere. It is shown that in southeastern Australia considerable evidence of aridity cannot be explained by merely displacing the westerlies more equatorward. To account for the aridity, a new circulation pattern is proposed. Noting that there is CLIMAP evidence of preferred equatorward extension of sea ice, a pattern is postulated that displays only small seasonal change and is characterized by an enhanced Indian Ocean trough, marked ridging at eastern Australian longitudes, and a further trough in the western Tasman. Such a basic flow is consistent with (i) a low rainfall over southeastern Australia, (ii) frequent cold outbreak conditions favorable for the maintenance of the New Guinea glaciers, and (iii) considerable precipitation to nourish the ice caps of Tasmania and the Australian and New Zealand Alps.

INTRODUCTION

At this time there is not a complete or adequate physical theory which allows a full understanding of climate change or the state of the climate at any one particular time. Without the aid of a general theory or explicit observations and climatic records, the construction of a coherent picture of the climate of a past age must depend entirely on the use of implicit indicators or proxy climatic data.

The description of a past climatic state thus depends on: (a) broad paleogeomorphological and paleoecological evidence and (b) meteorological interpretation of indicators from other disciplines in relation to present knowledge of the general circulation by (i) the use of current theories of atmospheric motions, (ii) the development of a physical model using proxy data, and (iii) the investigation of periods of extreme meteorological conditions of the present climate.

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Inferring past climate from random field observations requires a guideline for their selection and interpretation. The occurrence of identical signals from the various proxy data is rare and should not be expected from a region as large as Australia which not only experiences a gamut of climates through the ages but also exhibits a great *spatial* variation of climate at any one time, in the same manner as present climate varies in space (Galloway, 1971). Thus even with perfect dating, care must be taken not to generalize from one observation, which may represent only a local climate at that one time. Conversely, one contrary but well-founded observation does not necessarily negate other observations. Any single observation should therefore be considered as a statistic that defies full interpretation unless considered with other members of the statistical ensemble.

In the present study, we do not add to the collection of proxy climate data. We present a brief summary pertinent to later discussions. This will suffice as a number of excellent and comprehensive interdisciplinary surveys and discussions relating specifically to the Australian region that exist in the literature (e.g. Gentilli, 1961; Galloway, 1971, Bowler, 1971, Costin, 1972, Williams, 1975, and especially Bowler *et al.*, 1976, and Rognon and Williams, 1977). Here, we attempt to form a cohesive climatological envelope within which to contain the various interdisciplinary evidence and form a description of the large-scale atmospheric and oceanic controls which may have affected the distribution of proxy climatic data.

We follow methodology (b) above as already utilized by Webster and Streten (1972) and Streten (1974). The methodology is based on the hypothesis that meteorological extremes and attendant controls of the present climate may illuminate processes which dominated the past. Our procedure is similar to that of Lamb (1961) who suggested that ". . . the maximum phases of the Quaternary ice age were in essence merely an extension of the circumstances of the present day. . . ." If Lamb's surmise is correct, information can be obtained about the climate of a particular age when insight gained from the study of extremes of the present climate, coupled with a knowledge of the present climate, is used to weigh evidence accumulated by various paleoenvironmental disciplines.

INTERDISCIPLINARY EVIDENCE OF PAST CLIMATE

Geomorphological Data

Following Jennings (1971), who quotes the Timor Shelf observations of Van Andel *et al.* (1967), the 200-m submarine contours of present bathymetric maps were adopted as close approximations to the coasts at the last glacial maximum. Figure 1a shows the extended land mass based upon such an assumption. The most important features are the extensive plain areas occupied by the present Timor and Arafura Seas, the Gulf of Carpentaria and Torres Strait, the extension of the coastal plains along the northern coast of western Australia and the Great Australian Bight, a dry Bass Strait joining Tasmania to the mainland, and extended coastal plains along the eastern coast. In Indonesia and the South China Sea, a vast land area connected southeast Asia, Kalimantan (Borneo), and the Philippines. The decrease in sea level was a result of an accumulation of ice, principally in the Northern Hemisphere continents and the Antarctic.

The assumption of general large scale tectonic stability on the time scale of the late Quaternary is probably correct for most of continental Australia although some movement of the Selwyn Upwarp (located to the south of the Gulf of Carpentaria) has been noted by Twidale (1966). New Guinea, on the other hand, shows signs of intense and recent tectonism in the central mountain chain (Galloway *et al.*, 1973). Veeh and Chappell (1970) suggest a substantial uplift of as much as 140 m on the Finsch Coast

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(northern coast of New Guinea) during the last 50,000 yr. Despite extremely rapid variations of the topographical relief, at least relative to a geological time scale, it is unlikely that these have contributed substantially to climatic variations on the time scale of the last glaciation and such effects would be absent from the proxy data. Most likely, the topographic variations which have produced significant climate variations during the late Quaternary are those associated with the well-documented and world-wide drop in sea level.

During the last glacial maximum, extensive glaciation occurred in Tasmania and small glaciers were evident in the Snowy Mountains of the Australian Alps. In New Guinea (see Fig. 1b), substantial glaciation occurred in the higher parts of the Central and Maoke Ranges (Löffler, 1972; Bowler *et al.*, 1976). Mt. Wilhelm (4510 m, eastern Central Range) and Mt. Jaya (4884 m, Maoke Range)[1] were significantly glaciated and with other peaks provided a total estimated glaciated area of about 2000 km^2 (Löffler, 1972). This may be compared with the less than 8 km^2 at the present time which is confined to Mt. Jaya. Cirque and moraine remnants indicate postglacial protrusions down to at least 3000 m with the lowest snow line indicated near 3500 m (Löffler, 1972).[2] This is at least 1000 to 1500 m lower than the present level.

Bowler *et al.* (1976) note that glacial retreats began 15,000 to 14,000 yr B.P. with most peaks below 4500 m being ice free by 9500 yr B.P. Two advances in 11,600 yr B.P. and about 3000 yr B.P. interfere with this steady retreat. The glacial retreat in New Guinea appears to have lagged the retreats in southern Australia.

Reiner (1960) has noted that the late Pleistocene snow line on Mt. Wilhelm was probably some 150 to 300 m lower than on Mt. Jaya. This is substantiated by Löffler (1972) who sets the ancient snow lines at near 3650 m in the Owen Stanley Ranges (eastern New Guinea), 3500 to 3400 m in the Central Ranges, and 3650 m in Irian Jaya (western New Guinea). A large percentage of cirques on Mt. Wilhelm face toward the southeast (Gentilli, 1961) in contrast to the Mt. Jaya region where the present glaciers extend toward the northwest (Mercer, 1967).

[1] The former Mt. Carstenz.

[2] Löffler's method of determination of ancient snow levels is an empirical relationship based on the arithmetic mean of the altitudes of terminal moraines, the mean altitude of the catchment area, and the altitude of the lowest cirque floor.

Palaeoenvironmental Data

Using proxy climatological data, the CLIMAP Project Members (1976) (hereafter referred to as CLIMAP) attempted to reconstruct the surface conditions of the Ice Age earth (i.e. 18,000 yr B.P.). The determination of the sea-surface temperature distribution and the sea-ice limits is significant for the present study as it not only allows an estimate of the state of one of the most important climatic controls but allows local proxy data to be placed within a larger perspective. In the CLIMAP study, three planktonic groups were identified in various quantities in some 247 deep-sea cores and their relative abundance related to the sea-surface temperature. Sea-ice margins were identified using a combination of geological and biological evidence.

The section of the CLIMAP August 18,000-yr B.P. reconstruction which is directly pertinent to this study is shown in Fig. 2. The difference between the present and the ancient temperatures and the locations of the deep-sea cores used in the reconstruction are also shown in Fig. 2 and appear as dashed lines. The core distributions appear sufficient to define the ice margin to the south west of Australia, the temperature variation along the western Australian coast, and perhaps the temperature of the tropical oceans. The large deviations in the New Zealand area were deduced implicitly and are discussed by CLIMAP (1976).

In the Australasian region, CLIMAP sug-

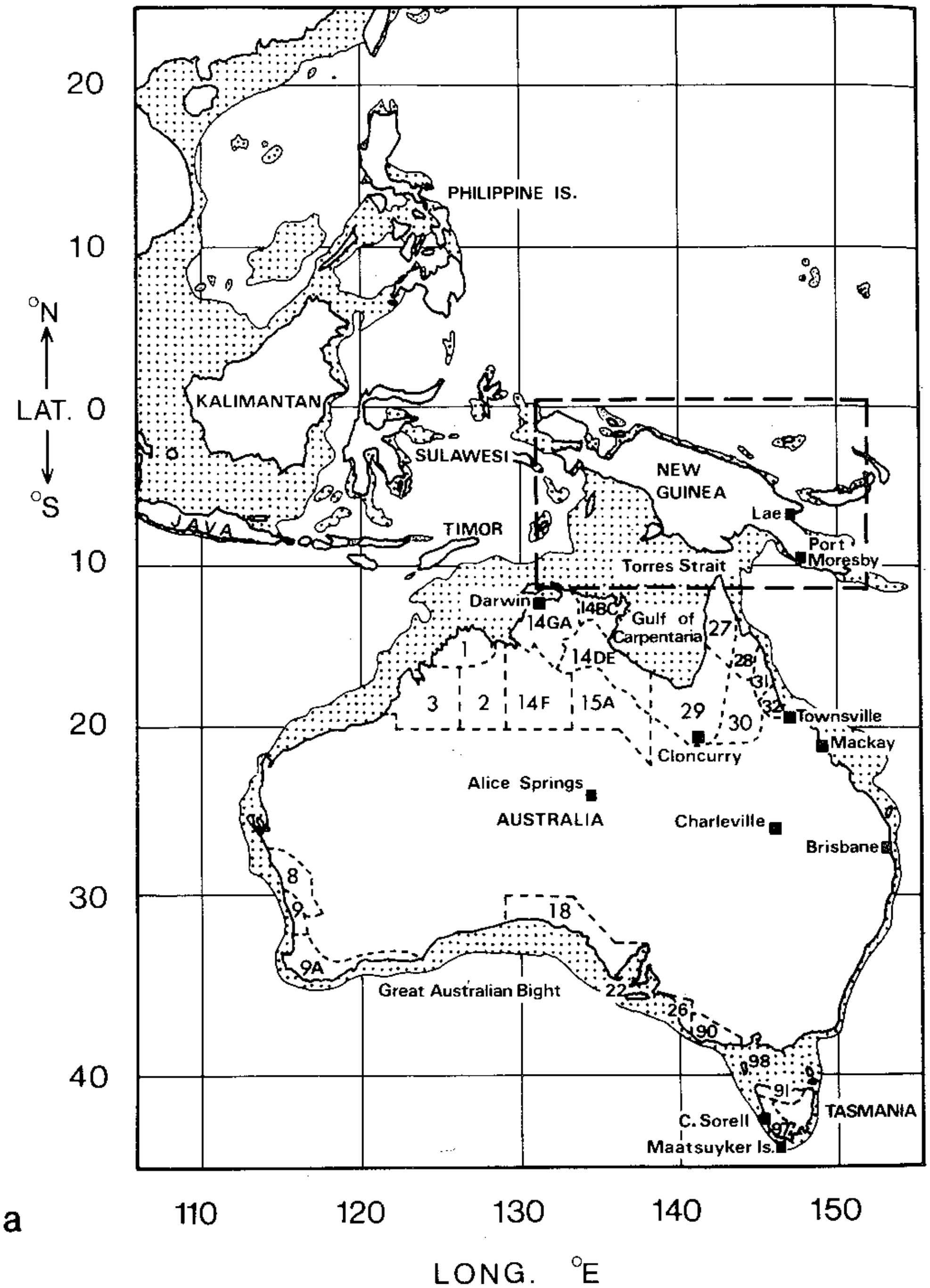
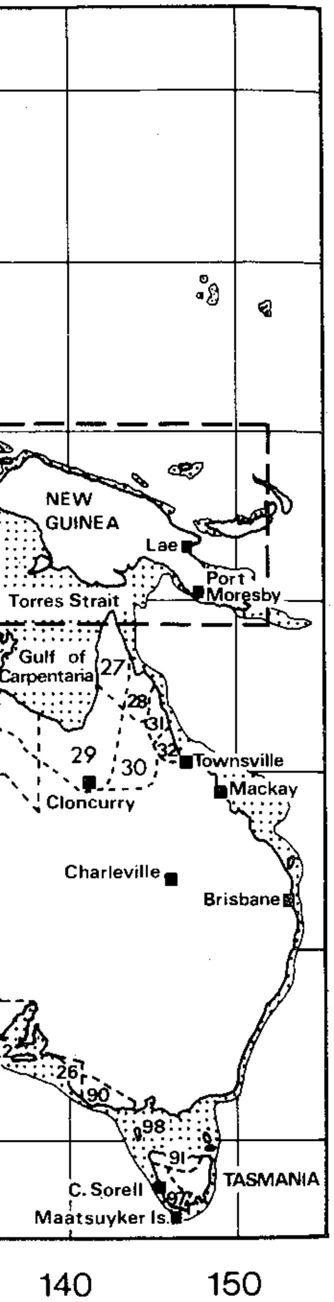


FIG. 1a. Map showing Australasian region with ancient exposed land stippled. Coastal demarcations indicate present coastal limit (inner contour) and the present 200-m bathymetric contour (outer contour) which approximates the ancient coastline during the last glacial maximum. Relevant place names and present Australian rainfall districts are indicated.



