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REVIEW

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The Indo-Pacific Warm Pool: critical to world oceanography and world climate

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Abstract

The Indo-Pacific Warm Pool holds a unique place on the globe. It is a large area [>30 × 10^6 km^2] that is characterised by permanent surface temperature >28 °C and is therefore called the 'heat engine' of the globe. High convective clouds which can reach altitudes up to 15 km generate much latent heat in the process of convection and this area is therefore called the 'steam engine' of the world. Seasonal and contrasting monsoonal activity over the region is the cause for a broad seasonal change of surface salinities, and since the area lies along the path of the Great Ocean Conveyor Belt, it is coined the 'dilution' basin due to the high incidence of tropical rain and, away from the equator, tropical cyclones contribute to a significant drop in sea water salinity. Discussion about what may happen in the future of the Warm Pool under global warming is presented together with a description of the Warm Pool during the past, such as the Last Glacial Maximum when sea levels had dropped by ~125 m. A call for urgent monitoring of the IPWP area is justified on the grounds of the significance of this area for global oceanographic and climatological processes, but also because of the concerned threats to human population living there.

Keywords: Global heat engine, Global steam engine, Dilution basin, Indonesian Archipelago, Indonesian Throughflow, ENSO, Fires, Palaeorivers, LGM

Introduction

Waters from the western Pacific Ocean are transferred into the eastern Indian Ocean via the many passageways across the Indonesian Archipelago. A large portion of those seas are shallow and saddle the equator. As a result, sea-surface temperatures remain very warm (>28 °C) the whole year, but water salinities vary greatly as a result of seasonal monsoonal activity and fluxes from large rivers. Because of the shallowness of the seas, especially around a large part of Indonesia and north of Australia, and their associated very warm temperatures, this area has been coined the Indo-Pacific Warm Pool (IPWP). This region is quite extensive as it covers a surface area equivalent to that of the entire USA.

The IPWP is directly affected by the monsoons which show contrasting characteristics: the main wind directions alternate (viz. go in opposite directions) between summer and winter. In addition, the position of the Intertropical Convergence Zone (ITCZ), which is a belt of low pressure, criss-crosses the equator in the IPWP region. It is generated by the convergence of trade winds originating from both the northern and southern hemispheres. The ITCZ is formed as a result of the vertical motion of convective clouds, most of which go to great heights (>15 km). Thus, the ITCZ is the ascending member of the Hadley Cell, and therefore of great importance for global atmospheric circulation.

In this paper, I will argue for the importance of the IPWP with respect to heat and moisture transfer to the atmosphere and with respect to a freshening of the waters that pass through the Indonesian Archipelago, being part of the global circulation, often coined the 'Oceanic Conveyor Belt' or at times 'Great Ocean Conveyor Belt' [see MacDonald (1998) and Rahmstorf (2003)]. Nevertheless, it is necessary to remind the reader that a large body of very warm (>28 °C) water accumulates along the east coast of Papua New Guinea and north of it as a result of zonal winds which maintain it, before some of it is transferred across the Indonesian Archipelago, thus forming the Indonesian Throughflow (= ITF, see Fig. 4).

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Characteristics of the Indo-Pacific Warm Pool

Water temperature

As the IPWP straddles the equator and adjacent areas, its surface waters are constantly warm, and maintain temperatures over 28 °C the whole year round (Fig. 1) (Yan et al. 1992). In addition, those waters maintain such temperatures down to approximately 200 m in most regions (Figs. 1, 2, 3). This is why the term '*warm pool*' has been coined, but the origin of this term is obscure. Thus the IPWP is often referred to as *the Heat Engine of the Globe*. Refer to Ganachaud and Wunsch (2000) for an assessment of the heat transport of global ocean waters in the region of the IPWP. As a consequence of the high temperatures and productivity at the sea surface, levels of dissolved oxygen drop rapidly to levels where biological activity is either poor or almost non-existent. This is in contrast to the waters near the equator in the eastern Pacific Ocean, where dissolved oxygen levels remain high well below the sea surface (see Fig. 2).

The lack of seasonality of surface water temperatures must have a great influence on the life cycle of numerous planktic organisms which, elsewhere, have to either migrate to warm waters in winter or cope with a broad range of temperatures. In addition, the lack of seasonality must also have some significance on life cycles of numerous species. An important question is asked nowadays: *under global warming, will the temperatures of the IPWP change*? The other question is: *were temperatures always as high in the past, such as during the Last Glacial Maximum?* These issues will be addressed later on in the paper.

Water salinity

Due to the fact that the IPWP is located in a region where monsoonal activity is predominant (Ramage 1968), sea-surface salinity does vary greatly between seasons. During the 'wet' season, rivers may also discharge a huge amount of water that will contribute to a change of sea water salinity (Figs. 1, 4). Away from the equator, cyclonic activity will cause huge downpours of water (Vecchi and Soden 2007; Dare and McBride 2011) and this water may either fall directly over the ocean or over rivers and their catchments that will eventually discharge much water to the ocean and contribute to a salinity change.

As a result of such 'dilution' in the Warm Pool region, the water that is being transferred from the western Pacific Ocean into the eastern Indian Ocean will change and this is why such region is called the '*dilution basin*' of the Great Conveyor Belt. As expected, low-salinity warm water will be of low density and therefore 'glide' for some distance over the rest of the global ocean and may not necessarily mix for quite some distance. Hence, there usually is a density contrast between the diluted and warm water and the water mass below. Let us remember that such low-density water may be quite shallow (≤200 m or so; see Figs. 1, 4), having been generated within the shallow seas of the IPWP. A good example is the throughflow of water that enters the eastern Indian Ocean, a branch of which travels across the Indian Ocean (Wijffels et al. 1998) to eventually reach the east coast of Africa, and another branch will become the Leeuwin Current (along the northwest coast of Western Australia, this current now coined the Holloway Current travels along the northwest coast of Australia; Fig. 5 and see D'Adamo et al. 2009). Consequently, the throughflow [often referred to as the 'Indonesian Throughflow' (ITF); see Fig. 5] can have much importance by conveying low salinity/density water across the Indian Ocean proper.

