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The status of the Indo-Pacific Warm Pool and adjacent land at the Last Glacial Maximum

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Abstract

Since the Climate: Long Range Investigation, Mapping and Prediction (CLIMAP) reconstructions for the Earth at the Last Glacial Maximum (LGM), there have been conflicting views on the extent of cooling of the oceans of tropical Australasia—here, referred to as the Indo-Pacific Warm Pool—in contrast with those temperatures registered on land. Based on sea-surface temperature (= SST) reconstructions for the Indo-Pacific Warm Pool, and on vegetation reconstruction for SE Asia as well as by considering the increase of land mass area engendered during low sea levels, we identify for the LGM a significant drop in precipitation in the Warm Pool region that would explain an increase in salinity while SST decreased by about 2 °C at the most. The latter would have caused a substantial decrease of large-scale atmospheric convection over the Indo-Pacific Warm Pool and suppressed deep atmospheric convection that would help maintain somewhat elevated SSTs. The drier atmosphere and diminished level of cloud cover would also have reduced nocturnal temperatures at elevation in the region and produced a steeper mean atmospheric lapse rate, forcing the tree line to drop and glaciers to be maintained down to much lower altitudes than today.

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1. Introduction

There has been considerable controversy caused by the Climate: Long Range Investigation, Mapping and Prediction (= CLIMAP) sea-surface temperatures (= SST) (CLIMAP Project Members, 1976, 1981; Webster and Stretten, 1978; Rind and Peteet, 1985; Betts and Ridgway, 1992; Thunell et al., 1994; Hoste-

tlar and Mix, 1999; see Crowley, 2000 for a review) reconstructions for the tropical regions, especially with the knowledge that in the high-altitude regions in the tropics, such as Papua New Guinea at the Last Glacial Maximum (LGM), glaciers were present. Terminal moraines were as far down as 3100 m below Mt. Wilhem (Galloway et al., 1973) and tree lines were lower (Walker and Flenley, 1979; Hope, 1983) and, yet, SST in the region has been diagnosed to have remained close to today's values (CLIMAP Project Members, 1976, 1981; Thunell et al., 1994; Martinez et al., 1997, 1999; Spooner, 2001). Several hypotheses were subsequently discussed, such as a change in atmospheric

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lapse rate from that seen today (Webster and Streten, 1978), incorrect interpretation of CLIMAP's data (Rind and Peteet, 1985), or variations in atmospheric CO₂ (Street-Perrott, 1994) or ultraviolet B (Flenley, 1996) that may also have affected vegetation growth at high altitude.

Recent re-examination of some of the CLIMAP cores, as well as additional ones from the Indo-Pacific Warm Pool region for the western Pacific (Thunell et al., 1994), the eastern Indian Ocean (Martinez et al., 1999), the South China Sea (Pflaumann and Jian, 1999), the Sulu Sea (Linsley and Thunell, 1990) and the Banda Sea, east of Timor (Spooner, 2001), converges in identifying little temperature difference between the present and the LGM; at the extreme, a drop of 2 °C was registered for the margins of the present-day Indo-Pacific Warm Pool (Thunell et al., 1994; Martinez et al., 1999; Wang, 1999). In addition, Bard et al. (1997) used the organic geochemical palaeothermometer U_{37^K} to indicate that tropical temperature changes of the order of 2 °C in the oceans are overall in agreement with CLIMAP's reconstructions. Adding to the controversy has been a series of general circulation models used for testing CLIMAP's LGM conditions. Pinot et al. (1999) summarised these models and concluded that cooling was more enhanced on land compared to the oceans. In several of the models compared by Pinot et al. (1999) for the tropics, atmospheric cooling at the sea surface proved to be lower (0.8 ± 0.1 °C) compared to the land (2.4 ± 0.4 °C). Such values differed in other models which averaged much cooler temperatures (2.1 ± 1.0 °C at the sea surface and 3.4 ± 1.2 °C on land). The surprising discrepancy between some models was the range of tropical temperatures from 1.8 to 5.4 °C. In particular, four particular models stand out (Ganopolski et al., 1998; Weaver et al., 1998; Bush and Philander, 1998; Hostetler and Mix, 1999). The first three were briefly reviewed by Mix et al. (2001). The surprising model is that of Bush and Philander (1998) which argues for more than a 6 °C drop in the western Pacific. This is in contrast with Crowley's (2000) review of the evidence of environmental changes in the tropics at the LGM, which argued for a 2.5 °C temperature decrease of the 'warm pool' [sic].

