

## **Sea Surface Temperature Changes During May and August in the Western Arabian Sea over the last 22 ka: Implications on Shifting of Upwelling Season**

Shital P. Godad<sup>1</sup>., Pothuri Divakar Naidu<sup>1\*\*</sup>., Bjorn Malmgren<sup>2</sup>

1. National Institute of Oceanography, Dona Paula 403 004, Goa, India.
2. Solvagen 17, SE – 761 64 Norrtälje, Sweden.

### **Abstract**

In the modern day the highest seasonal sea surface temperature (SST) difference has been noticed between May and August in the western Arabian Sea. In order to gain an understanding on how the monsoon upwelling has modulated the SST difference between these two months, we have computed SST based on census counts of planktonic foraminifers by using the artificial neural network (ANN) technique for the months of May and August. The SST difference between May and August exhibits three distinct phases: i) a moderate SST difference in the late Holocene (0-3.5 ka) is attributable to intense upwelling during August, ii) a minimum SST difference from 4 to 12 ka is due to weak upwelling during the month of August, and iii) the highest SST difference during the last glacial interval (19 to 22 ka) with high *Globigerina bulloides* % would be caused by prolonged upwelling season from May through July and maximum difference in the incoming solar radiation between May and August. On the whole, the variations in the SST difference between May and August reveal that the occurrence of intense upwelling has been shifting among the months of June, July and August, over the last 22 ka in the Western Arabian Sea.

---

\*\* Corresponding author: e-mail: [divakar@nio.org](mailto:divakar@nio.org), Telephone: 91-832-2450232; Fax: 91-832-2450603

## 1. Introduction

Seasonal reversal of the monsoon winds over the Arabian Sea influences surface circulation, productivity, biogenic and lithogenic fluxes, CO<sub>2</sub> uptake and heat budget in the region. In response to strong southwest (SW) monsoon winds during summer, intense upwelling occurs off the coasts of Somali and Oman due to the wind-induced offshore Ekman Transport (Wyrtki, 1973), which creates a ~4°C sea surface temperature (SST) gradient between west to east in the Arabian Sea (Levitus and Boyer, 1994). Northeast (NE) monsoon winds during winter do not create any upwelling cells in the Arabian Sea; however, NE monsoon winds (November to January) cause deep convective mixing in the upper thermocline (Banse, 1987), which results in cooling of surface waters in the north eastern Arabian Sea.

Overall, sea surface temperature of the Arabian Sea shows four phases: i) a warming phase during Spring (February to April), ii) a cooling phase during SW monsoon from (May to August), iii) warming in Fall-intermonsoon (September to mid-November), and iv) cooling during NE monsoon (mid-November to January) (Colborn, 1976). The uniqueness of the Arabian Sea SST pattern is driven due to the influence of the Southwest (SW) and Northeast (NE) Monsoons.

In the upwelling cells of the western Arabian Sea lower SSTs are observed in the summer months rather than in winter. In spite of lower solar insolation in the month of May than the months of June, July and August, highest SST is recorded at the core site for the month of May (Fig. 1) mainly due to intensity of upwelling during June through August controls the SST in the western Arabian Sea (WAS). Thus, SST changes in the Arabian Sea are markedly different from most of the other regions of the world ocean, which show only two phases: warming during spring and summer and cooling during fall and winter. In most regions of the global ocean, the winter to summer SST difference typically represents the maximum seasonal SST contrast. At present, the winter-summer SST difference at the study site is small (1-2°C), with coldest SST occurring in the summer. In contrast, the spring to summer SST contrast is large (5°C) (Fig. 1). Although earlier attempts have been made to reconstruct sea surface temperature variations in the Arabian Sea based on planktonic foraminifer species abundance (CLIMAP, 1981, Cayre and Bard, 1999, Naidu and Malmgren, 2005), organic proxies (Huguet et al., 2006), Mg/Ca ratios in foraminifer (Dahl and Oppo, 2006; Saher et al., 2007; Anand et al., 2008; Govil and Naidu, 2010), the main focus has been laid upon annual temperature changes or SST changes during August and February. Henceforth, no endeavour has been made to understand how the extreme SST changes in the WAS during May and August in the

past. Therefore, this study is devoted to reconstructions of SSTs for May and August by using the ANN technique to understand how the upwelling intensity varied from June through September in the WAS over the last 22 ka.