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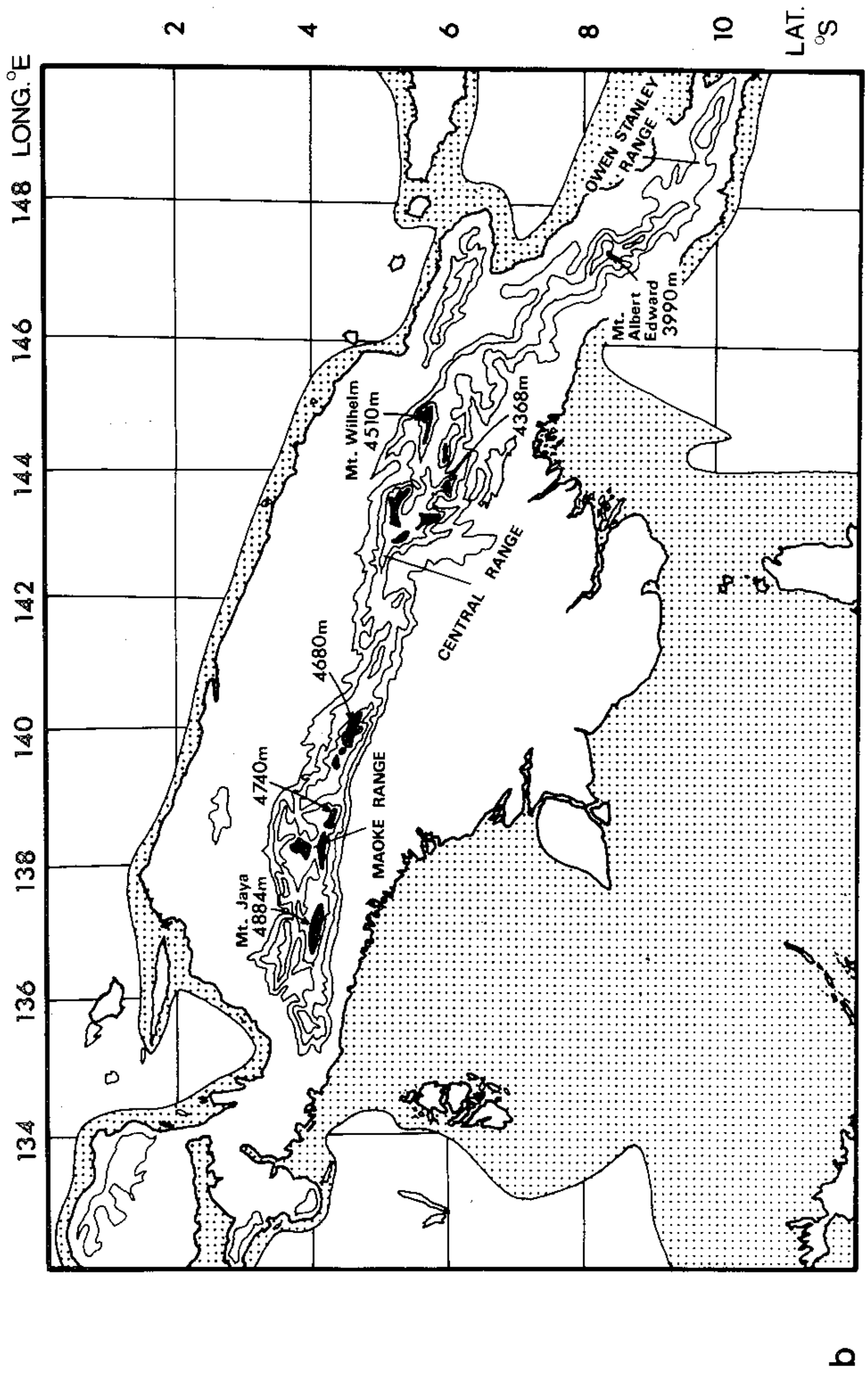


FIG. 1b. Insert relative to dashed line in Fig. 1a showing detail of the New Guinea orography. Contours are −200, 0, 1000, 2000, 3000, and 4000 m. Selected peak heights are indicated with place names.

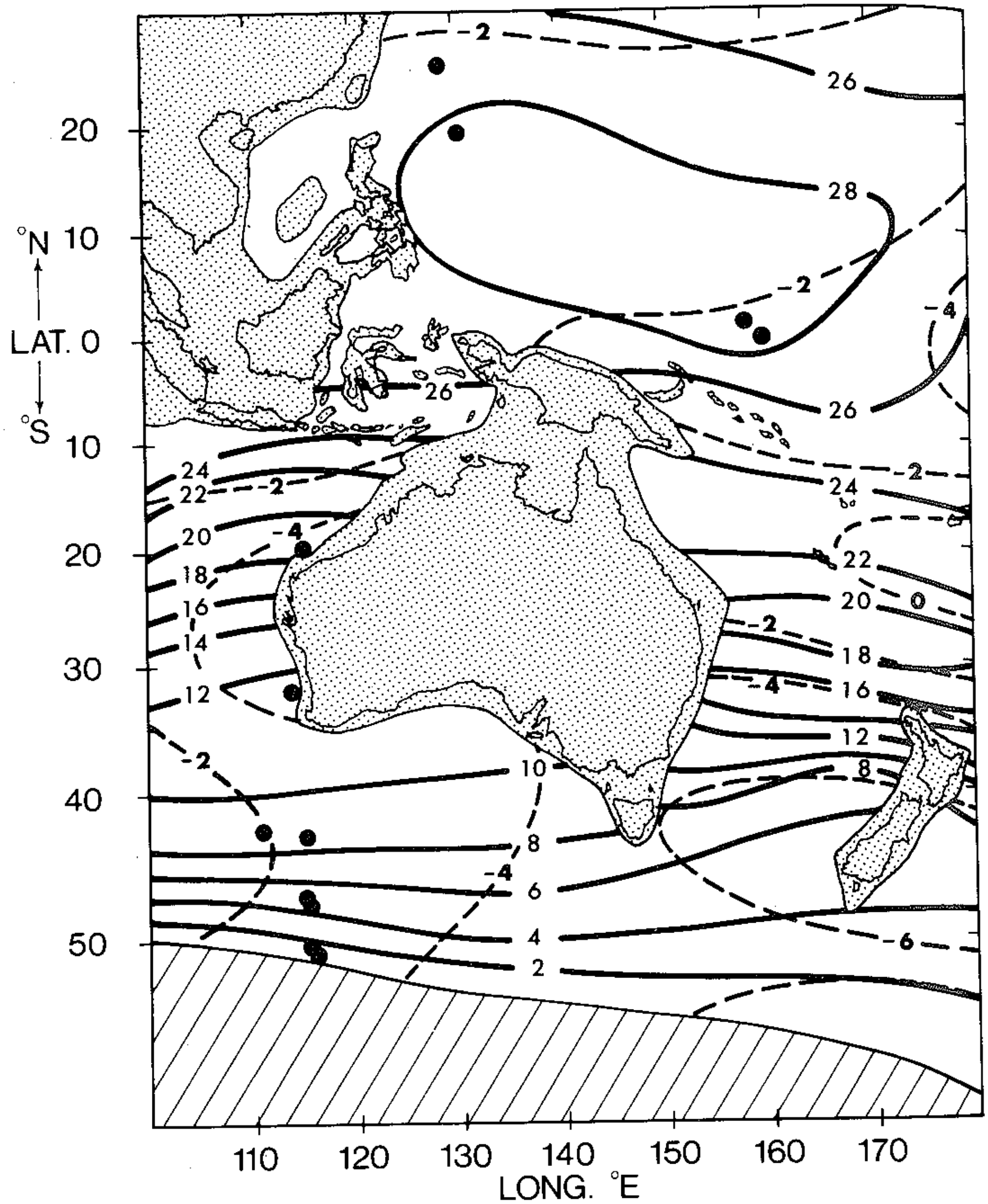
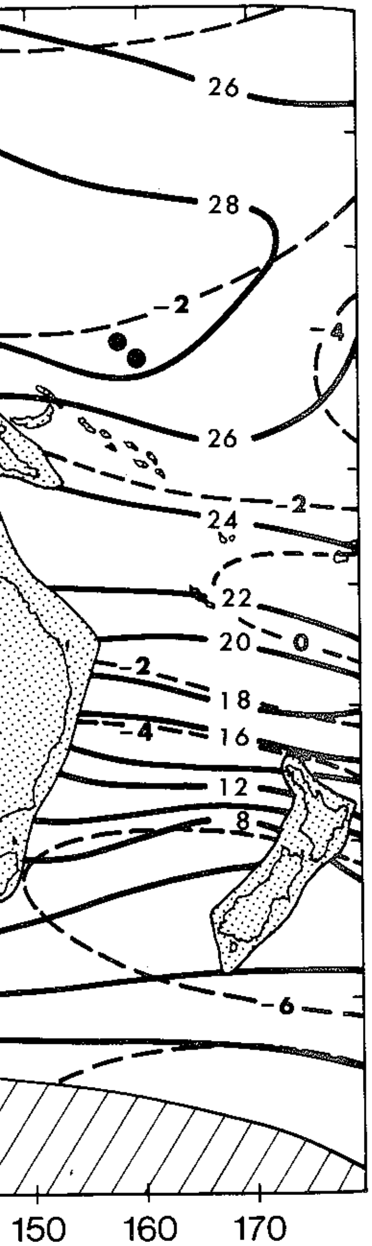


FIG. 2. Sea-surface temperature distribution (°C) at 18,000 yr B.P. (August) as determined by CLIMAP (1976). Dashed lines indicate local deviations from present August temperatures. Hatched area in the south indicates August sea-ice limits. Solid circles indicate deep-sea core locations used by CLIMAP in the sea-surface temperature reconstruction.

gests a probable 10 to 12° latitude equatorward migration of the Southern Hemisphere winter sea-ice margin. Sea-surface temperatures were about 4°C cooler than at present on the western Australian coast and 2°C cooler over the western equatorial Pacific. The latter point would suggest that the sea-surface temperature over the western



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Pacific Ocean was similar at low latitudes to that of the western Atlantic Ocean (Gardiner and Hays, 1976).

Data from tropical Australia indicate a generally drier climate during the last glaciation than at present (Bowler *et al.*, 1976). For example, the Atherton Tableland was significantly drier before 10,000 yr B.P. Precipitation was inferred from the pollen records from Lynch's Crater (Kershaw, 1974). Similar conditions prevailed in the northwest as indicated by extensive dune formation at that time. Evidence is interpreted to indicate a less pluvial period, an increased continentality, a decreased northwest monsoon circulation, and cooler and drier trades (Wright, 1964; Fairbridge, 1965; Gentilli, 1961; Bowler *et al.*, 1976). Interestingly, the period corresponding to the hypsithermal (5000 yr B.P.) was apparently much wetter than at present.

A number of sites in the New Guinea Highlands (e.g., Mts. Wilhelm and Jaya, Sirunki, Inim, and some others) provide evidence of climatic variation via carefully analyzed pollen histories. A thorough analysis is presented by Bowler *et al.* (1976) and we merely point out that all sites indicate a fairly consistent variation back from the present time through the maximum glaciation (18,000 yr B.P.) to the "preglacial" period (25,000 yr B.P.). The course of the ancient temperatures is summarized in Fig 3 where data from seven sites from Mts. Wilhelm and Jaya are plotted with appropriate error envelopes. The small inset curve in the lower right of Fig. 3 indicates the variation of the 1000-yr average temperature calculated by weighing all data equally. Two events appear well defined. These are the small relative temperature maximum (1.5° warmer than present) which probably corresponds to the hypsithermal between 4000 and 6000 yr B.P. and the cool period (6–8°C below present) between 16,000 and 18,000 yr B.P. The hypsithermal is well established by five estimates whereas two independent determinations fix the temperature at the glacial maximum.

PALEOENVIRONMENTAL INTERPRETATIONS

An understanding of the paleoenvironments which have produced the various poxy climatic clues must offer simultaneous explanations of all the features discussed above. Furthermore, it should allow a climatic description of the now submerged lands in the coastal regions of Australia which is of extreme importance from anthropological and paleoecological viewpoints.[3]

In the last section it was suggested that northern Australia was considerably drier and somewhat cooler and that there were generally cooler sea-surface temperatures with a maximum lowering of temperature of 4°C off the west, southwest, and southeast coasts of Australia but of only 2°C off the eastern and northern coasts. The land area of tropical continental Australia was significantly increased by the receding ocean level, and New Guinea, Australia, and Tasmania were physically joined. The largest temperature decreases occurred in the New Guinea Highlands where substantial glaciation was evident with a considerable lowering of the snow line.

An important aim of a paleoenvironmental interpretation is an attempt to discern whether or not a local indicator (e.g., anomalously drier conditions in northern Australia) resulted directly from the imposition of planetary scale controls (such as the strengthening of the Hadley Circulation) or as the result of the variation of a local control (such as the increased land area). Such a determination is of some importance as it allows a perspective through which the various proxy climatic data may be viewed.

Controls of the Current Climate

The present low-latitude climate is dominated by the release of latent heat

[3] See Walker, D. (1972). "Bridge and Barrier: The Natural and Cultural History of Torres Strait," conference proceedings, Research School of Biogeography and Geomorphology, Publication BG/3, Australian National University.

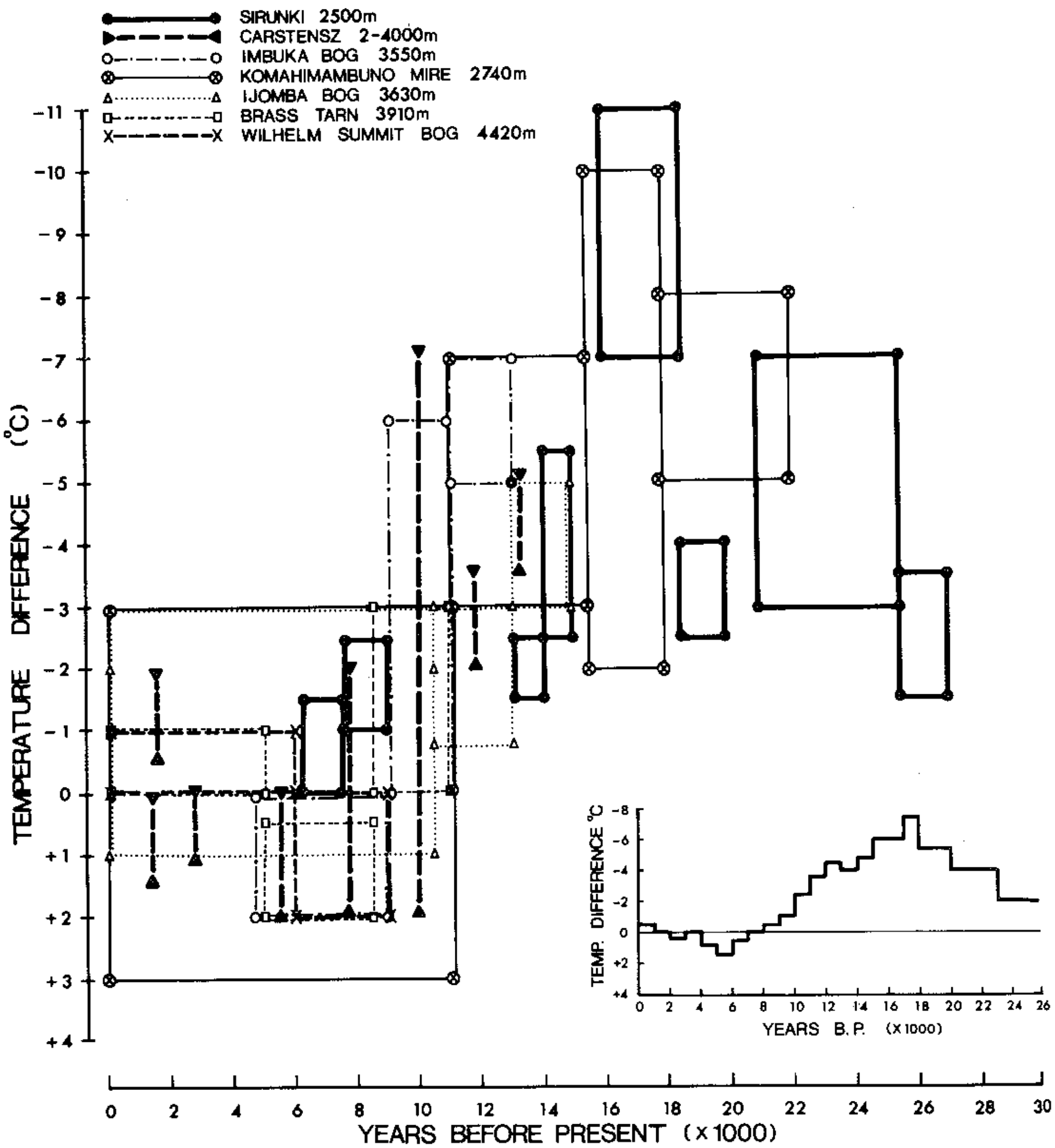
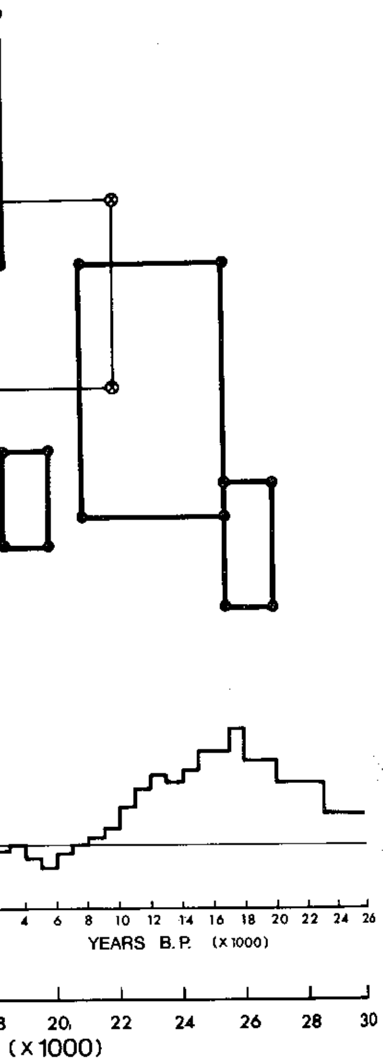