The present paper aims at examining *field* evidence, both on land and at sea, in the Indo-Pacific

Warm Pool, for modellers to check against the validity of their models and hopefully help better understand the processes of climate change in the tropics and link them with other regions of the globe.

2. The Indo-Pacific Warm Pool

The Indonesian Archipelago, often referred to as the "Maritime Continent" (Ramage, 1968), is a significant area on the globe with respect to heat and moisture transfer between the ocean and the atmosphere. The surface of the oceans in this region is also characterised by being the warmest on Earth, with temperatures consistently above 28 °C (Yan et al., 1992). This region is often referred to as the Western Pacific Warm Pool, even though it extends into the eastern Indian Ocean. This area is referred to here as the Indo-Pacific Warm Pool to avoid further confusion.

The Indo-Pacific Warm Pool is a key site on the globe, especially with respect to oceanic circulation. Today, it is the location of substantial ocean surface warming and salinity dilution because of the excessive rainfall caused by the monsoons. Fluctuations in the El Niño Southern Oscillation signal across the Pacific Ocean are directly affecting precipitation over the Maritime Continent, and will therefore affect the salinity signal of the Indo-Pacific Warm Pool. The Warm Pool–Maritime Continent region is a major source of latent heating for the global atmosphere, with this heat and moisture playing a fundamental role in driving the zonal Walker and meridional Hadley circulations in the region (Keenan et al., 1989, 2000). Rainfall of 2000–3000 mm is registered through much of the region, but there is considerable seasonal and inter-annual rainfall variability associated with the regional monsoon flow and with fluctuations in the intensity of the Walker circulation that are ENSO-related (Webster and Streten, 1978; Kirono et al., 1999). Sea-surface salinities are characteristically low in the Java and Banda Sea areas as well as west of Sumatra (Wyrski, 1961; Tomczak and Godfrey, 1994; Boyer and Levitus, 1997), but again with contrasting seasonal values reflecting monsoon influence on freshwater influx and wind direction (Webster and Streten, 1978).

The Indo-Pacific Warm Pool is also a key area with respect to the exchange between two major oceans;

the flux of low-salinity water today mirrors the transport of latent heat by the atmosphere (Wijffels, 2001) since the atmosphere and oceans together transport a huge amount of energy poleward (refer to Wijffels, 2001 and other chapters in Siedler et al., 2001). The transfer of water from the Pacific into the Indian Ocean is crucial to the transport of heat and ‘fresh-water’ for the global ocean. At present, estimates of such heat and throughflow of water vary greatly (Wijffels et al., 1998; Macdonald, 1998; Ganachaud and Wunsch, 2000). However, any changes in the nature of the Indo-Pacific Warm Pool and of the throughflow are fundamental to understanding global energy transfers and therefore climate.

