

## Reply to the Referee #1 comments

The authors are thankful to referee for his/her critical and constructive comments which helped in improvising the manuscript. The necessary changes in view of the comments made by the referee has been incorporated in the manuscript and would be send along with those as would be suggested by other reviewers. Here, we provide replies to the comments.

**Comment:** *I found the data/results relatively straight forward but the results were slightly over-interpreted in conjunction with other datasets. I think part of the issue might be resolved in annotating the figures with specific intervals better (e.g. YD and BA).*

**Reply:** The biogenic silica flux has been primarily used as proxy to reconstruct the Somali upwelling with SST records as secondary/supporting proxy. The data has been compared with the long-term trend of available palaeoclimatic records and have been summarized to the most appropriate conditions prevailed in the region. As suggested, the B/A and YD intervals have been marked in the figures 5 and 6.

**Comment:** *One of my major concerns is using TEX<sub>86</sub> values as sea surface temperature in an upwelling region. TEX<sub>86</sub> values record variable temperatures in upwelling regions (see Hertzberg et al., EPSL 2016). TEX<sub>86</sub> essentially records subsurface conditions in upwelling regions so interpreting the Huguet et al., 2006 record purely as sea surface temperature is incorrect. I would recommend excluding this temperature record from the regional climate discussion. This would change the discussion section significantly. In particular, much of the YD and BA discussion hinges on the TEX<sub>86</sub> record.*

**Reply:** We agree that the TEX<sup>86</sup> proxy records surface or sub-subsurface sea surface temperature on longer time scales dependant on the nutrient availability and surface productivity. The suggested publication Hertzberg et al., EPSL 2016 from east pacific region indicates the TEX<sup>86</sup> record co-vary with Mg/Ca SST during modern and Holocene, but differs during the LGM. However, our aim is to decipher the changes in SST with respect to the biogenic silica variation as recorded in the present study. Since we are not discerning quantitative changes in SST or the inconsistencies between various SST proxies, only the relative trend of increase / decrease in SST has been considered. Moreover, as seen in Fig.5, the Mg/Ca based SST record by Saher et al., 2007 also shows co-variance with minor amplitude. As suggested, we have modified the discussion accordingly.

**Comment:** *For comparisons of specific events like the YD and BA, I have some concerns about the age models. Many of the regional records are relatively low resolution. Are the age models, and frankly the sampling resolution, adequate to make the regional interpretations for the YD and BA? I think annotating these specific intervals on the figures would help the reader and the authors evaluate these interpretations.*

**Reply:** The sampling resolutions of the studies discussed were sufficient enough to make comparison and interpret multi-millennial scale events like B/A & YD. Although, the age models of the discussed sediment cores are of low resolution, but reasonably high for events like B/A and YD, thus we have not attempted to compute any correlation plot between regional records. The B/A and YD intervals have been marked in the figures 5 and 6 as per referee's suggestion.

**Comment:** *Could the authors clarify the selective preservation within the upwelling region (Lines 125-135)? In addition to the upwelling diatoms being more heavily silicified, presumably the flux of diatoms to the sediment during upwelling when nutrients are abundant also enhances their preservation? I'm not certain how the authors determined the preservation efficiency in the core. Is this based on the types of diatoms within the sediment?*

**Reply:** For determining the preservation efficiency of diatom in the core, we have used findings of previous study by Konning et al., 1997 and 2001 from the Somali basin, wherein preservation efficiency is based on sediment traps and surface sediment studies. They observed "two well-silicified upwelling species, *T. Nitzschioides* and the solution-resistant *Chaetoceros*, make up ~60% of the sediment, and dominate sediments both in the core tops and down core, thereby preserving a residual upwelling signal". The estimated preservation efficiency is derived from the productivity and type of diatoms preserved in sediments (Konning et al., 1997 and 2001). Detailed discussion has been incorporated in the manuscript.

#### **Minor Comments:**

**Comment:** *Please refer the reader to the specific figure (or figures) within the text. Figures should be labeled with region (e.g. Western Ghats) in addition to the author.*

**Reply:** The suggested corrections have been incorporated in the text as well as in the figure captions of the revised manuscript.

**Comment:** *Line 15: "positive to negative" is ambiguous. Could you make this sentence a little more clear?*

**Reply:** The suggested change has been made.

**Comment:** *Line 25: SST not defined write out sea surface temperature*

**Reply:** Sea surface temperature is introduced at line 25 of the revised manuscript.

**Comment:** *Lines 170-175: I think it would be best to start this line of argument with the colder SSTs in the LGP are related to global cooling and not a change in upwelling strength.*

**Reply:** The statement has been modified as suggested.

**Comment:** *Line 175: use suggested instead of envisaged*

**Reply:** The change has been made.

**Comment:** *Line 188: I don't see a reduction in temperatures during the B/A*

**Reply:** The B/A event marked between 15-13 ka BP shows prominent reduction in temperatures both by Anand et al, 2008 and Huguet et al., 2006, though, Mg/Ca SST by Saher et al., 2007 shows minor change comparatively. This is noticeable with B/A events marked in the comparison figures.

**Comment:** *Lines 209-211: I don't see this pronounced SST decrease in the Mg/Ca SST records, this is a TEX signal?*

**Reply:** Thanks for the observation as there is no pronounced SST decrease in the Mg/Ca SST records, however, Mg/Ca SST record of Saher et al., 2007 indicates only a marginal decrease at the beginning of Holocene period. The amplitude in the SST change differs between Mg/Ca and TEX<sup>86</sup> records, with latter showing prominent change. Necessary modification made in the text.

**Comment:** *Lines 231-235: I would recommend omitting this impact statement.*

**Reply:** This statement has been made to highlight the significance of the present study. However, the statement being emphatic in nature has been toned down and appropriately modified as “The Somali upwelling can possibly have a negative impact on southwest monsoon rainfall over south-western India throughout the Holocene. This finding would have implications in context of the modeling study by deCastro et al. (2016), which shows that Somali upwelling would increase during the twenty-first century.”

## Reply to the Referee #2 comments

The authors are thankful to referee for his/her critical and constructive comments which helped in improvising the manuscript. The necessary changes in view of the comments made by the referee have been incorporated in the manuscript and will be sent after the editor's decision. Here, we provide replies to the comments.

**Comment:** *The comparison of the productivity record with the SST records is misleading. As the authors state, high productivity could be expected during periods of strong upwelling, i.e. low temperatures. The SST records, however, are dominated by the strong glacial-interglacial temperature increase. So during this phase it looks like SST and productivities are positively correlated. The authors discuss this (chapter 4.2.1.) and thus start the comparison with a phase when it does not work; so the Figure still does not help much with the data interpretation. A comparison of other productivity records, concentrating on the Somali and Oman upwelling areas could be more illustrative. The SST records of the Holocene (after the strong glacial-interglacial) may be plotted with reversed scale in order to better illustrate whether and when there is an anti-correlation. In addition: there is some discussion in Huguet et al. (2006) about the TEX86 temperatures; it may not represent annual average temperatures but has a SW monsoon bias. This needs to be addressed and could actually support the authors.*

**Reply:** The high productivity is expected during the periods of strong upwelling and low SST, but only during southwest monsoon. Previous studies have shown that the southwest monsoon was weak/absent during LGM. Hence, modern relation of productivity and upwelling would not exist during LGM. The Mg/Ca based SST records are dominated by glacial-interglacial signal as it was measured in planktonic foraminifera *G.ruber*, which occurs throughout the year. But biogenic silica flux is dominated by southwest monsoon signal. The biogenic silica flux thus serves as a better proxy for upwelling rather than SST. This major observation is being underscored by comparing biogenic silica flux and SST and has been further elaborated in the revised manuscript. The other productivity records from Somali and Oman upwelling regions which record annual signal are either based on calcareous microfossils or organic matter. Therefore, comparison of biogenic silica flux with other productivity records would be improper. The TEX86 proxy related points of Huguet et al., (2006) have been included in the revised manuscript.

**Comment:** *The comparison of the biogenic opal fluxes from the Somali upwelling and the  $\delta^{18}O$  (precipitation) records is a new idea (not published by Tiwari et al.) but is too vague to be the main part of the paper. The anti-correlation of Western Ghats precipitation with western Arabian Sea upwelling was modelled for the present Arabian Sea and the authors cite only one paper (Izuma, see above). As the authors also discuss, differences in evaporation and also surface water inflow from the Bay of Bengal have impacted the salinity off the west coast of India during the past so that much of the changes are related to several different processes (see Vijit et al., 2016; Mahesh and Banakar, 2014). Furthermore, even the present relationship between precipitation on the Indian Subcontinent and upwelling/productivity in the Arabian Sea is not very clear (see Levine and Turner, 2012) so this topic needs at least some further discussion.*

**Reply:** Though the anti-correlation between western Arabian Sea upwelling/SST and rainfall in southwestern India is still open for investigation but few studies show evidence (Shukla, 1975; Arpe et al., 1998; Vecchi and Harrison, 2004; Izumo et al., 2008; Gimeno et al., 2010; Levine and Turner, 2012). Based on these modern observations, the comparison of upwelling and rainfall on longer time scales becomes an important aspect towards its understanding. As per reviewer's suggestion more studies on the modern climate are included in the revised manuscript.