FIG. 3. Summary of the New Guinea Highland temperature deviations from present temperatures (°C). Data, relative to legend in upper left of diagram, are plotted to indicate both temperature anomaly and temporal uncertainty. Inset (lower right): A composite of the temperature variation, obtained as an average of all proxy data equally weighted.

arising from weather systems forming and propagating within the tropics (e.g., Riehl, 1954; Riehl and Malkus, 1958). It is generally thought that the *in situ* release of latent heat influences the climate of the tropical regions to a greater extent than does the importation of heat and moisture from higher latitudes by the extratropical disturbances. In the last section, we noted evidence of a less pluvial tropical region during the last glaciation. It is important that we establish the mechanisms involved in the decrease of precipitation and, if possible, recognize them relative to the known facts of the present tropical atmosphere.

An indication of the main features of the



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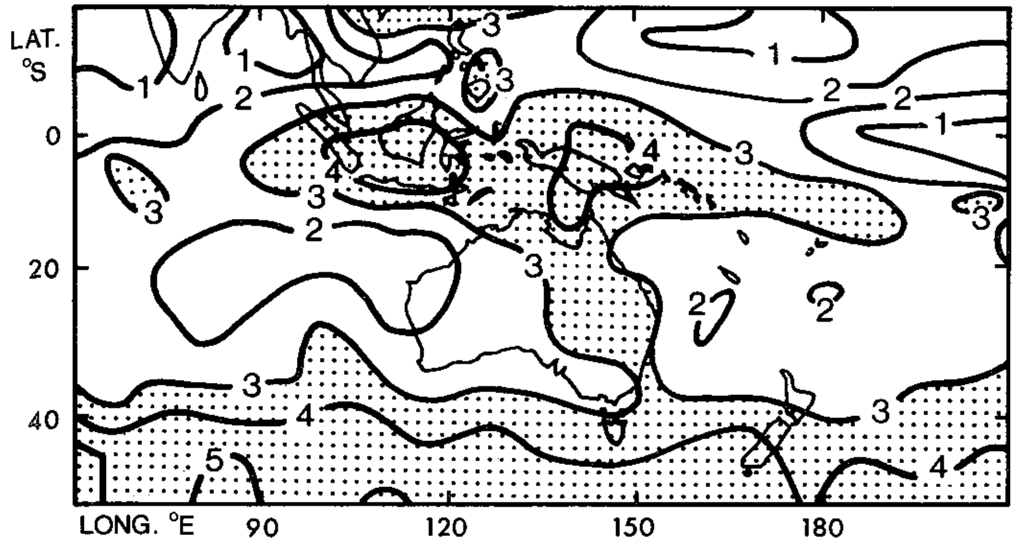

FIG. 4. Relative visual brightness for the Australasian region averaged over December, January, and February 1967 to 1968 from ESSA 3 and 5 satellites (after Taylor and Winston, 1968).

present moist atmosphere in the Australasian region is displayed in Fig. 4 where the satellite-viewed average visual brightness over the Australasian region for December, January, and February (1967–68) is shown. Two dominant features are evident. The first is the zone of low cloudiness[4] straddling the subtropics (15–35°S) which corresponds to the mean positions of the subtropical high pressure cells and an area of low precipitation. The second is the cloud band stretching zonally across tropical Australasia which corresponds to the near-equatorial trough of the Southern Hemisphere within which most of the tropical rain-producing disturbances develop and propagate. The near-equatorial trough zones are not only the most disturbed but also the wettest. Longitudinal variation of the disturbed region also exists with the eastern equatorial Pacific containing minimum cloudiness and precipitation. This is a manifestation of an east–west cell with rising motion in the vicinity of Indonesia and New Guinea (the region of maximum cloudiness in Fig. 4) and descending motion in the eastern Pacific Ocean. The circulation is termed the Walker Circulation (e.g., Webster, 1972) and is thought to be closely related to the sea-surface temperature distribution (Bjerknes, 1969) which exhibits a maximum in the western Pacific Ocean and a minimum in the east. The weak maximum extending meridionally over eastern Australia is associated with the relative trough which exists between two semipermanent high pressure cells. A similar maximum exists in the winter months.

Two general theories exist to explain the intensity and position of the disturbed near-equatorial trough. The first places most importance on the dynamics of the tropical boundary layer (Charney, 1969) while the second emphasizes the distribution of sea-surface temperature about the equator (Pike, 1971). Both are not mutually exclusive and each emphasizes the need for an equatorward flux of moist air via the trades. Both theories agree that if the trades were drier, perhaps due to a reduced evaporating surface or cooler sea-surface temperatures, then we may expect a weaker and less disturbed near-equatorial trough and possibly fewer disturbances.

[4] It is generally assumed that visual brightness is an indicator of cloudiness except in continental desert and ice cap regions of high surface albedo.

Two other classes of phenomena are responsible for the low-latitude precipitation distribution and which do not depend primarily upon a warm sea-surface temperature. These are the flow of a moist stream against an orographic barrier (e.g., the New Guinea Highlands or the Queensland coast) and the diurnal thunderstorms which are distributed near randomly and require principally a moisture supply and a warm lower boundary. Riehl (1954) suggests that some 75% of precipitation results from disturbances associated with the near-equatorial troughs. Consequently, the precipitation at a particular location may depend somewhat on its orographic structure but primarily upon the passage or development of tropical disturbances.

The histograms of Fig. 5 show the marked seasonal nature of the present rainfall regime in the selected rainfall districts of northern Australia (demarked on Fig. 1a). On the northern coast of Australia there is a rapid falloff of the summer rainfall averages (the wet season) with increasing distance of the district from the coast (cf. districts 14GA, 14DE, and 15A). Similar characteristics may be observed by comparing the eastern Cape York Peninsula stations with those inland (cf. 31 and 32 with 30); here the difference is accentuated by the inland stations being on the lee of the eastern highlands.

In the tropics, most of the precipitation is due to organized disturbances rather than to random thunderstorms. An investigation in South America (Olascoaga, 1950) showed that over a wide range of latitude, elevation and average annual rainful, 10 to 15% of rain days accounted for 50% of the total rainfall and that 25 to 30% of rain days accounted for 75% of total rainful. The fragmentary precipitation data that does exist for the New Guinea Highlands (summarized for the Mt. Wilhelm region by Hnatiuk *et al.*, 1976) suggests a similar distribution to that found by Olascoaga. For example, some 81% of precipitation fell at Pindaunde (Mt. Wilhelm) on 18% of days during 1972. Synoptic experience suggests that the decrease of rainfall inland in northern Australia primarily results from lack of organized weather systems at any considerable distance from the coast. Such dynamic systems draw upon the warm tropical sea surface as a source of much of their energy and decay rapidly after moving over land.

The ultimate development of tropical disturbances forming over the warm oceans is the tropical cyclone (also known as the typhoon or hurricane), which also weakens with passage over land. However, in contrast with the smaller scale and weaker tropical disturbance, they may on occasion maintain their circulation and rainfall production for a considerable period and distance after moving inland. Indeed the infrequent precipitation in many inland arid regions of Australia (notably inland western Australia) depends upon the occasional inland incursion of the remnants of a tropical cyclone (see districts 2 and 14F of Fig. 5).

Figure 6a illustrates the frequency of tropical cyclones crossing or passing within 160 km of the coast within well-defined particular sectors as determined by Coleman (1971).[5] Coleman's 50 yr of data (1909–1969) show very high frequencies off northern Queensland and across the north coast of Australia, especially in the Gulf of Carpentaria area. Further, there are a large number of disturbances which do not reach tropical cyclone intensity within the equatorial trough which passes through the Gulf of Carpentaria and the Arafura and Timor Seas. Figure 6b shows the distribution of tropical cyclogenesis (i.e., number of cyclones forming in a region during the data period). Note in particular the maximum in the Gulf of Carpentaria and the minimum over land. Significantly, tropical cyclones appear to require warm surface temperatures for their formation. In fact, evidence from studies by Riehl (1954) indicate that tropical cyclones do not form when sea-surface temperatures are

[5] These data have recently been updated to 1975 by Lourensz (1977).

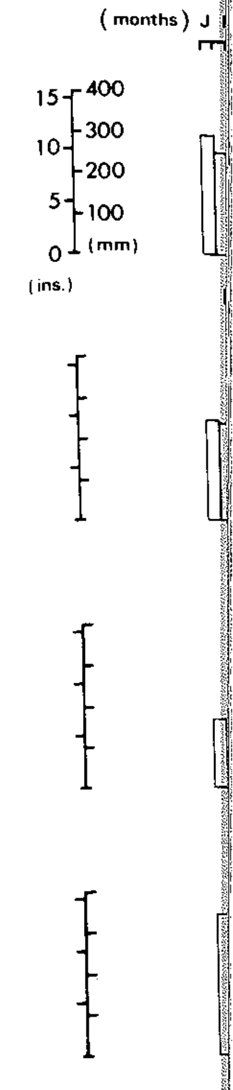

FIG. 5. Monthly distr
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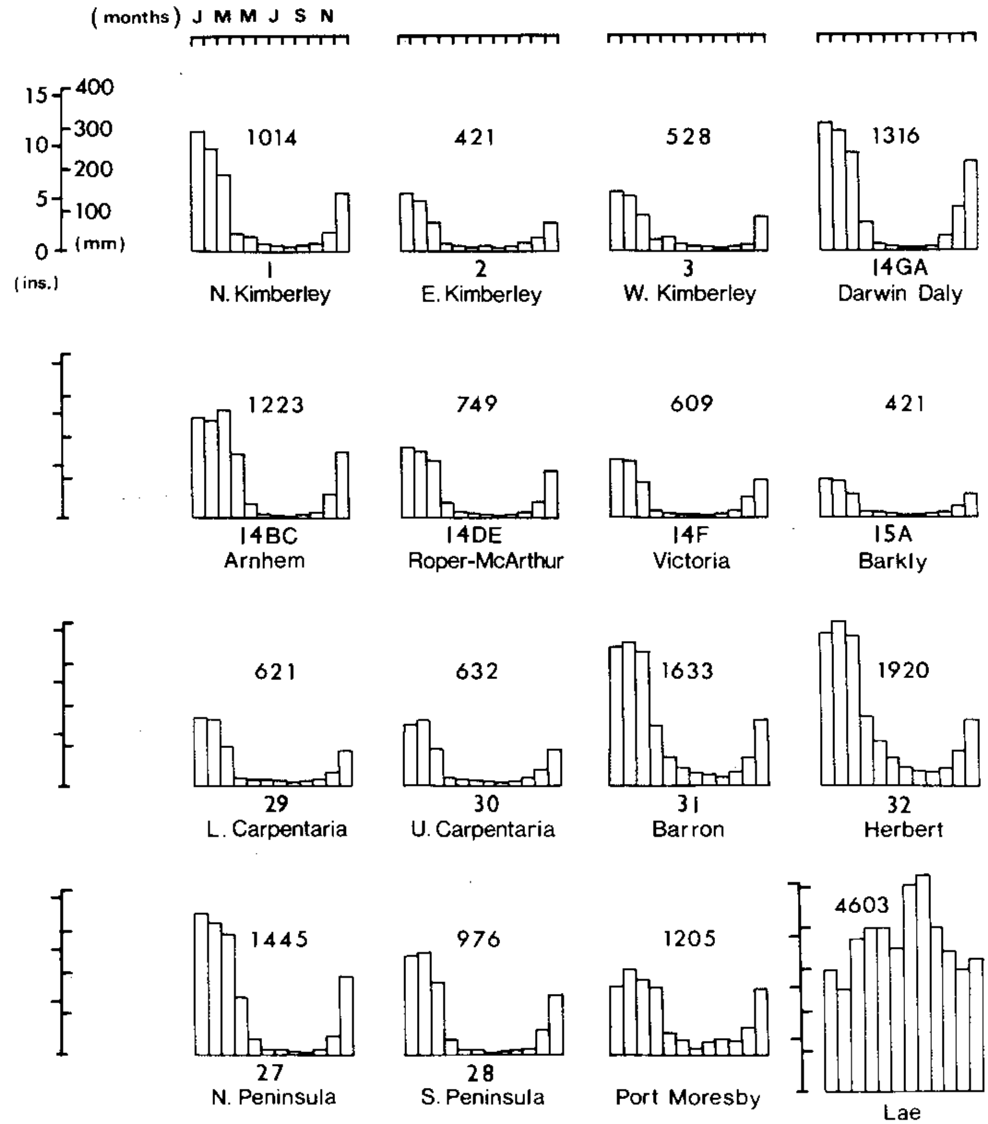


FIG. 5. Monthly distributions of precipitation for the northern Australian rainfall districts of Fig. 1 and two representative New Guinea stations. The annual rainfall in millimeters is shown above each histogram.

below 26 to 27°C. Also in regions of cool sea-surface temperature (e.g., the eastern and southeastern Pacific Ocean) tropical disturbances of all classes are unobserved. In summary, the effect of sea-surface temperatures on tropical disturbances is profound: their occurrence and formation are positively correlated with sea-surface temperatures.