3. Past environmental records for the Indo-Pacific Warm Pool region

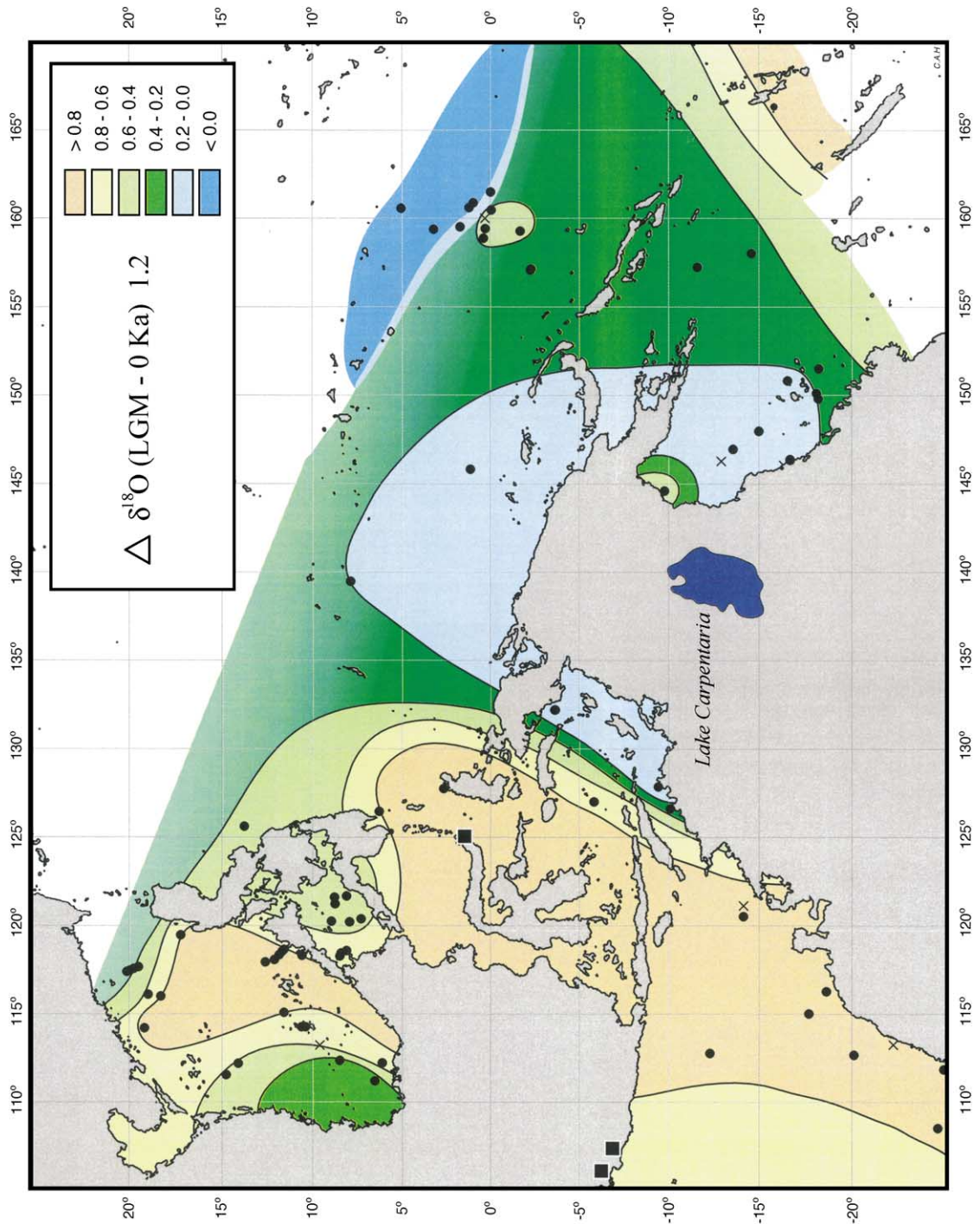
Several sites cored both on land and at sea (van der Kaars, 1991, 1998; van der Kaars and Dam, 1995; Dam et al., 2001; van der Kaars et al., 2001) in the Indonesian region have now been sufficiently studied for their vegetational reconstruction to determine that a broad trend of decreased precipitation (see Fig. 1 and caption) was registered throughout the area during the LGM. Similarly, in northern Australia (Gulf of Carpentaria to the east—Torgersen et al., 1988) and offshore Exmouth—van der Kaars and De Deckker, 2002), the broad vegetational reconstruction confirms the Indonesian scenario of significantly altered hydrological budgets; e.g. reduced precipitation and evapotranspiration. At that time, aridity was also confirmed for the Gulf of Carpentaria where the largest concentration of dust particles was recovered from Lake Carpentaria (De Deckker et al., 1991; De Deckker, *in press*). A controversy remains, however: how to explain the presence of glaciers in Papua New Guinea with a reduced precipitation in the region? This paper aims at providing the answer.

