CHAPTER-3

Somali upwelling and Southwest monsoon rainfall during the last 18.5 ka

A greater part of the world's population inhabits the tropical region, where climate is mainly controlled by monsoon rainfall. Understanding the causes of past climate changes thus plays a critical role in deciphering past, present and future monsoon variability. The economy of India, a tropical country, that supports a significant part of the world's population, is dependent to a large extent on the southwest monsoon (SWM) rainfall; hence, slight changes in SWM rainfall can lead to immense societal impacts. Several attempts have been made to identify the factors responsible for SWM rainfall variations. SWM rainfall variability is correlated with several global phenomena (Hahn and Shukla, 1976; Mooley et al., 1986; Parthasarathy et al., 1988; 1991; Pant and Kumar, 1997; Bamzai and Shukla, 1999; Goswami et al., 1999; Krishnan and Sugi, 2003; Annamalai and Liu, 2005; Goswami et al., 2006; Krishnamurthy and Krishnamurthy, 2016; Yadav, 2017). The extent of the IOWP is primarily affected by the Somali upwelling and partly by the latent heat flux increase in the Arabian Sea during the SWM season (Izumo et al., 2008). The Somali upwelling as well as SWM rainfall, are caused by the SWM winds during boreal summer.

Upwelling of deep water during the SWM brings nutrients up to the photic zone, enhancing surface productivity in the western Arabian Sea. Palaeoproductivity variations in the coastal regions off Somalia and Oman have been extensively studied to understand past changes in SWM-related upwelling (Sirocko et al., 1993; Naidu and Malmgren, 1996; Gupta et al., 2003; Tiwari et al., 2010). However, variations in siliceous productivity in the western Arabian Sea, which have direct implications for the strength of upwelling in the past, have not been understood. The present study thus aims to understand past variations in siliceous productivity in the Somali upwelling region, as well as palaeo-upwelling strength and its relationship with the southwest monsoon rainfall, using a sediment core (4018) retrieved from the western Arabian Sea.

3.1 Results

To achieve the proposed objective the biogenic silica flux in the western Arabian Sea was measured in 4018 sediment core. The chemical processing and measurement of biogenic silica is described in chapter 2. Biogenic silica concentrations varied from 3 % to 15.2 % during the last 18.5 ka (Table 3.1; Figure 3.1), with the lowest concentrations (3–4 %) being observed at the bottom of the core between 18.5 ka and 16 ka B.P. Subsequently, it increased continuously up to 13.5 ka B.P. (~9 %) and decreased to 6.5 % at ~13 ka B.P. No significant variations in biogenic silica concentrations were observed between 13 ka and 11.3 ka B.P. After 11.3 ka B.P., biogenic silica increased from 6.5 % to 10.5 % and remained stable for a period of almost 1000 years until 10 ka B.P. The biogenic silica concentration increased from 10.5 % to 12 % during 10–9.5 ka B.P., and it decreased subsequently to 8.5 % at 8 ka B.P. From 8 ka to 7.3 ka B.P., it changed from 8.5 % to 9.5 % with a peak at 7.7 ka B.P. (13.3 %), then it remained stable until 6 ka B.P. From 6 ka to 5 ka B.P., the biogenic silica concentration increased from 10 % to 12.5 % and then decreased at 4 ka B.P. After 4 ka B.P., a continuous increase to a maximum value of 15 % biogenic silica at 1.5 ka B.P. and a subsequent decrease to 12 % at 1 ka B.P. were observed. Biogenic silica concentrations showed no variations during the last 1 ka B.P.

Age (ka B.P.)	B. Si (%)	σ B.Si	B.Si flux ($g/m^2/y$)	σ B. Si flux	Age (ka B.P.)	B. Si (%)	σ B. Si	B. Si flux ($g/m^2/y$)	σ B. Si flux
0.00	12.58	0.22	5.51	0.79	12.23	6.41	0.11	3.29	0.41
0.54	12.58	0.25	5.44	0.80	12.54	6.49	0.16	3.36	0.42
1.09	12.58	0.28	5.05	0.80	12.86	6.49	0.20	3.40	0.42
1.63	15.20	0.20	6.62	0.96	12.95	7.76	0.13	4.03	0.49
2.17	14.81	0.14	6.80	0.93	13.04	7.37	0.18	3.76	0.47
2.72	13.06	0.05	5.70	0.82	13.13	7.24	0.09	3.77	0.46
3.26	11.70	0.21	5.34	0.74	13.22	7.74	0.13	3.99	0.49
3.81	10.23	0.17	4.66	0.65	13.47	9.06	0.21	4.68	0.58
4.35	11.79	0.10	5.33	0.74	13.72	8.23	0.16	4.27	0.52
4.90	12.49	0.13	5.78	0.79	13.97	6.83	0.11	3.56	0.43
5.44	11.64	0.22	5.59	0.74	14.22	6.83	0.22	3.52	0.44
5.81	10.52	0.17	5.19	0.67	14.47	5.41	0.10	2.84	0.34
6.18	9.74	0.04	4.74	0.61	14.72	6.11	0.16	3.16	0.39
6.55	10.52	0.29	5.21	0.68	14.89	5.74	0.09	3.04	0.36
7.29	9.59	0.12	4.76	0.61	15.06	5.49	0.19	2.64	0.36
7.93	9.59	0.15	4.71	0.61	15.24	5.24	0.14	2.59	0.34
8.20	8.31	0.19	4.23	0.53	15.41	5.07	0.15	2.27	0.32
9.02	9.35	0.10	4.73	0.59	15.58	5.08	0.04	2.21	0.32
9.29	11.88	0.09	6.03	0.75	15.83	4.94	0.08	2.24	0.31
9.56	12.28	0.19	6.17	0.78	16.09	4.53	0.17	2.07	0.29
9.84	11.57	0.14	5.72	0.73	16.34	3.66	0.11	1.65	0.23
10.12	10.43	0.21	5.26	0.66	16.85	3.54	0.13	1.63	0.23
10.29	10.57	0.10	5.47	0.67	16.94	4.75	0.20	2.22	0.31
10.46	10.82	0.14	5.58	0.68	17.03	4.17	0.15	1.92	0.27
10.63	10.59	0.20	5.38	0.67	17.11	4.04	0.17	1.89	0.27
10.80	10.45	0.11	5.27	0.66	17.20	4.17	0.08	2.02	0.26
10.97	9.47	0.12	4.89	0.60	17.29	3.05	0.12	1.44	0.20
11.28	7.04	0.17	3.59	0.45	17.87	3.52	0.09	1.68	0.22
11.60	6.59	0.09	3.48	0.42	18.44	3.25	0.11	1.57	0.21
11.91	6.92	0.17	3.45	0.44					

Table 3.1: Biogenic silica concentration and flux data (after Balaji et al., 2018).

The variations in biogenic silica fluxes show an overall increasing trend from 18.5 ka to present (Figure 3.1). The fluxes varied between 1.4 to 6.8 g.m-2.y-1. The minimum values (<2 g.m-2.y-1) occur at the bottom of the sediment core, i.e., between 18.5and 16 ka B.P., and the maximum flux value is observed at 2 ka B.P. Five distinct peaks in biogenic silica flux during the last 18.5 ka B.P. were observed between 14–13 ka, 11–10 ka, 10–9 ka, 6–4 ka and 2.5–1 ka B.P. Uncertainties in biogenic silica concentrations and fluxes are below 5 % and up to 15 %, respectively. The increase in uncertainty in the flux is due to the high standard error associated with the empirical derivation of the dry bulk densities.