## 2. Material and Methods

Ocean Drilling Program (ODP) Site 723A was drilled at a water depth of 808 m from the intense upwelling cell in the western Arabian Sea (Fig. 2). Earlier chronology for the ODP Site 723A has been established based on AMS  $^{14}\text{C}$  dates (Naidu and Malmgren, 2005), same chronology is adopted here. For last four decades planktonic foraminifer faunal assemblages have been used to estimate the sea surface temperature (Imbrie and Kipp, 1971). Primary principle behind such estimates lies in the empirical calibration between planktonic foraminifer faunal assemblages from core tops and modern measured SST from the same location of core tops. The most important property of a calibration data set is its coverage both in terms of geographic area and the range of SST that is being calibrated. By applying the empirical calibration arrived between core top between planktonic foraminifer faunal assemblages and SST to the planktonic foraminifer faunal assemblages in a sediment core it would be possible to derive the SST of past. Several statistical techniques such as transfer function technique (Imbrie and Kipp, 1971), Modern Analogue Technique (Prell, 1985), Artificial Neural Technique (Naidu and Malmgren, 2005) have been used to estimate the annual, seasonal and monthly SST estimates. It has been shown that ANN technique have at least the same potential for providing accurate SST as the Modern Analogue technique (Malmgren et al., 2001). Therefore, here we have used ANN technique to reconstruct SSTs for the months of May and August.

The artificial neural network (ANN) technique was applied to census counts of planktic foraminifer species in order to reconstruct SSTs for the months of May and August. As the basis for the training of the ANNs, 277 coretops from the Indian Ocean (latitudinal range  $55^{\circ}\text{S}$ - $22^{\circ}\text{N}$  and longitudinal range  $18^{\circ}$ - $142^{\circ}\text{E}$ ) were used. The training of the ANN was performed separately for May and August SSTs. In this application, the ANNs were trained on the planktonic foraminifera census of 277 core tops from the Indian Ocean. The core top database (277 core top samples) was randomly split into one training and one hold-back (HB) subset, using the partitioning option build into the iModel program used in the analyses. The training subset, comprising 80% of the samples (208 samples), was used for training or calibration, and the remaining 20% (69 samples) constituted the HB subset set from which the error rate was determined. The HB subset is thus not used in the training phase of the ANNs

but just for estimating the error rate. The stability of the error rate was assessed by repeating the training procedure ten times for both May and August.

Estimates of error rates in the core top data (differences between observed and predicted SSTs) were expressed as root-mean-square-errors of prediction (RMSEPs). The mean RMSEP over the ten training runs for May and August is 0.79°C and 1.02°C, respectively. Telford and Birks (2005, 2009) have suggested that evaluation of error rates of transfer functions, such as ANNs, in spatially structured environments, may lead to over-optimistic estimates of the performance of the transfer function due to the existence of spatial autocorrelation in such data. This, however, does not affect the predictive ability of a method in question.

Downcore SST reconstructions for May and August in Site 723 are represented by the mean estimated SSTs based on the ten separate ANN runs. We note that reconstructed SSTs for the top of this core agree closely with observed modern SSTs at this site. Further details of the ANN computations were elaborated in an earlier paper (Naidu and Malmgren, 2005).

### **3. Results**

SST varied from 21°C to 25.5°C and 26.5°C to 30°C during August and May, respectively, over the last 22 ka (Fig. 3a and b). August was 2°C cooler during the last glacial maximum (LGM) than at present, and May was 1°C cooler during the LGM than in the modern western Arabian Sea. Furthermore, August SSTs show greater fluctuations during the Holocene. In contrast, May SST fluctuations were at a minimum during the Holocene. The SST difference between May and August is moderate (>5°C) in the late Holocene (0-3.5 ka), minimum (<5°C) from 4 to 12 ka and maximum (5 to 6.5°C) during the last glacial interval (18 to 22 ka) (Fig. 3c).

