Western Pacific in glacial cycles: Seasonality in marginal seas and variabilities of Warm Pool *

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Abstract A series of low-latitude marginal seas, ranging from the southern South China Sea in the north to the Arafura Sea in the south, are located within the Western Pacific Warm Pool. As shown by micropaleontological, isotopical and organic geochemical analyses, the sea surface temperatures in the marginal seas at the last glacial maximum were much cooler than those in the open Western Pacific Ocean. The emergence of extensive shelves of the marginal seas at the glacial low sea-level stand and the decrease of surface temperatures in their deeper water parts resulted in a remarkable reduction of the ability of vapor and heat transport to the atmosphere, causing variabilities to the Warm Pool in the glacial cycles. The intensification of winter monsoon at the glacial stages not only led to a decrease of the surface water temperature and hence to an enhanced seasonality, but also carried moisture from the sea to the tropical islands, giving rise to the downward shift of snowline and mountainous vegetation zones there. It may offer a new alternative in solution of the "Tropical Ocean Paleo-temperature Enigma".

Keywords: Western Pacific, Warm Pool, marginal seas, glacial cycles, paleoclimate, East Asian monsoon.

1 "Paleotemperature enigma" in Western Pacific Warm Pool (WPWP)

Atmosphere-ocean coupling is the key to current climate problems. The air-sea interaction is most active in the tropical ocean which provides the main energy source for the global atmospheric circulation. The area with globally warmest sea surface temperature is a large pool stretching from the Western Pacific to the eastern Indian Ocean and straddling the equator. This is the WPWP approximately bounded by the 28 ℃ surface isotherm, and its core is located north of New Guinea with long-term average SSTs exceeding 29 ℃ (fig. 1) [1]. The WPWP plays a critical role in modulating world climate because of its vapor and heat transfer and its close relationship with the ENSO events. Therefore, the maintenance and stability of the WPWP within glacial cycles are of primary importance in Quaternary climate studies.

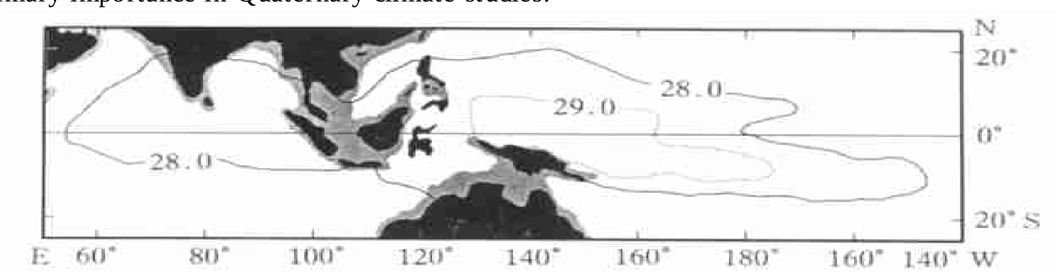

Fig. 1. The WPWP and the marginal seas. The 28 ℃ isotherm approximately outlines the Warm Pool, the shadow area indicates the shelf seas emerging during the last glacial maximum (LGM).

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On the basis of micropaleontological data, the CLIMATE project concluded in the late 1970s that during the LGM high-latitude SSTs were 6—10 ℃ lower than at present, whereas low-to-mid latitudes experienced little, if any, changes in SSTs[2]. Later, the oxygen-isotopic analyses also showed that the glacial-modern contrasts in SSTs in the tropical Western Pacific are less than 2 ℃[3]. This was supported by some recent authors who believe that the WPWP persisted through the glacial cycles and played a role similar to that at present even at the LGM[4].

However, a significant cooling at the glaciation has been revealed by terrestrial records from the islands in the Warm Pool area. Substantial geomorphological evidence shows snow lines in New Guinea at the glacial time to be over 1 000 m lower than at present which matches a 6—8 ℃ lowering of temperature in highland[5]. Pollen records from over 1 300 m on tropical mountains of Java and Sumatra suggest a downward shift of forest altitudinal boundaries at the glaciation, equivalent to temperature changes of 1.8—7 ℃[6]. All these have been reconfirmed by the recent studies[7][1)]. From the discrepancy between marine and terrestrial records emerges an enigma in tropical paleoclimate studies: the glacial SST was too warm to fit the significant cooling in highlands[8]. Two possible solutions have been proposed: either the marine or/and terrestrial paleotemperature records have serious estimation errors, or the lapse rates at the glaciation were much steeper than today. The reliability of the paleo-temperature estimations has since long been a matter of debate, but very significant errors are unlikely (see below). As to the steeper lapse rates, this is a hypothesis still active now[4], but its predestinate consequence is a significant change in relative humidity in the atmosphere and, hence, a very arid climate which is not conformable to the practical records, not to mention the denial of the hypothesis by the recent evidence from the noble gas content in glacial-age aquifers from North America[9].

