

***Pulleniatina* Minimum Events in the Andaman Sea (NE Indian Ocean): Implications for winter monsoon and thermocline changes**

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Abstract

The late Quaternary record of *Pulleniatina obliquiloculata* was investigated from two well dated sediment cores from the Andaman Sea (NE Indian Ocean) to examine its paleoceanographic significance and the presence of the *Pulleniatina* Minimum Events (PME) in the western North Pacific. As in the Pacific, our study shows that PMEs exist in the Indian Ocean albeit with a lower intensity. The Holocene PME occurs between 4.5 to 3.0 cal ka BP with a considerable reduction in *P. obliquiloculata* abundance, and which matches well with the Pacific records influenced by the Kuroshio Current. Additionally, two significant minimum events of *P. obliquiloculata* are also seen during the Younger Dryas (YD) and late Last Glacial Maximum (LGM, 20-18 cal ka BP). Overall, the PMEs of the Andaman Sea are not current driven events like in the western Pacific margin either by the weakening of the Kuroshio Current or reduced winter SSTs. The PMEs of the Andaman Sea are characterised by lower abundances of thermocline species indicating the increased depth of the thermocline (DOT) and reduced winter SSTs mainly during the minimum events of the YD and late LGM. The high SSTs during the Holocene PME make this event a mystery. However, the presence of PMEs in the Andaman Sea suggests that these events are not confined to areas influenced by the Kuroshio Current but may be responding to a broad scale oceanographic-climatic process or mechanism which needs to be explored with a detailed study.

Keywords: Andaman Sea; *Pulleniatina obliquiloculata*; thermocline; winter monsoon; late Quaternary; paleoceanography.

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1. Introduction

A *Pulleniatina* minimum event (PME) refers to the sudden decrease in abundance of the planktic foraminifera *Pulleniatina obliquiloculata* in Holocene sediments of the western Pacific Ocean; such as the one recorded between ~4.5 and 3 ka in deep-sea cores from the western North Pacific (Pflaumann and Jian 1999; Ujiie and Ujiie 1999; Yang and Jian 2009; Li et al., 1997; Wang et al., 1999; Jian et al., 2000; Yu et al., 2000; Huang et al., 2002; Ujiie et al., 2003; Lin et al., 2006; Xiang et al., 2009). In the South China Sea (SCS) another minimum event has been reported during Heinrich Event 1 (H1 PME) (Liu 2004; Pflaumann and Jian 1999; Yang and Jian 2009; Wang et al., 1999; Yu et al., 2000; Huang et al., 2002; Xiang et al., 2009). On the other hand, disappearance of *P. obliquiloculata* mainly during the middle of the last glacial period was also reported from the Atlantic Ocean (Prell and Damuth 1978). However, to our knowledge, no such minimum events are known in the Indian Ocean region.

In the modern ocean, *P. obliquiloculata* lives in the subsurface waters below the thermocline (e.g., Ravelo et al., 1990). Therefore, variations in its abundance can be interpreted as a change in the thermocline depth (Li et al., 1997). Currently, there are two views on the cause of PMEs in the western Pacific region. Low abundances of *P. obliquiloculata* are considered to be indicative of the weakening/diversion of the Kuroshio Current (Li et al., 1997; Ujiie and Ujiie 1999). Alternatively, according to plankton tow studies, this warm water, dissolution resistant species is most abundant when winter sea surface temperatures (SST) are relatively high (Bé and Tolderlund 1971; Ravelo and Fairbanks 1992). The Holocene PME has also been attributed to the intensification of the winter monsoon and consequently to decreased SST (Jian et al., 2000) which was correlated to the neoglacial cooling in China (Wu and Liu 2004; Peng et al., 2005). Another characteristic feature associated with the PME of the western Pacific is the high abundance of the thermocline species *N. dutertrei*, which was interpreted as related to the enhanced influence of gyre-margin water in the Okinawa Trough (Ujiie et al., 2003).

The Andaman Sea is a semi enclosed marginal sea which exchanges water with the Bay of Bengal (BOB) in the northern Indian Ocean and marginal seas of western Pacific mainly via shallow channels (Fig. 1a). It is interconnected with the BOB by the Deep Prepares Channel, Ten Degree Channel and the Great Channel. The oceanographic processes in these seas are however comparable only up to a depth of about 1000 m, as the deep water exchange between these two regions (Andaman Sea and BOB) is hampered by several sills which have significant influence on intermediate to deep water circulation in the Andaman Sea. The Sunda Shelf provides a shallow route to the eastern seas and to the Pacific Ocean, which is the southeast extension of the continental

shelf of southeast Asia. As in the Arabian Sea, the Andaman Sea also experiences a seasonal reversal in surface circulation triggered by the Indian monsoon. The Andaman Sea has been well documented as a productive sea owing to the prevailing upwelling during the winter monsoon (Wyrski, 1973). Biological productivity in the offshore region is $\sim 0.8\text{-}1.0 \text{ mgC/m}^2/\text{d}$ compared to lesser values ($<0.6 \text{ mgC/m}^2/\text{d}$) observed in the coastal areas (Janekarn and Hylleberg 1989). The Andaman Sea is characterized by a low surface salinity (Fig. 1b) ranging between 31.8 and 33.4 practical salinity units (psu), due to the influence of fresh water discharge from the Ayeyarwady-Salween river system (Sarma and Narvekar 2001). The average surface temperature of the Andaman Sea is 29°C , and is nearly homogenous up to a depth of 50 m leading to stratification, which hinders vertical mixing (Sarma and Narvekar 2001). The temperature decreases down to 13°C at a depth of 200 m and 9°C at a depth of 500-600 m and the total thermocline thickness is about 150 m (Saidova, 2008). Here, we report on the occurrence of more than one PME in the Andaman Sea. In addition, we make an attempt to understand the causes and paleoceanographic significance of *P. obliquiloculata* variability in this marginal sea.