The temperature of the free atmosphere (i.e., away from the ground) is an integral part of the present climatological state of the earth and is not independent of surface conditions or vice versa. Although rarely discussed in the literature because of obvious proxy data restrictions, the upper temperature structure of paleoenvirons must also be of similar importance. In anticipation of a discussion of the vertical temperature structure during the last glaciation in tropical Australasia, we make some points regarding

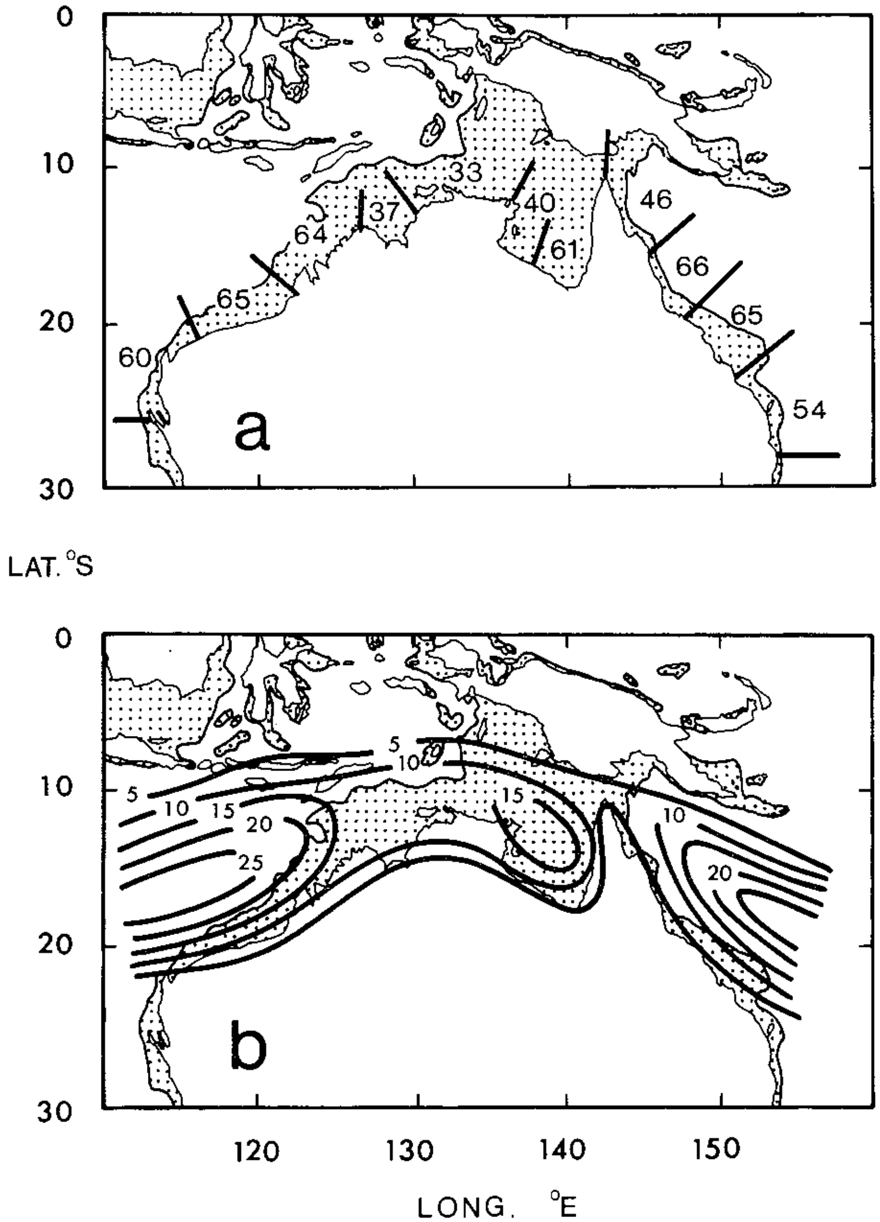
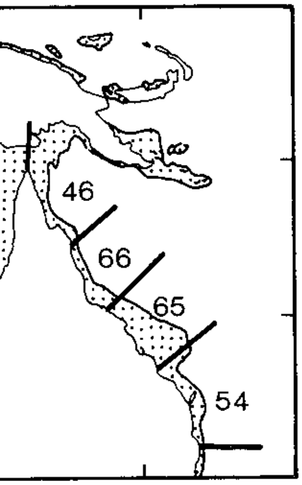
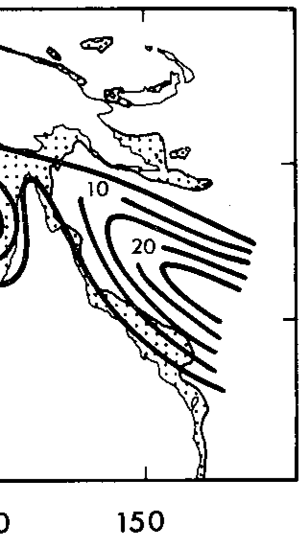


FIG. 6. Frequency of (a) tropical cyclones crossing or passing within 160 km of the coast within indicated sectors and (b) tropical cyclogenesis. Data are based on 60 yr (1909–1969) of records by Coleman (1972). Stippled area is that of exposed land at the last glacial maximum.

the present climate paying particular attention to the average lapse rates below about 5 km upon which the snow line depends.

Figure 7 shows the vertical temperature distributions of a number of stations (demarked on Fig. 1a) as a function of height. All stations show average profiles for June using 16 yr of data (except for Lae for which the January profile is also shown). Temperature is indicated as a function of height and displayed upon a background grid of dry adiabatic lapse rate curves (DALR) and





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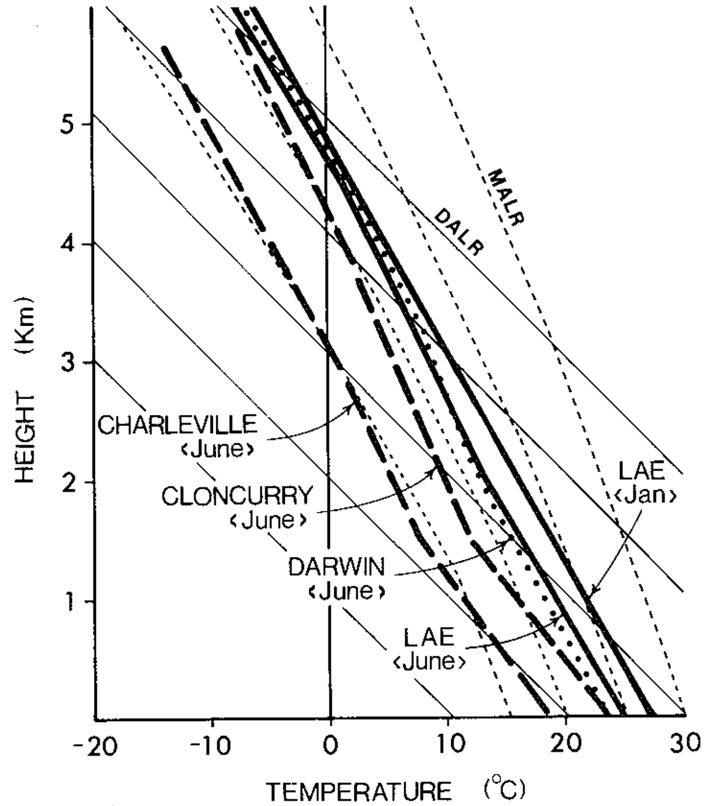

FIG. 7. Mean upper air temperatures for selected stations shown in Fig. 1 (see text).

moist adiabatic lapse rate profiles (MALR).[6] The most important feature is that all profiles from Charleville in the south to Lae in northern New Guinea possess moist adiabatic lapse rates above 1 to 1.5 km. Most significant is the moist character of the most southerly station shown (i.e., Charleville) and also Darwin, which in June are almost completely without rainfall; the trajectory of air over Darwin at this time of year is predominantly from the dry continent. The major difference between the Lae profile and that of Charleville is that the latter station is drier in the lower levels and hence has a steeper lapse rate. For example, the average lapse rate for Lae over the first 5 km is 5.6°K km^{-1} whereas for Charleville it is 5.8°K km^{-1}; that is, both lapse rates are a little greater than moist and are thus substantially less than the 9.8°K km^{-1} attributed to the dry adiabatic ascent.

There exists a correlation between the temperature of the free atmosphere at the coast of New Guinea and the temperature of elevated terrain. Figure 8 shows a plot of the June and January mean temperature profiles (enveloped by ±SD curves) for Lae against height. Superimposed upon these curves are the annual ranges of temperatures (winter on the left of the bar, summer on the right) as recorded at a number of levels on the slopes of Mt. Wilhelm. The temperatures were derived from the Mt. Wilhelm data by taking the mean of the maximum and minimum temperatures of Hnatiuk *et al.* (1976). Given that each site represents

[6] The moist and dry adiabatic lapse rates are the temperature variations a moist or dry air parcel is *constrained* to follow during vertical ascent. The lapse rates depend solely upon the magnitude of gravity and the composition of the atmosphere, which includes the water vapor content.

a different exposure, the agreement with the adjacent free atmospheric temperature (defined as the temperature above Lae) is good. Therefore we may be fairly certain that the temperature of the terrain at a particular height is matched by the temperature of the atmosphere at the same height over the adjacent tropical ocean.

With the aim of interpreting mean snow lines of various locations in Australasia, we show contours of the height of the freezing level assumed to be representative of the current era based on 10 yr of daily upper air soundings averaged over each month. These are shown in Fig. 9a in units of decameters. As expected, freezing level is a strong function of latitude with lowest levels in the south and highest levels in the north. The three main areas upon which permanent winter snow resides (Tasmania, southeast Australia, and the New Guinea Highlands) all show correspondence between mean snow level and mean freezing level although absolute verification is difficult. Present snow levels on Mt. Wilhelm (Hnatiuk *et al.*, 1976) agree well with the climatological distributions. Snow is observed to fall but only to remain in shady sections on the higher levels of Mt. Wilhelm. The height of Mt. Wilhelm and the climatological freezing level are almost the same during winter. Mt. Jaya remains at or above the freezing level throughout the year.

Figure 9b offers a different perspective of the annual freezing level by displaying its annual course for selected stations in low latitudes. Stations such as Charleville and Brisbane show variations of 1600 m from summer to winter with the lowest freezing level occurring about a month after the win-

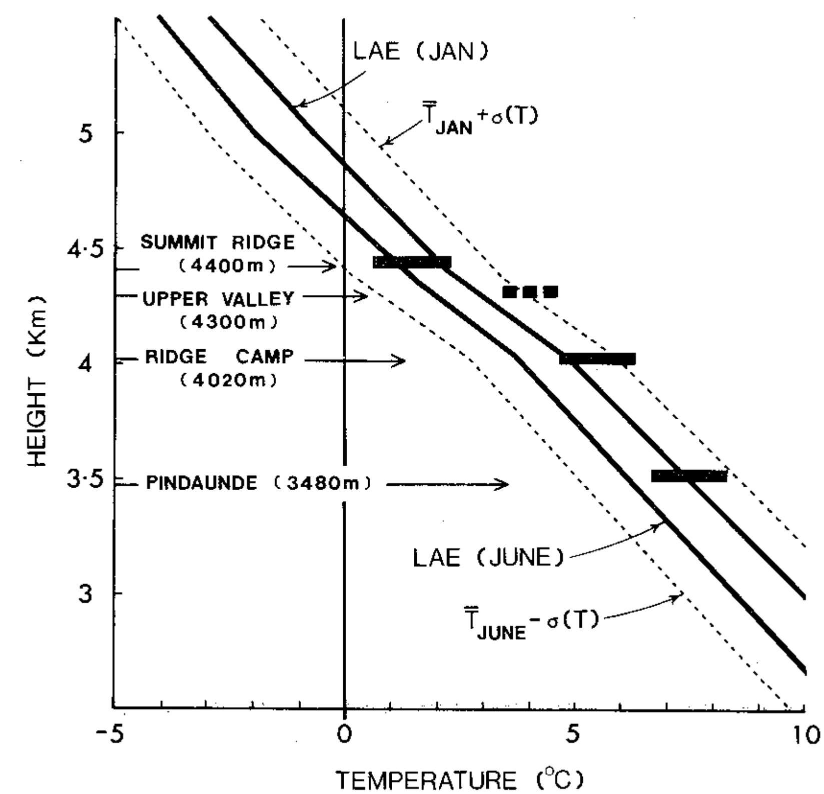

FIG. 8. Mean and SD of Lae upper air temperatures in January and June in relation to annual ranges of temperature at stations on the slopes of Mt. Wilhelm (see text).

and the New Guinea Highlands) correspondence between mean and mean freezing level although erification is difficult. Present s on Mt. Wilhelm (Hnatiuk *et al.*, well with the climatological dis- Snow is observed to fall but only in shady sections on the higher Mt. Wilhelm. The height of Mt. d the climatological freezing level the same during winter. Mt. Jaya or above the freezing level through- ar.

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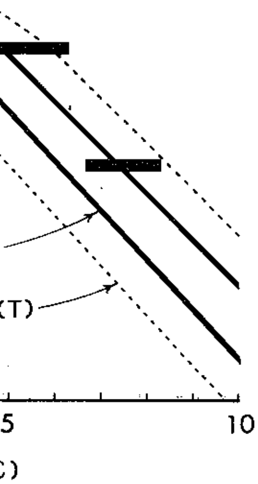

nd June in relation to annual ranges of

ter solstice. The near equatorial stations (e.g., Darwin and Lae) show variations of only 200 m or so. Remembering Löffler's snow line determinations, it is interesting to note that only air masses such as those characterized by Brisbane and Charleville possess freezing levels commensurate with ancient New Guinea snow levels during the entire winter months.

On time scales smaller than those indicated by the monthly averages shown in Fig. 9, significant variations occur in the local freezing level due to synoptic weather systems. The largest decreases in the tropical north are caused by cold polar air incursions. An example is shown in Fig. 10 which describes the development of an upper-level low pressure region in central Queensland during mid-July 1965. Similar incursions but of rather less severity occur irregularly but perhaps once every second year in the recent climatic era. Usually associated with cut-off low pressure regions off the east coast (Fig. 10a) such situations may cause extensive snowfall in southern Queensland extending at times into elevated areas of the tropical north (Fig. 10c). During this event, snowfall covered some 90,000 km^2 from 30°S to as far north as the highlands near Mackay (21°S), which was perhaps the maximum equatorial penetration of snowfall recorded this century.