4. Consequences of a change of sea level at the LGM

Two maps of southeast Asia (Fig. 2) covering the grid (20°N to 20°S and 90°E to 130°E) were constructed using ER Mapper and a digital elevation

model (DEM) described in Smith and Sanwell (1997), one with today’s sea level, and another for the LGM, having lowered sea level by 125 m (the value of 125 m is used here as it corresponds to the 125 ± 4 -m value recently calculated by Yokoyama et al., 2000, 2001 for cores from Bonaparte Gulf in northern Australia). The surface areas for land and ocean in the grid were compared for both maps (see Fig. 2) by counting the pixels representing the two types of surfaces (land and ocean). Results for different water depths—going from today’s sea level down to -125 m which are presented in Table 1—indicate that, at the LGM, exposed land almost doubled in area, to be 94% larger compared to today. A consequence of this change in surface area is that several of the shallow seas in the Indonesian region did not exist at the LGM, nor had been in existence for the majority of the last 150,000 years (De Deckker, *in press*; Stanley et al., 2001). This would have required a complete reorganisation over time of oceanic currents (such an attempt is presented in Fig. 2), as well as heat and moisture transport, in the region. Also, while the connection between the Pacific and the Indian Oceans was always maintained, the amount of throughflow must have been very different due to the decrease in the size and number of pathways compared to the present (Wang, 1999; De Deckker, *in press*). In addition, winds passing over the Indo-Pacific Warm Pool would have been unable to pick up as much moisture as today due to the reduced surface of the oceanic region.

Another important observation is that the ocean surface area, for the gridded region here (see Fig. 2), is currently 4.1 times the size of the land. In contrast, the value was only 1.6 times during the low sea level of 125 m during the LGM (Figs. 2 and 3 and Table 1). Therefore, during the LGM, the region could not claim to be the ‘Maritime Continent’ as it is today; this substantial land expansion alone would have had serious repercussions for regional atmospheric energy exchanges. Recent measurements during the monsoon transition season over the Tiwi Islands, north of Australia in the Timor Sea, have shown substantial surface flux differences between land and ocean (Keenan et al., 1989). Daily totals of net radiation and evaporative heat flux over the ocean were both 115% of that measured over an onshore grassland site, with sensible heat flux 43% of that measured at the