2. Materials and Methods

The sediment cores SK 168/GC-1 ($11^\circ42.463'\text{N}$; $94^\circ29.606'\text{E}$, water depth: 2064 m, core length: 4.20 m) and AAS 11 GC 1 (9°N ; $94^\circ17'\text{E}$, water depth: 2909 m; core length: 4.28 m) were collected from the Andaman Sea (Fig. 1). SK 168/GC-1 was collected during the 168th cruise of ORV Sagar Kanya from the Alcock Seamount Complex and core AAS 11/GC-1 was collected during the 11th expedition of RV AA Sidorenko. About 10 g of dried samples were soaked in Milli-Q water overnight and washed through a $63 \mu\text{m}$ mesh sieve. Later the dried filtrate was sieved through a $125 \mu\text{m}$ mesh sieve. The coarse fraction ($>125 \mu\text{m}$) was split into several aliquots to reduce the total number of planktic foraminifera to a minimum of 300 individuals which were used for quantitative and qualitative analyses of planktic foraminifera assemblages. Thermocline species are represented by the total percentages of *Globorotalia menardii*, *Neogloboquadrina dutertrei* and *Pulleniatina obliquiloculata*. Resistant species include *G. menardii*, *N. dutertrei*, *P. obliquiloculata*, *Globorotalia tumida*, *G. crassaformis*, *G. truncatulinoides*, *Candeina nitida* and *Sphaerodinella dehiscence*. The taxonomic identification to species level followed that of Kennett and Srinivasan (1983).

Approximately 10 to 16 tests of *Globigerinoides ruber* (white) exhibiting a wide morphologic variation in the size range of $250\text{-}315 \mu\text{m}$ were used for oxygen isotope analysis. Microscopic examination showed that the tests were well preserved with no apparent dissolution. The shells were placed in thimbles and crushed using a thin needle, then a few drops of methanol were added and the

shells were cleaned using an ultrasonic bath for 8-10 seconds. The cleaned tests were analysed for oxygen isotopes using an Isotope Ratio Mass Spectrometer (IRMS). The oxygen isotopic measurements of core SK 168/GC 1 were carried out at the National Institute of Oceanography, Goa, India, while the values presented here for core AAS 11/GC 1 were already published by Ahmad et al. (2000).

The age model for the cores (SK 168/GC-1 and AAS 11/GC-1) was constructed mainly using the Accelerator Mass Spectrometer (AMS) ^{14}C dates of planktic foraminiferal tests (*G. ruber* and *Globigerinoides sacculifer*). In core SK 168 oxygen isotope stratigraphy was also used to produce independent age controlling points for sediments older than 24 ka BP. AMS ^{14}C ages were determined for 17 horizons (for both cores) (Table 1) and calendar age calibration was based on the CalPal 2007 (Weninger et al., 2007, <http://www.calpal.de>). The AMS ^{14}C dates were corrected for a 460 year reservoir age following Butzin et al. (2005) and Cao et al. (2007). Oxygen isotope stratigraphy (core SK 168) was established by correlation of the oxygen isotopic values of *G. ruber* with the standard oxygen isotopic curve of Martinson et al. (1987). The boundary between marine isotope stage (MIS) 3 and MIS 2 (24.11 ka), and sub events of MIS 3 (3.1=25.42 ka and 3.13=43.88 ka) were also used as independent age controlling points (Fig. 2a and Fig. 3a). The low resolution oxygen isotope record in core AAS 11 limits its use for constructing an age model, whereas the faunal records of both cores are comparable for the last 30 ka (see Fig. 4). Older sediments (>30 ka) show a roughly 1 ka shift in the faunal composition between SK 168 and AAS 11, reflecting the upper limit of uncertainty for sections older than 30 ka in core AAS 11. Both cores have a continuous record since ~44 cal ka BP and they show distinct last glacial to interglacial changes. The ages for other horizons were assigned by interpolation/extrapolation of calibrated dates, assuming constant sedimentation rates. The average sedimentation rates are about 7.79 cm/ka and 9.37 cm/ka for cores SK 168 (Fig. 2a) and AAS 11 (Fig. 2b), respectively.

3. Results

The down core variation of the relative abundance of *P. obliquiloculata* in both cores is plotted with the oxygen isotope record of the planktic foraminifer *G. ruber*, the SST record of Andaman Sea (Rashid et al., 2007) and total planktic foraminifera tests per gram against calendar age in Fig. 3a-f. The abundance curves of *P. obliquiloculata* of both cores show good stratigraphic correlation mainly during the last 25 cal ka BP (Fig. 3b,c). Overall, a marked change in abundance of *P. obliquiloculata* is seen at 10 cal ka BP (Pleistocene-Holocene boundary) (Fig. 3b,c). The maximum abundances of *P. obliquiloculata* are seen at 33.5 ka and Heinrich Event 1 (H1, 14.5-16 cal ka BP) whereas minimum events occur during the late Last Glacial Maximum (LGM, 20-18 cal ka BP, Younger Dryas (YD,

13-10.5 cal ka BP) and late Holocene (4.5-3 cal ka BP). Northern core SK 168 shows distinctive minimum events and the intensity of variation reduces towards the south. The Holocene PME is a little longer in core SK 168 (4.5 to 2 cal ka BP) than that of AAS 11 (4.5 to 3 cal ka BP). PMEs of YD and LGM are correlatable with heavier oxygen isotope values and lower SST whereas Holocene PME is correlatable with lighter oxygen isotope values and higher SST. Total planktic foraminiferal numbers are characteristically high during the PME suggesting enhanced foraminiferal productivity.