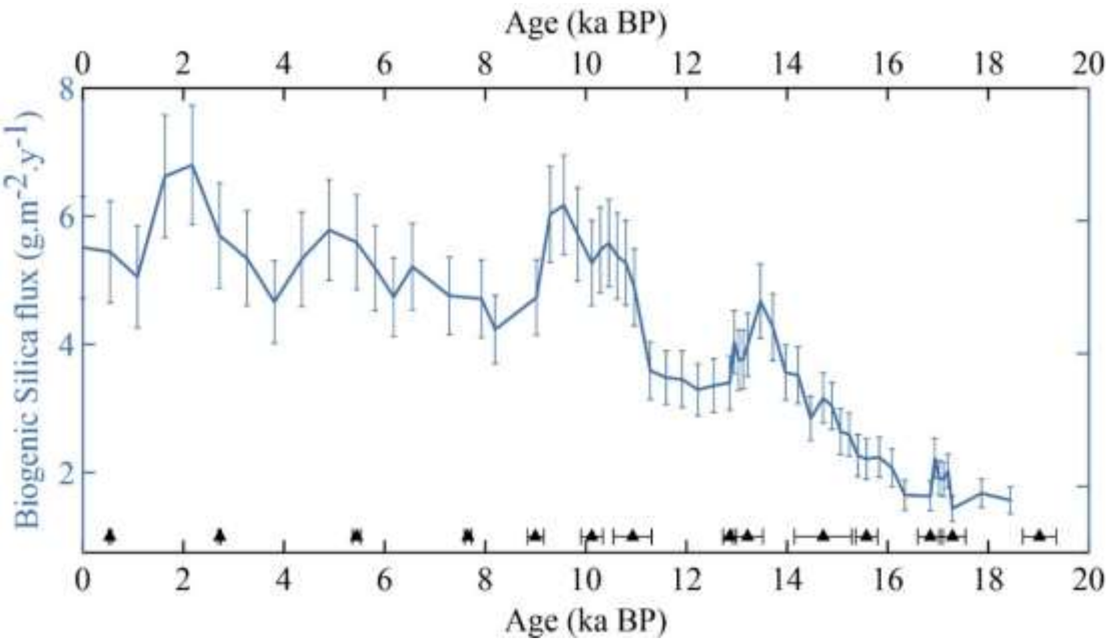

Figure 3.1: Temporal variation of Biogenic silica flux with two sigma uncertainty in sediment core 4018. Filled triangles at the bottom of the plot marks the age-control points with one sigma uncertainty (after Balaji et al., 2018).

3.2 Discussion

3.2.1 Biogenic silica flux as an upwelling proxy

The surface waters of the world oceans are mostly deficient in bioavailable silica (Hurd, 1973), which is a major nutrient for siliceous productivity. Apart from the Southern Ocean, high siliceous productivity can be observed in the major upwelling regions, where upwelled nutrient-rich water causes high primary production (Koning et al., 2001). The ocean is under saturated with respect to silica, and thus biogenic silica flux in sediments is a function of its export flux, which is controlled by its production at the surface and dissolution in the water column as well as at the sediment water interface (Hurd, 1973; Broecker and Peng, 1982). Thus, using biogenic silica as a proxy for the study of palaeo-upwelling requires understanding of its production and burial efficiency. Sediment trap studies from the western Arabian Sea indicated biogenic silica flux mimics the SWM upwelling (Figure 3.2; Nair, 1999; Haake et al., 1993).

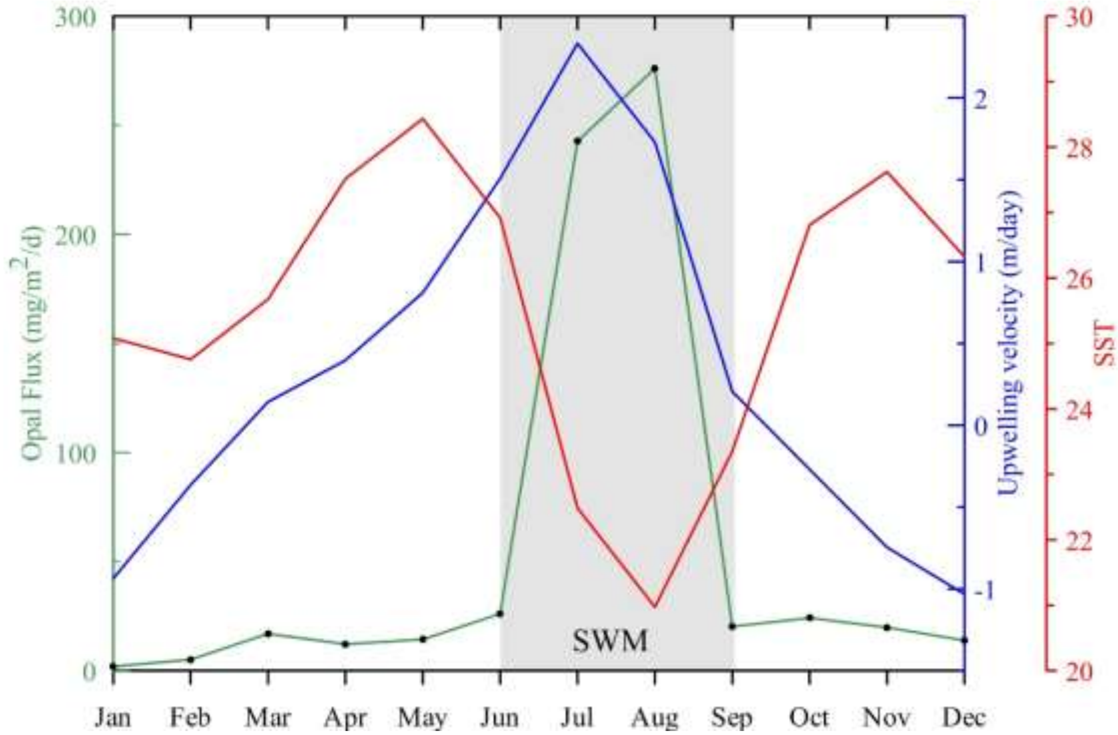

Figure 3.2: Modern oceanography of western Arabian Sea. Synchronous change in upwelling intensity and biogenic silica flux clearly indicate that the siliceous productivity in western Arabian Sea is controlled by SWM upwelling. Upwelling strength data is used from Nair, (1999) and Opal flux from Haake et al. (1993).

Studies of sediment trap data and surface sediments (Koning et al., 1997; Koning et al., 2001) of the Somali basin provides better estimates of the burial efficiency of biogenic silica i.e. ratio between diatom abundance in surface sediment upon trap, in the western Arabian Sea. Only 6.8–8.7 % of diatom (biogenic silica) productivity is preserved in the sediments of the Somali basin; the rest is dissolved in the water column as well as at the sediment water interface (Koning et al., 2001). One of the major findings from sediment traps in the Somali basin by Koning et al. (2001) is the selective preservation of upwelling-indicating diatoms in the sediments of the Somali region (Figure 3.3). This is linked to the silicification of diatom frustules; most pre- and post-upwelling produced diatoms are weakly silicified, enhancing their dissolution in the water column and leading to their low preservation in sediments. Better preservation of upwelling indicating diatoms may also be linked to the increased downward supply due to high surface production. Nutrient availability (Si:N) and concentration of dissolved iron also can affect diatom silicification that leads to variation in preservation (Hutchins and Bruland, 1998). In general it is noted that high silicate concentration and micro-nutrient depletion leads to more silicified and faster sinking diatoms (Hutchins and Bruland, 1998), which is the exact scenario during the late phase of SWM upwelling. If the observed variation in the biogenic silica flux is dominated by changes in burial efficiency (BE), result of low flux divided by low BE should be equal to high flux divided by high BE. High and low BE were assigned as per modern observation by Koning et al. (2001). In the present study, it was observed that the ratio of flux to BE was three times greater at the top as compared to the bottom, indicating the absence of preservation effect in our core record (Balaji et al., 2018).