Thus, the scientific community is still puzzled by the paleo-temperature enigma in the glacial tropical Western Pacific. The numerous high-resolution sequences of paleo-temperature records resulting from the recent paleoceanographic studies in the Western Pacific marginal seas have provided new approaches to the paleoclimate problem in the WPWP, and this is the motive of the present paper.

2 Environmental changes in marginal seas and Warm Pool

The development of a series of marginal seas is the most distinct feature of the connection between the Western Pacific Ocean and the continents of Asia and Australia. Because of the extensive shelves and numerous straits and seaways, the marginal seas are sensitive to glacial sea-level lowering when the emergence of shelves and the closure of seaways lead to a large-scale reorganization of circulation and, consequently, significant climatic consequences[10,11]. It is to note that the southern part of the South China Sea, the Sulu Sea, Celebes Sea, Java Sea, Banda Sea, Timor Sea and Arafura Sea with the Gulf of Carpenteria are within the limits of the WPWP (fig. 1), and the amplifying effects of marginal seas for environmental signals in the glacial cycles must have their impact on variabilities of the Warm Pool through changes in sea surface area and temperature.

1) Peterson, J., Hope, G., Hantoro, W. et al., Irian Java glaciers and late Quaternary tropical temperature estimated (Abstract), *International Symposium on the Environmental and Cultural History and Dynamics of the Australian-Southeast Asian Region*, Monash University, December 1996, Programme and Abstracts.

(1) Sea surface area. The globally broadest mid- to low-latitude shelf seas are developed in the Western Pacific marginal seas, the most extensive ones being the "Great Asian Bank", including the southern part of the South China Sea, the Gulf of Thailand, and the Java Sea, and the "Great Australian Bank", consisting of the Timor and Arafura Seas with the Gulf of Carpentaria, with areas of 1.80 million km^2 and 1.23 million km^2 respectively. Their glacial emergence reduced the sea surface area of the Warm Pool by over 3 million km^2.

(2) Sea surface temperature. The glacial changes in circulation patterns in the Western Pacific and its marginal seas brought about remarkable variations in sea surface temperature. The published and our new paleo-temperature data have enabled us to reconstruct the LGM paleo-SST maps for boreal winter and summer which include 24 sites from the China and Sulu seas and 18 sites from the open Pacific (fig. 2(a), (b)). The paleo-SST estimations are based on relative abundances of planktonic foraminiferal species, using paleoecological Transfer Function FP-12 developed by P. Thompson for the Western Pacific (with standard errors of 2.48 ℃ for winter and 1.46 ℃ for summer)[12]. In the result, the LGM summer SST for the South China and Sulu seas between 5° and 20°N ranges from 25.6 to 29.0 ℃, averaging 27.8 ℃, while in the open Western Pacific at some latitudes it ranges from 27.1 to 29.6 ℃ with an average of 28.7 ℃, very close to that in the marginal seas. The LGM winter SST varies from 16.0 to 24.0 ℃ in the South China and Sulu seas, averaging 21.1 ℃, and from 23.8 to 28.0 ℃ in the open ocean, averaging 26.0 ℃, or 4.9 ℃ higher than that in the marginal seas. Thus, the winter SST at the LGM was much cooler in the Western Pacific marginal seas than in the open ocean.