P. obliquiloculata variability in relation with other planktic foraminifera, thermocline and resistant species are given in Fig. 4a-j. *G. menardii* shows low abundance during the PMEs and high abundance during the H1 maximum event of *P. obliquiloculata* (Fig. 4e). Like *G. menardii*, *G. sacculifer* shows a characteristic low abundance during PMEs but high abundance during H1 (Fig. 4f). The planktic foraminifera assemblage of PMEs is characterised by the low abundances of *G. menardii*, *G. sacculifer*, total thermocline species, low to moderate abundances of *N. dutertrei* and high abundances of *G. bulloides*.

The resistant species show changes in abundance throughout the cores (Fig. 4i and j). During the PMEs, resistant species are very low in abundance with values as low as 8%. In general, resistant species are low in abundance during PMEs, YD and H1 and high in abundance during the Bølling/Allerød (B/A), and MIS 3/MIS 2 transition. Though the resistant species are very low in abundance during H1, it marks the maximum abundance of *P. obliquiloculata*. The thermocline species show a lower abundance during PMEs. During the last 40 cal ka BP, the lowest abundance of thermocline species is seen during YD (Fig. 4h). *G. sacculifer* is a shallow dwelling species and tolerates a wide range of temperature and prefers to live in the mixed layer condition with low seasonal changes in SST (Bé, 1977; Fairbanks et al., 1982). *G. sacculifer* has a low abundance during PMEs but higher abundance during H1.

4. Discussion

P. obliquiloculata is thick walled and highly resistant to dissolution (Berger, 1970) hence its relative abundance is usually high when carbonate dissolution is strong. In order to understand the variability of *P. obliquiloculata*, we have compared it with resistant species. The inverse relationship suggests that its variability is not related with carbonate dissolution in the Andaman Sea. If it were due to carbonate dissolution, a positive relationship between *P. obliquiloculata* and resistant species would have been witnessed. We used the oxygen isotope, SST record and other planktic foraminiferal proxies to understand the causes and paleoceanographic changes associated with the three minimum events (Holocene, YD and late LGM PMEs) occurring in the Andaman Sea.

The Holocene PME occurred from 4.5-3.0 cal ka BP (4.5 to 2.0 cal ka BP for core SK 168) and is marked by very low abundances of *P. obliquiloculata* which is in good agreement with western Pacific records (Ujiié et al., 2003; Lin et al., 2006; Xiang et al., 2009). During the Holocene PME in the Andaman Sea, the total planktic foraminifera were moderately high (Fig. 3f) which indicates that general foraminiferal productivity was high during this period. The important feature of the Holocene PME of the Andaman Sea was higher SSTs, whereas other minimum events were marked by lower SSTs (Fig. 3). The Holocene PME of the western Pacific was interpreted as a result of the weakening/diversion of the Kuroshio Current (Li et al., 1997; Ujiié and Ujiié 1999) or an intensification of the winter monsoons and consequently of decreased SSTs (Jian et al., 2000). *P. obliquiloculata* usually proliferates during high winter SST (Jian et al., 2000). Hence lower abundances during higher SSTs (Fig. 3) make this event (Holocene PME) unclear. The Holocene PME of the Andaman Sea might be due to an increase in the depth of the thermocline (DOT) marked by lower abundances of *G. menardii*, *N. dutertrei* and *G. sacculifer*.

The low abundances of *P. obliquiloculata* occur during the YD, which shows pronounced changes in the global atmospheric and oceanic circulation system especially in the north eastern Atlantic (Duplessy et al., 1981) and also in the Indian Ocean characterised by an abrupt weakening of the summer monsoon (Schulz et al., 1998). The oxygen isotope record of both cores shows heavier values during the YD (the average and heaviest YD values are -1.91‰ and -1.7‰) indicating either reduced SSTs or a change in salinity. The abundances of total planktic foraminifera and *G. bulloides* indicate an enhanced summer monsoon during BA and slight weakening during the late YD in the Andaman Sea. Similar low abundances of *P. obliquiloculata* during the YD period are also seen in the Okinawa Trough of the East China Sea (Li et al., 1997). The lowest percentage of thermocline species during the YD suggests a deepening of the DOT and reduced SSTs during an enhanced winter monsoon, which may have caused hostile conditions for *P. obliquiloculata*.

The third minimum event of *P. obliquiloculata* occurred between 20 to 18 cal ka BP and is characterised by relatively heavier oxygen isotope values (average LGM value is ~ -1‰ for both cores) and reduced SSTs (Rashid et al., 2007), marking the coolest period in the glacial Andaman Sea during the last 44 cal ka BP. The oxygen isotope record of *G. ruber* has shown that the LGM to Holocene ($\Delta\delta^{18}\text{O}$) amplitude is 2.09‰ from which the global ice volume effect would account for 1.2‰ and remaining 0.90‰ would either require an increase in salinity by 3‰ or a decrease in temperature by ~ 4.5°C. In the Andaman Sea, the Mg/Ca records have shown that the LGM temperature is 3°C less than that seen presently or during the Holocene (Rashid et al., 2007). This temperature change would thus account for an enrichment of 0.60‰ and the remaining 0.30‰ (of

LGM to Holocene $\Delta\delta^{18}\text{O}$ amplitude) will require an increase in salinity by 1‰ during the LGM. The estimated salinity change of 1‰ is negligible whereas the decrease in temperature by 3°C played a major role in the LGM PME.