**Comment:** *In the paper by Tiwari et al. (2010), which the authors cite, more data on core SS4018 are available such as carbonate contents and stable isotopes of carbon and nitrogen. These data can be utilized to better understand the processes in the Somali upwelling and would help to better understand the Holocene productivity changes. Tiwari et al. come to similar conclusions, e.g. that productivity does not decline during the late Holocene despite the decreasing insolation, based on a multiproxy study. The authors have now additional evidence that this is the case and can prove what Tiwari et al. suggested: the decline of carbonate could be due to the replacement of carbonaceous by siliceous primary producers. The carbonate/opal ratio could show this and strengthen the authors' point. The published data need to be included and elaborated on.*

**Reply:** Yes, there are more proxy data available in the same core. We also agree that Tiwari et al., 2010 have suggested siliceous productivity as an alternative for calcareous. The whole core is composed of carbonaceous sediments with some minor variations. The carbonate content variations in this case is a function of nutrient availability and upwelling due to southwest monsoon variability. Carbonaceous productivity requires nutrients and micro nutrients. Oceanic regions (like Southern Ocean) deficient in micro nutrients, equatorial regions and high upwelling regions are known to experience high siliceous productivity (Lizitzin, 1971). Somalia basin

known for strong upwelling, receives excessive nutrients brought from the sub-surface waters, is one region which results in relatively high primary productivity as a function of upwelling (Burkill et al., 1993). Synchronous increase of B.Si/carbonate and biogenic silica flux (Figure r1) attests to increasing upwelling in the Somalia region. However detailed discussion on the findings of Tiwari et al., 2010 have been included in the revised manuscript, as per reviewer's suggestion. If the referee still suggests the inclusion of previously published data by Tiwari et al., 2010 is necessary, then we are ready to incorporate in the revised manuscript.

**Minor Comments:**

***Comment: The authors use the term “glacial” and “deglaciation” without giving references for these phases. They should also give the correct time for the beginning of the Holocene. I think that the use of LGM is rather uncommon but LGM is more common and can be referenced (Clark et al, 2009).***

***Reply:*** The time for beginning of Holocene is modified from 11 ka to 11.7 ka BP in the revised manuscript text and figures. We agree with the referee that the use of LGM is more common, however, in this paper LGM has been used as it is a cumulative period comprising Heinrich event 1 and part of LGM, also explained in the beginning of chapter 4.2.1.

***Comment: Lines 55-59: it does not become clear why biogenic silica appears after carbonate, clarify in more detail.***

***Reply:*** Biogenic silica productivity as mentioned earlier are typical for regions like Southern Ocean, Equatorial Regions and high upwelling regions (like the present study site Somalia Basin). Silicate is low as compared to nitrate in surface and the intermediate ocean. Generally, in normal conditions in presence of nutrients and micro nutrients (Fe etc mostly supplied by terrestrial input or aeolian dust) or during the initial phase of upwelling (which brings high nitrate and low silicate water), it is mostly carbonaceous productivity which is dominated. But during high upwelling periods, due to excessive pumping of nutrients (silicate) to surface ocean by sub-surface waters (Haake et al., 1993), after initial carbonaceous productivity, depletion of micro nutrients to sustain excessive nutrient utilization and presence of more silicate results in siliceous productivity.

***Comment: Line 68: Is the age model used here different from the one used by Tiwari et al. for the same core, if yes, why? Is the same rate of sedimentation used for the whole core, despite available C14 ages? Why?***

**Reply:** Yes, we have used constant sedimentation rate to compute the flux. We considered that the variation in the sedimentation rate between 3-23 cm.ka<sup>-1</sup> in our 4018 core as published by Tiwari et al., (2010), is a result of age control point selection. To minimize this effect, we computed an average sedimentation rate for the whole core.

**Comment: Lines 130-134: difficult to understand, explain in more detail. Why should variations be three times greater?**

**Reply:** If the observed variation in the biogenic silica flux is dominated by changes in burial efficiency (BE), low BE can be attributed to low flux and high BE to high flux i.e. result of low flux divided by low BF should be equal to high flux divided by high BE. High and low BE were assigned as per modern observation by Konning 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 and the change in silica flux is exclusively a function of upwelling. Detailed explanation is presented in the revised manuscript.

**Comment: Lines 145-148: very short and therefore difficult to understand, explain in more detail (see also general comment on the comparison of SST and productivity records above). When do you expect a correlation, when an anti-correlation, why? This cannot be explained in two sentences.**

**Reply:** During southwest monsoon, with increase in upwelling anti-correlation exist between biogenic silica flux and SST. However, there is no relation between biogenic silica flux and SST in absence of southwest monsoon during LGP (18.5-15 ka BP). Detailed discussion on the comparison between biogenic silica flux and SST is now included in the revised manuscript.

**Comment: Line 181: I find the use of the deglacial period (DP; 15-11 ka BP) rather problematic as it covers the Pleistocene/Holocene boundary.**

**Reply:** We have used the deglacial period as the connecting phase between Holocene and LGP. The time range for deglacial period has been modified as 15-11.7 ka BP in the revised manuscript.

**Comment: Line 185: what does “entrainment of the SW monsoon” mean?**

**Reply:** We want to state that the northern limit of southwest monsoon was attained at the beginning of deglacial period onto the study site. The sentence has been modified as suggested.

**Comment:** *Lines 197-204: these lines again show that the comparison of moisture and upwelling does not work (see above). So when does it work and is it at all useful to show it for the whole period?*

**Reply:** The change in the relationship between upwelling and rainfall (moisture) at ~11 ka BP is the major finding of the present study. The upwelling-rainfall interaction was different during deglacial period than Holocene as well as modern. So the comparison for the whole period is necessary.

**Comment:** *Lines 221: very short and not convincing. How does the record from the Qunf Cave come into the picture? How is rainfall related with the monsoon on the Arabian Peninsula? Is chronology such a big problem that the correlation does not work?*

**Reply:** This part has been elaborated in the revised manuscript. Fleitmann et al., 2007 have used Qunf cave record as indicator of southwest monsoon rainfall. The location of the Qunf speleothem is very close to the study area. If southwest monsoon was the reason for rainfall in southern Oman then western Arabian Sea must be the moisture source and is the basis for comparing upwelling and Qunf cave record. This aspect is now included in the revised manuscript. Chronology limits the comparison of short time variations in upwelling and rainfall records, however, long-term trend comparison is possible.

**References suggested:**

1. Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S. W., and McCabe, A. M.: The Last Glacial Maximum, *Science*, 325, 710-714, 2009.
2. Levine, R. C. and Turner, A. G.: Dependence of Indian monsoon rainfall on moisture fluxes across the Arabian Sea and the impact of coupled model sea surface temperature biases, *Climate Dynamics*, 38, 2167-2190, 2012.
3. Mahesh, B. S. and Banakar, V. K.: Change in the intensity of low-salinity water inflow from the Bay of Bengal into the Eastern Arabian Sea from the Last Glacial Maximum to the Holocene: Implications for monsoon variations, *Paleogeogr. Paleoclimatol. Paleoecol.*, 397, 31-37, 2014.
4. Vijith, V., Vinayachandran, P. N., Thushara, V., Amol, P., Shankar, D., and Anil, A. C.: Consequences of inhibition of mixed-layer deepening by the West India Coastal Current for winter phytoplankton bloom in the northeastern Arabian Sea, *J. Geophys. Res.-Oceans*, 121, 6583-6603, 2016.

**Reply:** Suggested studies are included in the revised manuscript.



# Strengthening of the Somali upwelling during the Holocene and its impact on southwest monsoon rainfall

Balaji D.<sup>1,2</sup>, Ravi Bhushan<sup>2</sup>, L. S. Chamyal<sup>1</sup>

<sup>1</sup>Department of Geology, The Maharaja Sayajirao University of Baroda, India

5 <sup>2</sup>Geoscience Division, Physical Research Laboratory, Ahmedabad, India

Correspondence to: Balaji D. ([balaji.d86@gmail.com](mailto:balaji.d86@gmail.com))

**Abstract.** The history of the Somali upwelling during the last 18.5 ka has been reconstructed using biogenic silica fluxes estimated from a sediment core retrieved from the western Arabian Sea. Surface winds along the east African coast during southwest monsoon causes the Somali upwelling and therefore the intensity of this upwelling has been related to the southwest monsoonal variability. Variations in biogenic silica fluxes suggest ~~The reconstructed record demonstrates~~ periodic weakening and strengthening of the Somali upwelling ~~during the past 18.5 ka. Variations in biogenic silica fluxes suggest~~ A weakened upwelling during the last glacial period (18.5-15 ka BP) and ~~S~~ strengthened upwelling during the Bølling-Allerød ~~period~~ (15-12.93 ka BP) ~~points to suggest~~ post-glacial onset of the southwest monsoon. Whereas ~~t~~he Younger Dryas (12.93-11.7 ka BP) is ~~again~~ marked by reduced upwelling strength. Hintensification of the Somali upwelling at the beginning of the Holocene and a decline at 8 ka BP ~~are~~ have been observed. Increases in upwelling strength recorded since 8 ka BP suggest strengthening of the southwest monsoon during the latter part of the Holocene. These upwelling variations when compared with the southwest monsoon precipitation record, a reversal in the relationship between the strength of the Somali upwelling and southwest monsoon rainfall is observed at the beginning of Holocene. ~~Linking these upwelling variations with southwest monsoon precipitation, a major shift in the relationship between the strength of the Somali upwelling and southwest monsoon rainfall from positive to negative has occurred during the pre-Holocene to the Holocene.~~ The observed shift is attributed to the variation in the southwest monsoon strength due to the latitudinal shift of the Intertropical Convergence Zone (ITCZ) associated with changes in moisture sources.

## 1 Introduction

The greater part of the world's population inhabits the tropical region, where climate is mainly controlled by monsoon rainfall. Understanding the causes of past changes thus plays a critical role in deciphering past, present and future monsoon variability. The economy of India, which is a tropical country that contains 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, such as ENSO (Goswami et al., 1999; Annamalai and Liu, 2005),

30 Atlantic Sea Surface Temperature (SST): Goswami et al., 2006; Yadav, 2016), Eurasian snow cover (Hahn and Shukla, 1976; Pant and Rupa Kumar, 1997; Bamzai and Shukla, 1999), the pre-monsoon 500 hPa ridge (Mooley et al., 1986), the Indo-Pacific warm pool (Parthasarathy et al., 1988; Parthasarathy et al., 1991), the Pacific decadal oscillation (Krishnan and Sugi, 2003), and the Atlantic multi-decadal oscillation (Krishnamurthy and Krishnamurthy, 2015). In addition to these factors that influence SWM, the Indian Ocean Warm Pool (IOWP) has been identified as the prominent source of moisture for SWM  
35 rainfall (Ninomiya and Kobayashi, 1999; Gimeno et al., 2010). During its maxima, the IOWP extends throughout the northern Indian Ocean during the pre-monsoon period (April), and it almost reduces to half during the SWM (Izumo et al., 2008). 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.