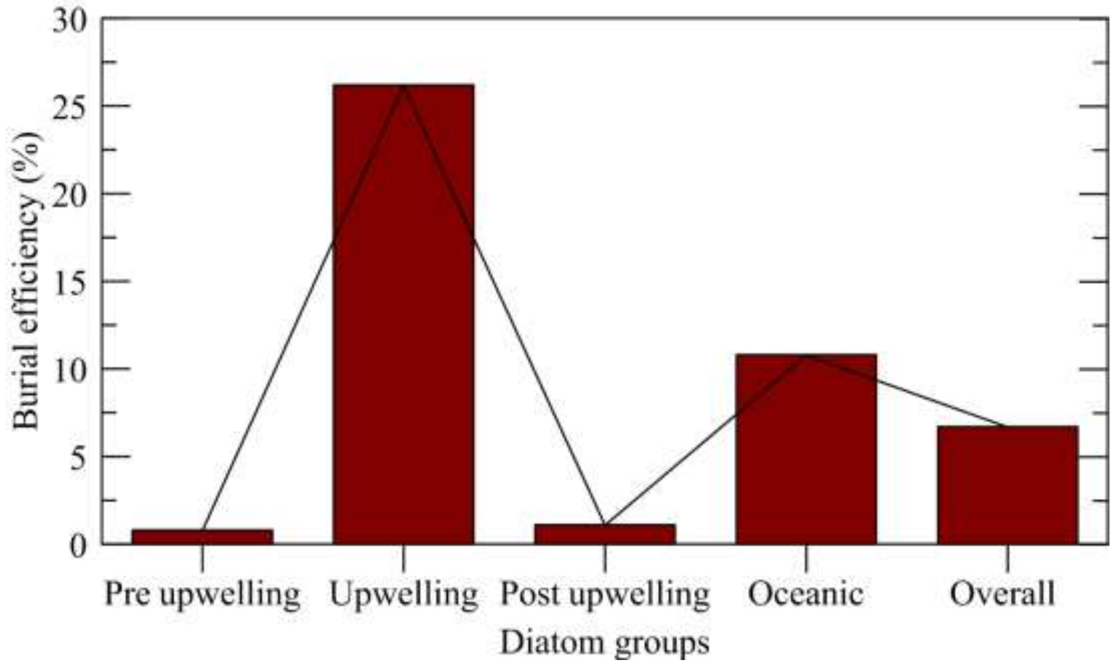

Figure 3.3: Biogenic silica burial efficiency in Somali Basin (Koning et al., 2001).

Apart from biogenic silica production and preservation efficiency, sediment redistribution can also influence the biogenic silica flux. However, considering the sediment core location and average sedimentation rate, it is likely that the influence of sediment focusing/winnowing on the flux record is minimal. The location of the sediment core is far from the continental slope (Figure 2.1) and not directly influenced by coastal currents or fluvial systems that would lead to redistribution of the sediment flux. The chronology of the sediment record is based on the published age-model given by Tiwari et al., (2010). The model, however, shows sizeable variations in the sedimentation rate. Because the calculated sedimentation rate is a function of the selected sampling depths (which may vary), the average rate of sedimentation has been considered in estimating the fluxes of biogenic silica. The high surface production of biogenic silica during SWM upwelling (Figure 3.2; Haake et al., 1993; Koning et al., 1997; Nair, 1999), together with the increased burial efficiency of upwelling-indicating diatoms (biogenic silica) in the western Arabian Sea sediments (Koning et al., 2001), makes biogenic silica flux a potential proxy for SWM-related upwelling in the study area.

3.2.2 Biogenic silica flux vs Sea Surface Temperatures (SST)

Similar to biogenic silica flux, the palaeo-SST reconstructions can be used as proxy for upwelling, because upwelling not only increases siliceous productivity but also reduces the SST (Balaji et al., 2018). However the opposite relation between siliceous productivity and SST is only valid during the SWM season and may not be related in other season or on annual scale. The SST reconstructions may be based on biomarker (TEX_{86} and $U^{K'}_{37}$; Huguet et al., 2006) or planktonic foraminifera shell chemistry ($\delta^{18}O$ and Mg/Ca; Emiliani, 1955; Chave, 1954) present in the marine sediment. However, whether the SST reconstruction is of seasonal or annual mean signal is dependent on the production of proxy material in any area. The $\delta^{18}O$ value of foraminifera shell not only depends on the SST but also the preservation of shell, carbonate ion concentration, salinity and $\delta^{18}O$ (ice-volume) of the original seawater (Lea, 2003), which makes the reconstruction more complicated. The Mg/Ca ratio is affected by species-dependency and dissolution (Lea, 2003). In most cases foraminifera based SST only preserves annual mean signal due to the year around presence of foraminifera production (Conan and Brummer, 2000; Dahl and Oppo, 2006), but the possibility of having seasonal signal depends on the local hydrography and productivity. On the other hand the biomarker based SST records may preserve seasonal signal, because they are mainly produced during monsoon season (Huguet at al., 2006). However there are other issues with the biomarker based SST records. Major limitation for the application of alkenone $U^{K'}_{37}$ in low latitude regions is that it saturates around 28°C (Prahl and Wakeham, 1987). On the other hand the TEX_{86} based SST are valid in the range of 5° to 30° C (Kim et al., 2008), with better estimates above 15° C (Kim et al., 2010). However there have been increasing evidence suggesting that TEX_{86} actually records sub-surface temperature rather than SST (Wuchter et al., 2006; Lee et al., 2008; Lopes dos Santos et al., 2013; Seki et al., 2014; Hertzberg et al., 2016). The nutrient availability and variation in productivity may also influence the TEX_{86} temperature (Hertzberg et al., 2016). Comparing the SST reconstructed using $U^{K'}_{37}$ and TEX_{86} from a sediment core in the western Arabian Sea, Huguet et al. (2006) suggested that the $U^{k}37$ SST are in phase with northern hemisphere dynamics during NE monsoon while TEX_{86} signal with varying fraction of SWM and NEM seasonal signals. Glacial boundary conditions have strong influence on the annual mean SST in the Arabian Sea irrespective of monsoon upwelling (Broccoli, 2000; Dahl and Oppo, 2006). It is comprehended that all SST proxies tend to record annual mean and biogenic silica flux is a better proxy than SST to understand SWM upwelling in the study area. Comparison of biogenic silica flux with other palaeo-SST records (Huguet et al., 2006; Saher et al., 2007; Anand et al., 2008) from nearby locations (Figure 3.4) are shown in figure 3.6 and 3.9. There is no single relation between biogenic silica flux and SST records in temporal scale. Also the SSTs using different proxies show inconsistent changes in the studied time span; the TEX_{86} SST is always higher than Mg/Ca SST (Figure 3.6 and 3.9). A general observation can be made that the biogenic silica flux and SST were low during 18.5 to 15 ka B.P., there after they show an anti-correlation. The anti-correlation is strong between biogenic silica flux and TEX_{86} SST during 15 to 11.7 ka B.P. (Figure 3.6). However during the last 11.7 ka the Mg/Ca based SST shows a strong anti-correlation with biogenic silica flux record, indicating variations in the influence of seasonal signal in different proxy (Figure 3.9).