The LGM is also characterised by low abundances of warm water species such as *G. menardii* and *G. sacculifer* and moderate abundances of *N. dutertrei*, marking reduced winter SSTs. According to Duplessy (1982) and Sarkar et al. (1990) the winter monsoon was stronger during the LGM. The weakening of the summer monsoon during the LGM is clearly indicated by the lower abundances of *G. bulloides* and total planktic foraminifera. Similar to the YD, the LGM is also characterised by a deepened DOT, which reduced the abundances of *P. obliquiloculata*, a species that usually proliferates when the DOT shoals (Lin and Hsieh 2007). The LGM PME in the Andaman Sea might be related to reduced winter SSTs, a deepened thermocline and low productivity. The PME during the late LGM (20 to 18 cal ka BP) was not recorded in the southern SCS, instead it is present during H1. While the Holocene PME is widely distributed in marginal seas of the western Pacific, the H1 PME has been only documented in the southern SCS (Yang and Jian 2009). The H1 PME in the SCS has been attributed to shoaling of the mixed layer due to changes in surface and subsurface temperatures and resultant changes in water column structure during the last deglacial warming period (Yang and Jian 2009) or due to a drop in winter SSTs due to an intensified winter monsoon (Xiang et al., 2009).

While the above paragraphs describe the minimum events, distinct maxima in the abundances of *P. obliquiloculata* are also seen at 33.5-35.5 cal ka BP and H1. High abundances of *P. obliquiloculata* at H1 are in contrast to a PME noticed in the southern SCS. The H1 *Pulleniatina* maximum in our cores from the Andaman Sea corresponds to lighter oxygen isotope values and moderate to high abundances of *G. sacculifer* and *G. menardii*, suggesting increased surface and subsurface temperatures during the deglacial. The high abundances of *P. obliquiloculata* during the late glacial to H1 marks the driest climatic period in the Andaman Sea (Rashid et al., 2007). The high abundances of *P. obliquiloculata* in the Andaman Sea during the early to middle glacial (cores SK 168, 20-23 and AAS 11 20-21 cal ka BP) and late MIS 3 are correlated with high abundances of thermocline species, suggesting that a shoaling of the thermocline caused the proliferation.

In general the PMEs of the Andaman Sea are characterised by low abundances of thermocline species suggesting a deepening of the DOT. No significant change in relative abundance of *N. dutertrei* was seen in the Andaman Sea, which is unlike that found in the Okinawa Trough where higher abundances were seen during the Holocene PME (Ujiié et al., 2003). The minimum events of the YD and LGM are the result of enhanced winter monsoons with reduced winter SSTs and

deepened DOT whereas the Holocene PME of the Andaman Sea is still a mystery, characterised by higher SSTs and deepened DOT. The presence of PMEs in the Andaman Sea affirms the view of Ujiie et al. (2003) that PMEs may not be local phenomena of the Kuroshio source region but may be responding to a broad scale oceanographic-climatic process or mechanism which needs to be explored with a detailed study.

Conclusions

This study reports on the presence of PMEs in the Indian Ocean. The abundances of *P. obliquiloculata* along with other planktic foraminiferal proxies from two well dated cores from the Andaman Sea show a relationship between PMEs and oceanographic conditions. In the Andaman Sea, the Holocene PME occurred between 4.5 to 3.0 cal ka BP where relative abundances of *P. obliquiloculata* show a considerable reduction which matches well with Pacific records. In addition, we report two other significant minimum events during the YD and the late LGM (20 cal ka to 18 cal ka). The H1 PME of the South China Sea is not seen here, but this period instead is characterised by high abundances of *P. obliquiloculata* which mark the driest climatic period in the Andaman Sea. Overall, the PMEs of the Andaman Sea are not current driven like that in the western Pacific margin. The minimum events of the YD and LGM seem to be controlled by enhanced winter monsoons with reduced SSTs and deepened DOT whereas the Holocene of the Andaman Sea is still a mystery and characterised by higher SSTs and deepened DOT.

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References

- Ahmad, S.M., Patil, D.J., Rao, P.S., Nath, B.N., Rao, B.R., Rajagopalan, G., 2000. Glacial-interglacial changes in the surface water characteristics of the Andaman Sea: Evidence from stable isotopic ratios of planktonic foraminifera. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* 109, 153-156.
- Bé, A.W.H., Tolderlund, D.S., 1971. Distribution and ecology of living planktonic Foraminifera in surface waters of the Atlantic and Indian Ocean. In: Funnell, B.M., et al., (Eds.), *Micropaleontology of Oceans*, Cambridge University Press, Cambridge, pp. 105-49.
- Bé, A.W.H., 1977. An ecological, zoogeographical and taxonomic review of recent planktonic foraminifera. In: Ramsay, A.T.S. (Ed.), *Oceanic Micropaleontology 1*, Academic Press, London, pp. 1-100.
- Berger, W.H., 1970. Planktic foraminifera: selective solution and the lysocline. *Marine Geology* 8, 111-138.
- Brown, B.E., 2007. Coral reefs of the Andaman Sea-an integrated perspective. In: Gibson, R.N., Atkinson, R.J.A., Gordon, J.D.M. (Eds.), *Oceanography and Marine Biology Annual Review 45*. Taylor and Francis, pp. 173-194.
- Butzin, M., Prange, M., Lohmann, G., 2005. Radiocarbon simulations for the glacial ocean: the effects of wind stress, Southern Ocean sea ice and Heinrich events. *Earth and Planetary Science Letters* 235, 45-61.
- Cao, L., Fairbanks, R.G., Mortlock, R.A., Risk, M., 2007. Radiocarbon reservoir age of high latitude North Atlantic surface water during the last deglacial. *Quaternary Science Review* 26, 732-742.
- Duplessy, J.C., Delibries, G., Turon, J.L., Pujol, C., Duprat, J., 1981. Deglacial warming of the north eastern Atlantic Ocean: correlation with the paleoclimatic evolution of the European continent. *Palaeogeography Palaeoclimatology Palaeoecology* 35, 121-144.
- Duplessy, J.C., 1982. Glacial to interglacial contrasts in the northern Indian Ocean. *Nature* 295, 494-498.
- Fairbanks, R.G., Sverdløve, M., Free, R., Wiebe, P.H., Bé, A.W.H., 1982. Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin. *Nature* 298, 841-844.
- Huang, C.C., Wu, S.M., Chen, M.T., Lee, M.Y., Wei, K.Y., Huang, C.Y., 2002. Planktic foraminifer faunal sea surface temperature records of the past two glacial terminations in the South China Sea near Wan-An Shallow (IMAGES core MD972151). *Western Pacific Earth Sciences* 2, 1-14.
- Janekarn, V., Hylleberg, J., 1989. Coastal and offshore primary production along the west coast of Thailand (Andaman Sea) with notes on physical chemical variables. *Phuket Mar. Biol. Cent. Res. Bull.* 51, 1-19.
- Jian, Z., Wang, P., Saito, Y., Wang, L., Pflaumann, U., Oba, T., Cheng, X., 2000. Holocene variability of the Kuroshio Current in the Okinawa Trough, north western Pacific Ocean. *Earth and Planetary Science Letters* 184, 305-319.