The variation of freezing level accompanying the incursion is shown in Fig. 10b. From July 15 to July 18, the freezing level at Cloncurry (CL), Charleville (C), and Townsville (T) fell by 1200 to 2000 m. Figure 11 displays the drop in freezing level averaged over five such polar incursions. Although the average fall is a little less than that of the extreme case a mean lowering of some magnitude occurred over much of the tropical north of Australia.

It will be argued that one could expect the polar incursions to be more prevalent during the last glaciation and that such events may have been extremely important in determining paleoenvironments in tropical Australia.

Effects of Changes in Climate Controls

The increase in tropical land area. The existence of a land bridge joining northern Australia and New Guinea and the exposure of much of the northwest shelf points toward changes in the paleoenvironment of tropical Australasia which may be inferred without recourse to any major change or displacement in the basic features and driving mechanisms of the atmosphere. In any event, it is worth viewing paleoecological evidence simply as a product of a local consequence of sea-level reduction before invoking models which involve changes in the global oceanic and atmospheric structure.

The sea-surface temperature of the tropical oceans possesses a profound and complicated influence upon the global circulation of the atmosphere and we therefore expect some influence in the Australasian region. The summer surface temperatures in the tropical north are generally 4°C higher than in winter. Considering the Timor Sea region, Van Andel and others (1967) speculated that the sea-surface temperature would be appreciably cooler as the warm current through Torres Strait would be blocked and thus allow a greater incursion of the cold waters northward up the coast of western Australia. Such an effect would be maximized in winter when the flow through Torres Strait is warm and westward, although at all times of year one could expect the temperature on the western side of the continent to be considerably cooler than on the east at a given latitude. Stronger and more equatorward Ice Age westerlies as have been advocated by various authors (Lamb, 1961) would also increase the cold water incursion up the western coast of Australia and render the climate of the western and northwestern coasts of the late Quaternary Australia similar to the western coast of the present South America. Without a Torres Strait there would be no alleviation of an increased cold water flux. Such modifications would probably extend through the summer and render the Timor Sea and east-

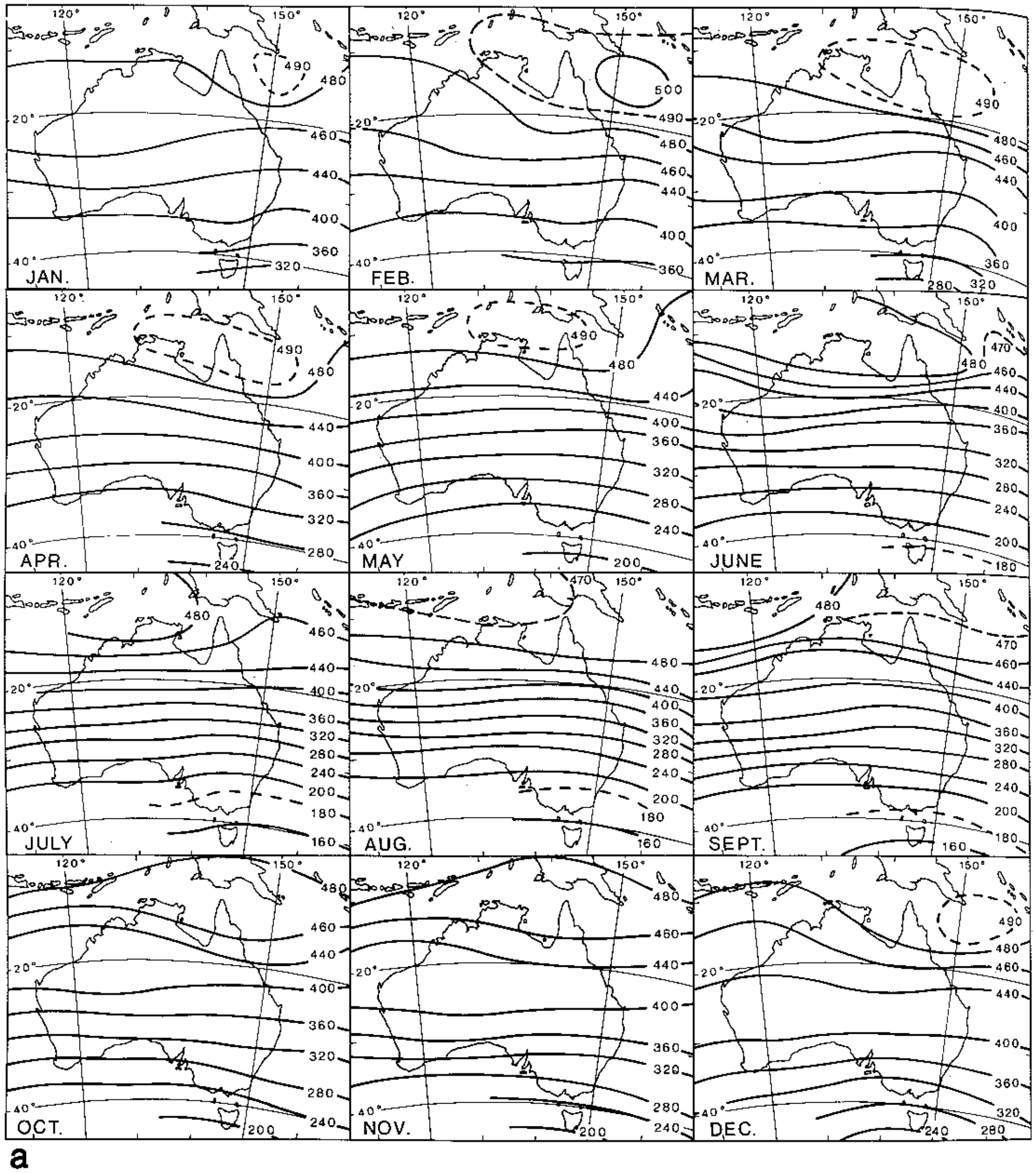

FIG. 9. (a) Mean height of the freezing level (F) over Australia (decameters). (b) Annual course of freezing levels at selected stations. A, Alice Springs; B, Brisbane; C, Charleville; CL, Cloncurry; D, Darwin; T, Townsville; L, Lae.

ern Indian Ocean relatively free from synoptic and subsynoptic scale tropical disturbances, the sea-surface temperature being generally too cool for their generation or maintenance.

In summary, given the late Quaternary land and sea distributions plus possibly lower sea-surface temperatures to the west and northwest of Australia and assuming an atmospheric circulation pattern similar to today, the following inferences may be made.

(i) Tropical cyclogenesis and the effect of tropical cyclones in the whole region were

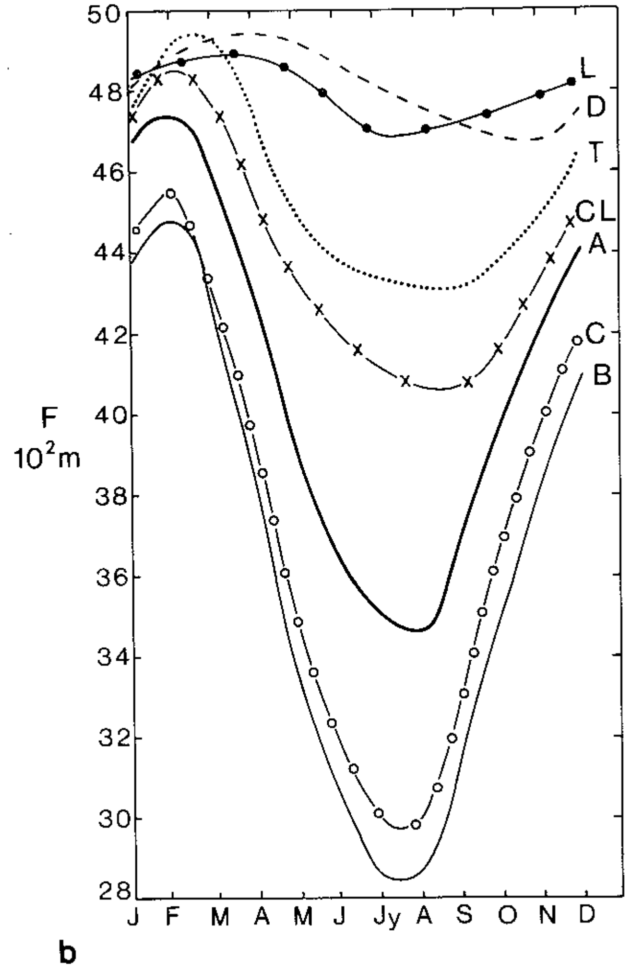

FIG. 9. *Continued*

reduced considerably. This is partly caused by the elimination of the Gulf of Carpentaria as a cyclogenetic area and by the cooler sea surface, especially in the western regions.

(ii) Owing to the distribution of tropical rainfall and the reduced availability of heat and moisture sources for maintaining smaller tropical disturbances, as well as tropical cyclones, the rainfall was greatly reduced along the present northern coastal belt. Much of the area was then more dependent on the summer thunderstorm activity for its precipitation. The climatic state of regions north and northeast of the present Arnhem Land may well have been similar to the present conditions of the climatic districts Victoria (14F) and Roper–McArthur (14DE). An annual precipitation of approximately half the present total may have been characteristic (Fig. 5).

(iii) Rainfall in the western areas would have been lower with a possible extension of the patterns of the present East Kimberley (2) and Victoria (14F) districts towards the northwest. As mentioned above, the present prevalent tropical cyclone activity of the Timor Sea would be markedly reduced or possibly eliminated by the probable ocean current variation in the region.

The geographic character of the great exposed plain between the present coasts of northern Australia and New Guinea would

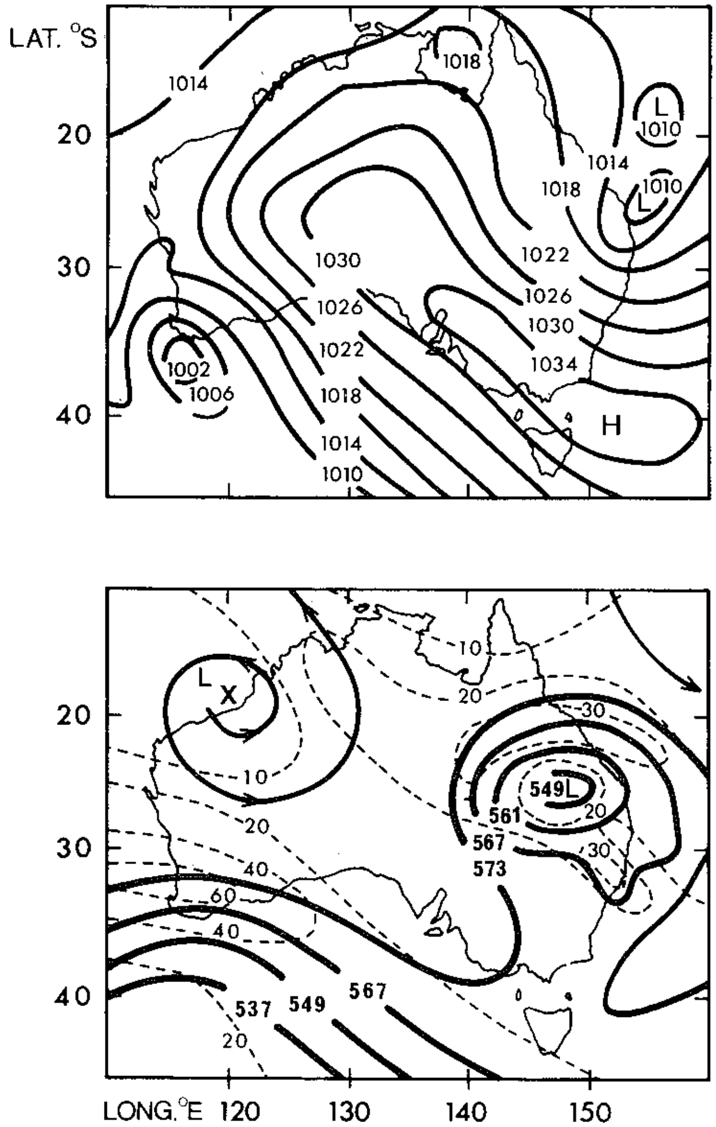

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FIG. 10. (a) The upper chart shows the mean sea-level pressure distribution in millibars for 2300 GMT on July 19, 1965. The lower chart is the corresponding one at the 500-mb level. Full lines are contours of geopotential (decameters) and dashed lines are isotachs (knots); in the tropics, contours are replaced by streamlines showing wind flow in the direction of the arrows. (b) Freezing level height anomaly (ΔH) (decameters) for the period of cold outbreak shown in Fig. 10a at Charleville, C; Cloncurry, CL; Darwin, D; and Townsville, T. (c) Snow-covered area during the cold outbreak shown in Fig. 10a (stippled). Crosshatched area had heavier falls.

have been largely determined by the climate controls discussed above but may also have been modified by the drainage pattern of the Gulf and of New Guinea. Streams may have traversed the plain and formed lakes or swamps in low lying areas[7] leading to a geography similar to the African Lake Chad

[7] Suggested by Nix and Kalma (personal communi., 1977).

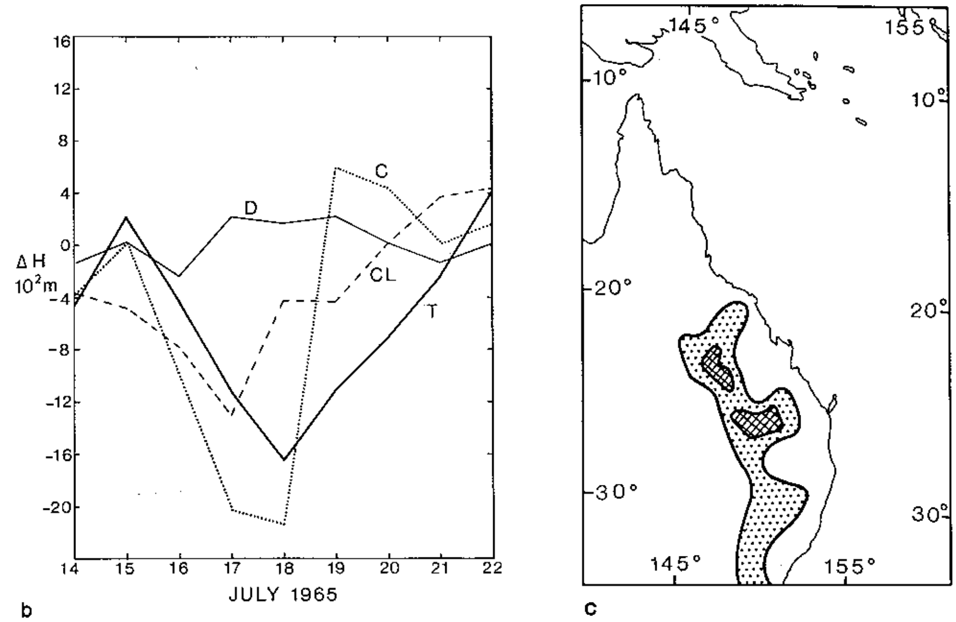

FIG. 10. *Continued.*

region. The local increase in available moisture may well have influenced the local thunderstorm activity.