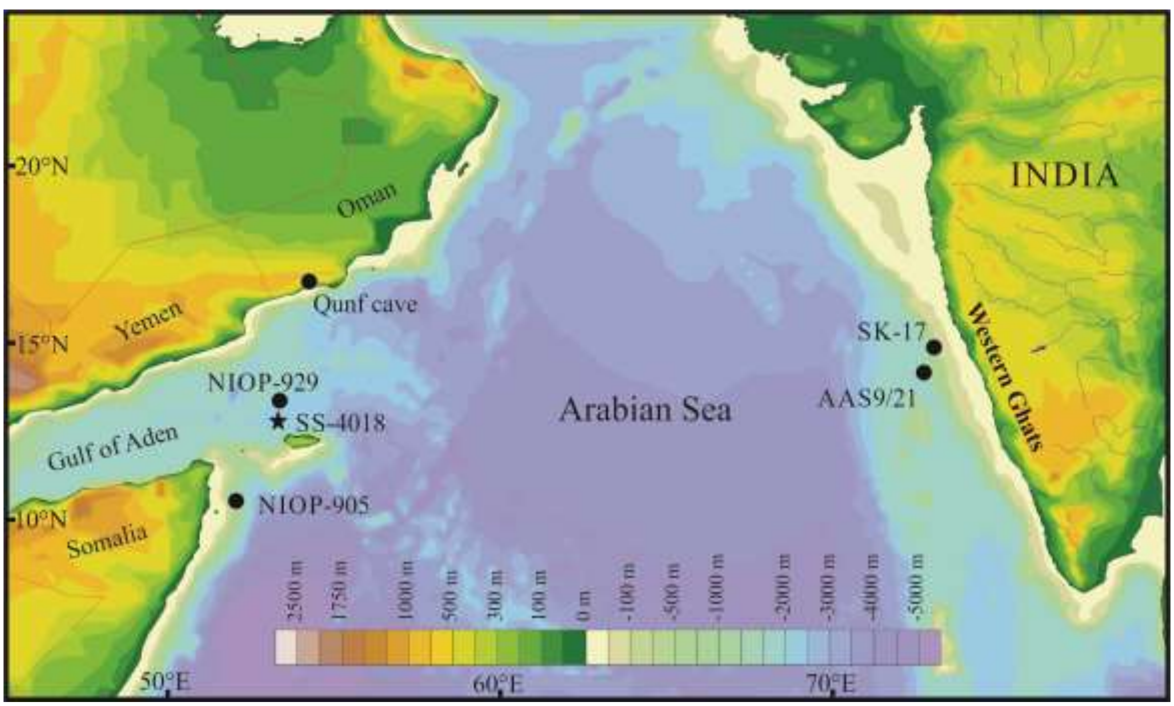

Figure 3.4: Location of sediment core 4018 (filled star) in the Arabian Sea. Also shown are the sites discussed in the paper: NIOP-929 (Saher et al., 2007), NIOP-905 (Huguet et al., 2006), SK-17 (Anand et al., 2008), Qunf cave (Fleitmann et al., 2007).

3.2.3 Somali upwelling strength versus southwest monsoon rainfall

Western Arabian Sea SSTs during SWM are directly related to upwelling strength (enhanced upwelling results in lower SSTs and vice versa; Figure 3.2). Previous studies have shown northern Indian Ocean and Arabian Sea in particular, to be an important source of moisture for SWM rainfall over India (Ninomiya and Kobayashi, 1999; Gimeno et al., 2010). Several relationships have been observed between SST, moisture and SWM rainfall. A first order relation would be positive, i.e. reduced SWM winds would cause reduced upwelling as well as reduced rainfall and vice versa. However the relation between Arabian sea SST and SWM rainfall is complicated due to the fact that SST modulates the moisture availability as well as the meridional temperature gradient (Levine and Turner, 2012). Modelling study by Shukla, (1975) has shown that the cold Arabian sea SST during SWM tend to reduce the SWM rainfall through reduced moisture transport. However Webster et al. (1999) and Clark et al. (2000) showed that the SWM rainfall has stronger connection with winter and spring SSTs rather than summer, and suggested a delayed influence of SST on rainfall. Arpe et al. (1998), through a model, have shown that warmer northern Indian Ocean leads to increased SWM rainfall over India through enhanced evaporation and moisture supply, while indicating the strong influence of pacific SST anomalies on monsoon. It was also suggested that Arabian Sea SST modulates the impact of ENSO on monsoon precipitation (Arpe et al., 1998; Lavine and Turner, 2012). An observational study by Vecchi and Harrison (2004) detected a strong positive correlation between western Arabian SSTs (50-60˚E, 5-10˚N) and SWM rainfall over the Western Ghats Mountains (72.5-77.5˚E, 7.5-20˚N) in India from 1982 to 2001 (Figure 3.5). It can be considered that any isolated cooling of the Arabian Sea will reduce SWM rainfall through reduced moisture supply, in the absence of other large-scale forcing (Lavine and Turner, 2012). An observational and modelling study by Izumo et al., (2008) indicates the causes for the variations in western Arabian Sea SSTs and their influence on SWM rainfall over the Western Ghats. According to Izumo et al (2008), increased Somali upwelling during the late spring reduces the westward extension of the IOWP during summer, which decreases moisture availability to the air mass that delivers rainfall to the western part of the Indian sub-continent. Though the upwelling-rainfall connection is not fully understood and difficult to model, the observations suggested an anti-correlation between Somali upwelling (western Arabian Sea SST during SWM) and SWM rainfall. Both, Somali upwelling and SWM rainfall, were caused by southwest monsoonal winds during SWM season, hence there anti-correlation indicates a negative feed-back within the system (Balaji et al., 2018).