- Kennett, J.P., Srinivasan, M.S., 1983. Neogene planktonic foraminifera. A Phylogenetic Atlas, Hutchinson Ross, Stroudsburg.
- Li, B., Jian, Z., Wang, P., 1997. *Pulleniatina obliquiloculata* as a paleoceanographic indicator in the southern Okinawa Trough during the last 20,000 years. *Marine Micropaleontology* 32, 59-69.
- Lin, Y.S., Wei, K.Y., Lin, I.T., Yu, P.S., Chiang, H.W., Chen, C.Y., Shen, C.C., Mii, H.S., Chen, Y.G., 2006. The Holocene *Pulleniatina* Minimum Event revisited: geochemical and faunal evidence from the Okinawa Trough and upper reaches of the Kuroshio Current. *Marine Micropaleontology* 59,153-170,doi:10.1016/j.marmicro.2006.02.003.
- Lin, H.L., Hsieh, H.Y., 2007. Seasonal variations of modern planktonic foraminifera in the South China Sea. *Deep Sea Research II, Topical Studies in Oceanography* 54, 1634- 1644, doi:10.1016/j.dsr2.2007.05.007.
- Liu, C.H., 2004. A Holocene planktic foraminifer record from an IMAGES high resolution core MD972146 of the South China Sea. MS thesis, Natl. Taiwan Ocean Univ. Keelung, Taiwan (in Chinese, with English Abstract).
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high- resolution 0 to 300,000 year Chronostratigraphy. *Quaternary Research* 27, 1-29.
- Peng, Y., Xiao, J., Nakamura, T., Liu, B., Inouchi, Y., 2005. Holocene East Asian monsoonal precipitation pattern revealed by grain-size distribution of core sediments of Daihai Lake in Inner Mongolia of north-central China. *Earth and Planetary Science Letters* 233, 467-479, doi:10.1016/j.epsl.2005.02.022
- Pflaumann, U, Jian, Z.M., 1999. Modern distribution patterns of planktonic foraminifera in the South China Sea and western Pacific: a new transfer technique to estimate regional sea-surface temperatures. *Marine Geology* 156, 41-83.
- Prell, W.L., Damuth, J.E., 1978. The climate-related diachronous disappearance of *Pulleniatina obliquiloculata* in late Quaternary sediments of the Atlantic and Caribbean. *Marine Micropaleontology* 3, 267-277.
- Rashid, H., Flower, B.P., Poore, R.Z., Quinn, T.M., 2007. A ~25 ka Indian Ocean monsoon variability record from the Andaman Sea. *Quaternary Science Reviews* 26, 2586- 2597, doi:10.1016/j.quascirev.2007.07.002.
- Ravelo, A.C., Fairbanks, R.G., Philander, S.G.H., 1990. Reconstructing tropical Atlantic hydrography using planktonic foraminifera and ocean model. *Paleoceanography* 5, 409-431.
- Ravelo, A.C., Fairbanks, R.G., 1992. Oxygen isotopic composition of multiple species of planktonic foraminifera: recorders of the modern photic zone temperature gradient. *Paleoceanography* 7, 815-831, doi:10.1029/92PA02092.
- Sarkar, A., Ramesh, R., Bhattacharya, S.K., Rajagopalan, G., 1990. Oxygen isotope evidence for a stronger winter monsoon current during the last glaciations. *Nature* 343, 549- 551.

Saidova, Kh. M., 2008. Benthic Foraminifera Communities of the Andaman Sea (Indian Ocean). *Oceanology* 48, 517-523.

Sarma, V.V.S.S., Narvekar, P.V., 2001. A study on inorganic carbon components in the Andaman Sea during the post monsoon season. *Oceanologica Acta* 24, 125-134.

Schulz, H., von Rad, U., Erlenkeuser, H., 1998. Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature* 393, 54-57.

Sijinkumar, A.V., Nath, B.N., Gupta, M.V.S., 2010. Late Quaternary record of pteropod preservation from the Andaman Sea. *Marine Geology* 275, 221-229, doi:10.1016/j.margeo.2010.06.003.

Ujiié, H., Ujiié, Y., 1999. Late Quaternary course changes of the Kuroshio Current in the Ryukyu Arc region, north-western Pacific Ocean. *Marine Micropaleontology* 37, 23- 40.

Ujiié, Y., Ujiié, H., Taira, A., Nakamura, T., Oguri, K., 2003. Spatial and temporal variability of surface water in the Kuroshio source region, Pacific Ocean, over the past 21,000 years: evidence from planktonic foraminifera. *Marine Micropaleontology* 49, 335- 364, doi:10.1016/S0377-8398(03)00062-8.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Grootes, P., Heilig, S., Ivanova, E., Kienast, M., Pelejero, C., Pflaumann, U., 1999. East Asian monsoon climate during the Late Pleistocene: high-resolution sediment records from the South China Sea. *Marine Geology* 156, 245-284.

Weninger, B., Jöris, O., Danzeglocke, U., 2007. CalPal-2007, Cologne Radiocarbon Calibration & Palaeoclimate Research Package, <http://www.calpal.de>.