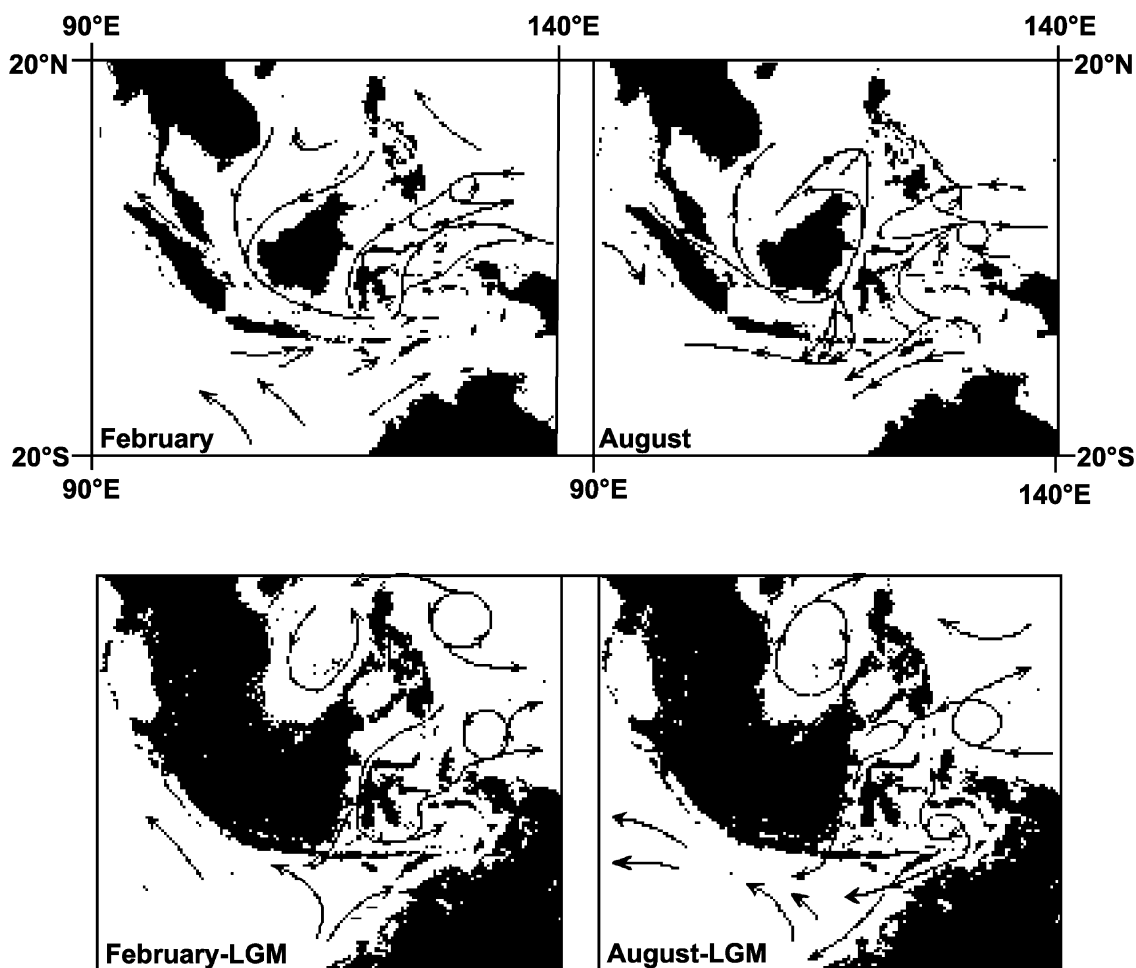


Fig. 2. Maps depicting the periphery of the land in a gridded area (20°N to 20°S and 90°E to 140°E) that encompasses a large portion of southeast Asia and the Indo-Pacific Warm Pool. The top maps show the regions above sea level today and surface currents are also shown for the contrasting seasons. The bottom maps show completely different lands that would have emerged above sea level during the LGM when sea level had dropped by 125 m. An attempt is made here at estimating the patterns of the oceanic currents for the two main seasons as a result of the closure of several of the shallow seas and passageways.

Fig. 1. Map showing the periphery of land areas in the Indo-Pacific Warm Pool region for the LGM by lowering sea level by 125 m. Contours show averaged values for $\Delta^{18}\text{O}$ (in per mil PDB) obtained by subtracting the $\delta^{18}\text{O}$ of LGM planktonic foraminifers from modern-day ones from the same core sites (black dots and crosses refer to outlier values). Those resulting positive $\Delta^{18}\text{O}$ values ([LGM-modern] $\delta^{18}\text{O}$ —1.2—see text for more information) indicate waters more saline from today as there was little temperature change around the tropics in the region at the LGM. Three continental sites (black squares) also indicate lower precipitation estimates (given in %) compared to today. These are: (A) Rawa Danau, West Java: 6°11' S; 105°58' E, 90 m asl, -30% to 50%; (B) Bandung basin, West Java: 6°59' S; 107°44' E, 660 m asl, -30%; (C) Lake Tondano, North Sulawesi: 1°17' N; 124°54' E, 680 m asl, -30% to 50% (van der Kaars and Dam, 1995; Dam et al., 2001; van der Kaars, unpublished data). Note that high $\Delta^{18}\text{O}$ values offshore Western Australia would be caused by significant temperature drops outside the Indo-Pacific Warm Pool (Martinez et al., 1999) per se, and that apparently, little salinity (and temperature) change was recorded in the western Pacific. This would explain the presence of the large inland Lake Carpentaria. However, reduced rainfall over PNG is identified by the lowered $\Delta^{18}\text{O}$ value in the Gulf of Papua (core data from L. Beaufort) reflecting reduced river discharge compared to today.

Table 1
Ratio of ocean over land for the gridded area (20°N to 20°S and 90°E to 140°E) for different sea levels

Water depth (m)	Area of ocean over land
0 (= present-day sea level)	4.063
– 5	3.179
– 10	3.095
– 15	3.039
– 20	2.933
– 25	2.844
– 30	2.678
– 35	2.569
– 40	2.399
– 45	2.291
– 50	2.182
– 55	2.101
– 60	1.973
– 65	1.920
– 70	1.856
– 75	1.817
– 80	1.781
– 85	1.734
– 90	1.706
– 95	1.682
– 100	1.660
– 105	1.647
– 110	1.633
– 115	1.622
– 120	1.613
– 125	1.606

onshore site. These measurements are consistent with published maps suggesting that contemporary annual evaporation is below 1000 mm over the interior of the larger islands of the Maritime Continent region and in the range 1100–1600 mm over the surrounding oceans (Baumgartner and Reichel, 1975; Brutsaert, 1982).