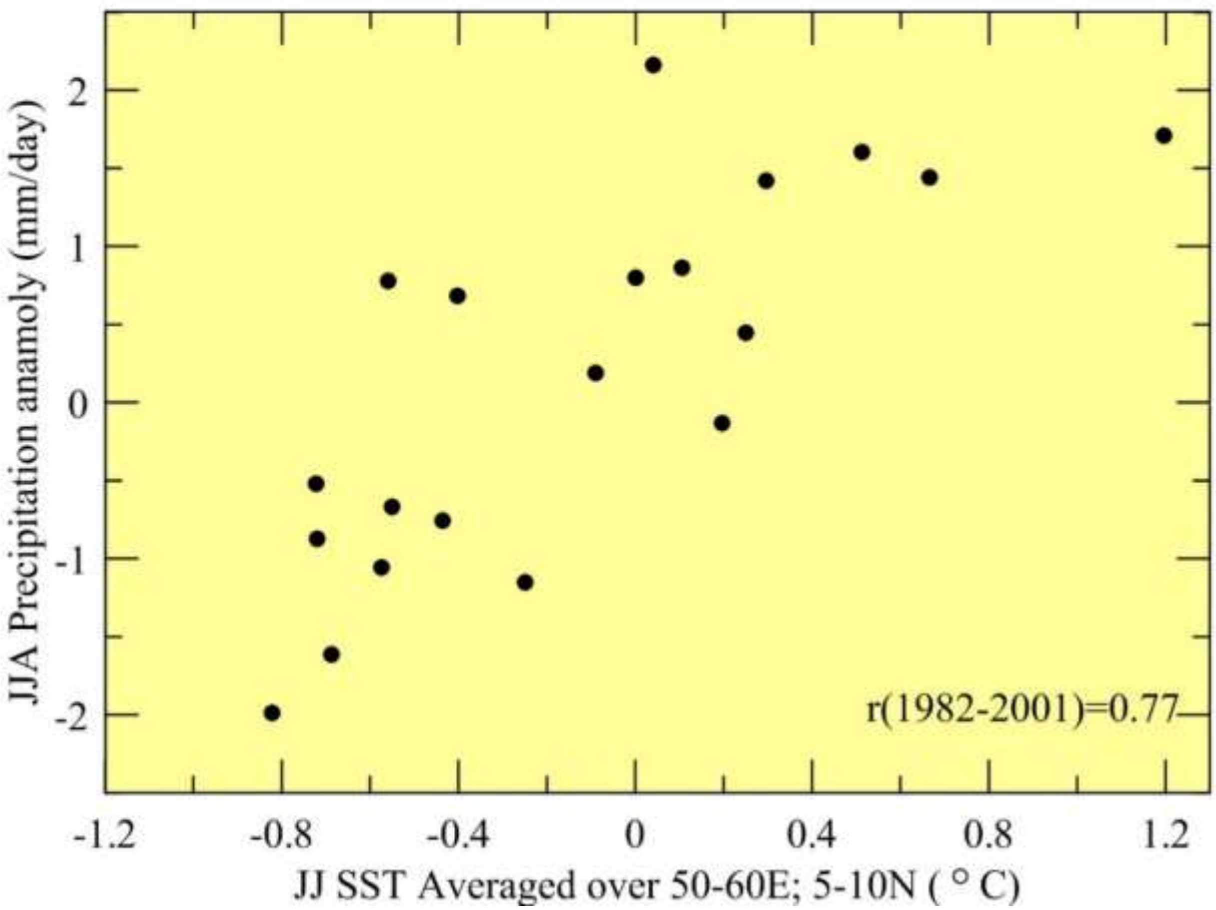

Figure 3.5: Western Arabian sea SST versus southwest monsoon rainfall in Western Ghats Mountains (data points are collected from Vecchi and Harison, 2004).

An obvious question to be answered is then if this anti-correlation between the Somali upwelling and SWM rainfall existed in the geological past. To answer this question, the record of palaeo-upwelling in the Somali region and palaeo-rainfall in the western part of India and adjoining areas needs to be investigated. There are no continuous terrestrial records of palaeo-rainfall covering the last 18.5 ka from the Western Ghats, but there are several palaeoclimatic records based on marine sediment cores from the eastern Arabian Sea. The biogenic silica flux temporal variability is compared (Figure 3.7 and 3.10) with palaeo-rainfall record ($\delta^{18}O_w$ IVF by Anand et al., 2008) from the eastern Arabian Sea and a speleothem record from Oman (Fleitmann et al., 2007). The $\delta^{18}O_w$ IVF is the Ice volume free oxygen isotopic composition of seawater based on the $\delta^{18}O$ of *G.ruber*. Anand et al. (2008) have shown that the reconstructed $\delta^{18}O_w$ IVF during the last 19 ka from a sediment core (SK-17) in eastern Arabian Sea was mainly controlled by the SWM rainfall in the Western Ghats. The Qunf speleothem record from Oman (Fleitmann et al., 2007) has been widely used as an indicator for SWM variation. The location of Qunf speleothem is very close to the present study area i.e. downwind side to the present study area during SWM season. If the SWM was the reason for the rainfall in southern Oman then western Arabian Sea must be the moisture source. Though there are no observational studies on the relation between upwelling strength and rainfall in Oman, a comparison has been made here to give a preliminary assessment. Since the records are from different regions and have irregular temporal resolutions, only the long-term trends have been examined.

3.2.3.1 Last Glacial Period (18.5–15 ka B.P.)

The biogenic silica flux record does not show any distinct variation between the previously identified Heinrich event 1 and the Last Glacial Maximum (LGM; Clark et al., 2009), so the period between 18.5 and 15 ka is considered here as the Last Glacial Period (LGP). Both biogenic silica fluxes (~2 g.m-2.y-1) were lowest during the LGP (Figure 3.6), which is similar to earlier findings of low productivity during glacial periods from the western Arabian Sea (Burckle, 1989; Sirocko et al., 2000; Ivanochko et al., 2005; Tiwari et al., 2010). Based on the modern pattern of biogenic silica productivity and its burial efficiency in the western Arabian Sea, the observed low fluxes of biogenic silica indicate that the Somali upwelling was very weak during the LGP. However, the lowest SSTs in the last 18.5 ka were recorded in the Somali basin during the LGP (Huguet et al., 2006; Saher et al., 2007; Anand et al., 2008) and are related to a basin wide cooling and not connected with upwelling strength (Figure 3.6). Dahl and Oppo, (2006) noted a reduction is Arabian sea SST of 2–4° C during LGP.

Thus, the formation of the IOWP (SST>28° C) during the LGP can be ruled out. When there is no IOWP then there would not be any relation between the Somali upwelling and rainfall. Palaeo-rainfall record from eastern Arabian Sea shows high $\delta^{18}O_w$ IVF values indicative of reduced freshwater flux and rainfall during this period (Figure 3.7b). Based on the weak upwelling in the western Arabian Sea and the reduced fresh water influx to the eastern Arabian Sea, it is concluded that the SWM was weak/absent during the LGP.