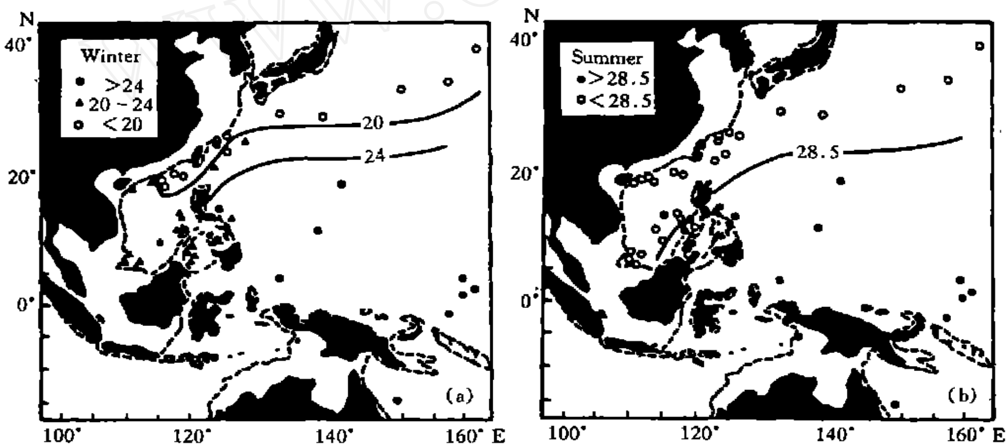

Fig. 2. Sea surface temperature (SST) in the low and middle latitude Western Pacific and marginal seas at the last glacial maximum. Th paleo-SST estimates are based on census of planktonic foraminifers using Transfer Function FP12-E[12]. (a) Winter; (b) summer.

The decrease in size and SST of the low-latitude marginal seas at the LGM reduced evaporation and, hence, the role of the WPWP in the air-sea interactions, implying a certain instability of the Warm Pool in the glacial cycles. Moreover, its size reduction is not restricted to the marginal seas. The southern limit of the WPWP retreated northwards as a result of the northern migration of the Tasman Front in the south Pacific[13] and the weakening of the Leeuwin Current in the eastern Indian Ocean[14], and the northern limit moved to the south due to the northern shift of the Polar Front in the north Pacific[15], leading to a reduction in latitudinal coverage of the WPWP[1)]. Thus, the Warm Pool experienced expansion and contraction with the glacial cycles. It remained through the glacial times[4], but with remarkable variations. The most prominent changes occurred in the marginal seas which are not so large in area in comparison with the entire pool (fig. 1), but have significant climate influence on the continent and islands.

3 East Asian monsoon and seasonality in marginal seas

The winter cooling of surface water in the glacial marginal seas, together with insignificant changes in summer, has resulted in an enhanced annual range of temperature, or seasonality. The summer/winter SST difference in the Western Pacific at the LGM is shown in fig. 3. As seen, the seasonal SST difference ranges from 1.3 to 4.4 ℃ in the open Pacific between 5° and 20°N, whereas it reaches 4.8—10.1 ℃ in the South China and Sulu seas at the same latitudes, showing the enhanced seasonality in the marginal seas.

Seasonality in the Western Pacific marginal seas is closely related to the East Asian monsoon. As shown by the modern monsoon studies, in winter the northerly flow from the cold Siberia High crosses the equator over the South China Sea area and becomes the strongest winter monsoon flow in the world[16]. In the northern South China Sea, the content of aeolian dust and pollen from the northern vegetation types drastically increased in the LGM deposits, indicating considerable intensification of the winter monsoon at the glaciation[2)] which led to a decrease of winter SST in the marginal seas and strengthened seasonality there. Thus, the enhanced seasonality at the LGM should be ascribed to the Eastern Asian monsoon and the semi-enclosed features of the marginal seas[17], and its absence is to be expected in the open Pacific outside of the monsoon prevalence.

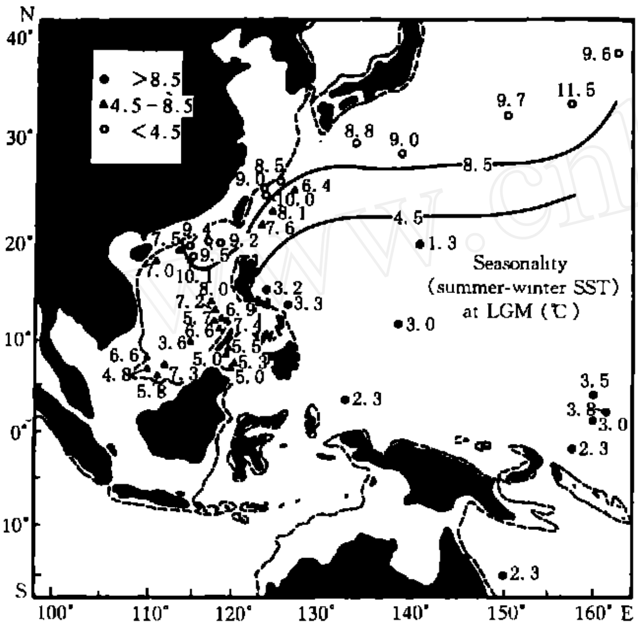

Fig. 3. Seasonality in SST (summer SST minus winter SST) at the LGM in the low and middle latitude Western Pacific and marginal seas.