Wu, W., Liu, T., 2004. Possible role of the “Holocene Event 3” on the collapse of Neolithic Cultures around the Central Plain of China. *Quaternary International* 117, 153-166, doi:10.1016/S1040-6182(03)00125-3.

Wyrtki, K., 1973. Physical oceanography of the Indian Ocean. In: Zeitzschel, B., Gerlach, S.A., (Eds.). *The Biology of the Indian Ocean*. Springer-Verlag, New York, pp. 18- 36.

Xiang, R., Chen, M., Li, Q., Liu, J., Zhang, L., Lu, J., 2009. Planktonic foraminiferal records of East Asia monsoon changes in the southern South China Sea during the last 40,000 years. *Marine Micropaleontology* 73, 1-13, doi:10.1016/j.marmicro.2009.06.004.

Yang, A.N., Jian, Z., 2009. *Pulleniatina* Minimum Event during the last deglaciation in the southern South China Sea. *Chinese Science Bulletin* 54, 4514-4519, doi: 10.1007/s11434-009-0290-4.

Yu, P.S., Chiu, T.C., Chen, M.T., Wei, K.Y., Chen, Y.G., 2000. Planktic foraminifer faunal assemblage and sea-surface temperature variations in a ‘warm-pool’ South China Sea record of the past 400,000 years: IMAGES core MD972142. *Journal of Geological Society of China* 43, 467-496.

Figure captions.

Fig. 1 Location of cores SK 168/GC 1 and AAS 11/GC 1, Andaman Sea, in the eastern Indian Ocean (modified from Sijinkumar et al., 2010): a) bathymetry of Andaman Sea along with core locations; b) salinity (annual salinity at the surface, World Ocean Atlas, 2009, www.nodc.noaa.gov) and monsoon currents in Andaman Sea; black arrow-summer monsoon, yellow arrow-winter monsoon, (modified from Brown, 2007 reference therein).

Fig. 2 Age-depth model with sedimentation rate; a) Core SK 168 (Sijinkumar et al., 2010) (based on 6 age control points to obtain this sedimentation rate. The ages represented by black circles are based on the calibrated AMS ^{14}C ages, and the open circles based on the oxygen isotope records (refer text for details); b) Core AAS 11 (based on 12 AMS ^{14}C dates).

Fig. 3 Planktic foraminiferal (*G. ruber*) oxygen isotope record of cores SK 168 and AAS 11 in relation with *Pulleniatina* Minimum Events (PMEs) of Andaman Sea; a) Oxygen isotope record of core SK 168 (Sijinkumar et al., 2010); b) Relative abundance of *P. obliquiloculata* in core SK 168; c) Relative abundance of *P. obliquiloculata* in core AAS 11; d) Oxygen isotope record of core AAS 11 (Ahmad et al., 2000 plotted with ^{14}C AMS dates); e) SST ($^{\circ}\text{C}$) of core RC 12-344 (Rashid et al., 2007); f) Total number of planktic foraminiferal tests per gram in core SK 168. Marine Isotope Stage (MIS), Younger Dryas (YD), Bølling–Allerød (B/A), Heinrich Event 1 (H1) last glacial maximum (LGM) are shaded. The long arrow indicates the depth horizon for ^{14}C AMS dating and small arrow indicates MIS 3/MIS 2 boundary and sub stages of MIS 3 (See text for details).

Fig. 4 Comparison of *P. obliquiloculata* record with other planktic foraminiferal proxies in core SK 168 and AAS 11; a) Relative abundance of *P. obliquiloculata* in core SK 168; b) Relative abundance of *P. obliquiloculata* in core AAS 11; c) and d) Relative abundance of *N. dutertrei* (SK 168 and AAS 11); e) Relative abundance of *G. menardii* (SK 168); f) Relative abundance of *G. sacculifer* (SK 168); g) Relative abundance of *G. bulloides* (SK 168); h) total thermocline species % (SK 168); i) and j) total planktic foraminifera resistant species % (SK 168 and AAS 11)