40 Upwelling of deep water during the SWM brings nutrients up to the photic zone, enhancing surface productivity in the western Arabian Sea. Paleoproductivity 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  
45 in siliceous productivity in the Somali upwelling region, as well as paleo-upwelling strength and its relationship with the southwest monsoon rainfall, using a sediment core retrieved from the western Arabian Sea (Fig.1).

### 1.1 Modern Oceanography and Productivity

The surface water circulation in western Arabian Sea is controlled by seasonal changes in atmospheric wind pattern related with annual migration of ITCZ (Wyrcki, 1973). During boreal winter, ITCZ stays south of equator and shifts to north during  
50 boreal summer. This northward shift of ITCZ during southwest monsoon (SWM, June-September) season drives the southern hemisphere eastern trade winds across equator that turns clockwise and becomes southwest winds (Findlater, 1977; Fig. 2). These southwest winds help to form the Somali current along the east African coast towards north. The Somali current is generally associated with near shore upwelling and eddies such as southern gyre, great whirl and Socotra eddy (Schott et al., 1990; Beal and Chereskin, 2003; Schott et al., 2009). These eddies induce intense upwelling which pumps out the low  
55 temperature and nutrient rich subsurface water to the surface along the east coast of Africa (Young and Kindle, 1994).

Productivity in the western Arabian Sea reflects the seasonal changes in surface ocean characteristics (Qasim, 1977; Brock et al., 1991). More than half of the annual productivity in the western Arabian Sea occurs during southwest monsoon due to intense upwelling (Haake et al., 1993). Total flux (biogenic + dust) also peaks at the same time when productivity is at its maximum, means-indicating that SWM not only causes high productivity in the western Arabian Sea but also contributes to  
60 high dust flux (Sirocko and Lange, 1991; Haake et al., 1993). Bhushan et al., 2003 observed that the concentration of nitrate and phosphate increased at the bottom of the mixed layer at the core location, whereas, significant increase in silicate concentration occurs only at the depth of thermocline. During the onset of SWM upwelling, nitrate and phosphate rich waters

surfaced more compared to silicate due to the upwelling of shallow waters. In presence of high nitrate and phosphate along with the micronutrients (derived by dust flux), the calcareous primary producers dominated the surface productivity. Sediment trap studies in the western Arabian Sea recorded that during the onset of SWM, high biogenic carbonate dominates particle flux, at the onset of SWM upwelling (Haake et al., 1993). During the late phase of SWM upwelling, the surfacing of deeper waters increased silicate concentration in surface waters. High silicate content and depletion of micro-nutrients to sustain excessive nutrient utilization results in siliceous productivity and subsequent biogenic silica flux to the sediments while the end of SWM is dominated by biogenic silica flux (Fig.3; Konning et al., 2001). This late SWM appearance of biogenic silica flux is caused by the increased surface silicate concentration of upwelled deep water. Initially, this upwelled deep waters surfaced at Somali coastal upwelling zone and transported towards the mouth of Gulf of Aden (core location) through the Socotra channel i.e. between the Socotra Island and Somalia (Young and Kindle, 1994).

## 2 Material and methods

Sediment core SS4018 was collected off the Horn of Africa (north of Socotra island), in from the western Arabian Sea (13° 12.80' N, 53° 15.40' E; water depth 2830 m; core length 130 cm; Fig. 1) during FORV Sagar Sampada cruise SS-164 in 1998. Sub-sampling at 2-cm intervals was carried out. The age-depth model (Fig. 43) as well as the calcareous and organic productivity proxies of this sediment core have been presented elsewhere (Tiwari et al., 2010). Dry bulk density (DBD) was computed using an empirical equation based on the calcium carbonate concentrations (Clemens et al., 1987). The flux rate was estimated using an average sedimentation rate computed based on the age-depth model given by Tiwari et al., (2010). However, the published ages of the individual samples were considered. The sedimentation rate at the core site as given by Tiwari et al., (2010) is variable, the lowest being 3.5 and highest at 22.7 cm.ka-1. Since the age model depends on the sample selection criteria and may change according to depth of age control points, an average sedimentation rate was computed for the entire core.

The biogenic silica concentration was measured in each sample using the method described by Carter and Colman (1994). Dried homogenized samples weighing 50 mg were placed in centrifuge tubes. Five milliliters of 10 % H<sub>2</sub>O<sub>2</sub> was added to each sample at room temperature, and the samples were stored for 2 hours to remove organic matter. Five milliliters of 1N HCl was added to each tube. After acid treatment, 20 ml of distilled water was added, and the samples were centrifuged for 15 minutes. Sample tubes were kept in an oven after removal of the supernatant. Thirty milliliters of 2 M Na<sub>2</sub>CO<sub>3</sub> was added to each sample tube, and the tubes were kept in a shaker bath at 95<sup>0</sup> C for 5 hours. After 5 hours, the samples were centrifuged for 5 minutes, and 3 ml of hot supernatant was pipetted out of each sample and added to exactly 30 ml of distilled water in pre-cleaned sample tubes. These solutions were was acidified by adding 0.9 ml of concentrated HNO<sub>3</sub>. Sample tubes were sealed after effervescence. Silicon and aluminum/Aluminium concentrations were measured in these samples using ICP-AES (Jobin-Yvon, Model 38S at Physical Research Laboratory, Ahmedabad). The silicon concentrations were then corrected for clay mineral dissolution by using the formula given by Carter and Colman (1994) (Eqn 1):

95  $\Delta Si = Si - (Al * 1.93)$  (1)

Where,  $\Delta Si$  is the corrected silicon concentration,  $Si$  and  $Al$  are the measured concentrations of silicon and aluminium in the sample, and 1.93 is the Si to Al ratio in smectite. Smectite is an abundant clay mineral in the northern Arabian Sea (Sirocko et al., 1991). Biogenic silica concentrations were calculated using the formula given below (Eqn 2):

$Biogenic\ silica = \Delta Si * K$  (2)

100 Where,  $K$  is a constant that equals 2.4, which accounts for the ~10 % water content in biogenic silica (Mortlock and Frolich, 1989). Overall, the error associated with the biogenic silica measurement is less than 5 % based on repeat measurements. The biogenic silica flux is calculated by multiplying the biogenic silica fraction by the sedimentation rate (SR) and the dry bulk density (DBD) (Eqn 3),

$B.Si.flux(g.m^{-2}.y^{-1}) = B.Si * SR(m.y^{-1}) * DBD(g.m^{-3})$  (3)

105 The uncertainties associated with the biogenic silica concentration (B.Si) is estimated from the error in Aluminium and Silicon concentration based on measurements of repeat and standard material. The maximum error in biogenic silica concentration is within 5%. Dry bulk density (DBD) is calculated from  $CaCO_3$  concentration using an empirical equation suggested by Clemens et al., 1987. The standard uncertainty in DBD calculation is 0.091 g/cm<sup>3</sup>. The uncertainty in average sedimentation rate (SR) is 0.12 cm/ky. Finally the uncertainty associated with biogenic silica flux (B.Si flux) is propagated using the below  
110 equation,

$\sigma_{B.Si\ flux} = B.Si\ flux * \sqrt{\{(\sigma_{B.Si}/B.Si)^2 + (\sigma_{DBD}/DBD)^2 + (\sigma_{SR}/SR)^2\}}$  (4)

Where, prefix “ $\sigma$ ” stands for uncertainty. Uncertainty in biogenic silica concentration is below 5%. But the uncertainty in flux are up to 15%. This increase in uncertainty is due to the high standard error associated with empirical derivation of Dry bulk density.

### 115 **3 Results**

Biogenic silica concentrations varied from 3 % to 15.2 % during the last 18.5 ka (Table 1), with the lowest concentrations (3–4 %) being observed at the bottom of the core between 18.5 ka and 16 ka BP. Subsequently, it increased continuously up to 13.5 ka BP (~9 %) and decreased to 6.5 % at ~13 ka BP. No significant variations in biogenic silica concentration-s were observed between 13 ka and 11.3 ka BP. After 11.3 ka BP, biogenic silica increased from 6.5 % to 10.5 % and remained stable  
120 for a period of almost 1000 years until 10 ka BP. The biogenic silica concentration increased from 10.5 % to 12 % during 10–9.5 ka BP, and it decreased subsequently to 8.5 % at 8 ka BP. From 8 ka to 7.3 ka BP, it changed from 8.5 % to 9.5 % with a peak at 7.7 ka BP (13.3 %), then-further it remained stable until 6 ka BP. From 6 ka to 5 ka BP, the biogenic silica concentration increased from 10 % to 12.5 % and then decreased at 4 ka BP. After 4 ka BP, a continuous increase to a maximum value of 15 % biogenic silica at 1.5 ka BP and a subsequent decrease to 12 % at 1 ka BP were observed. Biogenic silica concentrations  
125 showed no variations during the last 1 ka BP.

The variations in biogenic silica fluxes show an overall increasing trend from 18.5 ka to present (Fig. 54). The fluxes varied between 1.4 to 6.8 g.m<sup>-2</sup>.y<sup>-1</sup>. The minimum ~~values—flux~~ (<2 g.m<sup>-2</sup>.y<sup>-1</sup>) ~~occur—was observed~~ at the bottom of the sediment core, i.e., between 18.5 and 16 ka BP, and the maximum flux ~~value is observed~~ at 2 ka BP. Five distinct peaks in biogenic silica flux during the last 18.5 ka BP were observed between 14–13 ka, 11–10 ka, 10–9 ka, 6–4 ka and 2.5–1 ka BP. 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.