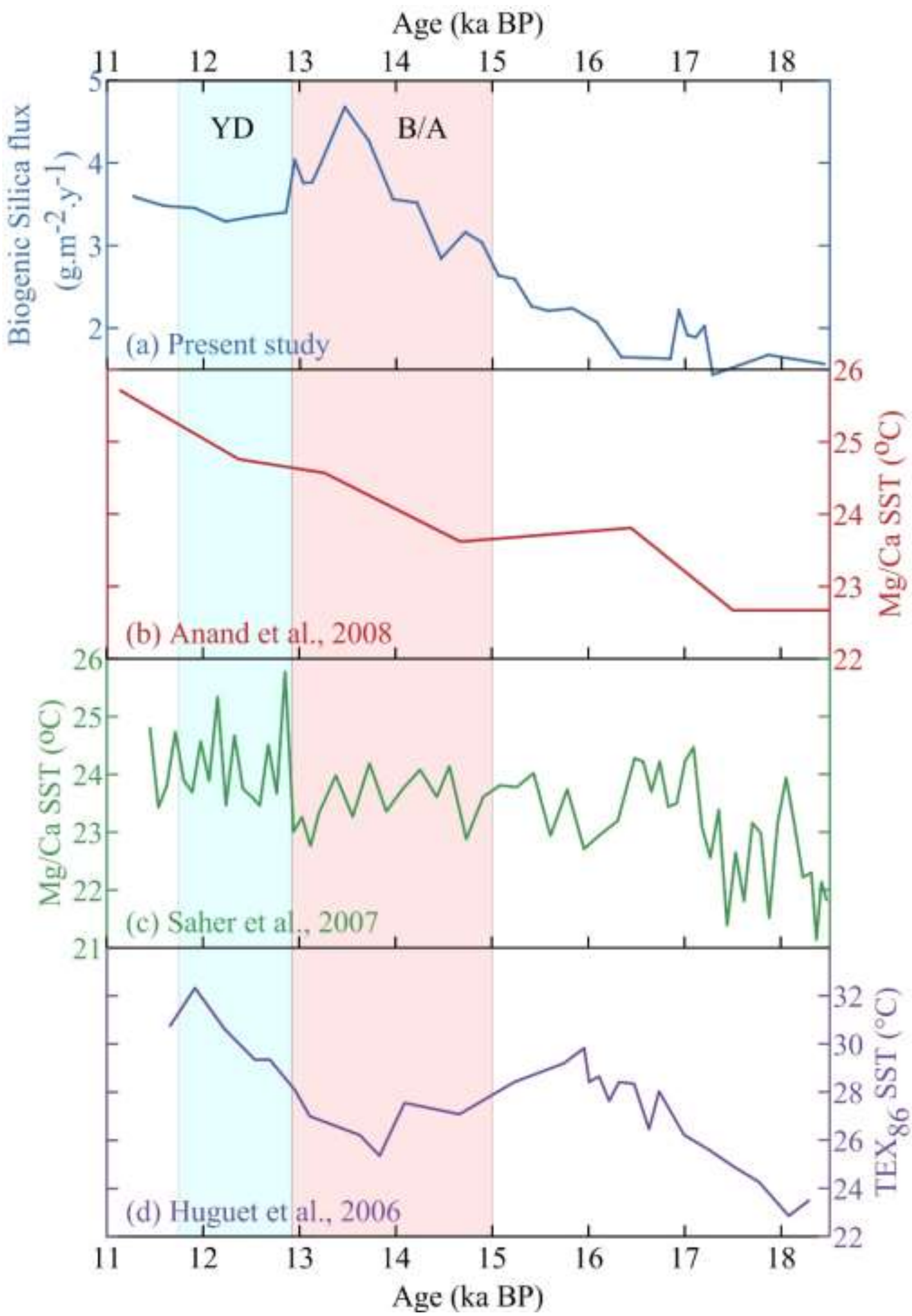

Figure 3.6: Comparison of biogenic silica flux with SST records from western Arabian Sea for pre-Holocene time (18.5-11.7 ka B.P.). a)Biogenic silica flux, b) Mg/Ca based SST from NIOP-905 core (Anand et al., 2008), c) Mg/Ca based SST from NIOP-929 core (Saher et al., 2007), d) TEX_{86} SST from NIOP-905 core (Huguet et al., 2006).

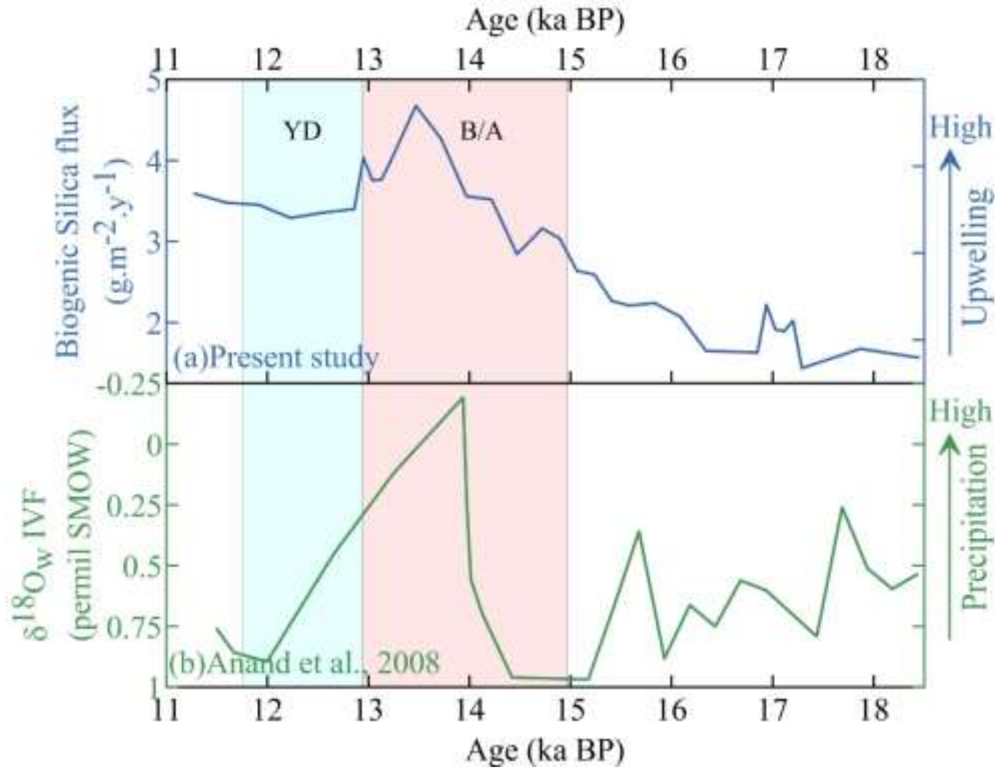

Figure 3.7: Comparison of biogenic silica flux with rainfall record from eastern Arabian Sea for pre-Holocene time (18.5-11.7 ka B.P.). (a) Biogenic silica flux (present study), (b) $\delta^{18}O_w$ IVF (Anand et al., 2008).

3.2.3.2 Deglacial Period (15–11.7 ka B.P.)

The Deglacial Period (DP) is a connecting phase between two entirely different climatic periods, the LGP and the Holocene. The DP is actually a composite of two millennial scale events between 15–12.9 ka and 12.9–11.7 ka B.P. The period occupied by these two events nearly coincides with well-known climatic events, specifically the Bølling-Allerød (B/A) event and the Younger Dryas (YD) event. The beginning of the B/A was marked by an abrupt increase in biogenic silica flux (Figure 3.6a), attributed to the effect of northern limit of southwest monsoon that was attained at the study site and the subsequent increase in Somali upwelling strength. This is further supported by investigation of Zr/Hf in two independent sediment cores near the 4018 core site, showing an increasing flux of windborne dust from the Horn of Africa (an indicator of the SWM) at the onset of the B/A (Sirocko et al., 2000; Isaji et al., 2015). The reduction in TEX_{86} SST during the B/A in the Somali basin (Huguet et al., 2006) also supports this view (Figure 3.6d), however the Mg/Ca SST does not show this change (Figure 3.6b and 3.6c). The inconsistency between the two SST records (TEX_{86} and Mg/Ca) might be related to the seasonal production of proxy material.

The $\delta^{18}O_w$ IVF record from core SK-17 (Anand et al., 2008) shows depleted values, indicating higher influx of fresh water from the Western Ghats caused by high SWM rainfall, during the B/A (Figure 3.7b). The positive correlation between Somali upwelling (high biogenic silica flux) and SWM rainfall in the Western Ghats (high fresh water influx to the eastern Arabian Sea) during the B/A contrasts with the present-day scenario as observed by Vecchi and Harrison (2004). Presently, the moisture source for SWM rainfall is the Arabian Sea and the central Indian Ocean (IOWP), which is affected by SWM upwelling (Izumo et al., 2008). If the central Indian Ocean were the only source of moisture for SWM rainfall during the B/A, then the observed co-variation is possible. Thus, it is proposed that the moisture source for SWM rainfall over Western Ghats during the B/A event was different from the modern source. The other possibility, that rainfall in south-western India was enhanced due to a strong NE monsoon during the B/A, is unlikely because the siliceous productivity in the western Arabian Sea related to the NE monsoon has not been reported (Koning et al., 1997; Ramaswamy and Gaye, 2006). In contrast to the B/A, the upwelling in the western Arabian Sea was weak during the YD, as revealed by the low biogenic silica fluxes and high SSTs (Figure 3.6; Huguet et al., 2006). This is in agreement with the previous studies from Arabian Sea which show decreased productivity during YD due to reduction in SWM (Altabet et al., 2002; Ivanochko et al., 2005). Furthermore, the high $\delta^{18}O_w$ IVF in the eastern Arabian Sea (Anand et al., 2008), which were caused by low freshwater influx, also points to weak SWM rainfall (Figure3.7).