### **4. Discussion**

Most of the upwelling occurs during the SW monsoon season (June through September) in the WAS (Wyrтки, 1973). Although the upwelling occurs from June through September the vertical temperature profile at the present core location reveals that the intensity of the upwelling is highest during August (Fig. 1). Relative abundance of *G. bulloides* % from the ODP Site 723A (Fig. 3d) Naidu and Malmgren (1996) and other cores from western Arabian Sea (Overpeck et al., 1996) and several other evidences such as SST (Naidu and Malmgren, 2005, Saher et al., 2007) and Oxygen isotope ratios

in planktonic foraminifer shells (Sirocko et al., 1993; Naidu and Malmgren, 2005) reveals that the intensity of upwelling was stronger from 10 to 5 ka than in the last glacial period. Taking these findings at face value we interpret the May and August SST variations at this site.

SST variations during August show greater amplitude changes than May in the Holocene in the WAS (Fig. 3a and 3b), suggesting that the intensity of upwelling has varied significantly in this region. Although the intensity of upwelling was high from 10 to 5 ka in the WAS, as evidenced by the upwelling indices record (Naidu and Malmgren, 1996), August SST was higher than modern day SST at this site indicating two features: i) the intensity of upwelling during August was not as intense as that in the modern day, ii) the upwelling must be more intense during other summer months (June, July) than in August.

Comparison of solar insolation changes at 20°N and SST for the months of May and August reveals that the SST variability for the month of August overall follows solar insolation changes (Fig 3b). Whereas, for the month of May SST and solar insolation patterns are not corresponding well, for example between 19 and 12 ka, the strongest incoming solar insolation at 20°N was during May which coincides with relatively low SST (Fig 3a). Probably an early initiation of upwelling would suppress the May SST. This is possible because although the modern May insolation is not as strong as it was from 19 to 12 ka, the modern strong SW winds in the northern Arabian Sea sets in the month of May.

Comparison of SST reconstructions for August based on the modern analogue technique (MAT) from the eastern Arabian Sea (EAS) (Cayre and Bard, 1999) and ANN methods from the WAS (present study) show a 4°C gradient, with 23°C in the WAS and 27°C in the EAS. Furthermore, core MD77194 from the EAS documents minimum fluctuations during the Holocene, reflecting the fact that August SST in the non-upwelling regions of the Arabian Sea generally did not vary as much as that in the upwelling regions of the Arabian Sea. Greater amplitude changes in August SST in both upwelling and non-upwelling regions during the last glacial period suggest regional temperature fluctuations in the Arabian Sea. Similarly, SST reconstructions based on Mg/Ca ratios also confirm that the Holocene-to-glacial SST shift is greater in the EAS than in the WAS (Dahl and Oppo, 2006; Anand et al., 2008).

#### ***4.1 Difference in SST between May and August:***

The modern-day SST difference between May and August at the present core location is 5.2°C (Fig. 1). The highest SST difference is noticed between 0 and 3.5 ka and 19 and 22 ka, and the minimum SST difference is found between 12 and 4 ka (with the exception of one or two data points; Fig. 3c). The

maximum SST difference from 0 to 3.5 ka suggests that the intensity of upwelling was stronger and hence August SST was lower during this period, whereas May SST was more or less the same as that of modern-day values. This pattern very much resembles the modern-day SST changes at this site. In spite of intense monsoon upwelling from 10 to 5 ka (Naidu and Malmgren, 1996; Overpeck et al., 1996) a minimum SST difference is noticed between May and August at this site. This suggests that the intense upwelling from 10 to 5 ka, documented in the upwelling indices, must have occurred during other months of the SW monsoon (June, July) rather than in August, as evidenced from the strongest insolation forcing from 10 to 5 ka was during June and July at 20°N (Berger and Loutre, 1991) . Therefore, we propose here that although upwelling occurs during the SW monsoon season, its intensity has been shifted and was not consistently occurring in August over the last 22 ka in the Oman Margin. However, the observed shift in the upwelling intensity at this site might be due to geographical shift of the upwelling cell in the WAS. In any case a shift in upwelling season would affect the northward-shift of summer Inter Tropical Convergence Zone (ITCZ) in the region, which has direct implication on the rainfall in the Indian sub-continent. Further, a shift in upwelling intensity and lengthening of upwelling season would have large scale implications on ocean – atmosphere interaction as evidenced from the Pacific Ocean during Mid Holocene (Koutavas et al., 2006).