Once again, one can ask the following question: *under global warming, will the salinity characteristics of the IPWP change*? With the corollary question: *was the salinity regime the same in the past, such as during the Last Glacial Maximum?* These issues will be addressed later on in the paper.

Water masses mixing during the throughflow

It is necessary also to mention that, during the passage of waters through the Indonesian Archipelago and associated seas, mixing of several water masses does actively occur. This is caused not only by monsoonal wind-induced upwelling, but also by very strong tidal forces (Ffield and Gordon 1996; Gordon et al. 1997; Gordon 2005; Koch-Larrouy et al. 2008), especially along some of the narrow straits between several islands. As a consequence, these phenomena induce isohaline profiles as documented by Sprintall et al. (2014) which affect sea–air interactions and atmospheric convection to very high altitudes (see also Jochum and Potemra 2008). Although some recent studies have addressed this problem (Robertson and Ffield 2008; Robertson 2011; Nagai and Hibiya 2015), a more detailed investigation of tidal mixing in the Indonesian Archipelago is essential for a more accurate prediction of temperature and salinity in the IPWP region (Robin Robertson, pers comm.).

Source of terrestrial carbon and sediment supply

In a review of the discharge of rivers to the coastal ocean, Milliman and Farnsworth (2013) indicated that many of the large rivers located in the IPWP contribute a large amount of terrestrial material, some of which is carbon rich.

The reason for such high discharge in the region is that annual rainfall is overall >2 m/yr and there are excessive values reaching over 10 m/yr in New Guinea mountains. For the IPWP region, Milliman and Farnsworth (2013) provide a total value of 11,000 km^3/yr with Papua New

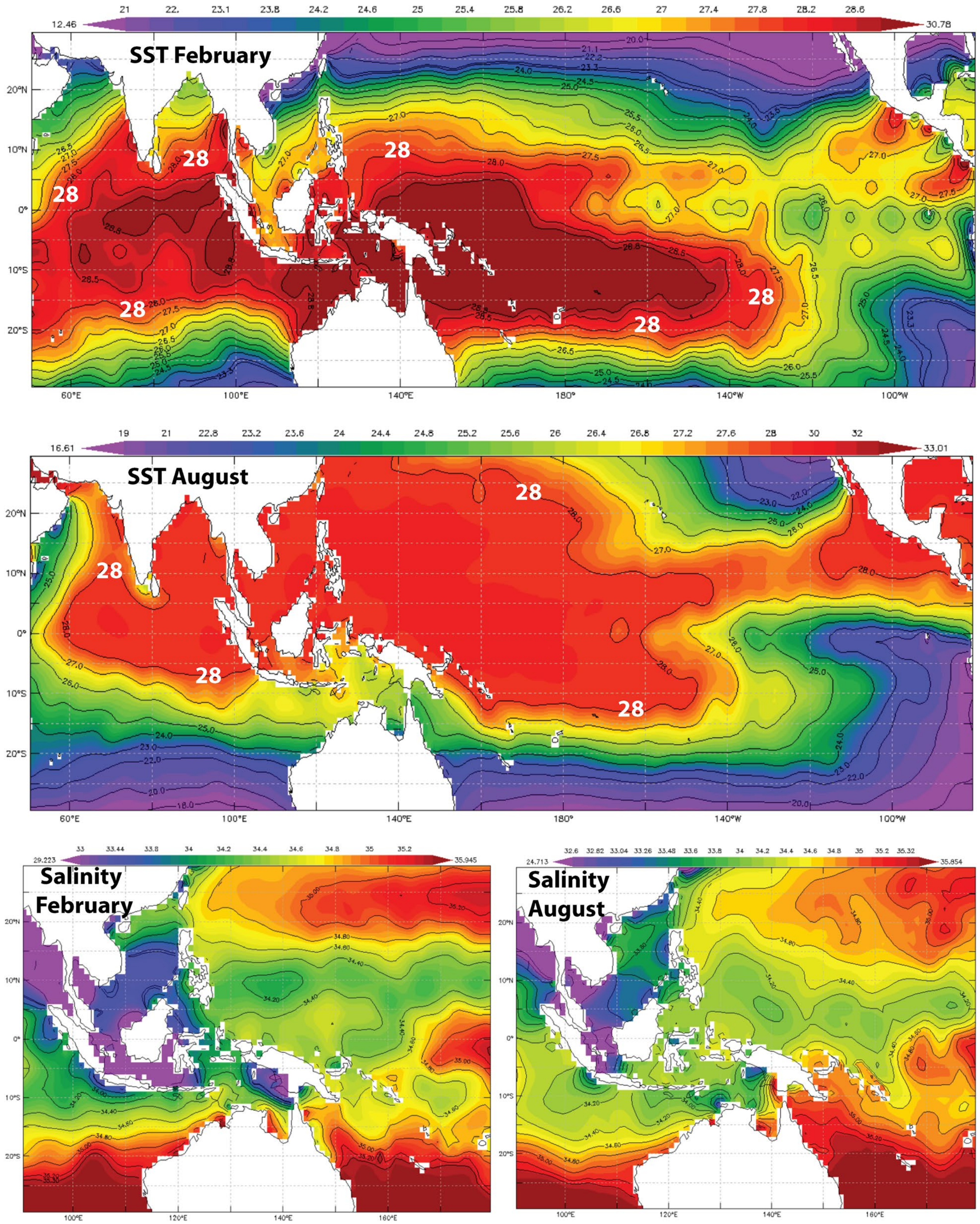


Fig. 1 Characteristic sea-surface temperatures (SST) of the Indo-Pacific region that delineate the Warm Pool, being the region with temperatures >28 °C. *Top image* represents average February SST and below average August SST. The *bottom* two *figures* represent sea-surface salinity (SSS) for the same contrasting months. Note that SSS is much lower in February when monsoonal rains contribute to a drop in SSS. All data were obtained from the World Ocean Atlas 2005 and were accessed at http://ferret.pmel.noaa.gov/thredds/dods/PMEL/WOA5