3.2.3.3 Holocene (11.7–0 ka B.P.)

The beginning of the Holocene is marked by an abrupt increase in biogenic silica flux (Figure 3.9a). This sudden increase in biogenic silica fluxes between 11.7 ka and 9 ka B.P. can be attributed to the intensification of the SWM (extended season) caused by the northward shift of the ITCZ following the peak in Northern Hemisphere solar insolation (Fleitmann et al., 2007). Somali basin SST records (Saher et al., 2007; Huguet et al., 2006; Anand et al., 2008) also show a marginal decrease at the onset of the Holocene, but not up to the levels seen during the B/A (Figure3.9). The TEX_{86} SST show more variation than Mg/Ca at the beginning of Holocene, however the Mg/Ca SST gives a mirror image like pattern with biogenic silica flux during

Holocene indicating the dominance of seasonal signal in Mg/Ca SST during this period (Figure 3.9b). Based on the stable isotopic composition of organic carbon and nitrogen in the 4018 core Tiwari et al (2010) also suggested an increase in productivity during Holocene and attributed to the strengthening of Somali upwelling. The synchronous changes in the biogenic silica flux with biogenic silica/carbonate ratio (Figure 3.8) indicates a change in dominant plankton community (carbonaceous to siliceous) due to increased upwelling, such as that suggested by Tiwari et al. (2010). The $\delta^{18}O_w$ IVF (Anand et al., 2008) display values similar to those of the YD during the early Holocene (Figure 3.10c), indicating reduced rainfall (lower fresh water influx) over the Western Ghats. This anti-correlation between Somali upwelling and SWM rainfall over south-western India during the early Holocene (11.7 ka to 9 ka B.P.), marks the establishment of the modern-day climate system. The increased Somali upwelling in the western Arabian Sea during the early Holocene (11.7 to 8 ka B.P.; Figure 3.10a) might have reduced the IOWP expanse during the SWM season, thereby resulting in lower moisture availability and subsequent reduced rainfall over the Western Ghats. Oman speleothem record also shows decreased precipitation during early Holocene (Figure 3.10b) and supports the interpretation of low moisture availability.

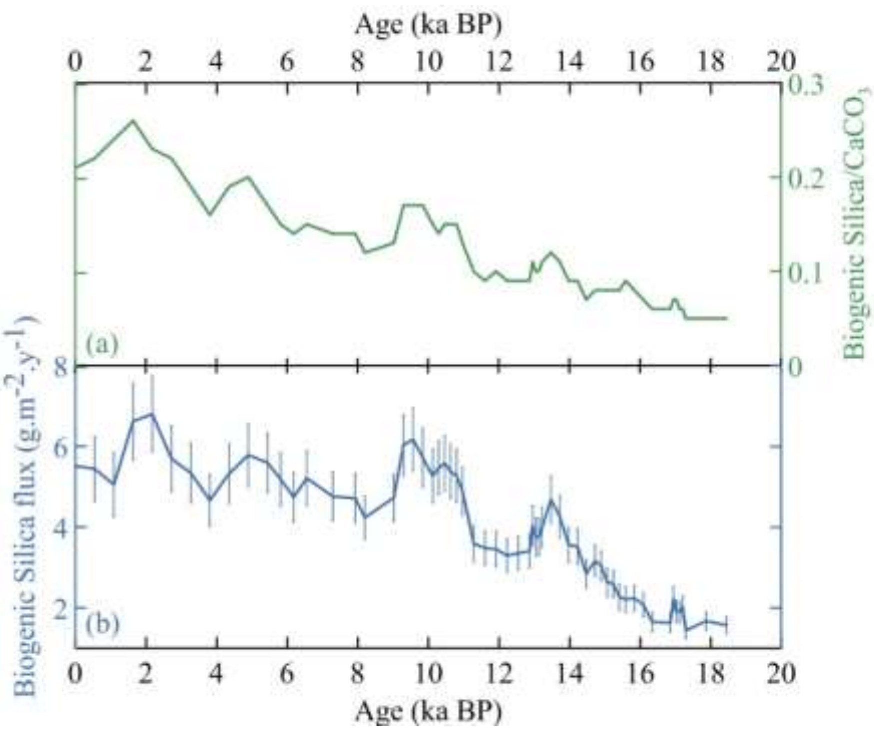

Figure 3.8: Comparison of biogenic silica flux with silica to carbonate ratio in 4018 sediment core. Synchronous changes in both parameters indicate the dominance of biogenic silica flux on the ratio.

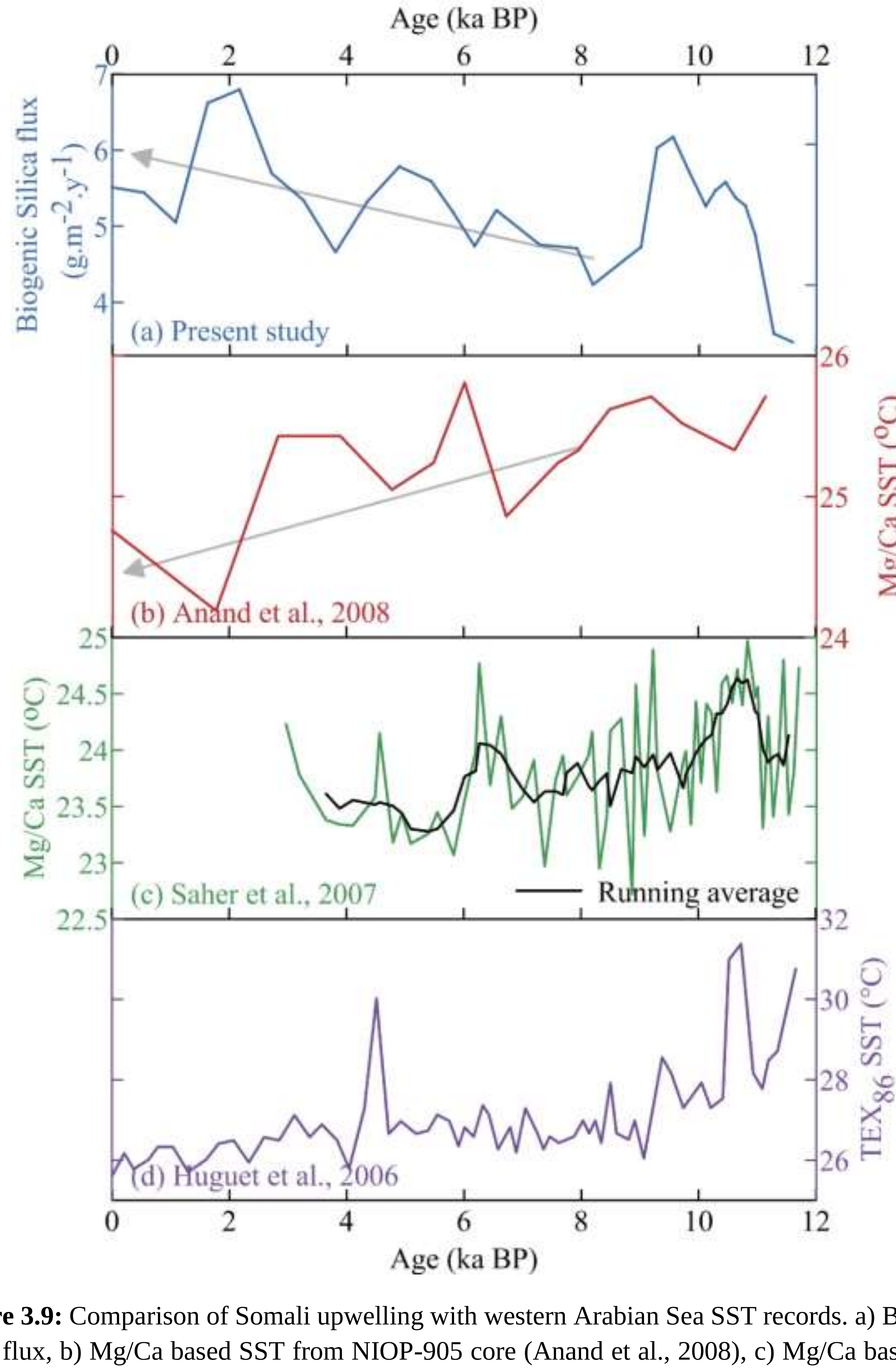

Figure 3.9: Comparison of Somali upwelling with western Arabian Sea SST records. a) Biogenic silica flux, b) Mg/Ca based SST from NIOP-905 core (Anand et al., 2008), c) Mg/Ca based SST from NIOP-929 core (Saher et al., 2007), d) TEX_{86} SST from NIOP-905 core (Huguet et al., 2006). Grey arrow indicate the trend of proxy records during the last 8 ka B.P.