The highest SST difference between May and August is found from 22 to 19 ka (Fig. 3c), when the intensity of upwelling was weaker than in the early Holocene 10 to 5 ka (Fig. 3c). This is attributable to the fact that the August SST was generally cooler during glacial than May values because the August insolation between 22 to 19 ka is about  $30\text{W/m}^2$  lower than the May insolation ( $430$  vs  $460\text{W/m}^2$ ). This can certainly account for cooler August SST relative to May SST. In addition, high abundance of *G. bulloides* % during last glacial interval (22 to 19 ka) coincides with maximum SST difference between May and August reveals a prolonged upwelling season as evidenced by early season radiation for the month of May creating longer duration of upwelling season in glacial scale. Furthermore, glacial-to-Holocene SST shift was  $1^\circ\text{C}$  was recorded for May, whereas for August a  $\sim 2^\circ\text{C}$  SST shift is documented at this site. Earlier it has been reported that no SST difference or less than a  $1^\circ\text{C}$  shift between the Holocene and LGM occurs in the Arabian Sea (CLIMAP, 1981). In contrast, the extent of cooling during the LGM documented for May and August in this study is greater than the earlier estimates of CLIMAP (1981) in the Arabian Sea.

## 5. Conclusions

SST variations for May and August were reconstructed based on planktonic foraminifer by using the ANN technique. The SST variations during these months and the SST difference between May and August infer that the season of the most intense upwelling month has changed through time over the last 22 ka in the WAS. Further, during last glacial interval prolonged upwelling season caused due to early seasonal incoming solar insolation during May. Overall, inter play between monsoon upwelling and incoming solar insolation accounts the observed SST changes at this site.

## Acknowledgements

We thank Dr. Ellen Thomas, Dr. Steven Clemens and anonymous reviewer for providing constructive comments which improved the presentation and interpretations. This study is funded by ISRO-GBP. This is National Institute of Oceanography contribution no.....

## References

- Anand, P., Kroon, D., Singh, A. D., Ganeshram, R. S., Ganssen, G., Elderfield, H., 2008. Coupled sea surface temperature seawater  $\delta^{18}\text{O}$  reconstructions in the Arabian Sea at the millennial scale for the last 35ka. *Paleoceanography* 23, PA4207, doi:10.1029/2007PA001564.
- Banse, K., 1987. Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea. *Deep Sea Research, Part A* 34, 713-723, doi:10.1016/0198-0149(87)90032-X.
- Berger, A., Loutre, M. F., 1991. Insolation values of the climate of the last 10 million years. *Quaternary Science Review* 10, 297-237.
- Cayre, O., Beaufort, L., Vincent, E., 1999. Paleoproductivity in the equatorial Indian Ocean for the last 260,000yr: A transfer function based on planktonic foraminifera. *Quaternary Science Review* 18, 839-857.
- Cayre, O., E. Bard., 1999. Planktonic foraminiferal and alkenone records of the last deglaciation from the eastern Arabian Sea. *Quaternary Research* 52, 337-342, doi : 10.1006/qres.1999.2083.
- CLIMAP Project Members, 1981. seasonal reconstruction of the Earth's surface at the last glacial maximum, Map Chart ser. MC-36, Geol. Soc. Am., Boulder, Colorado.