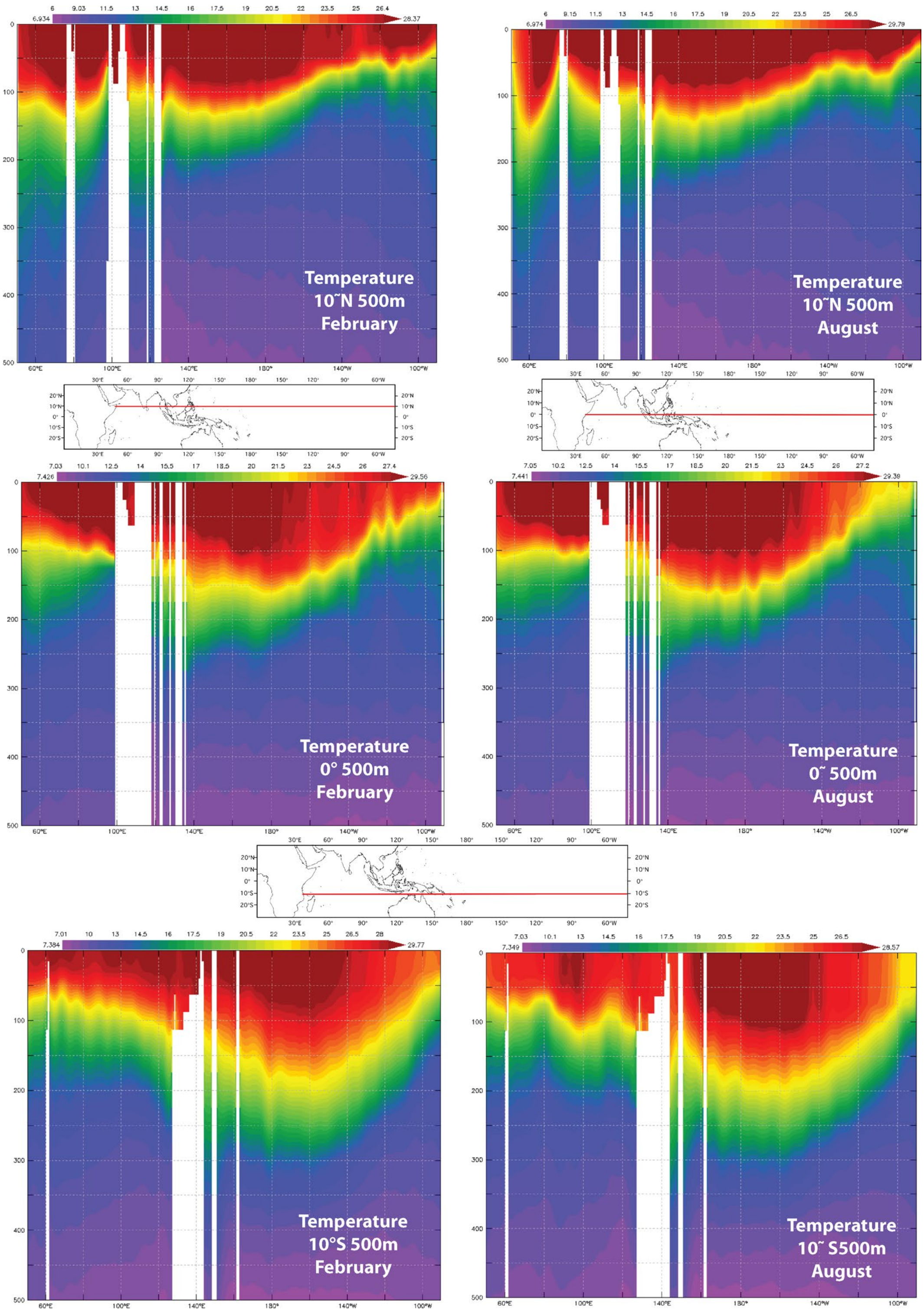
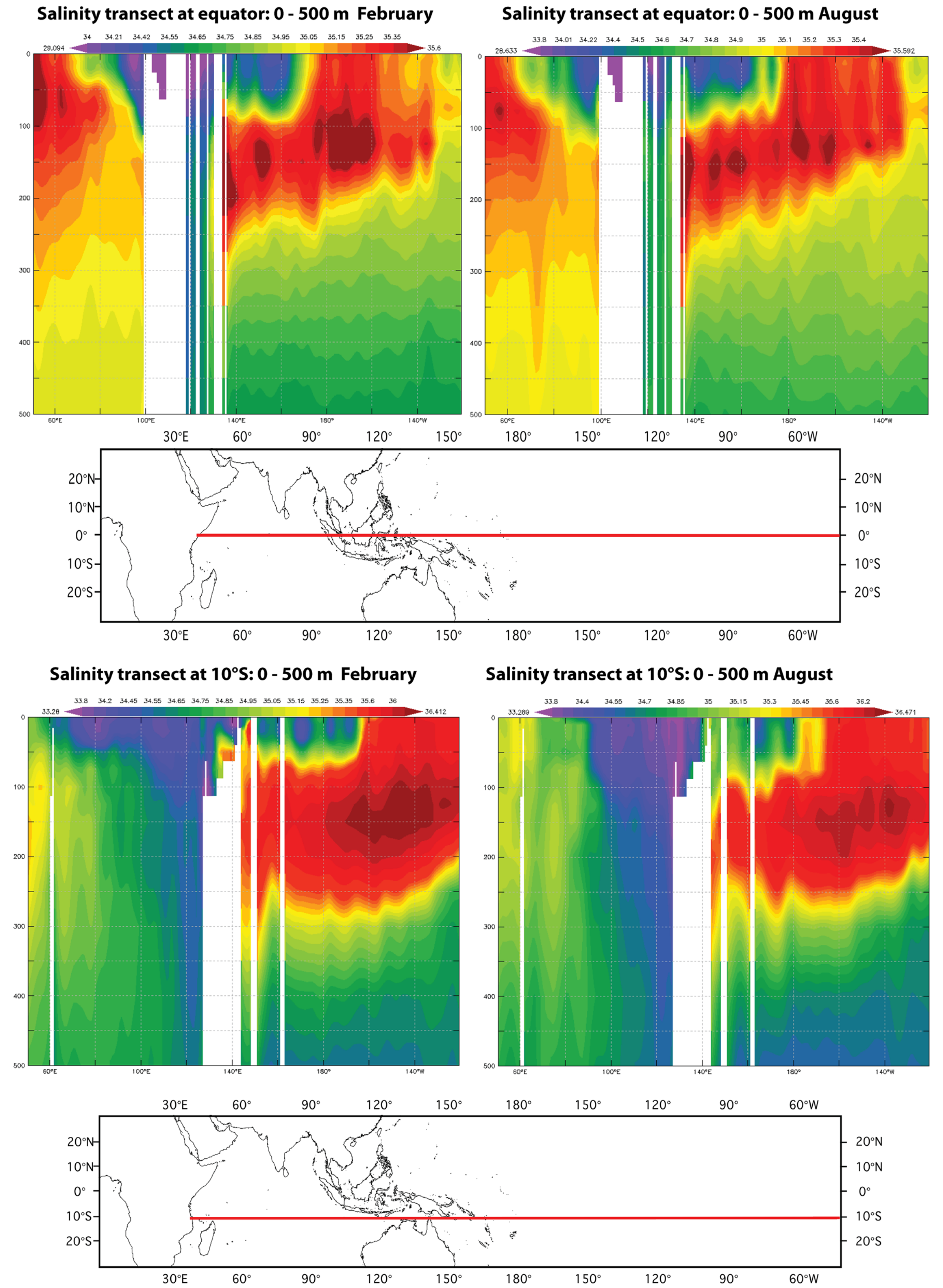