5. High convective clouds in the Indo-Pacific Warm Pool region—present and past conditions

It is apparent that during glacial times, the significant reduction in oceanic surface area would have forced a reduction in the moisture transfer to the atmosphere. In addition, the recognition that there is a very sharp and important threshold with respect to SST (at 27.5 °C) in the tropical oceans and large-scale organised cloud convection [measured as outgoing longwave radiation (OLR) or highly reflective cloud

(HRC) (Graham and Barnett, 1987; Waliser and Graham, 1993; Waliser et al., 1993)] is crucial for the Indo-Pacific Warm Pool, and more so for past atmospheric conditions (see Fig. 4). Current Warm Pool SSTs ensure that this region has the most extensive coverage of organised deep convective cloud on Earth. This cloud cover, and associated moist adiabatic lapse rate, also maintain the freezing-level height at high altitude, especially in equatorial regions [the altitude of the 0 °C isotherm in PNG today is 4.4 km at the Summit Ridge of Mt Wilhelm in June but is much higher in December (~ 5.2 km) (Webster and Streten, 1978)]. Overall, within the 26.5–29 °C range, organised convection is much increased, but above 29.5 °C, deep atmospheric convection is suppressed (Waliser and Graham, 1993), but an explanation for this phenomenon remains a mystery (Webster, 1994). On the lower end of this temperature range, deep convection also disappears, and we assume here that if the same relationship may have applied during the LGM, with slightly diminished SSTs compared to today (Thunell et al., 1994; Martinez et al., 1999). This would readily explain the substantial precipitation decreases registered in the Southeast Asian region (van der Kaars, 1998; Barma-widjaja et al., 1993), and also the significantly higher sea-surface salinities interpreted from subtracting the $\delta^{18}\text{O}$ of LGM planktonic foraminifers from modern-day ones from the same core sites (data from Martinez et al., 1997, 1999; Wang, 1999; Spooner, 2001; Beaufort personal communication) from which an additional 1.2 value was subtracted as a result of the lowered sea level at the LGM (for discussion, refer to Martinez et al., 1999). Those resulting positive $\Delta^{18}\text{O}$ values ([LGM-modern] $\delta^{18}\text{O}$ —1.2) in Fig. 1 indicate waters more saline from today as there was little temperature change around the tropics in the region at the LGM (Thunell et al., 1994; Martinez et al., 1999; Spooner, 2001). Note that the work of Lea et al. (2000) identified no change of sea-surface salinity except for the 1.2 value related to sea-level change at the LGM for a site offshore Papua New Guinea (ODP site 806B; 0°19.1' N, 159°21.7' E), thus confirming our data presented here that SSS was similar or even perhaps slightly lower than today's value (see Fig. 1).

However, it may also be that a different salinity could affect the threshold defined by Waliser and Graham (1993); certainly there are clear reductions