In their studies of tropical Western Pacific including marginal seas, Thunell et al. (1994) found that at the LGM "tropical SSTs differed by less than 2 ℃ from the present; away from the tropics (30°N and 30°S) SSTs were at least 3 ℃ cooler". Accordingly, they concluded that "LGM climatic conditions in the tropical Western Pacific were similar to those at present"[4]. However, their data are mean annual SSTs estimated from the planktonic foraminiferal consensus using the

1) Martinez, I., De Deckker, P., The Western Pacific Warm Pool during the last glacial maximum (Abstract), *International Symposium on the Environmental and Cultural History and Dynamics of the Australian-Southeast Asian Region*, Monash University, December 1996, Programme and Abstracts.

2) Wang, L., Sun, X., Personal communication, 1996.

modern analogue technique (MAT) without seasonal variations taken into account. And the results are in contradiction to those by the same group of authors in the tropical marginal seas using transfer function[18]. Therefore, inappropriate conclusions may easily result from a discussion on climate evolution in a monsoon region, when the role of seasonality is overlooked.

The glacial intensification of the winter monsoon may offer an approach to the above-discussed paleo-temperature enigma in the tropical Western Pacific. The climate variations on islands around the low-latitude marginal seas, such as Java, Sumatra and New Guinea, are under their direct influence. The modern winter monsoon transfers vapor from the marginal seas to the islands together with cold air, and the monsoon fluctuations are responsible for the variations of monsoon rainfall over the islands[1)]. Accordingly, the intensification of the boreal winter monsoon at the LGM must have led to a combination of decreased temperature and enhanced vapor supply, which in turn might have caused the snowline lowering in New Guinea[5] and downward shift of alpine vegetation zones[6,7].

4 Verification of paleo-SST estimations

The above-discussed paleo-temperature differences between marginal seas and the open ocean are based on transfer function SST estimates. However, it has been debated whether the transfer function technique is applicable to the tropics for paleotemperature estimations. Therefore, independent paleo-SST proxies, based on organic and isotopic geochemistry are needed to verify our conclusions drawn from micropaleontology.

The unsaturation ratio of long-chain alkenones ($U_{37}^{k'}$) biosynthesized by coccolithophorids is closely correlated with SST. Up to now, there are at least four cores analyzed for $U_{37}^{k'}$ measurements in the South China Sea, and the resulting LGM/Holocene SST contrast is 4—4.5 ℃ in the north and 2.5 ℃ in the south, all exceeding that in the open Pacific (only 0.7 ℃) (see table 1), agreeing well with our micropaleontology-based conclusions.

Table 1 $U_{37}^{k'}$ SST estimates for the South China Sea and the Western Pacific

	Site	Location	LGM/modern SST contrast	Reference
South China Sea	17940	20°07′N, 117°23′E	4.5 ℃	a
	SCS90-36	18°00′N, 111°30′E	4 ℃*	b
	SO50-31KL	18°45′N, 115°52′E	4 ℃	[19]
	17961	8°30′N, 112°20′E	2.5 ℃	a
West Pacific	W8402A-14GC	0°57′N, 138°57′E	< 2.0 ℃ (0.7 ℃)	[20]

a, Pelejero, C., Grimalt, J. O., Sarnthein, M., Wang, L., Variations in $U_{37}^{k'}$ sea surface temperature and marine/terrestrial biomarkers in the South China Sea during the last 130 000 years (Abstract), IGC-30, Abstracts, 2:253.

b, Huang, C-Y., Wu, S.-F., Zhao, M. et al., Surface ocean and monsoon climate variability in the South China Sea since the last glaciation, *Mar. Micropaleontol.*, in the press.

* Contrast between the modern and 14 ka records.