## 4 Discussion

### 4.1 Biogenic silica flux as an upwelling proxy

The surface waters of the world ocean 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 ~~preservation~~ in sediments is a function of its export flux, which is controlled by its production at the surface and dissolution ~~—both~~ in the water column as well and at the sediment water interface (Hurd, 1989; Broecker and Peng, 1982). Thus, using biogenic silica as a proxy for the study of paleo-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 (Fig. 3; Nair, 2000; 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 ~~is~~ to its concentration in the sediment, 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~~ remineralised in the water column as well as and 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. 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 can also affect diatom silicification that leads to variation in preservation (Hutchins and Bruland, 1998). In general, it is noted that high silicate concentration along with micro-nutrient depletion leads to more silicified and faster sinking diatoms (Hutchins and Bruland, 1998), which is most plausible scenario during the late phase of SWM upwelling. If burial efficiency (BE) is the primary controller of biogenic silica flux variation, ratio of low flux to low BE should have been similar to the ratio of high flux to high BE. However, in the present record using the modern high and low BE values (Koning et al., 2001), the ratio of high flux to high BE (top) is almost three times more than the ratio of low flux to low BE (bottom), thereby indicating the absence of preservation effect in the biogenic silica flux. Despite attributing the lowest preservation efficiency to the low biogenic silica fluxes observed at the

~~bottom of the core and the highest preservation efficiency to the high biogenic silica fluxes at the top, the variation is still approximately three times greater. Hence, the influence of preservation efficiency on our core record is minimal.~~

160 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 (Fig. 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  
165 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 (Fig. 3; Haake et al., 1993; Koning et al., 1997), 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 as a potential proxy for SWM-related upwelling in the study area.

## 170 4.2 Biogenic silica flux vs SST

Similar to biogenic silica flux, the paleo-SST reconstructions can serve as proxy for upwelling, as upwelling increases siliceous productivity with reduction in SST. However, the inverse relation between siliceous productivity and SST is valid only during the SWM season and not even on annual scale. Mostly the SST reconstructions are based on biomarker (TEX<sub>86</sub> and U<sup>K</sup><sub>37</sub>; Brassell et al., 1986; Schouten et al., 2002) or from planktonic foraminifera shell chemistry ( $\delta^{18}\text{O}$  and Mg/Ca; Emiliani, 1955; Chave, 1954). However, the annual mean signal of SST or its reconstruction on seasonal scale depends on the signature of the productivity proxies for the region. The  $\delta^{18}\text{O}$  value of foraminifera shell is not only dependent on the SST, but also gets modulated with the preservation of shell, carbonate ion concentration, salinity and  $\delta^{18}\text{O}$  (ice-volume) of the original seawater (Lea, 2003), which makes the reconstruction rather complex. The SST reconstruction based on Mg/Ca ratio is affected by species-dependency and dissolution (Lea, 2003). In most of the cases, it is foraminifera based SST which preserves better signature of annual mean signal due to the foraminifera production throughout the year (Conan et al., 2000; Dahl and Oppo, 2006), but the possibility of preserving seasonal signal depends on local hydrography and productivity. While, the biomarker based SST records may preserve seasonal signal, because they are mainly produced during monsoon season (Huguet et al., 2006). However, there are other limitations with the biomarker based SST records. Major limitation for the application of alkenone U<sup>K</sup><sub>37</sub> in low latitude regions is that it saturates around 28°C (Prah and Wakeham, 1987). While, the TEX<sub>86</sub> 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 are numerous evidence suggesting TEX<sub>86</sub> records sub-surface temperature rather than SST (Hertzberg et al., 2016; Lee et al., 2008; Lopesdos Santos et al., 2010; Seki et al., 2012; Wuchter et al., 2006). The nutrient availability and variation in productivity may also influence the TEX<sub>86</sub> temperature (Hertzberg et al., 2016). Comparing the SST reconstructed using U<sup>K</sup><sub>37</sub> and TEX<sub>86</sub> from a sediment core in the western Arabian Sea, Huguet et al., 2006 suggested that the U<sup>K</sup><sub>37</sub> SST are in phase with northern hemisphere dynamics during NE monsoon, while, TEX<sub>86</sub> SST are controlled by SW monsoon. All SST proxies

175  
180  
185  
190

tend to record annual mean signal with varying fraction of seasonal signal. 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). While, the biogenic silica flux has been controlled by the SWM upwelling signal due to the fact that it is produced during southwest monsoon season and preserves upwelling signal. Hence, the biogenic silica flux can be identified as a better proxy than SST to understand SWM upwelling in the study area. Comparison of biogenic silica flux with other paleo-SST records (Anand et al., 2008; Sahar et al., 2007; Hugué et al., 2006) from nearby locations are shown in figure 6 and 8. There is no definitive relation between biogenic silica flux and SST records on temporal scale. Also, the SST using different proxies show inconsistent changes in the studied time span, the TEX<sub>86</sub> SST is always higher than Mg/Ca SST (Fig. 6&8). A general observation is that both biogenic silica flux and SST were low during 18.5 to 15 ka BP, later showing an anti-correlation (Fig. 6). The anti-correlation is strong between biogenic silica flux and TEX<sub>86</sub> SST during 15 to 11.7 ka BP (Fig. 6). However, during the last 11.7 ka the Mg/Ca based SST shows a strong anti-correlation with biogenic silica flux record, indicating variation in influence of the seasonal signal for different proxies (Fig. 8). Temporal relation between biogenic silica flux and SST is discussed in the following section.

To validate this we have compared the SST records (Hugué et al., 2006; Sahar et al., 2007; Anand et al., 2008) from the Somali upwelling region with our biogenic silica flux record (Fig. 5). Synchronous but opposite (upwelling induce high biogenic silica flux and low SST) changes in biogenic silica flux and SST indicates the potential of biogenic silica flux as important proxy for upwelling in our study area.

#### **4.32 Somali upwelling strength versus southwest monsoon rainfall**

The wWestern Arabian Sea ~~surface temperatures~~SSTs during SWM are directly related to upwelling strength (enhanced upwelling results in lower SSTs and vice versa; Fig. 3). Previous studies have shown that northern Indian ocean and in particular the Arabian Sea to be an important source of moisture for SWM rainfall over India (Ninomiya and Kobayashi, 1999; Gimeno et al., 2010). There are several kind of relationship observed between SST, moisture and SWM rainfall. 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) showed 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. A modelling study by Arpe et al (1998) demonstrated 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) ~~observed~~detected a strong positive correlation between western Arabian SSTs and SWM rainfall over the Western Ghats Mountains in India from 1982 to 2001. Overall, it has been

suggested that any isolated cooling of the Arabian Sea will reduce SWM rainfall through reduced moisture supply, in absence of other large-scale forcing (Lavine and Turner, 2012). An observational and modelling study by Izumo et al (2008) signals 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 SWM-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 suggest 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 their anti-correlation indicates a negative feed-back within the system.

Did this anti-correlation exist between the Somali upwelling and SWM rainfall in the geological past? To answer this question, we need to investigate the record of paleo-upwelling in the Somali region and paleo-rainfall in the western part of India and adjoining areas. There is no continuous terrestrial records of paleo-rainfall covering the last 18.5 ka from the Western Ghats, but there are several paleoclimatic records based on marine sediment cores from the eastern Arabian Sea. The biogenic silica flux temporal variability is compared (Fig. 7 & 10) with paleo-rainfall records ( $\delta^{18}\text{O}_w$  IVF of surface water by (Anand et al., 2008), surface water salinity (Govil and Naidu, 2010)) from the eastern Arabian Sea and a speleothem record from Oman (Fleitmann et al., 2003; Fig. 6). The  $\delta^{18}\text{O}_w$  IVF is the Ice Volume Free oxygen isotopic composition of seawater based on the  $\delta^{18}\text{O}$  of *G.ruber*. Anand et al. (2008) showed that the reconstructed  $\delta^{18}\text{O}_w$  IVF during the last 19 ka from a sediment core (Sk-17) in the eastern Arabian Sea was mainly controlled by the SWM rainfall in the Western Ghats. The Qunf speleothem record from Oman (Fleitmann et al., 2003) had 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 study on the relation between upwelling strength and rainfall in Oman, a comparison is made to give a preliminary assessment. Since records are from different regions and have irregular temporal resolutions, we only examine the long-term trends have been examined.

#### 4.32.1 Last Glacial Period (18.5–15 ka BP)

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 thus is considered here as the Last Glacial Period (LGP). Both biogenic silica concentrations (3–5 %) and fluxes ( $\sim 2 \text{ g.m}^{-2}.\text{y}^{-1}$ ) were lowest during the LGP (Fig. 54), which is similar to earlier findings of low productivity during glacial periods from the western Arabian Sea (Burckle, 1989; Sirocko et al., 1991; 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 recorded 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) ~~are related to basin wide cooling and not connected with upwelling strength, is contrary to our interpretation~~ (Fig. 65). ~~These low SSTs in the Somali basin might have been caused by a basin wide reduction in SST by at least 2–4° C during the LGP (Dahl and Oppo, 2006), rather than by the SWM upwelling observed a reduction in Arabian Sea SST of 2–4° C during LGP. Thus, it is unlikely that the formation of the IOWP (SST>28° C) formed during the LGP can be ruled out. In absence of IOWP, any relation between the Somali upwelling and rainfall is unexpected. Paleo-rainfall record from the eastern Arabian Sea shows high  $\delta^{18}\text{O}_w$  IVF values indicative of reduced freshwater flux and rainfall during this period (Fig. 7) Weakened SWM rainfall during the LGP has also been envisaged by Anand et al. (2008) based on high  $\delta^{18}\text{O}$  in sediment core off Goa, while Govil and Naidu (2010) observed evidence of high salinities in a sediment record from off Goa that was attributed to high evaporation and low fresh water influx. Based on the weak upwelling in the western Arabian Sea and the increase in evaporation and reduced fresh water influx to the eastern Arabian Sea, it is can be concluded that the SWM was weak/absent during the LGP.~~