Fig. 2 Transects across the IPWP down to 500 m water depth for the contrasting periods (February and August) along three separated longitudes (*top*: 10°N, *middle*: equator, and *bottom*: 10°S). These images clearly show the shallow nature of the Warm Pool with temperatures dropping below 25 °C within less than 100 m water depth. Note the accumulation of very warm water to a greater depth offshore Papua New Guinea along the equator and at 10°S. Data accessed at the same web site listed in Fig. 1


Salinity transect at equator: 0 - 500 m February

Salinity transect at equator: 0 - 500 m August

Salinity transect at 10°S: 0 - 500 m February

Salinity transect at 10°S: 0 - 500 m August

Fig. 3 Transects across the IPWP down to 500 m water depth along transects: the equator and at 10°S for two contrasting periods (February and August) that clearly show the *upper part* of the water column with low salinities (<34°S) resulting from significant monsoonal rains over the IPWP. Note the salinity stratification in the region. Data accessed at the same web site as that listed in Fig. 1

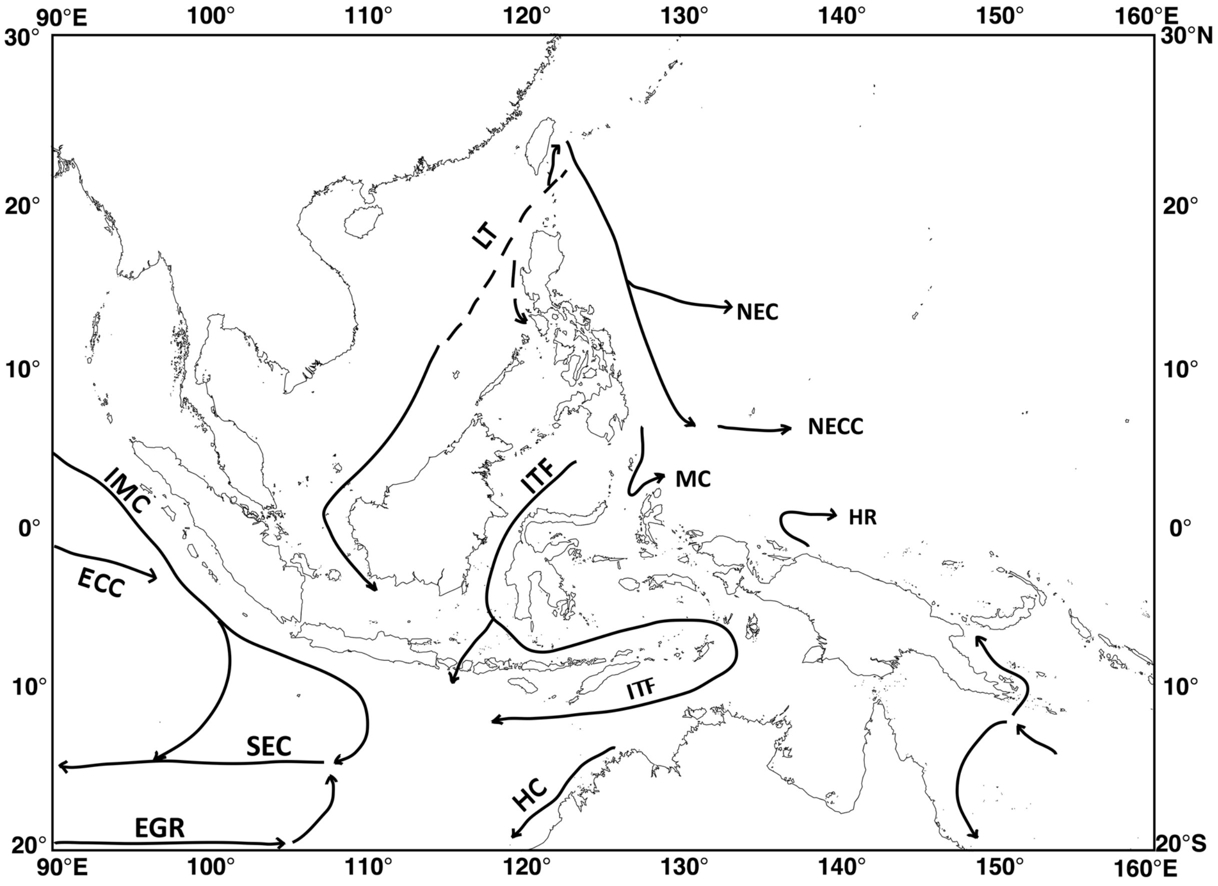


Fig. 4 Map showing a compilation of surface ocean currents in the IPWP region from several sources (Gordon and Fine 1996; Wijffels et al. 1998; Sprintall et al. 2014). *EEC* East Equatorial Current, *EGR* Eastern Gyral Current, *IMC* Indian Monsoon Current, *HC* stands for Holloway Current which is one of the currents contributing to the Leeuwin Current (see D'Adamo et al. 2009; Domingues et al. 2007); *ITF* Indonesian Throughflow, *LC*: *MC* Mindanao Current, *NEC* North Equatorial Current, *NECC* North Equatorial Counter Current, *SEC* South Equatorial Current, *SJC* South Java Current. The thickness of the *arrows* indicate the importance in volume of the different currents, although the ITF is quite substantial but it branches into several other currents. Also, some currents change directions between seasons. Note that during the LGM there was still a throughflow of water across the Indonesian seas, despite the fact that they had significantly decreased in size. Deep channels still permitted the thoroughfare of water and the flow may have even been stronger compared to today by the narrow nature of some of some 'corridors'

Guinean rivers reaching a volume of 3300 km^3/year. In contrast, the Amazon basin discharges 6300 km^3/yr (Milliman and Farnsworth 2013). In addition the sediment load for the IPWP region (called 'Austral-Asia' by Milliman and Farnsworth 2013) is estimated to be $12,500 \times 10^6$ t/yr [the total for the world being $19,000 \times 10^6$ t/yr]. The same authors claim that 'rivers draining Indonesia and the Philippines are particularly important in terms of basin erosion and sediment discharge for the entire IPWP region, accounting for more than half of the sediment discharged.' Put differently, the rivers in 'high regions contribute an estimated 6.8 billion tons of sediment annually to the coastal ocean and this represents ~40 % of the global sediment supply (Milliman and Farnsworth 2013)!

In addition, the flux of total dissolved solids for the region is enormous, and again Milliman and Farnsworth (2013) provide a value of 395×10^6 t/yr for Indonesia, Borneo and New Guinea, and for the Malay Peninsula and combined: 105×10^8 t/yr together with a supply of dissolved silica for the entire region reaching a value of 67.10^8 t/yr, in contrast to 56.10^8 t/yr for the Amazon basin! Consequently, we must view the IPWP as a major supplier of terrigenous material. By analogy, the IPWP ought to be coined a '*major feeder of total dissolved solids and sediment to the global ocean*'. A question remains, however: *would the same figures hold for the IPWP during the Last Glacial Maximum?* This will be discussed later in the paper.