- Colborn, J. G., 1976. Thermal structure of the Indian Ocean . International Indian Ocean Expedition Oceanographic Monography., No.2, University Press of Hawaii, 173pp.
- Dahl, K. A. Oppo, D. W., 2006. Sea surface temperature pattern reconstruction in the Arabian Sea. *Paleocenography* 21, PA1014, doi: 1029/2005PA001162.
- Govil, P., Naidu, P.D., 2010. Sea Surface Temperature and Seawater  $\delta^{18}\text{O}$  Variations of the eastern Arabian Sea over the last 68,000 years: implications on evaporation\_precipitation budget. *Paleoceanography*, 25, PA1210, doi:10.1029/2008PA001687.
- Huguet, C., Kim, J.H., Damaste, S.S.S., Schouten, S., 2006. Reconstruction of sea surface temperature variation in the Arabian Sea over last 23 kyr using organic proxies TEX86 and UK37. *Paleoceanography*, 21, PA3003, doi:10.1029/2005 PA001215.
- Imbrie, J., Kipp N.G. A new micropaleontologic method for quantitative paleoclimatology: Application to Late Pleistocene Caribbean core, in *The Late Cenozoic Glacial Ages*, edited by K. K. Turekian, pp. 71-182, Yale University, New Haven, Conn, 1971.
- Koutavas, A, deMenocal, P. B., olive, G. C., Lynch-Stieglitz, J., 2006. Mid-Holocene El Nino-Southern Oscillation (ENSO) attenuation revealed by individual foraminifera in eastern tropical Pacific sediments. *Geology* 34, 993-996.
- Levitus, S., Boyer, T. P., 1994. *World Ocean Atlas 1994. vol.4, Temperature*, NOAA Atlas NESDIS, vol. 4,129 pp. NOAA, Silver Spring, Md.
- Malmgren, B.A., Kucera, M., Nyberg, J., Waelbroeck, C., 2001. Comparison of statistical artificial neural network techniques for estimating past sea-surface temperatures from planktonic foraminifer census data. *Paleoceanography* 16, 520-530.
- Naidu, P.D., 2004. Isotopic evidences of past upwelling intensity in the Arabian Sea. *Global and Planetary Research*, 40, 285-293.
- Naidu, P.D., Malmgren, B.A., 1996. A high-resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera. *Paleoceanography* 11, 129-140.
- Naidu, P. D., Malmgren, B. A., 2005. Seasonal sea surface temperature contrast between the Holocene and last glacial period in the western Arabian Sea (Ocean drilling Project site 723A): Modulated by monsoon upwelling. *Paleoceanography* 20, PA1004, doi: 10.1029/2004PA001078.
- Overpeck, J. T., Anderson, D. M., Trumbore., S., Prell, W. L., 1996. The southwest Indian monsoon over the last 18,000 years. *Climate Dynamics* 12, 213-225.

- Prell, W.L., 1985. The stability of low-latitude sea-surface temperatures, an evaluation of the CLIMAP reconstruction with emphasis on the positive SST anomalies. Rep. TR025, US Dept. of Energy, Washington, DC.
- Saher, M. H., Jung, S. J. A., Elderfield, H., Greaves, M. J., Kroon, D., 2007. Sea surface temperatures of the western Arabian Sea during the deglaciation. *Paleoceanography* 22, PA2208, doi:10.1029/2006PA001292.
- Sirocko, F., Sarnthein, M., Erlenkeuser., Lange, H., Arnold, M., Duplessy, J.C., 1993. Century-scale events in monsoonal climate over the past 24000 years. *Nature*, 364, 322-324.
- Telford, R.J., Birks, H.J.B., 2005. The secret assumptions of transfer function. *Quaternary Science Reviews* 24, 2172-2179, doi:10.1016/J. quascirev.2005.05.001.
- Telford, R.J., Birks, H.J.B., 2009. Evaluation of transfer functions in spatially structured environments. *Quaternary Science Reviews* 28, 1309-1316. doi:10.1016/J.quascirev.2008.12.020.
- Wyrтки, K. 1973. Physical oceanography of the Indian Ocean, in *The Biology of the Indian Ocean*, edited by B. Zeitzschel and S.A. Gerlach, pp. 18-36, Springer, New York.