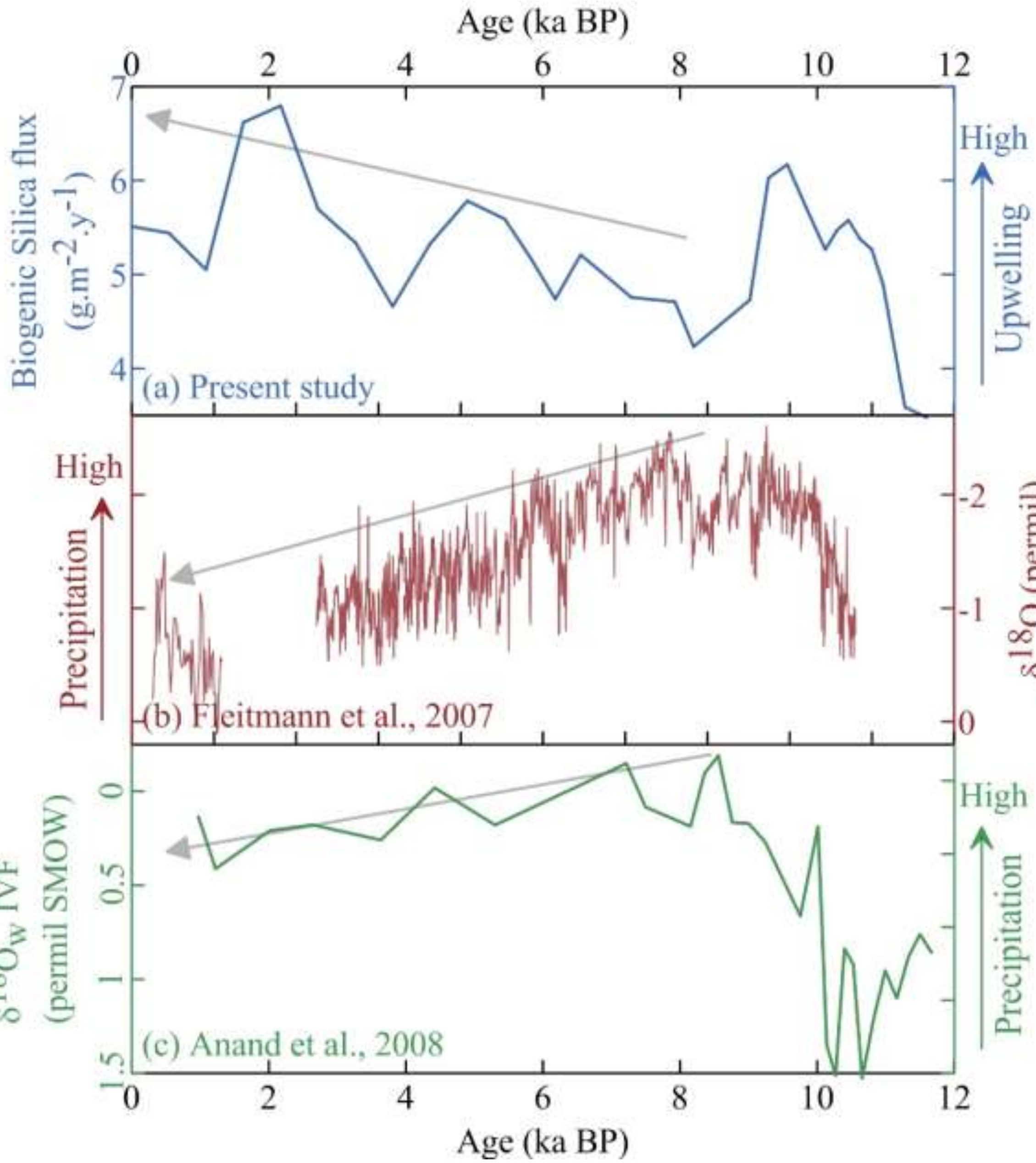

Figure 3.10: Comparison of Somali upwelling with southwest monsoon rainfall records during Holocene. (a) Biogenic silica flux (present study), (b) Oman speleothem record, (c) $\delta^{18}O_w$ IVF data from eastern Arabian Sea. Grey arrow indicate the trend of proxy record during the last 8 ka B.P.

At ~8 ka B.P. (Figure 3.10a) Somali upwelling strength is seen to have decreased as compared to the early Holocene but persisted above YD and B/A levels, indicating the presence of the SWM with reduced wind strengths relative to the early Holocene. The SST record also shows a higher value at ~8 ka B.P. (Figure 3.10b) indicating reduction in Somali upwelling. This reduction in upwelling at 8 ka B.P. might have allowed the westward extension of the IOWP during the SWM season that increased both, moisture availability over the Arabian Sea and rainfall over the Western Ghats. The $\delta^{18}O_w$ IVF value is low at 8 ka B.P., pointing towards an increase in fresh water influx from the Western Ghats at this time (Anand et al., 2008) due to increased SWM rainfall (Figure 3.10c). Oman speleothem record also shows a decrease in $\delta^{18}O$ value at 8 ka B.P. (Figure 3.10b) which suggests an enhanced SWM rainfall.

Somali upwelling had a gradual increase during the last 8 ka with minor positive changes at around 5 and 2 ka B.P. (Figure 3.10a). The increase in SWM induced Somali upwelling during the last 8 ka contrasts the idea that SWM followed the northern hemisphere insolation during Holocene (Gupta et al., 2003; Fleitmann et al., 2003 and references therein). However our interpretation is in agreement with other studies from Arabian Sea which point towards a slight increase in SWM during Holocene (Agnihotri et al., 2003; Tiwari et al., 2010). These short term increase in Somali upwelling at 5 and 2 ka B.P. is also observed by reduction in the Mg/Ca SST record (Figure 3.9b). Oman speleothem record shows an increase in $\delta^{18}O$ during the last 8 ka indicating reduction in SWM rainfall (Figure 3.10b). The hiatus in Oman speleothem record at 2 ka B.P. coincides with the strengthened Somali upwelling, however it is difficult to explain (Figure 3.10a&b). The SK-17 record (Anand et al., 2008) shows slight increase in the $\delta^{18}O_w$ IVF of surface waters during the last 8 ka (Figure 3.10c) indicating reduction in SWM rainfall. The opposite trend in upwelling and rainfall record during the last 8 ka indicate the negative impact of Somali upwelling on SWM rainfall and might have been caused through a change in the area of IOWP and moisture availability. However the short term variations in upwelling are not observed in eastern Arabian Sea rainfall record. The Somali upwelling possibly had a negative impact on southwest monsoon rainfall over south-western India and Oman throughout the Holocene.