#### 4.32.2 Deglacial Period (15–11.7 ka BP)

The Deglacial Period (DP) is a connecting phase between two entirely different climatic periods, the LGP and the Holocene. The DP is ~~actually basically~~ a composite of two ~~bi~~-millennial scale events between 15–~~12.943~~ ka and ~~12.943~~–11.7 ka BP. ~~This~~ period occupied by these two events nearly coincides with well-known climatic ~~events phases~~, specifically the Bølling-Allerød (B/A) ~~event period~~ and the Younger Dryas (YD) event. The beginning of the B/A is marked by an abrupt increase in biogenic silica flux (Fig. 65a) ~~is, which we attributed~~ to the effect of ~~northern limit of southwest monsoon, was attained on at the study site entrainment of the SWM at our core site and the with~~ subsequent increase in Somali upwelling strength. This is further supported by ~~investigation of~~ Zr/Hf in two independent sediment cores near our core site, which shows 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<sub>86</sub> SSTs~~ during the B/A in the Somali basin (Huguet et al., 2006; ~~Saher et al., 2007; Anand et al., 2008~~) also ~~suggest increased upwelling supports our view~~ (Fig. 5), ~~however the Mg/Ca SST does not show this change (Fig. 6). The inconsistency between the two SST records (TEX<sub>86</sub> and Mg/Ca) might could be related to the control on seasonal production of the proxy material.~~

The  $\delta^{18}\text{O}_w$  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 (Fig. 76c). ~~The AAS9/21 record (Govil and Naidu, 2010) shows decreased sea surface salinity during the B/A caused by increased fresh water flux into the eastern Arabian Sea that was derived from SWM rainfall (Fig. 6d).~~ The positive correlation between Somali upwelling (high biogenic silica fluxes ~~and lower SSTs~~) and SWM rainfall in the Western Ghats (high fresh water influx to the eastern Arabian Sea) during ~~the 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

290 ~~event period~~ 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 (Fig. 6; Hugué et al., 2006). This is in agreement with the previous studies from Arabian Sea which showed a decreased productivity during YD due to reduction in SWM (Altabet et al., 2002; Ivanochko et al., 2005). Furthermore, the high  $\delta^{18}\text{O}_w$  IVF and high surface salinity values in the eastern Arabian Sea (Anand et al., 2008; ~~Govil and Naidu, 2010~~), ~~which~~ were caused by low freshwater influx, ~~also~~ points to weak SWM rainfall (Fig. 7).

#### 4.3.3 Holocene (11.7–0 ka BP)

The ~~beginning onset~~ of the Holocene is marked by an abrupt increase in biogenic silica flux (Fig. 8a). This sudden increase in biogenic silica fluxes between 11.7 ka and 9 ka BP ~~might could~~ have been caused by the intensification of the SWM (extended season) ~~may have caused by resulting in the~~ due to a 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; Hugué et al., 2006; Anand et al., 2008) also shows a ~~marginal pronounced~~ decrease at the onset of the Holocene, but not up to the levels seen during the B/A (Fig. 8). The  $\text{TEX}_{86}$  SST show more variation than Mg/Ca at the beginning of Holocene, however, the Mg/Ca SST gives shows a mirror image like pattern with the biogenic silica flux pattern during Holocene, indicates the dominance of seasonal signal in Mg/Ca SST during this period (Fig. 8b). 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 it to the strengthening of Somali upwelling. The synchronous changes in the biogenic silica flux with biogenic silica/carbonate ratio (Fig. 9) indicates a change in dominant plankton community (carbonaceous to siliceous) due to increased upwelling, such as that suggested by Tiwari et al. (2010). The  $\delta^{18}\text{O}_w$  IVF and salinity records (Anand et al., 2008; ~~Govil and Naidu, 2010~~) display values ~~similar to like~~ those of the YD during the early Holocene (Fig. 10c ~~and 6d~~), indicating reduced rainfall (lower fresh water influx) over the Western Ghats. This ~~negative eanti-~~ correlation between Somali upwelling and SWM rainfall over south-western India during the early Holocene (11.7 ka to 9 ka BP), 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 BP; Fig. 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 (Fig. 10b) and supports our this interpretation of low moisture availability. At ~8 ka BP upwelling strength decreased after 9 ka BP (Fig. 10a), in the western Arabian Sea Somali upwelling strength has 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 an increased value at ~8 ka BP (Fig. 8b) indicating reduction in Somali upwelling. This reduction in upwelling at 8 ~~at 9~~ ka BP ~~might can allowed support~~ the westward extension of the IOWP during the SWM season, thereby that increased both, moisture availability over the

Arabian Sea and rainfall over the Western Ghats. The SK-17 and AAS9/21 records show decreases in the  $\delta^{18}\text{O}_{\text{w}}_{\text{IVF}}$  of surface water value ~~has decreased~~ and surface salinity, respectively, after 9 at 8 ka BP, ~~pointing towards indicating~~ an increase in fresh water influx from the Western Ghats ~~at this time~~ (Anand et al., 2008; Govil and Naidu, 2010) ~~due to increased SWM rainfall~~ (Fig. 10c). Oman speleothem record ~~also too~~ shows ~~and~~ decreased  $\delta^{18}\text{O}$  value at 8 ka BP (Fig. 10b) ~~which suggesting~~ increased SWM rainfall.

Somali upwelling had a gradual increase ~~D~~ during the last 8 ka with minor positive ~~changes excursion~~ at around 5 and 2 ka BP (Fig. 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~~ this interpretation is well in agreement with other studies from the Arabian Sea which shows that SWM ~~has did~~ slightly increase during Holocene (Agnihotri et al., 2003; Tiwari et al., 2010). These ~~short term short-term~~ increase in Somali upwelling ~~is at 5 and 2 ka BP~~ ~~is can~~ also be observed ~~by with~~ reduction in the Mg/Ca SST record (Fig. 8b). Oman speleothem record shows an increase in  $\delta^{18}\text{O}_{\text{d18O}}$  during the last 8 ka ~~that suggest theing~~ reduction in SWM rainfall (Fig. 10b). The hiatus in Oman speleothem record at 2 ka BP coincides with the strengthened Somali upwelling, however, it is difficult to explain (Fig. 10a & b)., along with the gradually increasing upwelling trend, there are two events showing enhanced upwelling centered on 5 and 2 ka BP, marked by slight increases in biogenic silica fluxes in our record from core 4018 and decreases in Somali basin SSTs (Huguet et al., 2006; Saher et al., 2007; Anand et al., 2008). However, ~~t~~ The SK-17 record (Anand et al., 2008) shows slight increase~~s~~ in the  $\delta^{18}\text{O}_{\text{w}}_{\text{IVF}}$  of surface waters during the last 8 ka (Fig. 10c) ~~indicating~~ reduction in SWM rainfall. The opposite trend in upwelling and rainfall record during the last 8 ka indicates the negative impact of Somali upwelling on SWM rainfall through changing the area of IOWP and moisture availability. However, the short term variations in upwelling is not observed in the eastern Arabian Sea rainfall record ~~record~~. The asynchronous short variations may be due to dissimilarities in sampling intervals and chronology. The core AAS9/21 (Govil and Naidu, 2010) shows low salinity values for the last 8 ka BP, with a noticeable period of low salinity between 5 and 3 ka BP. The low biogenic silica fluxes observed in our core during the same time period (5 to 3 ka BP) indicate lower upwelling but more rainfall during the SWM (reflecting a wider IOWP). The speleothem record from Oman (Fleitmann et al., 2007) also exhibits anti correlation with the Somali upwelling record (Fig. 6b), indicating the influence of Somali upwelling on rainfall over the Arabian Peninsula during the SWM.

The Somali upwelling possibly had a negative impact on southwest monsoon rainfall over south-western India and Oman throughout the Holocene. This finding would have implications in context of the modelling study by deCastro et al. (2016), which shows that Somali upwelling would increase during the twenty-first century. Overall, it has been noted that the Somali upwelling had a negative impact on southwest monsoon rainfall over south western India throughout the Holocene. This finding becomes more alarming in context of the modelling study by deCastro et al. (2016) which shows that the Somali upwelling would increase during the twenty first century.

## 5 Conclusions

355 The present study demonstrates the use of biogenic silica fluxes as a proxy for the temporal variations in the strength of the Somali upwelling during the last 18.5 ka. Some of the salient findings of the present study are summarized below:

1. The Somali upwelling was weak during the LGP coeval with the weak southwest monsoon.
2. The post-glacial onset of the southwest monsoon was marked by an increase in the strength of the Somali upwelling at 15 ka BP, with [the](#) eastern Arabian Sea records showing increased southwest monsoon rainfall.
- 360 3. The Somali upwelling was weak between [12.943](#) and [11.7](#) ka BP, indicating another phase of weak southwest monsoon similar to that of the LGP. Overall, records of the Somali upwelling and southwest monsoon rainfall exhibit positive correlations between 18.5 and [11.7](#) ka BP.
- 365 4. ~~A change in correlation from~~[Shift in](#) positive to negative [correlation](#) between the strength of the Somali upwelling and southwest monsoon rainfall occurred at [11.7](#) ka BP at the beginning of the Holocene, which marks the establishment of modern day climate system.
5. Enhanced Somali upwelling during the last [11.7](#) ka BP, except for the decline at 8 ka BP, had a negative impact on southwest monsoon rainfall.
6. Both, latitudinal shifts in the Intertropical Convergence Zone (ITCZ) and changes in moisture source regions act as causative factors for the reversal in the relationship between upwelling and southwest monsoon rainfall.
- 370 7. Future observational and modelling studies on southwest monsoon rainfall reconstruction and prediction should incorporate variations in the moisture source region.

## Acknowledgments

Balaji D. is thankful to the Council of Scientific and Industrial Research (CSIR) of India for providing support through a CSIR-NET-Senior Research Fellowship. Ravi Bhushan thanks the Director of the PRL for research grant support. We thank Dr. Alpa Sridhar for critical comments and suggestions on the manuscript. [We thank the two anonymous reviewers for their constructive comments which helped us in improving the manuscript.](#)

## References

- [Agnihotri R, Bhattacharya SK, Sarin MM, Somayajulu BLK.: Changes in the surface productivity and subsurface denitrification during the Holocene: a multiproxy study from the eastern Arabian Sea. The Holocene 13: 701–713, 2003.](#)
- 380 [Altabet, M. A., Higginson, M. J., & Murray, D. W.: The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO<sub>2</sub>. Nature, 415\(6868\), 159, 2002.](#)
- Anand, P., Kroon, D., Singh, A. D., Ganeshram, R. S., Ganssen, G., and Elderfield, H.: Coupled sea surface temperature–seawater  $\delta^{18}\text{O}$  reconstructions in the Arabian Sea at the millennial scale for the last 35 ka, Paleoceanography, 23, 2008.