## Figure Legends

Figure 1. A vertical section of temperature changes at the location of ODP Site 723A in the western Arabian Sea and annual variations of solar insolation at 20°N.

Figure 2. Location of ODP Site 723A in the western Arabian Sea.

Figure 3. Variation of SST (a) August, (b) May for the last 22 ka at the ODP Site 723A and May and August solar insolation variations at 20°N (Berger and Loutre, 1991), (c) Temperature difference between May and August for the last 22 ka, (d) fluctuations in *Globigerina bulloides* % at the ODP Site 723A, which represent upwelling variations over the last 22 ka (Naidu and Malmgren, 1996).

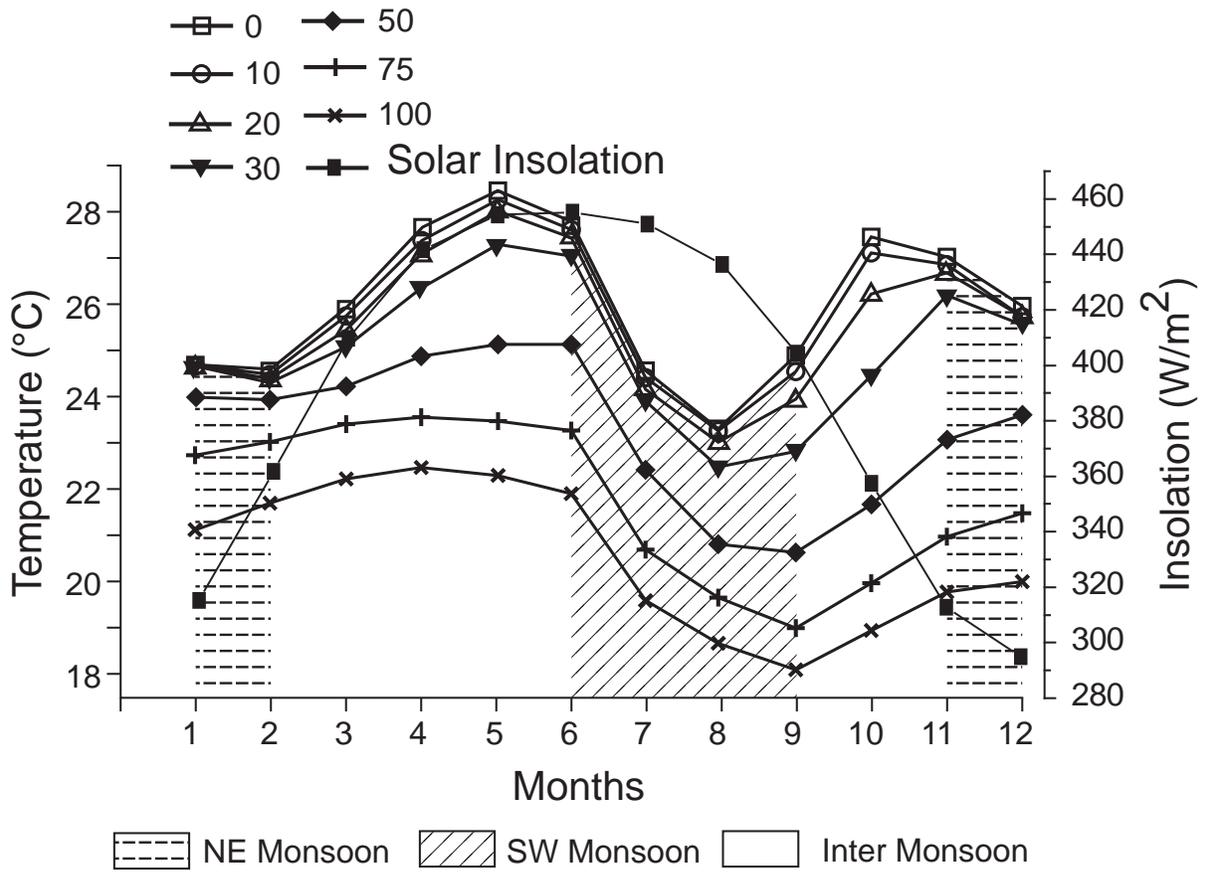


Figure 1

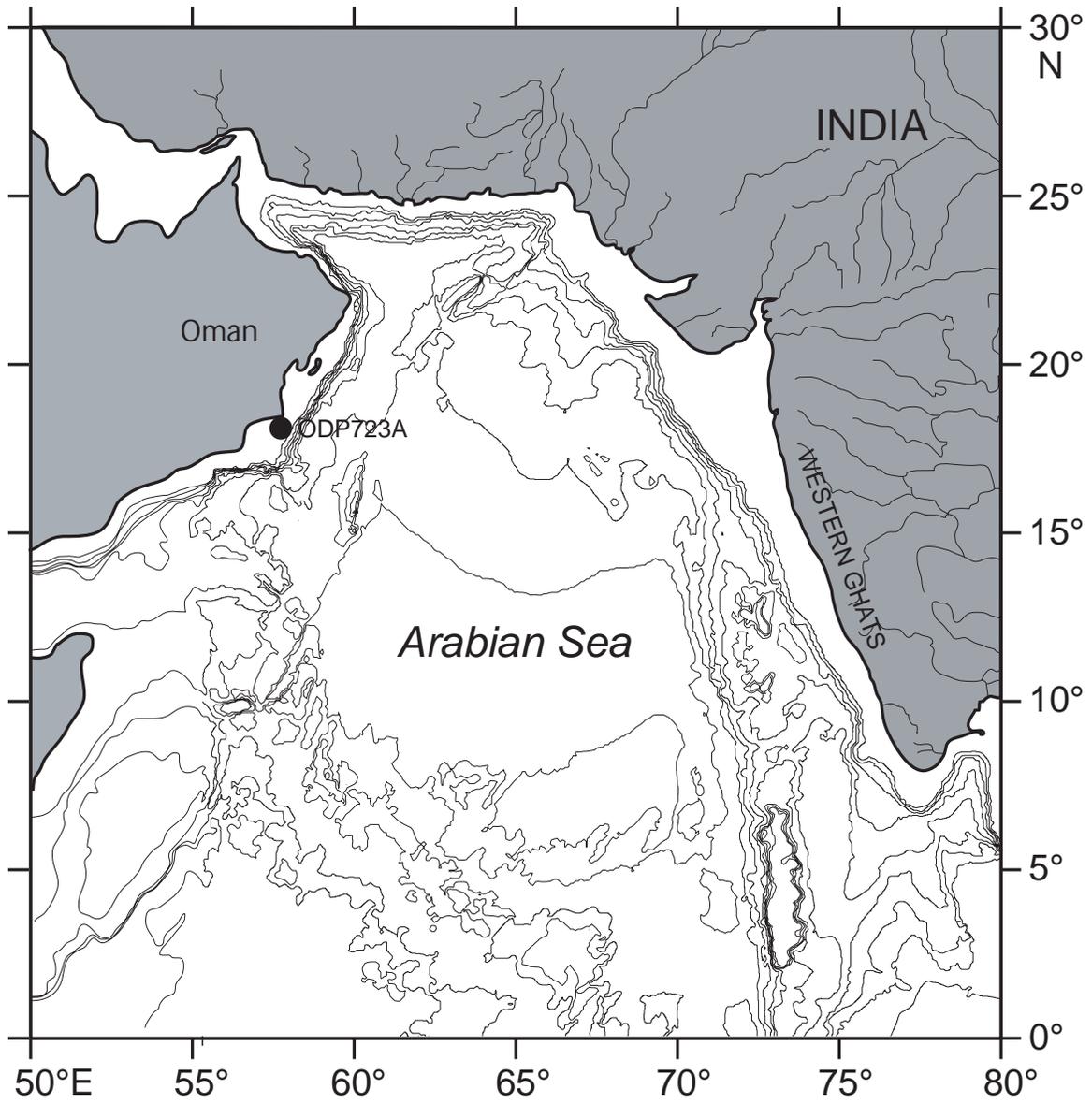


Figure 2

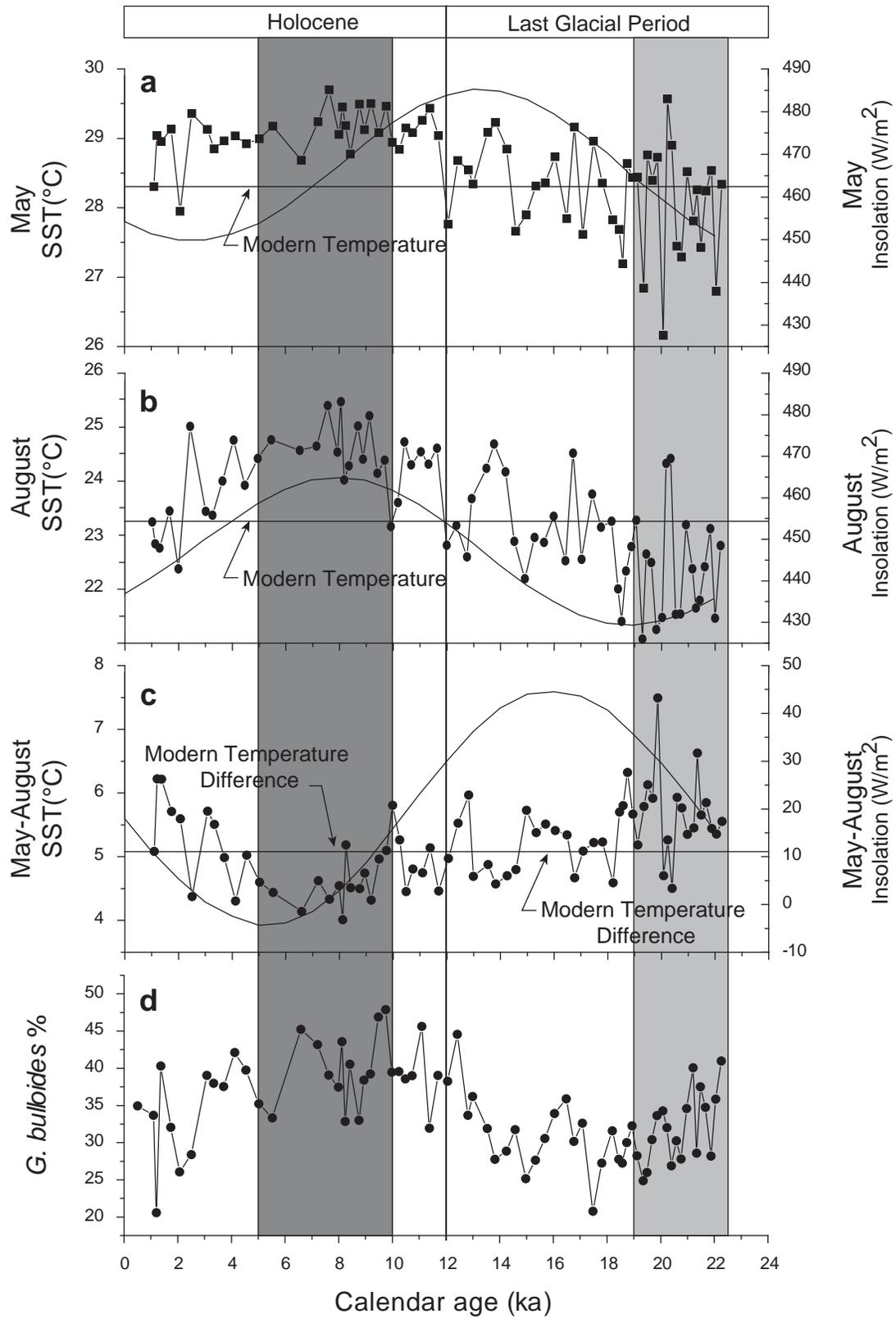


Figure 3