CHAPTER 3
Sea Surface Temperature Changes During May and August in the Western Arabian Sea over the last 22kyr: Implications as to Shifting of the Upwelling Season

1. Introduction

Seasonal reversal of the monsoon winds over the Arabian Sea influences surface circulation, productivity, biogenic and lithogenic fluxes, CO$_2$ uptake and heat budget in the region. In response to strong southwest (SW) monsoon winds during the summer, intense upwelling occurs off the coast of Somali and Oman due to the wind induced offshore Ekman Transport (Wyrtki, 1973). This creates a ~4°C sea surface temperature (SST) gradient between west and east in the Arabian Sea (Levitus and Boyer, 1994). Northeast (NE) monsoon winds during winter do not create any 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 the cooling of surface waters in the northeastern 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 the SW monsoon from (May to August), iii) warming in Fall - intermonsoon (September to mid - November) and iv) cooling during the NE monsoon (mid - November to January) (Colborn, 1976). The uniqueness of the Arabian Sea SST pattern is due to the influence of the SW and NE monsoons.

In the upwelling cells of the western Arabian Sea (WAS) lower SSTs occur in the summer months rather than in winter. Despite lower solar insolation in the month of May than in the months of June, July and August, the highest SST at the core site studied is recorded in May (Fig. 3.1), mainly due to the intensity of upwelling of colder waters during June through August, which controls the SST. Changes in SST in the Arabian Sea are thus markedly different from those in most other regions of the
world ocean, which show only two phases, i.e., 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 in the WAS 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. 3.1). Although earlier attempts have been made to reconstruct SST 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), and 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 upon annual temperature changes or SST changes during August and February. Henceforth, no endeavour has been made to understand how extreme SST changes in the WAS during May and August. Therefore, this study aims to reconstruct SSTs for May and August using the ANN technique to understand how the upwelling intensity in the WAS varied from June through September over the last 22 kyr.

![Diagram](image)

Fig. 3.1. 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.
2. Materials and Methods

Ocean Drilling Program (ODP) Site 723A was drilled at a water depth of 808m in the area of intense upwelling in the western Arabian Sea (Fig. 3.2). The age model for this site is based on AMS $^{14}$C dates (Naidu and Malmgren, 2005). For the last four decades planktonic foraminifera faunal assemblages have been used to estimate the sea surface temperature (Imbrie and Kipp, 1971). The primary principles behind such estimates lies in the empirical calibration between planktonic foraminifer faunal assemblages from core tops and modern measured SST from the same location. 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.

![Fig. 3.2 Location of ODP Site 723A in the western Arabian Sea.](image-url)
By applying the empirical calibration established between core top planktonic foraminifera faunal assemblages and measured SST to the planktonic foraminiferal faunal assemblages in a sediment core, one can derive the SST of the past. Several statistical techniques, including the transfer function technique (Imbrie and Kipp, 1971), the Modern Analogue Technique (Prell, 1985), and the Artificial Neural Technique (ANN, Naidu and Malmgren, 2005) have been used to estimate annual, seasonal and monthly SST. The latter technique has at least the same potential for providing accurate SST. The latter technique has at least the same potential for providing accurate SST as the modern Modern Analogue Technique (Malmgren et al., 2001). And we used this technique to reconstruct SSTs for the months of May and August.

The artificial neural network (ANN) technique was applied to census counts of planktonic foraminifer species in order to reconstruct SSTs for the months of May and August. As the basis for the training of the ANNs, planktonic foraminifer census counts data on 277 core tops from the Indian Ocean (Prell et al., 1999) (latitudinal range 55oS -22° N and longitudinal range 18-142°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 data 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 calibrations, 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 only to estimate 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

to the existence of spatial autocorrelation in such data. This, however, does not affect the predictive ability of a method in question.

Down core SST reconstructions for May and August in Site 723A 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 23.5°C to 30°C during August and May, respectively, over the last 22ka (Fig.3.3a 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 presently. 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 was moderate (>5°C) in the late Holocene (0 - 3.5ka), minimum (<5°C) from 4 to 12ka and maximum (5 to 6.5°C) during the last glacial interval (18 to 22ka) (Fig.3.3c).

4. Discussion

Most upwelling in the WAS occurs during the SW monsoon season (June through September) (Wyrtki, 1973). Although upwelling occurs from June through September, vertical temperature profile at the present core location shows that the intensity of upwelling is highest in the August (Fig 3.1). The relative abundance of G. bulloides % at ODP Site 723A (Fig 3.3d) (Naidu and Malmgren, 1996) and the other cores in WAS (Overpeck et al., 1996), as well as the other evidence such as reconstructed SSTs (Naidu and Malmgren, 2005; Saher et al., 2007) and oxygen isotope ratios in the planktonic foraminifer tests (Sirocko et al., 1993; Naidu, 2004) all indicate 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 the ODP Site 723A.