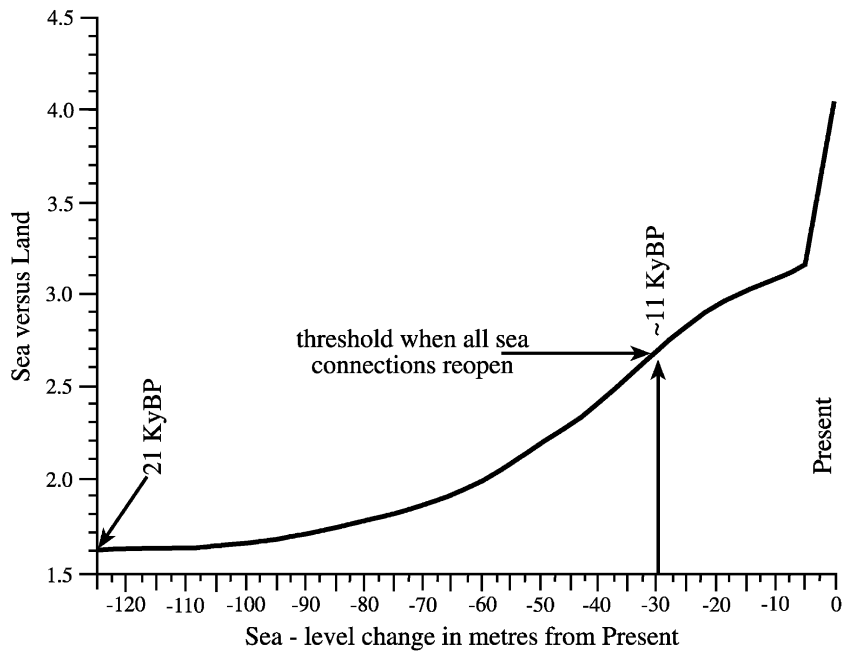


Fig. 3. Diagram to show the change in the ratio between the surface occupied by the ocean and that of land as a result of sea-level change from the LGM (when sea level at 21 cal. ka BP was ~ 125 m below the present level) to the present for the gridded region from 20°N to 20°S and 90°E to 140°E . Note that it is only when sea level rose to -30 m, at approximately 11 ka BP, that all the seaways became interconnected as seen today. This -30 -m threshold is considered to have played a significant role in the atmospheric reorganisation over the Indo-Pacific Warm Pool at the Late Pleistocene/Holocene boundary, a time when the wettest conditions occurred in northwestern Australia (De Deckker, 2001a,b) and which may have been characteristic of the warm pool region of the eastern Indian Ocean.

in saturation vapour pressures over water with increasing salinity (Gill, 1982) and this would result in smaller surface-atmosphere vapour gradients and reduced evaporation.

The decrease in convective cloud over the Indo-Pacific Warm Pool would help maintain fairly high SSTs despite the overall much cooler temperatures reconstructed for higher latitudes in the Pacific (Thunell et al., 1994; Martinez et al., 1997; Wang, 1999; Barrows et al., 2000) and the eastern Indian Ocean (Martinez et al., 1999; De Deckker, 2001b; unpublished data). An additional consequence of a major decrease in cloud cover at the LGM in the Indo-Pacific Warm Pool would be increased longwave radiative loss at night and consequent lower nocturnal temperatures. Dry, relatively cloud-free El Niño years have long been associated with frost and vegetation damage at high elevations of the Maritime Continent region (Allen et al., 1989). This was again experienced in the highlands of Papua New Guinea during

the last major ENSO drought of 1997–1998, with severe nocturnal frosts killing most crops (Bierwirth and McVicar, 1998). Persistence of such conditions would help explain the documented vegetational gradients through a combination of cooler night temperatures at least and a significant decrease in moisture availability. It has already been shown (Betts and Ridgway, 1992) that a conservative 1.4°C mean fall of tropical SST, along with at least a 10 hPa increase in tropical sea-surface pressure as a consequence of lowered sea levels of ~ 125 m (which is equivalent to 10–12 hPa), would lower freezing levels by about 550 m. In other words, a decrease in sea level has more implications than just a pressure change. Nevertheless, the impact of these factors is still well short of the documented lowering of snowline in Papua New Guinea (PNG) by up to 1 km (Galloway et al., 1973; Hope, 1983). However, a shift to steeper atmospheric lapse rates in a drier atmosphere, higher evaporation rates, and lower wind speeds (Betts and Ridgway,