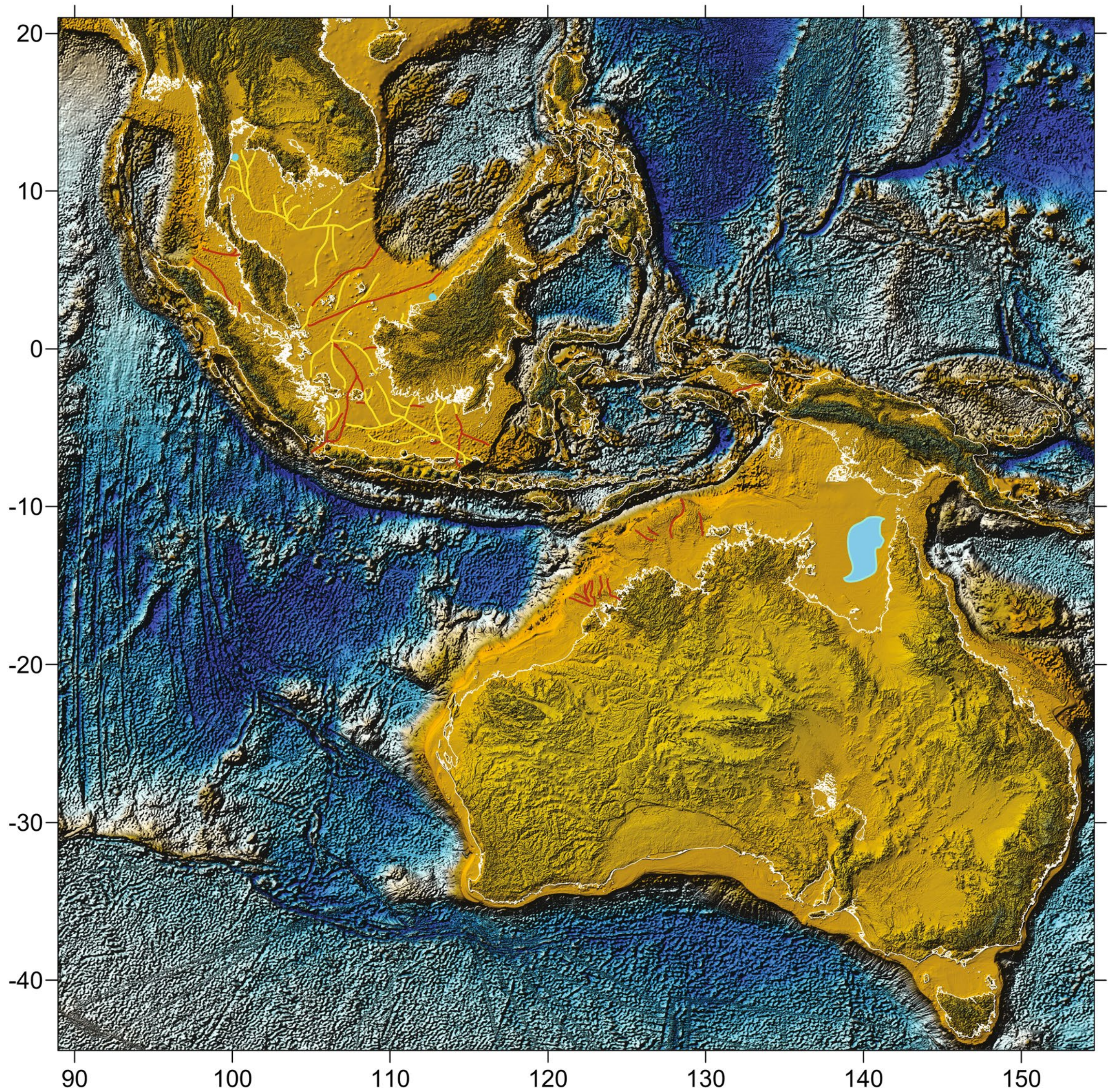


Fig. 5 Map of the southeast Asian and Australian regions combined showing a bathymetry having lowered sea level by 120 m, so as to show what the periphery of the landmasses would have looked like at the LGM. Note the increase in size of Australia, in particular in its northern portion showing an significantly exposed Sahul Shelf and also the exposed Sunda Shelf spanning from the Gulf of Thailand down to south of Borneo and north of the tip of Java. Plotted on this LGM topography is a system of palaeo-rivers, some of which had already been delineated by Molengraaf and Weber (1919), Kuenen (1950) and updated by Solihuddin (2014), all plotted in *white*, with a new interpretation of additional rivers shown here in *red*. The map was generated using the ETOPO1 global relief data set available at the following web site: http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/docs/. The *pale blue* colouration relates to large lakes that held water during the LGM. North of Australia is the large 'Lake Carpentaria' [see Chivas et al. (2001) and Yokoyama et al. 2001]. The other two LGM lakes were identified in maps (in the northern end of the Gulf of Thailand and northwest of Borneo) generated by Sathiamurthy and Voris (2006). Note that most of the palaeo-rivers flow in the southerly direction, thus indicating a northern source of water

Concerning the amount of carbon transferred to the deep ocean, it is clear that the rivers of the IPWP provide a large amount of dissolved organic carbon to the region. Nevertheless, we note that mangrove forests abound in the Indonesian region, the most significant being the west coast of Irian Jaya and parts of Papua New Guinea, both facing the Arafura Sea, some parts of Kalimantan and the east coast of Sumatra, and to a lesser extent Java [Fig. 6; see also the map on page 120 in Stone (1994)]. It is in mangrove forests that a large amount of carbon is stored and eventually processed by natural decay (Lee et al. 2014) and methanogenesis (Donato et al. 2011).