- 385 Annamalai, H., and Liu, P.: Response of the Asian summer monsoon to changes in El Niño properties, *Quarterly Journal of the Royal Meteorological Society*, 131, 805-831, 2005.
- [Arpe K, Du`menil L, Giorgetta MA.: Variability of the Indian monsoon in the ECHAM3 model: sensitivity to sea surface temperature, soil moisture, and the stratospheric quasi-biennial oscillation. J Clim 11:1837–1858, 1998.](#)
- Beal, L. M., and Chereskin, T. K.: The volume transport of the Somali Current during the 1995 southwest monsoon, *Deep Sea Research Part II: Topical Studies in Oceanography*, 50, 2077-2089, 2003.
- 390 Berrisford, P., Kållberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A., Poli, P., and Sato, H.: Atmospheric conservation properties in ERA-Interim, *Quarterly Journal of the Royal Meteorological Society*, 137, 1381-1399, 2011.
- [Bhushan, R., Dutta, K., Mulson, S., Povinec, P. P., & Somayajulu, B. L. K.: Distribution of natural and man-made radionuclides during the reoccupation of GEOSECS stations 413 and 416 in the Arabian Sea: temporal changes. Deep Sea Research Part II: Topical Studies in Oceanography, 50\(17-21\), 2777-2784, 2003.](#)
- 395 [Brassell, S. C., G. Eglinton, I. T. Marlowe, U. Pflaumann, and M. Sarnthein.: Molecular stratigraphy: A new tool for climatic assessment, Nature, 320, 129– 133, 1986.](#)
- [Broccoli, A. J.: Tropical cooling at the Last Glacial Maximum: An atmosphere–mixed layer ocean model simulation. Journal of Climate, 13\(5\), 951-976, 2000.](#)
- Burckle, L. H.: Distribution of diatoms in sediments of the northern Indian Ocean: Relationship to physical oceanography, *Marine Micropaleontology*, 15, 53-65, 1989.
- 400 Carter, S. J., and Colman, S. M.: Biogenic silica in Lake Baikal sediments: results from 1990–1992 American cores, *Journal of Great Lakes Research*, 20, 751-760, 1994.
- [Chave, K. E.: Aspects of the biogeochemistry of magnesium. 1. Calcareous marine organisms, J. Geol., 62, 266–283, 1954.](#)
- [Clark CO, Cole JE, Webster PJ.: Indian Ocean SST and Indian Summer Rainfall: predictive relationships and their decadal variability. J Clim 13:2503–2519, 2000.](#)
- 405 [Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W. and McCabe, A.M.: The last glacial maximum. Science, 325\(5941\), pp.710-714, 2009.](#)
- Clemens, S. C., Prell, W. L., and Howard, W. R.: Retrospective dry bulk density estimates from southeast Indian Ocean sediments—comparison of water loss and chloride-ion methods, *Marine geology*, 76, 57-69, 1987.
- 410 [Conan, S. H., & Brummer, G. J. A.: Fluxes of planktic foraminifera in response to monsoonal upwelling on the Somalia Basin margin. Deep Sea Research Part II: Topical Studies in Oceanography, 47\(9-11\), 2207-2227, 2000.](#)
- Dahl, K. A., and Oppo, D. W.: Sea surface temperature pattern reconstructions in the Arabian Sea, *Paleoceanography*, 21, 2006.
- [Emiliani, C.: Pleistocene temperatures, J. Geol, 63, 538– 578, 1955.](#)
- 415 Findlater, J.: Observational aspects of the low-level cross-equatorial jet stream of the western Indian Ocean, in: *Monsoon Dynamics*, Springer, 1251-1262, 1978.

- [Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., & Matter, A.: Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. \*Science\*, 300\(5626\), 1737-1739, 2003.](#)
- 420 Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-Subbary, A. A., Buettner, A., and Hippler, D.: Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra), *Quaternary Science Reviews*, 26, 170-188, 2007.
- [Gimeno L., Drumond A., Nieto R., Trigo RM, Stohl A.: On the origin of continental precipitation. \*Geophys Res Lett\* 37:L13804, 2010.](#)
- 425 Goswami, B., Krishnamurthy, V., and Annmalai, H.: A broad-scale circulation index for the interannual variability of the Indian summer monsoon, *Quarterly Journal of the Royal Meteorological Society*, 125, 611-633, 1999.
- Goswami, B., Madhusoodanan, M., Neema, C., and Sengupta, D.: A physical mechanism for North Atlantic SST influence on the Indian summer monsoon, *Geophysical Research Letters*, 33, 2006.
- Govil, P., and Naidu, P. D.: Evaporation-precipitation changes in the eastern Arabian Sea for the last 68 ka: Implications on monsoon variability, *Paleoceanography*, 25, 2010.
- 430 Gupta, A. K., Anderson, D. M., and Overpeck, J. T.: Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, *Nature*, 421, 354-357, 2003.
- Haake, B., Ittekkot, V., Rixen, T., Ramaswamy, V., Nair, R., and Curry, W.: Seasonality and interannual variability of particle fluxes to the deep Arabian Sea, *Deep Sea Research Part I: Oceanographic Research Papers*, 40, 1323-1344, 1993.
- Hahn, D. G., and Shukla, J.: An apparent relationship between Eurasian snow cover and Indian monsoon rainfall, *Journal of the Atmospheric Sciences*, 33, 2461-2462, 1976.
- 435 [Hertzberg, J. E., Schmidt, M. W., Bianchi, T. S., Smith, R. W., Shields, M. R., & Marcantonio, F.: Comparison of eastern tropical Pacific TEX<sub>86</sub> and Globigerinoides ruber Mg/Ca derived sea surface temperatures: Insights from the Holocene and Last Glacial Maximum. \*Earth and Planetary Science Letters\*, 434, 320-332, 2016.](#)
- Huguet, C., Kim, J. H., Sinninghe Damsté, J. S., and Schouten, S.: Reconstruction of sea surface temperature variations in the Arabian Sea over the last 23 kyr using organic proxies (~~TEX<sub>86</sub>~~TEX<sub>86</sub> and U<sub>37K'</sub>), *Paleoceanography*, 21, 2006.
- Hurd, D. C.: Interactions of biogenic opal, sediment and seawater in the Central Equatorial Pacific, *Geochimica et cosmochimica acta*, 37, 2257IN12267-22662282, 1973.
- Isaji, Y., Kawahata, H., Ohkouchi, N., Ogawa, N. O., Murayama, M., Inoue, K., and Tamaki, K.: Varying responses to Indian monsoons during the past 220 kyr recorded in deep-sea sediments in inner and outer regions of the Gulf of Aden, *Journal of Geophysical Research: Oceans*, 120, 7253-7270, 2015.
- 445 Ivanochko, T. S., Ganeshram, R. S., Brummer, G.-J. A., Ganssen, G., Jung, S. J., Moreton, S. G., and Kroon, D.: Variations in tropical convection as an amplifier of global climate change at the millennial scale, *Earth and Planetary Science Letters*, 235, 302-314, 2005.
- Izumo, T., Montégut, C. B., Luo, J.-J., Behera, S. K., Masson, S., and Yamagata, T.: The role of the western Arabian Sea upwelling in Indian monsoon rainfall variability, *Journal of Climate*, 21, 5603-5623, 2008.
- 450

- Kim, J.-H., Schouten, S., Hopmans, E., Donner, B., Sinninghe Damsté, J.S.: Global sediment core-top calibration of the TEX86paleothermometer in the ocean. *Geochim. Cosmochim. Acta*72, 1154–1173, 2008.
- 455 Kim, J.-H., van der Meer, J., Schouten, S., Helmke, P., Willmott, V., Sangiorgi, F., Koc, N., Hopmans, E., Sinninghe Damsté, J.S.: New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: implications for past sea surface temperature reconstructions. *Geochim. Cosmochim. Acta*74, 4639–4654, 2010.
- Koning, E., Brummer, G.-J., Van Raaphorst, W., Van Bennekom, J., Helder, W., and Van Iperen, J.: Settling, dissolution and burial of biogenic silica in the sediments off Somalia (northwestern Indian Ocean), *Deep Sea Research Part II: Topical Studies in Oceanography*, 44, 1341-1360, 1997.
- Koning, E., Van Iperen, J., Van Raaphorst, W., Helder, W., Brummer, G.-J., and Van Weering, T.: Selective preservation of upwelling-indicating diatoms in sediments off Somalia, NW Indian Ocean, *Deep Sea Research Part I: Oceanographic Research Papers*, 48, 2473-2495, 2001.
- 460 Krishnamurthy, L., and Krishnamurthy, V.: Teleconnections of Indian monsoon rainfall with AMO and Atlantic tripole, *Climate Dynamics*, 46, 2269-2285, 2016.
- Krishnan, R., and Sugi, M.: Pacific decadal oscillation and variability of the Indian summer monsoon rainfall, *Climate Dynamics*, 21, 233-242, 2003.
- 465 Lea, D. W.: Elemental and isotopic proxies of past ocean temperatures, in *Treatise on Geochemistry*, vol. 6, *The Ocean and Marine Geochemistry*, edited by H. D. Holland and K. K. Turekian, pp. 365–390, Elsevier, New York, 2003.
- Lee, K.-E., Kim, J.-H., Wilke, I., Helmke, P., Schouten, S.: A study of the alkenone, TEX86, and planktonic foraminifera in the Benguela Upwelling System: implications for past sea surface temperature estimates. *Geochem. Geo-phys. Geosyst.*9, Q10019, 2008.
- 470 Levine RC, Turner AG.: Dependence of Indian monsoon rainfall on moisture fluxes across the Arabian Sea and the impact of coupled model sea surface temperature biases. *Clim Dyn* 38:2167–2190, 2012.
- Lopes dos Santos, R., Prange, M., Castañeda, I.S., Schefuß, E., Mulitza, S., Schulz, M., Niedermeyer, E.M., Sinninghe Samsté, J.S., Schouten, S.: Glacial-interglacial variability in Atlantic meridional overturning circulation and thermocline adjustments in the tropical North Atlantic. *Earth Planet. Sci. Lett.*300, 407–414, 2010.
- 475 M., d., Sousa, M., Santos, F., Dias, J., and Gómez-Gesteira, M.: How will Somali coastal upwelling evolve under future warming scenarios?, *Scientific Reports*, 6, 2016.
- Mooley, D., Parthasarathy, B., and Pant, G.: Relationship between Indian Summer Monsoon Rainfall and Location of the Ridge at the 500-mb Level along 75° E, *Journal of climate and applied meteorology*, 25, 633-640, 1986.
- 480 Mortlock, R. A., and Froelich, P. N.: A simple method for the rapid determination of biogenic opal in pelagic marine sediments, *Deep Sea Research Part A. Oceanographic Research Papers*, 36, 1415-1426, 1989.
- Naidu, P. D., and Malmgren, B. A.: A high-resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera, *Paleoceanography*, 11, 129-140, 1996.