The variation of ancient snow lines with longitude and the orientation of the New Guinea highland cirques can be interpreted in terms of the location of the increased exposed land area. For example, Galloway *et al.*, (1973) have proposed that the higher snow line in the west suggests that the increased aridity of the low latitudes during the last glacial age was more evident in the west than in the rest of New Guinea indicating different moisture sources (or air mass trajectories) for various parts of the New Guinea Highlands. Gentilli (1961) indicates that Mt. Jaya would lie in what was then a more continental region (Fig. 1a) so that southerly flows would have restricted moisture content after crossing the dry land mass. Thus the Mt. Jaya area would have to depend less upon precipitation from the south and southeast but more from a northwest circulation. By contrast Mt. Wilhelm could receive higher precipitation from the southeast although possibly some from the northwest as well. Note that currently Mt. Jaya exhibits a substantially wetter climate than does Mt. Wilhelm.

It appears that the effects of the increased land areas in tropical northern Australia were fundamental in determining the local climate. However, away from the exposed regions the changes must result from other factors.

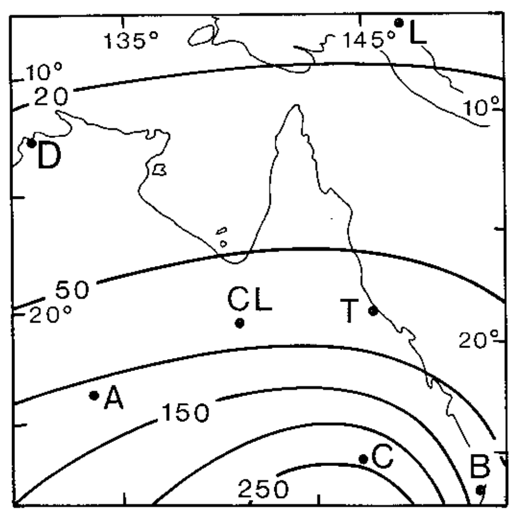

FIG. 11. Anomaly of freezing level (decameters) at indicated stations (Fig. 1) averaged for five cold outbreak situations.

That is, we are eventually faced with consideration of the influence upon local climates of the gross changes of the global climate.

Variation of the axes of the main pressure belts and the positioning of atmospheric long waves. Considerable evidence has been advanced to suggest that during the maximum of the Ice Ages the midlatitude zonal westerly winds of the Northern Hemisphere expanded or migrated equatorward by as much as 10 to 15° of latitude (e.g., Flohn, 1952, 1953). This may have been caused by the increase in thermal gradient between equator and pole which is consistent with the equatorward extension of sea ice. As the ice buildups were nonuniform in longitude, variable latitudinal temperature gradients around the hemisphere must also have been produced. The result would have been to cause a meandering westerly maximum, or, in other words, stationary waves of different orientation to those of today.

We expect that the stationary wave pattern in the Southern Hemisphere would be simpler than in the Northern Hemisphere. Ice buildup over land areas excluding Antarctica was small and the effects of the non-ice-covered midlatitude continents would have been relatively small, as they are today. The most significant change in the structure of the Southern Hemisphere was the equatorial extent of the sea ice which was probably an average of 10° equatorward of its present location (CLIMAP). Total sea-ice area was estimated to be in excess of 35×10^6 km^2 which is larger by a factor of 2 than at present. The increase was not uniform about the Antarctic continent but ex-

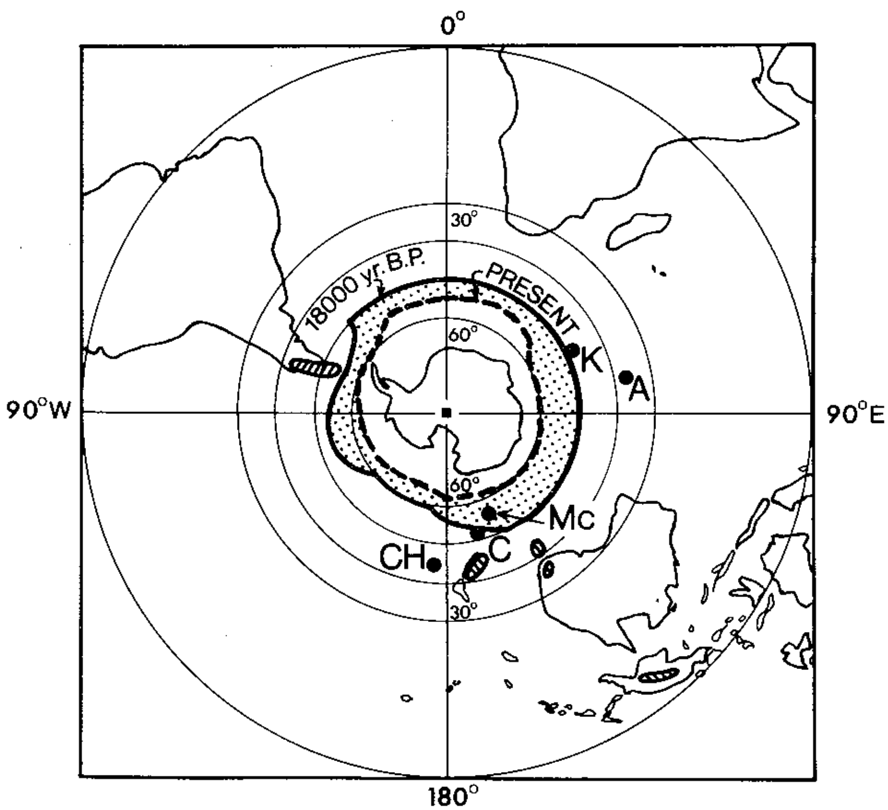

FIG. 12. The Southern Hemisphere showing winter sea-ice extent for the present and glacial maximum eras. Stippling displays the excess of winter sea ice and hatching the permanent ice caps at the glacial maximum. Letters indicate islands (see legend to Fig. 13).

tended further equatorward in the Eastern Hemisphere than in the west. Figure 12 shows a comparison between the present late winter ice limit and the 18,000-yr B.P. CLIMAP determination. The region of largest extent corresponds to the elevated section of eastern Antarctica although it is not known by how much the ice dome exceeded its present 4000-m thickness.

An enlarged sea-ice extent is physically consistent with a stronger and more equatorward westerly wind regime in midlatitudes by the fact that the ice extent would enhance the latitudinal temperature gradient. Observationally, Streten (1973) has provided some evidence that the strength of the present Southern Ocean surface westerlies is positively correlated with the equatorward location of the ice margin. Gates (1976) shows similar results from a general circulation model using CLIMAP boundary conditions.

An immediate consequence of stronger and more equatorward westerly winds is to increase the incursion of cold midlatitude water into the tropics along the sides of the eastern Southern Hemisphere oceans. This is because the circumpolar ocean current, which coincides with the band of maximum westerlies, would also move further north and thus impinge upon the west coast of Australia. In this manner, Australia becomes an effective mechanical barrier to the current causing a northward deflection. Furthermore, it can be argued from momentum conservation arguments that the strengthening and equatorial movement of the westerlies must be accompanied by stronger tropical easterlies. Stronger easterlies would increase the upwelling of cold bottom water at low latitudes as the easterly winds move off the west coast of the continent. The CLIMAP reconstructions indicate considerable longitude asymmetry in sea-surface temperature cooling with maximum coolings occurring in the eastern oceans.

Stronger westerlies might also be expected to produce larger amplitude perturbations of the atmospheric flow when incident upon the mountain ranges[8] of the Southern Hemisphere and when flowing over the differentially heated land and ocean regions. Such an effect could be expected even without a change in the surface orography. However, as we have noted in Fig. 12, a considerable asymmetry has been indicated in the sea-ice extent at 18,000 yr B.P. Consequently not only may we expect larger amplitudes in the standing waves, we can also expect changes in phase. Gates (1976) shows considerable difference in the mean surface trough and ridge structure compared to the present day.

CONSISTENCY WITH REGIONAL CLIMATES

So far, for tropical Australasia, we have attempted to provide some physical arguments to explain the existence of a cooler dry tropical climate for a specific geographical region during the peak of the Würm–Wisconsin glaciation although there is strong evidence that aridity was a feature of the entire tropics (Williams, 1975). The extent of the aridity seems consistent with the calculations of Newell *et al.* (1975) who suggest lower average global rainfall at the maximum of the glaciation on the basis of calculated radiative heating rates and the energy balance of atmospheric columns. Kraus (1973) also suggests that decreases in rainfall at about 20,000 yr B.P. would follow from the presence of a presumed lower evaporation rate, a factor which he believes follows from an overall cooler climate.

Two regional climates appear anomalous when inserted into the continental scale scenario described above. These are the glaciated highlands of New Guinea and the apparent aridity of the southern part of Australia. We will use these two examples to test the consistency of the overall climate model.

[8] To be more precise it can be shown to first approximation, the amplitude of a perturbation in the westerlies caused by an obstacle such as a mountain barrier is proportional to the slope of the mountain and the strength of the incident flow (e.g. Webster, 1972).

The Late-Quarternary Climate of Southern Australia

There is considerable evidence for lower effective rainfall in southern Australia. The review of Bowler *et al.* (1976), the earlier studies of Galloway (1965), and Bowler (1973), together with the Wyrie Swamp data of Dodson (1977) all indicated that at the height of the glaciation the climate over southeastern Australia was colder and effectively drier than at present. This evidence is based primarily on the interpretation of ancient lake levels and on the glacial geomorphology of the Australian Alps. Such aridity is difficult to reconcile with a stronger, or at least more equatorward westerlies, and a sea-ice extent reaching 50°S in winter.

In the present climate regime, average annual rainfall for coastal districts (where topography is not extreme) increases almost linearly with latitude at the northern fringe of the westerlies between latitude 30 and 40°S (Fig. 13). Poleward of about latitude 45°S the few sub-Antarctic island precipitation measurements that exist indicate somewhat lower annual figures. We consider, as an analog, the present precipitation at the sub-Antarctic islands which lie in the broad stream of the westerlies some 6 to 10° northward of the existing winter sea-ice margin. The available data (reviewed by Streten, 1977) point to a very uniform seasonal distribution with annual totals somewhat less than similarly exposed stations at around 45°S (e.g., Maatsuyker Is. and Cape Sorell in Fig. 13). Referring to Fig. 13, we postulate that rainfall at the time of maximum glaciation over the exposed continental edge of southeastern Australia from 35 to 40°S was similar to that presently experienced at around 45 to 50°S. That is, we could have expected around 800 to 1200 mm annually compared with 500 to 900 mm at present. If lower total moisture existed in the atmosphere at the time of the glaciation, these estimates would have been reduced as inflow of moist air from low latitudes during disturbed times in midlatitudes is usually required for high rainfall. Further, the increased land area of Bass Strait would tend to decrease the maritime aspect of its climatology and increase its continentality.

In summary, consideration of the present rainfall regime at higher latitudes and topographical changes in southern Australia suggests that annual rainfall over southeastern Australia at the time of the glaciation was either the same as at present or greater. However, we note that at the present time, greater cloudiness exists at high latitudes than in southeastern Australia so that we could expect more effective rainfall (i.e., because of less evaporation) over the southeastern Australian region during the glacial period than at present. Overall it is difficult to account for the much drier conditions indicated in southeastern Australia if only an equatorward extension of the zonal westerlies is considered.

It appears necessary to postulate some further special condition over southeastern Australia in order to explain the differences between the expected wetter climate and the observed aridity. One possibility is a glacial age enhancement of the amplitude (and perhaps slight eastward displacement) of the hemispheric longwave pattern in the atmosphere over the region. This would result in a semipermanent ridge pattern in the upper westerlies (which is consistent with more frequent surface anticyclones) over the eastern part of the continent and intensified troughs in the Indian and western Pacific/Tasman region (consistent with more frequent cyclones or disturbances). Persistence of such a long-wave flow pattern as portrayed in Fig. 14 would suggest that southeastern Australia would be under a predominantly northwesterly circulation with most precipitating disturbances being diverted over and south of Tasmania to the southeast with fewer incursions over the continent than would occur at present with the presently existing long-wave pattern. Such a pattern is consistent with the studies of the cirque orientations associated with Tasmanian

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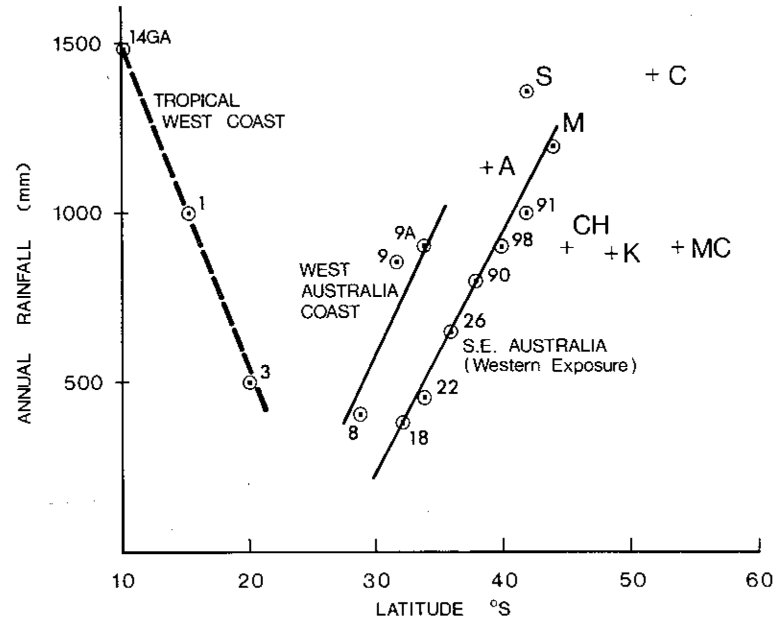

FIG. 13. Variation of annual rainfall with latitude for three exposed coastlines. Numbers refer to rainfall districts in Fig. 1. Cape Sorell (S) and Maatsuyer Is. (M) are also shown in Fig. 1. Southern ocean island locations shown in Fig. 12 are A, Amsterdam Is.; C, Campbell Is.; CH, Chatham Is.; K, Kerguelen Is.; MC, Macquarie Is.

snowfall of the most recent glaciation (Derbyshire, 1971). The southeastern part of Australia would experience frequent high pressure systems, and, in general, air trajectories would be from the dry interior of the continent.[9]

In the present climatic regime of the Southern Hemisphere only small seasonal variations are evident in the weakly developed wave patterns at midlatitudes. The most notable change in the circulation pattern from winter to summer is at Australian longitudes where a southward retreat of over 10° of latitude occurs in the axis of the high pressure belt; elsewhere, the patterns of change are much smaller. The southward extension of the high pressure belt in summer over the Australian region is accompanied by an eastward extension of the Indian Ocean subtropical anticyclone from a center at 70°E in winter to around 85°E in summer. Both of these effects result from the influence of the Australian–Asian monsoon. If, during the glacial period, the northern Australian summer monsoon circulation was weaker, as discussed earlier, then a slightly higher glacial-age pressure (resulting from the weaker monsoon trough) over lower latitude Australia would lead to a restriction of the southward migration of the subtropical high pressure belt. Further, it is unlikely that the sea ice would retreat either as rapidly or as far poleward as now occurs in summer. The anomalous ice extent would be maintained in east Antarctica so that strong temperature gradients would continue to exist over the Southern Ocean, and winter circulation would be dominant at the latitudes of southern Australia for a much greater part of the year than at present. Thus, it seems possible that the proposed long-wave pattern of Fig. 14 could be maintained throughout much of the year.