Fig. 1

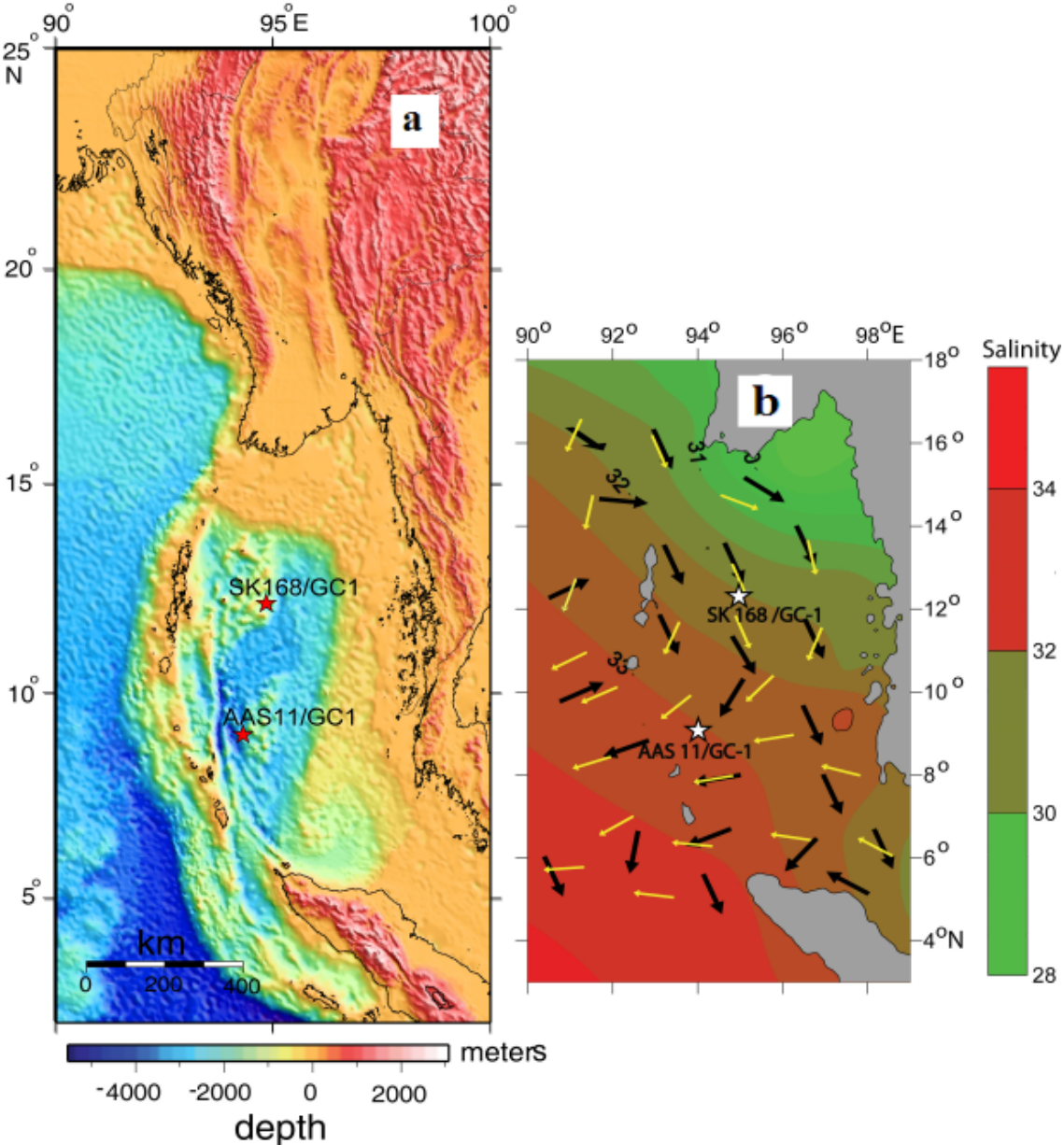


Fig. 2

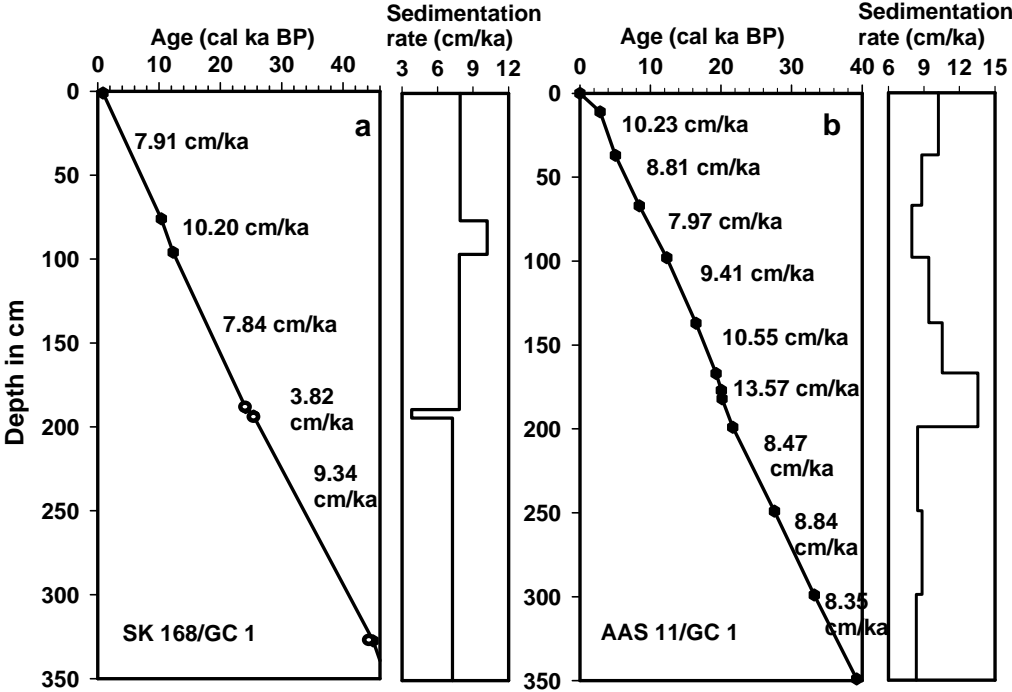


Fig. 3

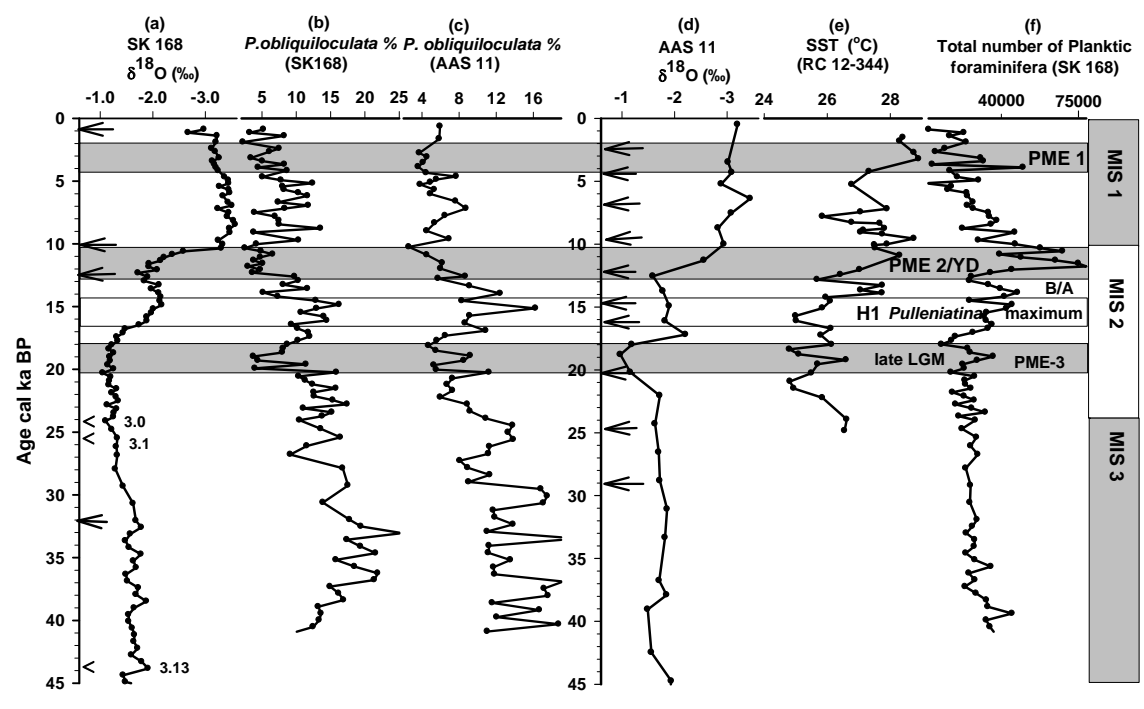


Fig. 4

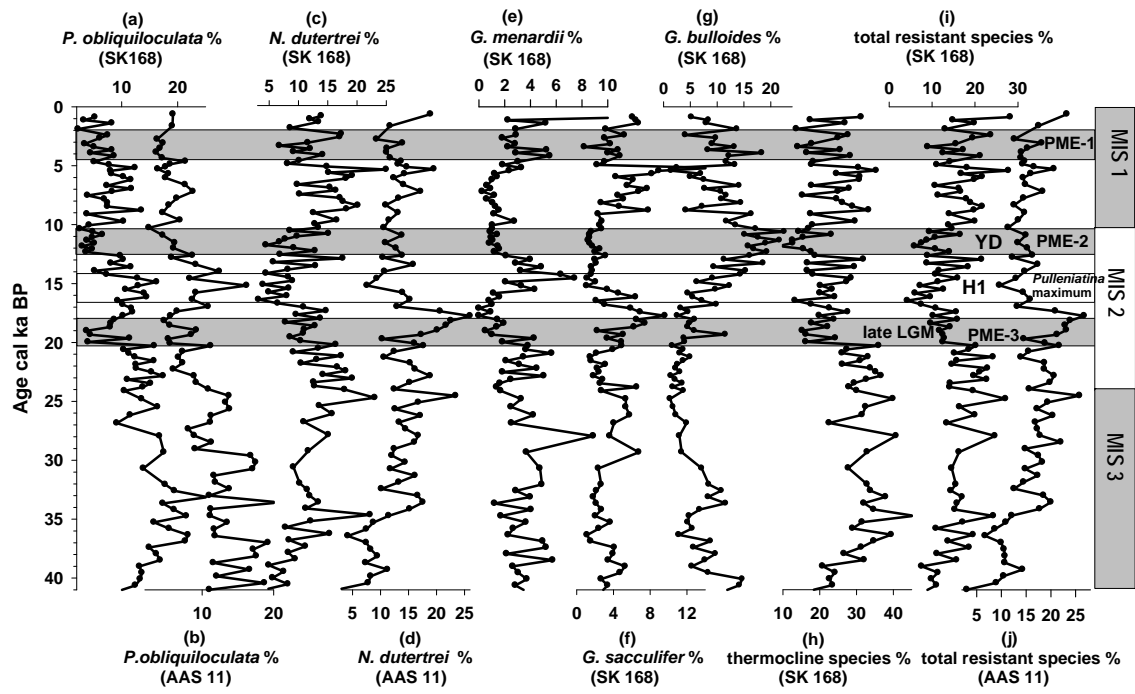


Table 1 AMS ¹⁴C dates and calibrated ages of sediment samples for SK 168/GC-1 and AAS 11

Depth in core (cm)	Material	Accession No.	Radiocarbon age (¹⁴ C age in years)	Calendar age (Cal year BP)
SK168/0-2	Mixed Planktic foram	OS-64674	1440±30	883 ± 47
SK168/75-77	Mixed Planktic foram	OS-64675	9650±30	10361 ± 76
SK168/95-97	Mixed Planktic foram	OS-64676	10850±50	12321 ± 178
SK168/215-220	Mixed Planktic foram	OS-64677	27900±220	32055 ± 215
SK168/330-335	Mixed Planktic foram	OS-64678	41300±530	44363 ± 820
AAS11/10-12	Mixed Planktic foram		3085± 50	2872.5 ±203
AAS11/36-38	Mixed Planktic foram		4755± 35	5021.5 ±211
AAS11/66-68	Mixed Planktic foram		7995± 50	8428 ±191
AAS11/97-99	Mixed Planktic foram		10850± 70	12316 ±366
AAS11/136-138	Mixed Planktic foram		14245± 100	16462.5 ±455
AAS11/166-168	Mixed Planktic foram		16645± 120	19306.5 ±269
AAS11/176-178	Mixed Planktic foram		17310± 150	20064.5 ±306
AAS11/181-183	Mixed Planktic foram		17450± 130	20160.5 ±300
AAS11/198-200	Mixed Planktic foram		18700± 155	21665.5 ±534
AAS11/248-250	Mixed Planktic foram		23465± 260	27570 ± 471
AAS11/299-300	Mixed Planktic foram		28795± 495	33224 ± 580
AAS11/348-350	Mixed Planktic foram		34020± 940	39215 ± 1528

Mixed planktic foram (*Globigerinoides ruber* + *Globigerinoides sacculifer*)