1) Lim, J. T., Tuen, K. L., Sea surface temperature variations in the South China Sea during the Northern Hemisphere monsoon, *Proceedings of the Second WESTPAC Symposium, December* 1991, *Penang, Malaysia*, IOC, 113—144.

Oxygen isotope data for the late Quaternary are now available from many sites in the Western Pacific marginal seas, in particular the South China Sea. As seen from the LGM-Holocene changes in the oxygen isotope of shallow-dwelling planktonic foraminifers (*Globigerinoides sacculifer* or *G. ruber*) (fig. 4), the contrast is again much more significant in the marginal seas than in the open ocean at the same latitudes. The LGM-modern difference in $\delta^{18}O$ attributed to ice volume is 1.3 ‰[21], and the residual value should be caused by changes in SST or salinity. As shown in fig. 4, the residual value varies from - 0.4 ‰ to + 0.3 ‰ in the open ocean south of 20 °N, while it is much higher in the marginal seas at the same latitudes, measuring between + 0.4 ‰ and + 1.0 ‰. If all the residual value is ascribed to SST or salinity changes, it would mean a LGM-Holocene contrast in water temperature of 2.0—5.0 ℃ or in salinity of 0.8 ‰—2 ‰. Since at the glacial time the rivers could discharge directly into the deeper water area in the marginal seas, but the postglacial intensification of the summer monsoon might bring more precipitation to the continent, it is still very difficult to judge the direction of salinity change. On the other hand, the trend of paleo-SST changes discussed above is well supported by the $\delta^{18}O$ data.

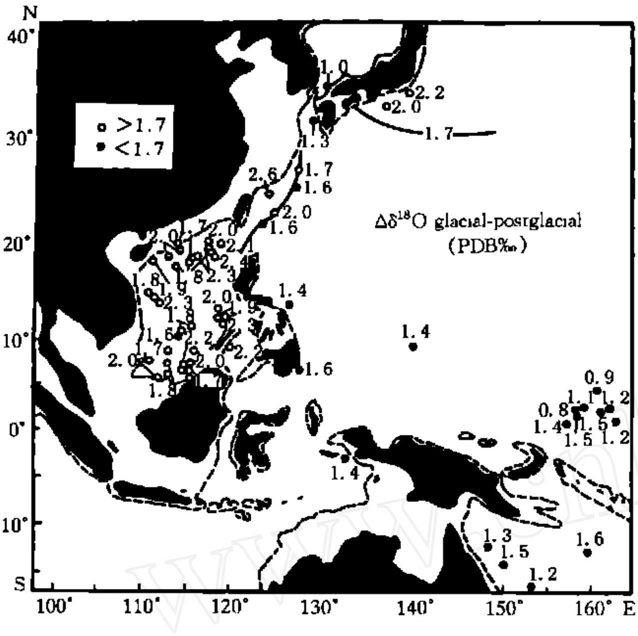

Fig. 4. LGM/Holocene difference in oxygen isotope values of shallow-dwelling planktonic foraminifers in the low and middle latitude part of the Western Pacific.

In sum, the different SST responses of marginal seas and open ocean to the glacial cycles are proved by all the three independent proxies, suggesting glacial variabilities of the WPWP.

5 Conclusions

1) The response to the glacial cycles is different in the different parts of the WPWP. In the open ocean the SST varies slightly within the glacial cycles, while in the marginal seas the glacial exposure of extensive shelves and the drastic decrease of winter SST led to an area contraction and temperature decline of the WPWP, resulting in a remarkable decrease of energy and vapor to the atmosphere and a certain reduction of the climate role of the Warm Pool.

2) The analyses for long-chain alkenones and oxygen isotopes supported the paleo-SST based on planktonic foraminiferal assemblages, indicating different responses to glacial cycles in the marginal seas and open ocean at the same latitudes. Therefore, at least a part of the WPWP has displayed a certain instability in the glacial cycles.

3) The winter decrease in SST and strengthening of seasonality in the marginal seas in the glaciation must have resulted from the intensification of the winter East Asian monsoon. Together with the increase of vapor supply to the islands by the enhanced winter monsoon, this might be a

factor responsible for the glacial lowering of mountainous vegetation zones and snowlines on islands there, offering a new possible solution of the paleo-temperature discrepancy between the tropical SST and island climate during the glacial time.

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