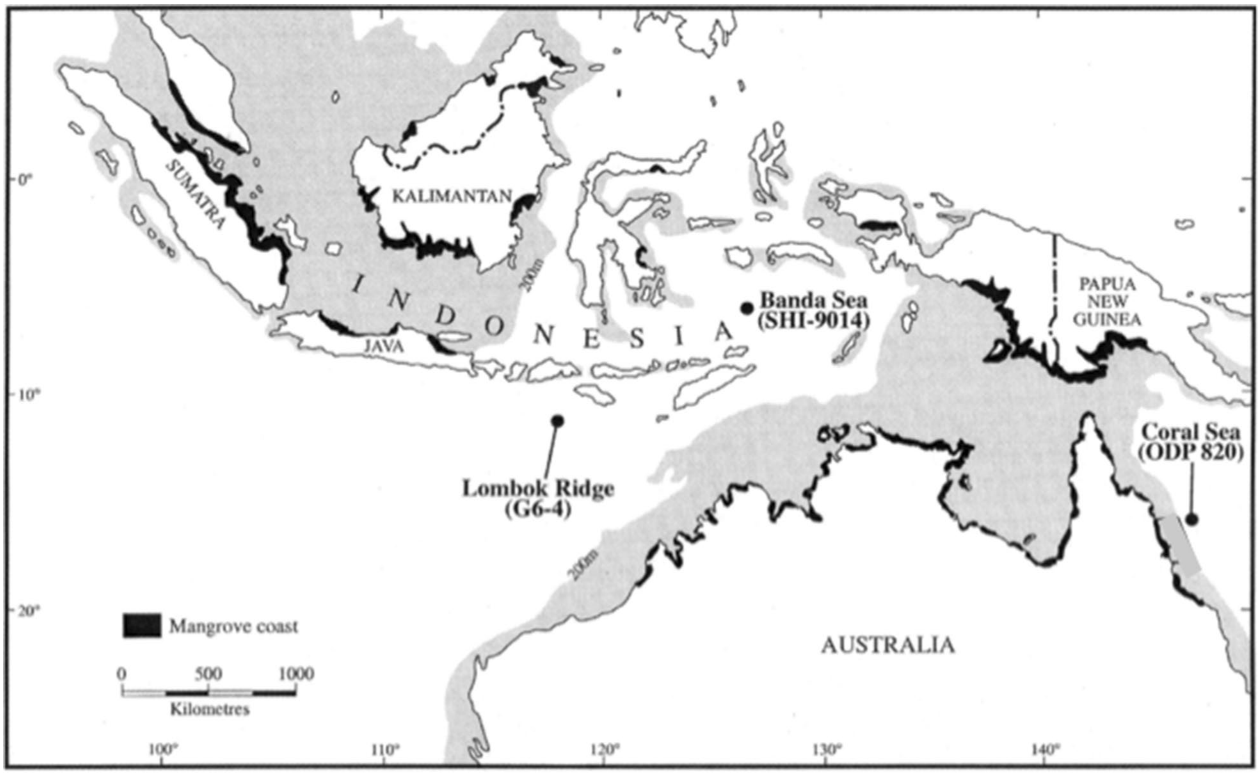


Fig. 6 Map showing today's distribution of mangroves in the southern portion of the Indonesian region and adjacent lands as well as in northern Australia. The location of cores from which mangrove pollen were recovered for the LGM and subsequent periods is indicated and they are discussed in the text. The *grey shading* identifies areas that would have been exposed at the LGM. Map modified from Grindrod et al. (2002)

Coastal erosion and readjustment, as well as shifting rivers, will induce redistribution of this carbon 'pool'. In addition, during periods of sea level changes, erosion of carbon-rich sediments occurs and this material is eventually transported to the deeper ocean. Nevertheless, an important question that prevails now is *how much of the coastal zone in the past was colonised by mangrove forests?*

Role of the IPWP in atmospheric CO_2 uptake/venting

As a result of constantly very warm waters that make the IPWP, CO_2 must be vented from such waters, but this only applies to the shallow warm waters that make the 'pool'. This shallow area (≤200 m; see Figs. 1, 2, 3) acts like a barrier between the atmosphere above the ocean and the cooler waters below (see Figure 29b in Webster 1994), and therefore the venting of oceanic CO_2 is not as important as for other regions of the global ocean.

An additional feature of the region is that it is riddled with active volcanoes, which themselves discharge a large quantity of gases, including CO_2. This does not preclude the presence of other gases such as SO_2 and CH_4 which emanate from volcanoes and which have important implications with respect to greenhouse gases.

Finally, due to the vast amount of water evaporation in the IPWP area, humidity is naturally excessive. Hence, water vapour that occurs in vast quantities in the atmosphere above the IPWP, especially during high convection to very high altitudes, must be accounted for as well as being a significant contributor to the greenhouse effect. Again, with diminished high convective cloud formation during the LGM, the transport of water molecules to high altitude would have been diminished during that time.

The Indo-Pacific Warm Pool in the past

A significant sea level drop at the LGM, with values reaching up to ~125 m (Yokoyama et al. 2000; De Deckker and Yokoyama 2009), would naturally have had a significant impact not only on the size of the IPWP, but also affect many of the processes discussed above, such as deep atmospheric convection. In addition, in 1976, CLIMAP members had postulated that SST in the IPWP region had decreased by only 2 °C (CLIMAP 1976; but see also Crowley 2000) despite the fact that at the time the snow line in Papua New Guinea was well known to have dropped between 900 and 1100 m in altitude (Hope and Peterson 1975) at the LGM.

Since then, using clumped isotope analysis of planktic foraminifers, Tripati et al. (2014) identified that glacial SST were much lower than previously thought. Their reconstructed values range between 4 and 5 °C lower than today. This is matched by lower snow lines in many high-altitude regions in the IPWP such as Irian Jaya and Papua (see Tripati et al. 2014). In addition, these authors indicated that the entrainment of ambient air into rising air masses would significantly alter the vertical temperature structure of the troposphere in the IPWP. As a consequence, this would also have an impact on the greenhouse gases in the region, and in this particular case there would be fewer water molecules in the upper atmosphere.