SST variation during August show greater amplitude changes than SST variations in May in the Holocene (Fig 3.3a and b), suggesting that the timing of the
intensity of upwelling, or the intensity itself has varied significantly. Although the intensity of upwelling was high from 10 to 5 ka, as shown by the upwelling indices (Naidu and Malmgren, 1996), the August SST was higher than the modern-day SST at this site indicating two features: i) intensity of upwelling during August was not as intense as that in the modern day, and ii) upwelling must have been more intense during summer months (June, July) than in the August.

Comparison of the solar isolation changes at 20°N and the SST for the months of May and August reveals that the SST variability for the month of August overall follows the solar insolation changes (Fig 3.3b). On the other hand, May SST and the solar insolation patterns are not similar: for example between 19 and 12 ka the strongest incoming solar insolation at 20°N was in May, with relatively low SST (Fig 3.3a). We speculate that the early initiation of upwelling could have suppressed May SST. Although modern May insolation is not as strong as it is from 19 to 12 ka, the modern strong SW winds in the northern Arabian Sea are active in the month of May.

Comparison of SST reconstructions for the eastern Arabian Sea (EAS) for August based on the modern analogue technique (MAT) (Cayre and Bard, 1999) and ANN methods for the WAS (this study) show a 4°C East - West gradient, with 23°C in the WAS and 27°C in the EAS. Furthermore the SST record from the core MD77194 in the EAS documents minimum SST fluctuations over the Holocene, reflecting the fact that the August SST in the non-upwelling regions of the Arabian Sea generally did not vary as much as those in the upwelling regions of the Arabian Sea. Greater amplitude changes in August SST in both the upwelling and non-upwelling regions during the last glacial period suggest that the regional temperature fluctuations occurred in the Arabian Sea. Similarly, SST reconstructions based on Mg/Ca ratios in the planktonic foraminifer species *Globigerinoides ruber* in the EAS and WAS (Dahl and Oppo, 2006; Anand et al., 2008) also confirm that the Holocene-to-glacial SST shift is greater in the EAS than in the WAS.
Fig. 3.3 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).
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 3.1). The highest SST difference over the last 22 kyr occurred between 0 to 3.5 ka and 19 and 22 ka, and the minimum SST difference between 12 and 4 ka (with the exception of one or two data points; Fig 3.3c). 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 the May SST was more or less same as today. This pattern very much resembles the modern-day SST fluctuations at this site. In spite of intense monsoon upwelling from 10 to 5 ka (Naidu and Malmgren, 1996; Overpeck et al., 1996), SST differences between May and August were minimal at this site. This suggests that the intense upwelling from 10 to 5ka, documented in the upwelling indices, must have occurred in other months of the SW monsoon (June and July) rather than in August, as evidenced from the strongest insolation forcing at 20°N from 10 to 5 ka during June and July (Berger and Louter, 1991). Therefore, we propose that upwelling occurred during the SW monsoon over the last 22ka along the Oman Margin in the WAS, but the time of its highest intensity shifted and thus was not consistently in August. However, the observed shift in the upwelling intensity at this site might also be due to a geographical shift of the upwelling cell in the WAS, from close to Site 723A to another location. A shift in upwelling season would affect the northward-shift of the summer Inter Tropical Convergence Zone (ITCZ) in the region, which has direct implications for the rainfall on the Indian sub-continent. In addition, a shift in upwelling intensity and lengthening of upwelling season would have large scale implications for ocean-atmosphere interactions, as evidenced for the Pacific Ocean during Mid Holocene (Koutavas et al., 2006).

The highest SST difference May and August is found from 22 to 19 ka (Fig.3.3c), when the intensity of upwelling was weaker than in the early Holocene (10 to 5 ka) (Fig.3.3c). This is attributable to the fact that the August SST was generally cooler during glacial times than the May values, because the August insolation between 22 and 19ka was about 30 W/m² lower than the May insolation (430 vs 460 W/m²). This can certainly account for the observed cooler August SST relative to the May SST. In addition, a high abundance of G. bulloides% during the last glacial
interval (22 to 19ka) coincided with maximum SST difference between May and August, indicating that the upwelling season was prolonged, as shown by the early season radiation for the month of May, causing a longer duration of the upwelling season during glacial times. Furthermore, the glacial - to - Holocene SST shift of ~1°C was recorded for May, whereas for August a ~2°C SST occurred at the present location. It has been reported that no SST difference, or a difference of less than a ~1°C shift occurred in the Arabian Sea between the Holocene and LGM (CLIMAP, 1981), but the extent of cooling during the LGM documented for May and August is greater than these earlier estimates.

5. Conclusions

SST variations for May and August were reconstructed based on planktonic foraminiferal relative abundance data by using the ANN technique. The SST variations during these months and the SST difference between May and August suggest that the month of most intense in the WAS has changed over time during the last 22kyr in the WAS. In addition, a prolonged upwelling season during May. Overall, the interplay between monsoon upwelling and incoming solar insolation accounts for the observed SST changes at this site.