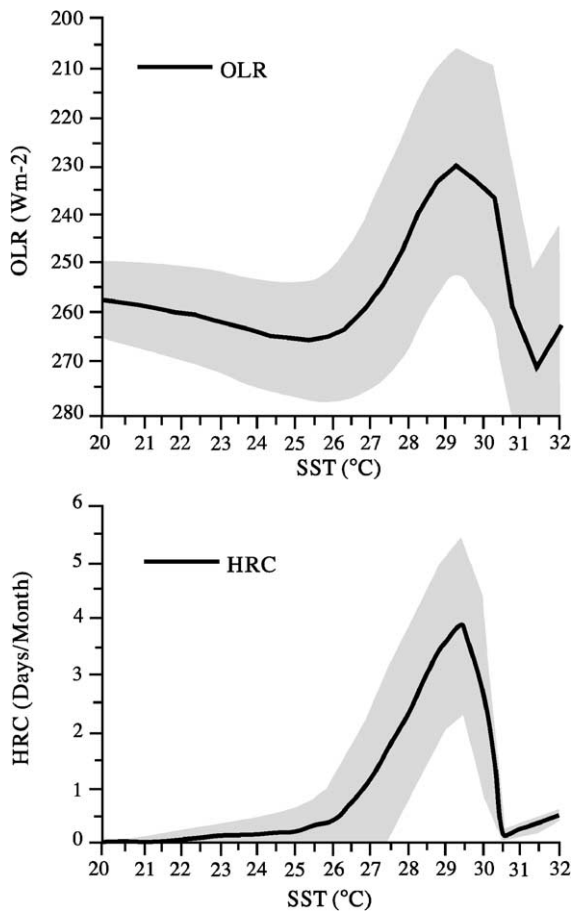


Fig. 4. Diagram to show that large-scale convection [as represented by outgoing longwave radiation (=OLR) and high reflective cloud (=HRC) over the tropical Indian and Pacific Oceans commences above a sea-surface temperature of 27.5 °C, peaks at ~ 29.5 °C, and drops almost completely upon reaching 30.5 °C. The shading represents the standard deviations of the means for the 1982–1987 period for the global tropical ocean (encompassing 25°N–25°S) as presented in Graham and Barnett (1987), Waliser and Graham (1993) and Waliser et al. (1993). Diagrams adapted from those references. Note that *if* the SST of the Indo-Pacific Warm Pool dropped by just 1 to 2 °C at the LGM, e.g. from 28 to 26 °C, large-scale convection would almost completely disappear in the region, thus forcing a major change in atmospheric precipitation.

1992) in the region could explain the difference, in addition to the lowered SSTs and sea levels as argued above. In addition, as already suggested (Galloway et al., 1973; Webster and Stretten, 1978), PNG at the LGM was likely under the influence of a much more continental climate because of the exposure of all the continental shelves in the region. Bard (1999) has

shown an amplification factor of ~ 1.3 for tropical continental land surface cooling in comparison with tropical ocean surface temperature despite reduced precipitation in the Maritime Continent region at the LGM. These influences would have allowed any wet season snowfall to persist throughout the year at much lower levels than observed today.

Similarly, wind direction may have been different as shown for southeastern Australia (Bowler, 1975), and an enhanced trough existed in the Indian Ocean and the Tasman Sea (Webster and Stretten, 1978). Oceanic fronts had also moved northward at the LGM in both the western Pacific (Martinez et al., 1997) and eastern Indian Oceans (Martinez et al., 1999) and this was further substantiated by the dust plume's northward shift in the Tasman Sea (Hesse, 1994).

6. Conclusion

We believe that during the LGM, the Walker circulation system (Webster et al., 1998) was locked into a system of atmospheric circulation that was somewhat different from today coinciding with cooler (than present) SSTs in the eastern Pacific (Hostetler and Mix, 1999) (but not as low as the -3 °C as Hostetler and Clark, 2000 require to the western Pacific) combined with very dry conditions over southeast Asia and slightly lower SSTs in the western Pacific and likely slightly lower salinities around the equator around 160°E (see Fig. 1). This scenario may have been maintained until flooding of the Sunda–Sahul shelf occurred at the end of the deglaciation (Fig. 4). Of importance is that an abrupt intensification of the summer rainfall associated with a rapid westward shift of monsoonal fronts in west China has been documented through a major shift in the isotopic record of rainfall registered in carbonate sediments from several lakes in China (Wei and Gasse, 1999). This sudden shift in atmospheric conditions seems to have occurred at ~ 12–11 cal. ka BP and coincided with the supply of terrigenous clays by major rivers bordering the South China Sea (Wang, 1999); this phenomenon seemed to have occurred earlier (~ 13 cal. ka) along the northwestern coast of Australia (De Deckker, 2001b; unpublished data), although Wyrwoll and Miller (2001) claimed 'active flood regime' by ca. 14 cal. ka in the Kimberley region of northern Australia.

The same authors refer to a substantial increase in precipitation just prior to 13 cal. ka on the Atherton Tablelands of northeastern Australia (Wyrwoll and Miller, 2001). All those dates, when considering their level of uncertainties and different carbon reservoirs, indicate the beginning of the monsoonal climatic conditions over the ‘flooded’ Indo-Pacific Warm Pool region around 13–14 cal. ka BP.

The Indo-Pacific Warm Pool remained a feature of the Global Ocean during the LGM. The flooding of the various continental shelves there during the deglaciation may have dramatically altered atmospheric circulation in the tropics, and possibly affected climatic conditions worldwide. It is more likely that the monsoonal climatic conditions, as we know them today, did not operate during the glacial period. The ‘Maritime Continent’ that SE Asia is today was instead a “dry” one during the LGM!

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