The proposed long-wave pattern appears to correspond to anomalous precipitation regimes in the present climate. Webster and Streten (1972) using an analysis of some 60

[9] Such a climatological pattern was persistent during the very dry winter of 1972.

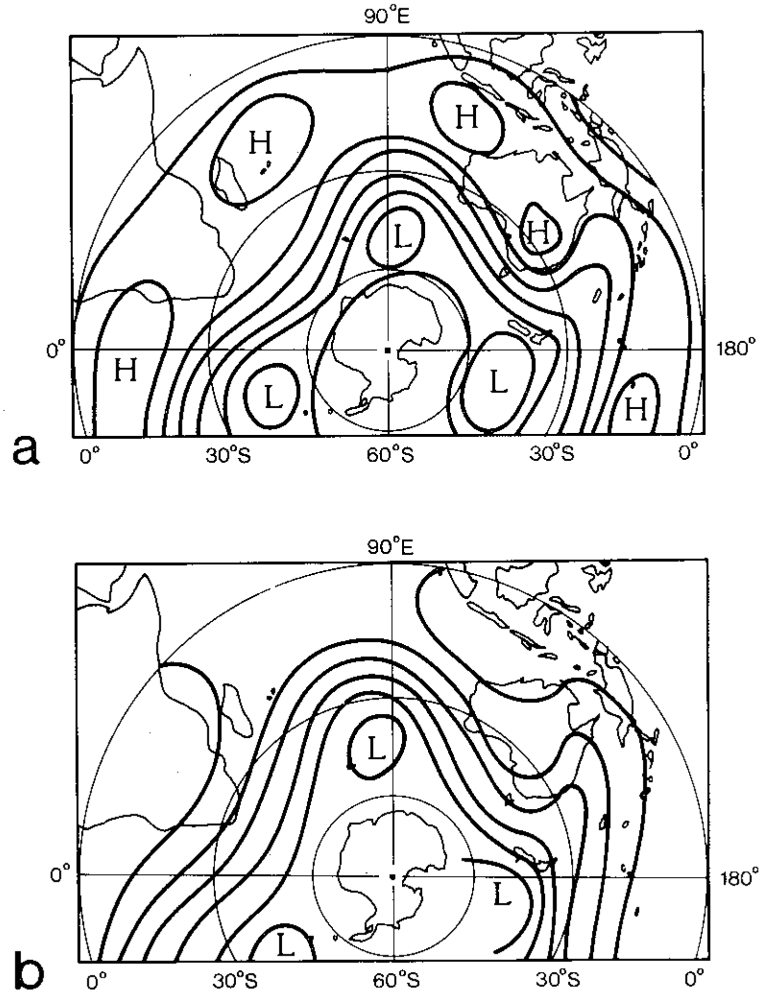

FIG. 14. Hypothetical Ice Age smoothed long-wave flow pattern for the Southern Hemisphere in winter (a) at mean sea level and (b) at the 500-mb level.

yr of district rainfall showed that anomalous mean seasonal precipitation regimes were correlated with variations in the mean axes of the subtropical high pressure systems. Using recent data they showed that low rainfall in northern Australia (i.e., rainfall districts 1, 2, 3, . . . 14GA and etc. of Fig. 1) correlated well with low rainfall in southern Australia (districts 9, 9A, 26, 90, and etc. which possess westward exposure).[10] The occurrence of rainfall anomaly coincided with a more southern and westward displacement of the high pressure belts at the longitudes of southern Australia.

The long-wave patterns envisaged for southern Australia are also consistent with the wind trajectories suggested by Bowler (1975) in order to explain the southern Australian lunettes and linear dunes which were active during the last glaciation. Bowler suggests a general westnorthwest to northwest-prevailing wind across southern Australia occurring in summer, which would be warm and dry and would reduce the effective precipitation (i.e., increase evaporation). Consequently it would be difficult for the lakes to maintain themselves through

[10] This corresponds to Webster and Streten's Type 2 precipitation-ridge distribution (1972).

n for the Southern Hemisphere in winter

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summer. We thus extend Bowler's argument by suggesting that the winter precipitation would also be less if a trough ridge structure similar to that of Fig. 14 prevailed during the glacial maximum. Figure 12 indicates that the greatest difference between the present and 18,000-yr B.P. CLIMAP ice extents lies in the Indian Ocean sector. Thus it is there that an associated atmospheric circulation pattern different from the present might be expected. The marked poleward retreat of the CLIMAP 18,000-yr B.P. ice edge between about 150°E and 170°W (Fig. 12) is clearly suggestive that a more pronounced ridge pattern then existed over the longitudes of southeastern Australia. Thus, an intensified trough ridge pattern over the Indian Ocean–Australia region anchored by the anomalous ice extent (which is itself a probable consequence of the northward extension of the Antarctic continent in these longitudes), would cause the rain-producing disturbances of the westerlies to be ducted to the Southeast.

In summary, ridge-trough redistribution suggested above as a consequence of the anomalous sea-ice extension in the Eastern Hemisphere agrees well with the ridge orientation necessary to provide a drier southern Australia. Furthermore it agrees with the position of the major trough-ridge systems that have occurred during anomalously dry years in southern Australia in recent years.

The intensified trough in the Tasman/southwest Pacific region downstream of the ridge over eastern Australia would lead to frequent cold outbreaks northward along the continental east coast and occasionally into the tropics. A similarity may be noted between the broad surface and upper air trough-ridge orientation pattern shown in Fig. 14 with the cold outbreak situation of Fig. 10 when snow accumulated as far north as the highlands near Mackay.

The New Guinea Highlands Glaciation

The substantial glaciation in the higher ranges of New Guinea poses a number of important problems for paleoclimatic reconstruction. Most important is the manner by which the glaciers and extremely low snow lines could be maintained in a region of high insolation in what was probably a generally drier climatic regime. The glaciation is important from another point; it emphasizes inconsistencies between various proxy data determinations, in particular between the CLIMAP determination of sea-surface temperature in the New Guinea region and the paleogeomorphological evidence from the highlands themselves.

The discrepancies may be summarized as follows. CLIMAP, on one hand, suggests a sea-surface temperature in the eastern New Guinea region of about 26°C, a reduction of 2°C from the present value. The glacial and snow line data, on the other hand suggest a reduction of nearly 7°C for the highlands. Such reductions are substantiated by vegetation remnants; the inferences from which are summarized in Fig. 3. Figure 3 further indicates that the temperature reduction was not confined to the higher peaks but that it was also a feature of at least the lower highlands below the snow level. In this regard the data from Sirunki (2500 m), Komahimambuno Mire (2740 m), and from lower Mt. Jaya (2000–4000 m) are of significance.

The inconsistencies between the two sets of data are substantiated in Figs. 15 and 16. In Fig. 15, the freezing level is determined starting at the present surface temperature (A) and the CLIMAP surface temperature (B) for a realistic estimate of the glacial-age temperature profile as approximated by that of Lae and an extreme estimate as approximated by that of Charleville, i.e., typical of the air mass almost 20° to the south. The results, summarized in Table 1, indicate that a CLIMAP sea-surface temperature is consistent with a freezing level some 1000 m higher than "observed" ancient freezing levels using the Lae estimate or 500 m using the Charleville lapse rate estimate. Figure 16 and Table 2 show the reverse procedure where the *surface temperature* is determined by using the same assumptions but starting with the "observed" ancient freezing levels of Mts. Wilhelm and Jaya. This

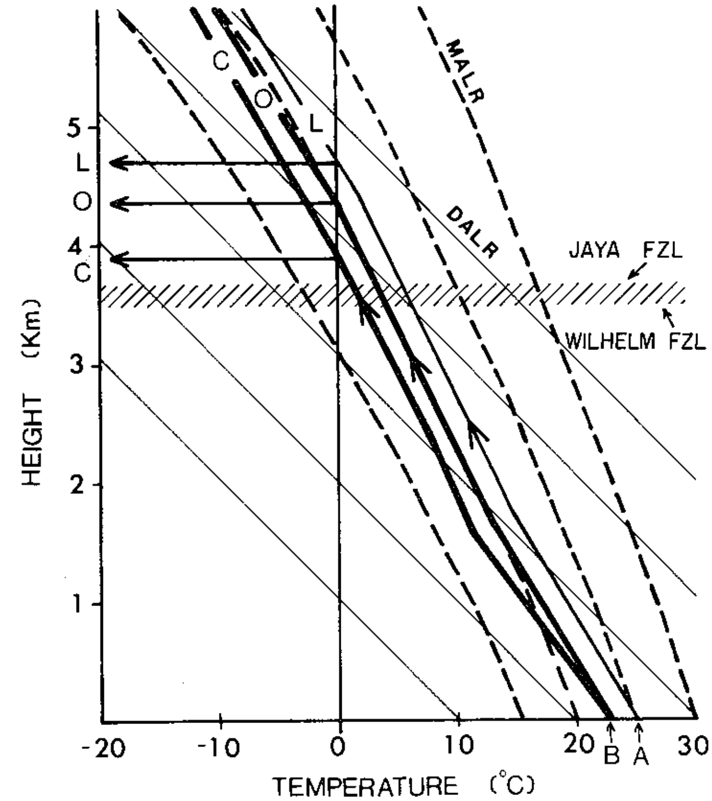

FIG. 15. Estimated freezing levels: L, present surface temperature and lapse rate at Lae; 0, Ice Age sea-surface temperature and realistic (Lae) lapse rate; and C, Ice Age sea-surface temperature and conservative (Charlesville) lapse rate (see text and Table 1).

procedure results in temperature some 5°C cooler than the CLIMAP estimates.

From a strictly thermodynamical perspective it is difficult to envisage a situation where a cold anomaly of a magnitude of 5 to 7°C could be maintained in the atmosphere without gravitational instability causing the colder (and denser) air to mix down through the atmosphere. Figure 3 indicates significant cooling as low as 2500 m (Sirunki) which would cause a lapse rate of near dry adiabatic magnitude which is impossible to maintain in a moist atmosphere. Consequently it would appear that the difference in the reduction of the highland temperatures and those at the surface contain an apparent physical paradox. It may be explained in terms of an error in interpretation of proxy climatological data or in terms of a neglected physical phenomenon. For example, we may suggest:

(i) The CLIMAP reconstructions in the vicinity of New Guinea were such as to provide an overestimate of sea-surface temperatures by at least 5°C.

(ii) The interpretations of the glacial and paleobotanical record are incorrect and have resulted in an underestimate of the elevated surface temperature by about 5°C.

(iii) The vertical lapse rate (i.e., the variation of temperature with height) and the attendant thermodynamics which control it were somehow different during the last glacial period than at present.

(iv) The temperature of the atmosphere over a tropical land mass such as New Guinea and the air mass over the oceans are unrelated.

(v) The local modification of the atmosphere adjacent to the highlands by the presence of ice and snow was insufficient to lower the temperatures as indicated by the paleobotanical and glacial data.

(vi) Variation in the geomorphology of the region due either to tectonism or exposure of marine beds by the retreating sea level caused sufficient circulation variation to modify the climate of the New Guinea region.

(vii) The circulation of the tropical atmosphere, the source of moisture, or the effect of the circulations at higher latitudes on the New Guinea climate were significantly different from the present day.

Points iii, iv, v, and vi may be dismissed. The thermodynamics which determine the atmospheric structure in the vertical are governed by strict physical laws. We expect the vertical temperature profile to be close to moist adiabatic even if the atmosphere were drier, as indicated by the winter temperature–height diagrams of Darwin, Cloncurry, and Charleville shown in Fig. 7. We also expect similarity between the temperatures above the adjacent ocean regions and at corresponding levels on elevated terrain. This was shown for the present climate in Fig. 8 between Lae and Mt. Wilhelm and is true for nonglaciated or nonsnow-covered terrain. For surfaces with a high albedo (such as the ancient snow-covered Mt. Wilhelm) the temperature may have been lower due to the reduced net radiation at the surface but this does not explain the similar lower temperatures at lesser elevations as shown on Fig. 3 (see the Sirunki and Komahimambuna Mire data) which are below the ancient snow lines and glacial snouts. Lastly, the effect of tectonism was most certainly small compared to the climatic influence of increasing the land area which produced a more arid tropical north.

It is unlikely that the land-based proxy

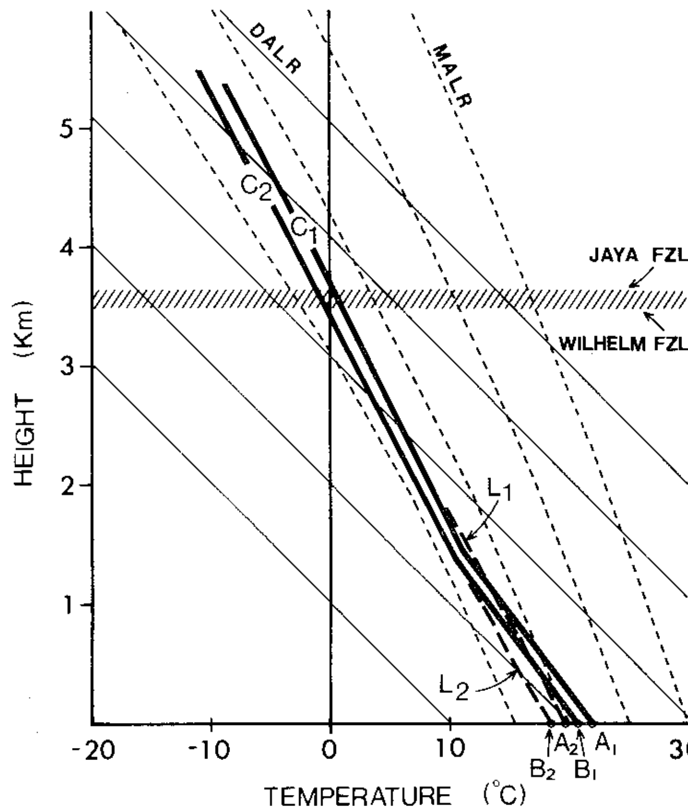

FIG. 16. Estimated surface temperature from "observed" Ice Age freezing levels on Mt. Jaya and Mt. Wilhelm (see text and Table 2).