Already, De Deckker et al. (2002) estimated what sea-surface salinities [SSS] in the IPWP were at the LGM and identified the absence of low salinity water at the sea surface, resulting from a decrease in atmospheric convection over the IPWP. These authors postulated that, during the LGM, a shift of high convective clouds towards the central part of the Pacific Ocean must have occurred as indicated by lower salinities in that ocean at the time. The decrease in rainfall in the region at the LGM had a significant impact on the vegetation in the IPWP as seen from palynological investigations such as those by van der Kaars and Dam (1997) and van der Kaars et al. (2010), which clearly identify a significant drop in rainforest taxa along with an increase in herbaceous taxa. Recent investigations by Dubois et al. (2014) now provide a better picture, with vegetation on northeast Borneo having had similar vegetation spectra at the LGM compared with today, but information obtained from a core off the coast of Sumba indicates an expansion of C4 herbs during the LGM, thus implying enhanced aridity and water stress during the dry season (Dubois et al. 2014). This tends to indicate that high convective clouds and associated high rainfall would have shifted northwards. See additional discussion below for additional geomorphic evidence on ancient rivers. As a consequence, this major shift in floral associations at the LGM would generate a significant diminution of carbon export to the world ocean. One would expect that mangrove swamps and similar coastal environments that are carbon rich may have spread over a large portion of southeast Asia bordering the IPWP, but so far no evidence is available. This is of no surprise, however, since it is well known that mangrove pollen does not travel far (Grindrod et al. 2002) and thus its presence in LGM cores is lacking. Equally, with the hydrological budget having been modified during the LGM, less terrigenous material would have been shed into the ocean. Nevertheless, ancient river systems did operate during the LGM. A relict system of river channels had already been identified by Molengraaf and Weber (1919) and further documented by several other investigators, including Kuenen (1950) and more recently by Solihuddin (2014) who reviewed past evidence together with new bathymetric data. An attempt was made here to provide a new map of the exposed Sunda Shelf using published maps as well as information obtained from the Shuttle Radar Topography Mission (STRM) that was downloaded from https://dds.cr.usgs.gov/srtm/ (USGS 2004). The image is 3-arc second resolution data for the global relief model from http://glcf.umd.edu/data/srtm/, and is presented here in Fig. 5. The important implication seen from this map showing ancient river channels when the Sunda Shelf was exposed is that, during the LGM, a vast array of river systems actively operated. Evidence points out to rivers having drained regions that received substantial rains, and investigations by Dubois et al. (2014) indicate that the belt of convective clouds would have occurred over northeast Borneo and likely also over Thailand and adjacent regions. This is in contrast with the findings of Wurster et al. (2010) who postulated that forests contracted in north equatorial Southeast Asia during the LGM. Nevertheless, we can be sure that export of terrigenous sediments to the deeper ocean would have been smaller compared with today.