- 485 Ninomiya, K., and Kobayashi, C.: Precipitation and Moisture Balance of the Asian Summer Monsoon in 1991, Journal of the Meteorological Society of Japan. Ser. II, 77, 77-99, 1999.
- Pant, G. B., and Kumar, K. R.: Climates of south Asia, John Wiley & Sons, 1997.
- Parthasarathy, B., Diaz, H., and Eischeid, J.: Prediction of all-India summer monsoon rainfall with regional and large-scale parameters, Journal of Geophysical Research: Atmospheres, 93, 5341-5350, 1988.
- 490 Parthasarathy, B., Kumar, K. R., and Munot, A.: Evidence of secular variations in Indian monsoon rainfall–circulation relationships, Journal of Climate, 4, 927-938, 1991.
- [Prahl, F.G., Wakeham, S.G.: Calibration of unsaturation patterns in long-chain ketone compositions for paleotemperature assessment. Nature330, 367–369, 1987.](#)
- Qasim, S.: Biological productivity of the Indian Ocean, Indian Journal of Marine Sciences, 6, 16, 1977.
- R., S.: Ocean Data View, 2016.
- 495 Ramaswamy, V., and Gaye, B.: Regional variations in the fluxes of foraminifera carbonate, coccolithophorid carbonate and biogenic opal in the northern Indian Ocean, Deep Sea Research Part I: Oceanographic Research Papers, 53, 271-293, 2006.
- Saher, M., Jung, S., Elderfield, H., Greaves, M., and Kroon, D.: Sea surface temperatures of the western Arabian Sea during the last deglaciation, Paleoceanography, 22, 2007.
- Schott, F., Swallow, J. C., and Fioux, M.: The Somali Current at the equator: annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, Deep Sea Research Part A. Oceanographic Research Papers, 37, 500 1825-1848, 1990.
- Schott, F. A., Xie, S. P., and McCreary, J. P.: Indian Ocean circulation and climate variability, Reviews of Geophysics, 47, 2009.
- 505 [Schouten, S., E. C. Hopmans, E. Schefuss, and J. S. Sinninghe Damsté': Distributional variations in marine crenarchaeotal membrane lipids: A new tool for reconstructing ancient sea water temperatures?, Earth Planet. Sci. Lett., 204, 265– 274, 2002.](#)
- [Seki, O., Schmidt, D., Schouten, S., Hopmans, E., Sinninghe Damsté, J., Pancost, R.: Paleoceanographic changes in the eastern Equatorial Pacific over the last 10 Myr. Paleoceanography27, PA3224, 2012.](#)
- 510 [Shukla J.: Effect of Arabian Sea-surface temperature anomaly on Indian summer monsoon: a numerical experiment with the GFDL model. J Atmos Sci 32\(3\):503–511, 1975.](#)
- Sirocko, F., and Lange, H.: Clay-mineral accumulation rates in the Arabian Sea during the late Quaternary, Marine Geology, 97, 105-119, 1991.
- Sirocko, F., Sarnthein, M., Lange, H., and Erlenkeuser, H.: Atmospheric summer circulation and coastal upwelling in the Arabian Sea during the Holocene and the last glaciation, Quaternary Research, 36, 72-93, 1991.
- 515 Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., and Duplessy, J.: Century-scale events in monsoonal climate over the past 24,000 years, Nature, 364, 322-324, 1993.



Sirocko, F., Garbe-Schönberg, D., and Devey, C.: Processes controlling trace element geochemistry of Arabian Sea sediments during the last 25,000 years, *Global and Planetary Change*, 26, 217-303, 2000.

520 Tiwari, M., Ramesh, R., Bhushan, R., Sheshshayee, M. S., Somayajulu, B. L., Jull, A., and Burr, G. S.: Did the Indo-Asian summer monsoon decrease during the Holocene following insolation?, *Journal of Quaternary Science*, 25, 1179-1188, 2010.

Vecchi, G. A., and Harrison, D.: Interannual Indian rainfall variability and Indian Ocean sea surface temperature anomalies.. In *Earth Climate: The Ocean-Atmosphere Interaction*, C. Wang, S. P. Xie & J.A. Carton (eds.), American Geophysical Union., *Geophysical Monograph*, 147, 247-259, 2004.

525 [Webster PJ, Moore AM, Loschnigg JP, Leben RR.: Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98. \*Nature\* 401:356-360, 1999.](#)

[Wuchter, C., Schouten, S., Wakeham, S.G., Sinninghe Damsté, J.S.: Archaeal tetraether membrane lipid fluxes in the northeastern Pacific and the Arabian Sea: implications for TEX86paleothermometry. \*Paleoceanography\*21, PA4208, 2006.](#)

Wyrski, K.: Physical oceanography of the Indian Ocean, in: *The biology of the Indian Ocean*, Springer, 18-36, 1973.

530 Yadav, R. K.: On the relationship between east equatorial Atlantic SST and ISM through Eurasian wave, *Climate Dynamics*, 48, 281-295, 2017.

Young, D. K., and Kindle, J. C.: Physical processes affecting availability of dissolved silicate for diatom production in the Arabian Sea, *Journal of Geophysical Research: Oceans*, 99, 22619-22632, 1994.