TABLE 1

SUMMARY OF FIG. 15 SHOWING THE FINAL FREEZING LEVEL ASSUMING AN ASCENT FROM VARIOUS SURFACE TEMPERATURES USING THE MORE REALISTIC LAE SOUNDING (L AND O) AND THE CONSERVATIVE CHARLEVILLE SOUNDING (C)[a]

Symbol	Surface temperature (°C)	Assumed lapse rate (from Fig. 7)	Freezing level (m)
L	27 (Present)	Lae	4800
O	23 (CLIMAP)	Lae	4500
C	23 (CLIMAP)	Charleville	3950

[a] Conservative estimates of the CLIMAP temperature were used with twice the observational error subtracted from the temperature indicated in Fig. 2.

data were all in error by some 5°C (point ii). Data were obtained from many sites which would minimize random errors in the determinations. Large amplitude systematic errors of such a magnitude appear unlikely.

Only three possibilities are left. CLIMAP could be in error (point i), the circulation features may have been different (point vii), or a combination of the two points may have combined to provide indications of different climatic regimes. Although CLIMAP sea-surface temperature data for the western South Pacific are not in agreement with some earlier general estimates (e.g., Lamb, 1961; Heusser, 1966), they are internally consistent with the other measurements on a global scale and are thus not easily dismissed.

If Gates's (1975) determination of the tropical mean circulation is accurate and it was similar to the present situation, then for point vii to be correct, differences in circulation must have occurred on time scales *less* than seasonal. That is, atmospheric circulation features would be required to operate frequently at time scales less than seasonal which would provide precipitation (snow) to the New Guinea Highlands and allow the freezing level to be reduced by at least 1000 m also at regular intervals. A possible circulation feature is the polar outbreak in the eastern Australian region. We have previously argued that we expect more disturbances at higher latitudes to propagate to low latitudes as a consequence of the general equatorward movement of the belt of westerlies. If the disturbances maintained their present structure although allowing for the general equatorward displacement of weather systems, we may be able to associate reductions in freezing levels, which now occur at Charleville, with what may have occurred in the New Guinea region some 18,000 yr B.P.

Finally, it should be stressed that the pro-

TABLE 2

SUMMARY OF FIG. 16 SHOWING THE FINAL SURFACE TEMPERATURE ASSUMING A DESCENT FROM THE JAYA AND WILHELM FREEZING LEVELS USING THE MORE REALISTIC LAE SOUNDING (L1 AND L2) AND THE CONSERVATIVE CHARLEVILLE SOUNDING (C)

Sounding symbol	Initial freezing level (m)		Assumed lapse rate (from Fig. 7)	Surface temperature	
				Symbol	Magnitude (°C)
L1	Mt. Jaya	3650	Lae	A1	19
L2	Mt. Wilhelm	3500	Lae	B1	17
C1	Mt. Jaya	3650	Charleville	A2	20.5
C2	Mt. Wilhelm	3500	Charleville	B2	19

...NG AN ASCENT FROM VARIOUS SURFACE
...SOUNDING (L AND O)
...UNDING (C)[a]

...pse rate (...g. 7)	Freezing level (m)
	4800
	4500
...ville	3950

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...URE ASSUMING A DESCENT FROM THE
...E REALISTIC LAE SOUNDING
...ILLE SOUNDING (C)

...ate	Surface temperature	
	Symbol	Magnitude (°C)
	A1	19
	B1	17
	A2	20.5
	B2	19

posed trough-ridge structure which is consistent with the drier conditions in southern Australia is conducive to propagation of disturbances equatorward through the western Tasman Sea. Such outbreaks would affect the eastern New Guinea Highlands. A prolonged trajectory of the cold midlatitude air across the exposed land area of what is now the Gulf of Carpentaria and the Timor Sea would occur before its incidence with the elevated terrain in western New Guinea. This could account for the lower snow line on Mt. Wilhelm than on Mt. Jaya.

From consideration of these points it would seem that the most likely explanation lies in some form of circulation reconstruction along the general lines of that shown in Fig. 14. This accommodates most of the proxy data from continental Australia and is at least qualitatively in agreement with what may be inferred about the general hemispheric circulation from the presently available evidence.

It should be emphasized that the cool temperatures that existed at the Sirunki and Komahimambuno Mire site in the lesser elevations of the New Guinea Highlands cast some doubt that the intrusions of cold air from higher latitudes forms the complete solution to the puzzle. Whereas it is possible for the snow line to be maintained between the infrequent visits of cold air, it would seem more unlikely that the vegetation at a level of 1 km below the snow line to be only a function of the midlatitude incursions. Consequently, one cannot completely ignore the possibility of errors in the CLIMAP determination as being partly responsible for the apparent paradox.

CONCLUDING REMARKS

The present discussion has attempted to outline some of the apparent paradoxes in the proxy data on the late Quaternary glacial climate of Australia. Explanations have been advanced for some of these problems in terms of both local effects and broad scale hemispheric circulation features. In particular the ideas of Bowler (1973, 1975) have been extended by a proposed change in the amplitude and position of the hemispheric long-wave pattern particularly over the Indian Ocean and the southwestern Pacific region. Such a pattern, which is consistent with what can be inferred from CLIMAP data of hemispheric ice extent, agrees with lower precipitation in both winter and summer over continental Australia and allows considerable precipitation over Tasmania and New Zealand, in particular in winter. It allows for frequent cold outbreak conditions over the eastern Australian coast which in turn would provide nourishment for the southeastern continental ice caps and permit periodic influxes of cold air into the New Guinea Highlands. The latter process goes some way to explaining the apparent inconsistency of CLIMAP-derived sea-surface temperature over the southwestern Pacific and the observed height of the freezing level in the New Guinea mountains. However we have noted that the lower New Guinea Highland data appear difficult to reconcile solely as a function of cold air incursions.

The results of the most recent experiments with a numerical global general circulation model attempting to simulate the Ice Age circulation, given the CLIMAP derived boundary conditions of sea-surface temperature and surface albedo, have been published while this paper was in preparation (Manabe and Hahn, 1977). These reveal some degree of similarity with the suggestions which we have made in relation to the glacial age broadscale winter circulation of the Southern Hemisphere.

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REFERENCES

Bjerknes, J., (1969). Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, **97**, 163–172.

Bowler, J. M. (1971). Pleistocene salinates and climatic change: Evidence from lakes and lunettes in southeastern Australia. *In* "Aboriginal Man and Environment in Australia" (D. J. Mulvaney and J. Golsen, Eds.), pp. 47–65. Australian National University Press, Canberra.

Bowler, J. M. (1973). Clay dunes: Their occurrence formation and environmental significance. *Earth Science Reviews* **9,** 315–338.

Bowler, J. M. (1975). Deglacial events in southern Australia: Their age, nature and palaeoclimatic significance. *In* "Quaternary Studies—Selective Papers from IX INQUA Congress Christchurch New Zealand 2–10 December 1973" (R. P. Suggate and M. M. Cresswell, Eds.), pp. 75–82. Royal Society of New Zealand, Wellington.

Bowler, J. M., Hope, G. S., Jennings, J. N., Singh, G., and Walker, D. (1976). Late Quaternary climates of Australia and New Guinea. *Quaternary Research* **6,** 359–394.

Charney, J. G. (1969). The intertropical convergence zone and the Hadley circulation of the atmosphere. *In* "Proceedings of the WMO-IUGG Symposium on Numerical Weather Prediction, Tokyo, Japan, Nov–Dec 1968." Japanese Meteorological Agency, Tokyo.

CLIMAP project members (1976). The surface of the ice age earth. *Science* **191,** 1131–1137.

Coleman, F. (1972). "Frequencies, Tracks and Intensities of Tropical Cyclones in the Australian Region, November 1909 to June 1969." Bureau of Meteorology, Melbourne.

Costin, A. B. (1972). Carbon-14 dates from the Snowy Mountains area south-eastern Australia and their interpretation. *Quaternary Research* **2,** 579–590.

Derbyshire, E. (1971). A synoptic approach to the atmospheric circulation of the last glacial maximum in southeastern Australia. *Paleogeography, Paleoclimatology, Paleoecology* **10,** 103–129.

Dodson, J. (1977). Late Quaternary paleoecology of the Wyrie Swamp, southeastern Australia. *Quaternary Research* **8,** 97–114.

Fairbridge, R. W. (1965). African ice-age aridity. *In* "Problems in Paleoclimatology" (A. E. M. Nairn, Ed.), pp. 356–363. Wiley–Interscience, New York.

Flohn, H. (1952). Allgemeine atmosphärische zirkulation und palaoklimatologie, *Geologische Rundschau* **40,** 153–178.

Flohn, H. (1953). Studien uber die atmosphärische zirkulation in der letzten Eiszeit. *Erdkunde* **7,** 266–275.

Galloway, R. W. (1965). Late Quaternary climates of Australia. *Journal of Geology* **73,** 603–618.

Galloway, R. W. (1971). Evidence for late Quaternary climates. *In* "Aboriginal Man and Environment in Australia" (D. J. Mulvaney, and J. Golson, Eds.), pp. 14–25. Australian National Univ. Press, Canberra.

Galloway, R. W., Hope, G. S. Loeffler, E., and Peterson, J. A. (1973). Late Quaternary glaciation and periglacial phenomena in Australia and New Guinea. *Paleoecology of Africa and of the Surrounding Islands and Antarctica* **8,** 125–138.

Gates, L. (1976). Modelling the Ice Age climate. *Science* **191,** 1138–1144.

Gentilli, J. (1961). Quaternary climates of the Australian region. *Annals of the New York Academy of Science* **95,** 465–501.

Hnatiuk, R. J., Smith, J. M. B., and McVean, D. N. (1976). "The Climate of Mt. Wilhelm: Mt. Wilhelm Studies 2," Research School of Pacific Studies, Department of Biogeography and Geomorphology, Publication BG/4. Australian National University, Canberra.

Heusser, C. J. (1966). Pleistocene climatic variations in the western United States, *In* "Pleistocene and Post-Pleistocene Climatic Variations in the Pacific Area–A Symposium" (D. I. Blumenstock, Ed.), Tenth Pacific Science Congress, Hawaii, 21st August to 6th September 1961. Bishop Museum Press, Honolulu.

Jennings, J. N. (1971). Sea level changes and land links. *In* "Aboriginal Man and Environment in Australia" (D. J. Mulvaney, and J. Golson, Eds.), pp. 1–13. Australian National Univ. Press, Canberra.

Kershaw, A. P. (1974). A long continuous pollen sequence from northeastern Australia. *Nature (London)* **251,** 222–223.

Kraus, E. B. (1973). Comparison between ice age and present general circulations. *Nature (London)* **245,** 129–133.

Lamb, H. H. (1961). Fundamentals of climate. *In* "Descriptive Paleoclimatology" (A. E. M. Nairn, Ed.), pp. 8–44. Wiley–Interscience, New York.

Löeffler, E. (1972). Pleistocene glaciation in Papua and New Guinea. *Zeitschrift für Geomorphologie Supplement Band* **13,** 32–58.

Lourensz, R. S. (1977). "Tropical Cyclones in the Australian region, July 1909 to June 1971." Bureau of Meteorology, Melbourne.

Manabe, S., and Hahn, D. G. (1977). Simulation of the tropical climate of an ice age. *Journal of Geophysical Research* **82,** 3889–3911.

Mercer, J. H. (1967). "Southern Hemisphere Glacier Atlas United States Army Natick Laboratories." Technical Report 67-76-ES, Natick, Mass.

Newell, R. E. (1975). Decreased global rainfall during the past ice age. *Nature (London)* **253,** 33–34.

Olascoaga, M. J. (1950). Some aspects of Argentine rainfall. *Tellus* **2,** 312–318.

Pike, A. C. (1971). The intertropical convergence zone studied with an interacting atmosphere and ocean model. *Monthly Weather Review* **99,** 464–477.

Reiner, E. (1960). The glaciation of Mount Wilhelm, Australian New Guinea. *Geographical Review* **50,** 490–503.

Riehl, H. (1954). "Tropical Meteorology." McGraw-Hill, New York.

Riehl, H., and Malkus, J. S. (1958). On the heat balance in the equatorial trough zone. *Geophysica* **6,** 503–538.

Rognon, P., and Williams, M. A. J. (1977). Late Quaternary climatic changes in Australia and north Africa: A preliminary interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology* **21**, 285–327.

Streten, N. A. (1973). Satellite observations of the summer decay of the Antarctic sea ice. *Archivfeur Meteorologie, Geophysik und Bioklimatologie, Serie A; Meteorologie und Geophysik* **22**, 119–134.

Streten, N. A. (1974). Some features of the summer climate of interior Alaska. *Arctic* **27**, 273–286.

Streten, N. A. (1977). Seasonal climatic variability over the southern oceans. *Archivfuer Meteorologie, Geophysik und Bioklimatologie, Serie B: Klimatologie, Umweltmeteorologie, Strahlungsforschung* **25**, 1–19.

Taylor, V. R., and Winston, J. S. (1968). "Monthly and Seasonal Mean Global Charts of Brightness from ESSA 3 and 5 Digitized Pictures, February 1967–February 1968." Environmental Sciences Services Administration, Technical Report NESC 46, Washington, D. C.

Twidale, C. R. (1966). Late cainozoic activity of the Selwyn Upwarp northwest Queensland. *Journal of the Geological Society of Australia* **13**, 491–494.

Van Andel, T. H., Heath, G. R., Moore, T. C., and McGeary, D. F. R. (1967). Late Quaternary history, climate and oceanography of the Timor Sea northwestern Australia. *American Journal of Science*, **265**, 737–58.

Veeh, H. H., and Chapell, J. (1970). Astronomical theory of climatic change: support from New Guinea. *Science* **167**, 862–865.

Webster, P. J. (1972). Response of the tropical atmosphere to local steady forcing. *Monthly Weather Review* **100**, 518–541.

Webster, P. J., and Streten, N. A. (1972). Aspects of late Quaternary climate in tropical Australasia. *In* "Bridge and Barrier: The Natural and Cultural History of Torres Strait" (D. Walker, Ed.), Department of Biogeography and Geomorphology, Publication BG/3, pp. 39–60. Australian National University, Canberra.

Williams, M. A. J. (1975). Late Pleistocene tropical aridity synchronous in both hemispheres? *Nature (London)* **253**, 617–618.

Wright, R. L. (1964). Geomorphology of the West Kimberley area. *In* "General Report on Lands of the West Kimberley Area," pp. 103–118. Land Research Series CSIRO No. 9, Melbourne.