Significant changes must have occurred in the region when the exposed shelves became submerged once again during the rapid sea level rise postdating the LGM. Ocean transgression, which was really rapid for short periods, such as during the global 'meltwater pulses' occurring at 14.08–13.61 ka and 11.4–11.1 ka (Camoin et al. 2012), and which have affected human occupation on the shelves in places (for more information, refer to Oppenheimer 1998), was a pertinent feature when deglaciation commenced until about 6000 years ago when sea levels were approximately the same as today and remained so for 6 millennia. Kuhnt et al. (2015) identified that monsoonal activity became fully established by 14–15 ka in the Banda Sea and at 13.4 ± 0.3 ka in the Timor Strait. De Deckker et al. (2014) determined that northwestern Western Australia came under the influence of monsoonal rains by 13 ka. It is clear therefore that the ITCZ migrated further south through time. Its position seems not to have changed since then, so we can assume that today's levels of river discharge were fully established over the IPWP by 13 ka, with ensuing consequences of organic and inorganic carbon and terrigenous sediments discharged into the deeper global ocean.

Gindrod et al. (2002), in their extensive overview of mangrove pollen records from continental shelves and ocean cores in the northern Australian–Indonesian region, determined an overall trend: during the LGM, mangrove pollen was present in cores in the Banda Sea (core SHI 9014) as well as on Lombok Ridge (G6-4) (see Fig. 6), but levels were low compared with the period that saw sea level rising. This feature is apparently widespread in all the regions studied by Grindrod et al. (2002).

What does the future hold for the Indo-Pacific Warm Pool?

There are a number of serious concerns facing human population in the IPWP area. These are related to SST increases as anticipated as a result of anthropogenic activities. As stated above, the IPWP is defined on the basis of SST being on average over 28 °C, but as documented by Waliser and Graham (1993), Waliser et al. (1993), Webster (1994) and Webster et al. (1998), high convective clouds seem to vanish if SST are well above 31.5 °C. As a result of such high temperatures, cloud cover would significantly decrease and that would eventually cause an increase in long wave radiation. and, therefore, force a drop in nocturnal temperatures. Particularly, this would apply at high altitudes in Papua New Guinea [PNG], West Papua and Sulawesi. Already, during the strong El Niño event in 1997, serious drought affected PNG (McVicar and Bierwith 2001) as well as West Papua and Sulawesi. At that time, most crops in the highlands died in PNG, thus causing a devastating famine, with numerous human casualties. The same situation currently prevails, having started during El Niño conditions in mid-2015 with close to a third of the PNG population enduring famine due to crop failure [see: http://www.lowyinterpreter.org/post/2015/09/03/The-impact-of-the-worst-frost-and-drought-in-Papua-New-Guinea-since-1997.aspx].

As a result of drought conditions that prevail during El Niño episodes, fires (many of which are started by humans) can become prevalent all across the IPWP region, and in particular in Indonesia. As a result, health-threatening haze conditions may reach as far as Singapore and the Malaysian Peninsula, unless human-induced fires are curtailed, and with El Niño conditions set to increase in the future under increasing global temperatures (with SST in the IPWP region going above 30 °C) (Power et al. 2013). These authors predict that by mid- to late twenty-first century, an intensification of drought driven by El Niño conditions will prevail in the Western Pacific. Nevertheless, Smith et al. (2013) identified that the drying trend will be patchy for some part of the New Guinea region. This combined with the decrease of river discharge during periods of drought will also affect ocean productivity in the coastal zone, further affecting the survival of local fishing communities.

Already, there is evidence that the depth and velocity of the core of the Indonesian Throughflow [ITF] has varied with the El Niño/Southern Oscillation and Indian Ocean Dipole over the last few decades (Sprintall et al. 2014). The authors have shown that the ITF slows and shoals during El Niño events and, consequently, this affects the surface and subsurface heat content as well as sea level in the Indian Ocean between 10° and 15° S. This in turn would affect currents offshore Western Australia such as the Leeuwin Current which is driven by steric height changes (Godfrey and Ridgway 1985), with potential consequences for fisheries along the Western Australian coast (see Lenanton et al. 2009). Unfortunately, it has not been possible to find documentation on the impact of an increase of El Niño events on fisheries and livelihood of people in the IPWP who mostly depend on sea products.

The effect of sea level rise, as predicted for the future (Chapter 13, in Working group 1 of IPCC5 2014), is also a significant concern of communities bordering the ocean, and even more so for people living on low-lying islands in the IPWP region. Fairly rapid changes in the coastal zone, such as the displacement of mangroves which are also important for fisheries, needs monitoring.

In summary, environmental changes, be they natural or anthropogenic, in the IPWP are already serious and will continue to be so in the near future. This is a highly populated region of the world that will require eventually much international aid. Equally, this region will be in great need of monitoring scientifically, since it is also located at a crucial place on the globe, at the confluence of two important oceans, where atmospheric processes are significant and also where biodiversity on land and in the oceans is unique. The IPWP deserves close scrutiny and investment for a better future of humanity and the health of our planet.

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Competing interests

The author declares that he has no competing interests.

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