535

540

545

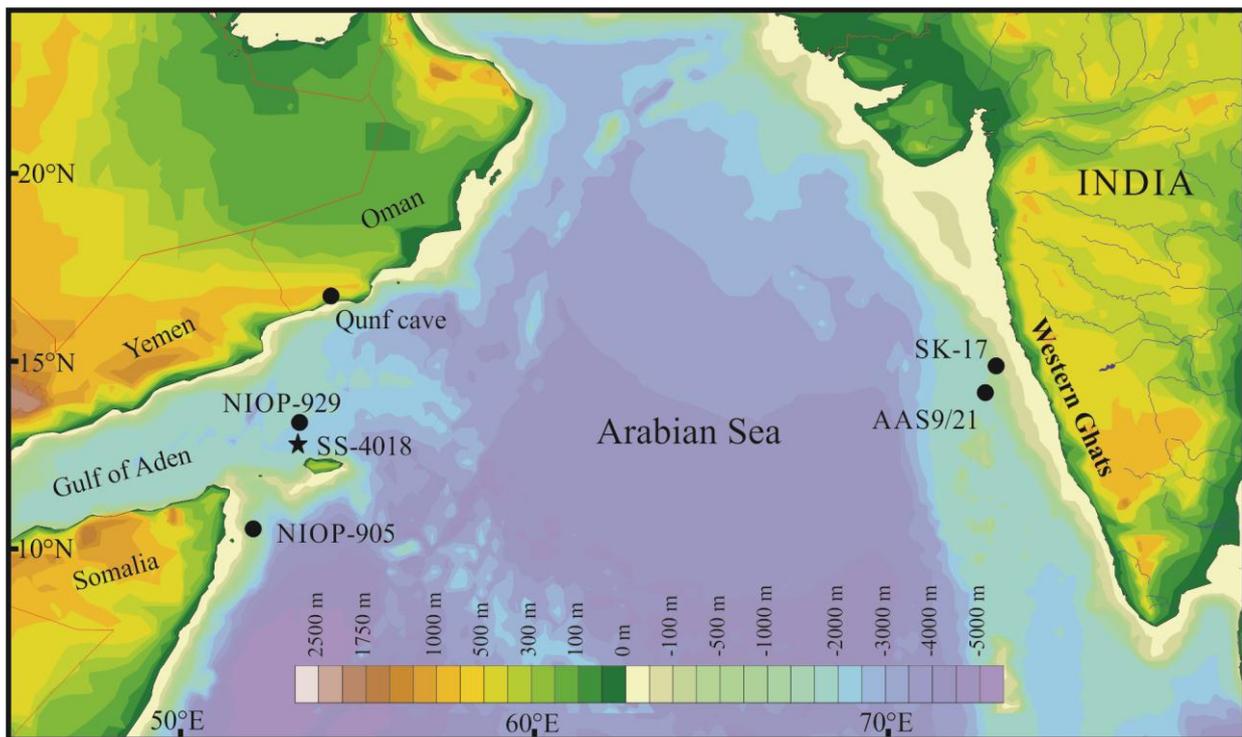
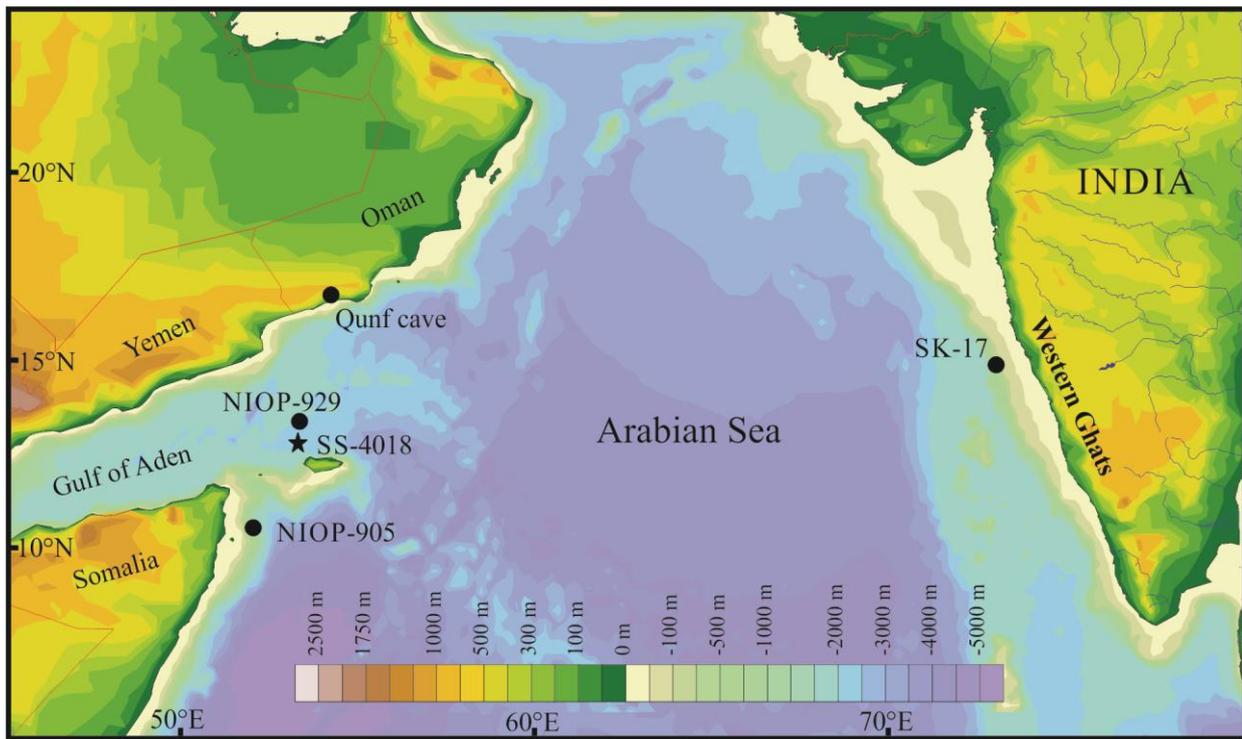
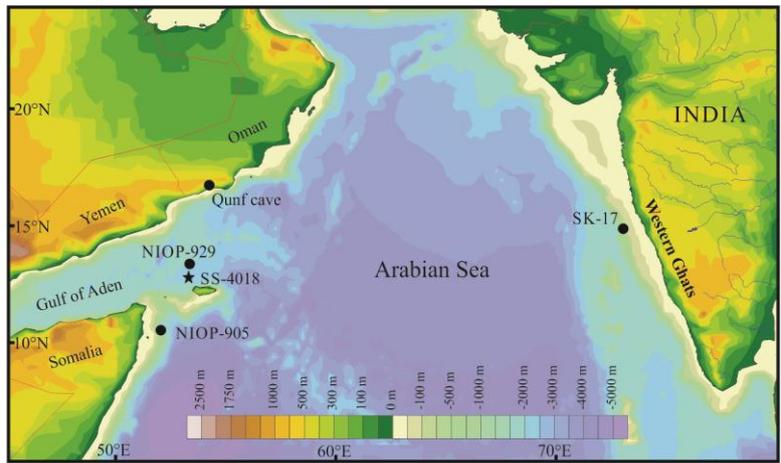
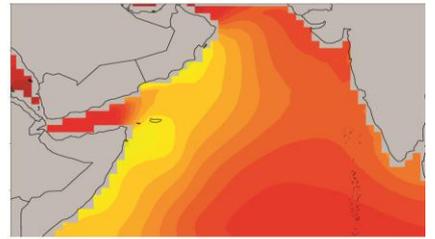
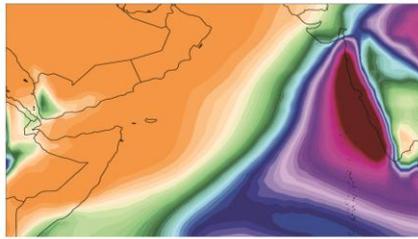
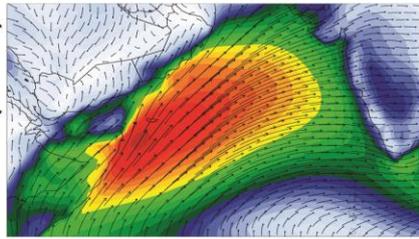


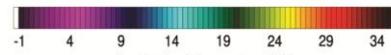
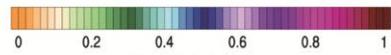
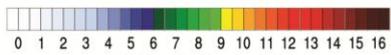
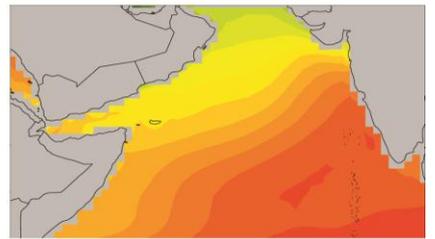
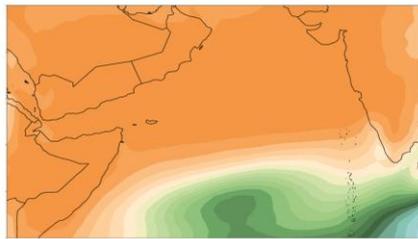
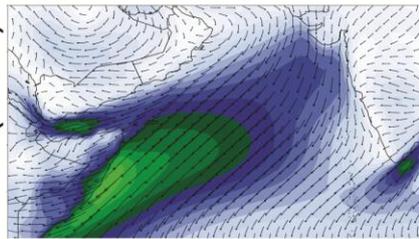
Figure 1: Location of sediment core SS-4018 (filled star) in the Arabian Sea. Also shown are the sites discussed in the paper: NIOP-929 (Saher et al., 2007), NIOP-905 (Huguet et al., 2006), SK-17 (Anand et al., 2008), Qunf cave (Fleitmann et al., 2007), ~~AAS9/21 (Govil and Naidu, 2010).~~



SWM (JJA)



NEM (DJF)



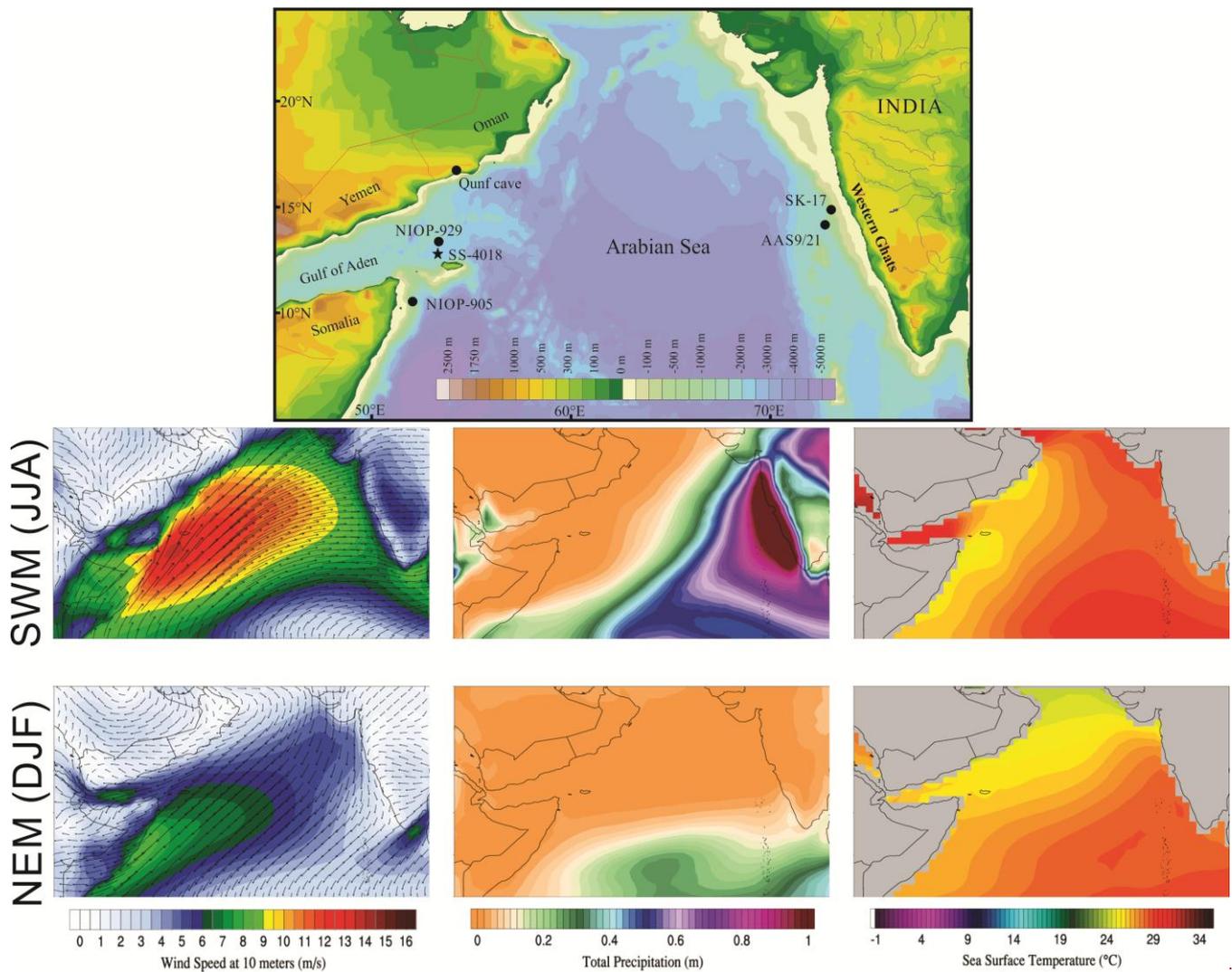
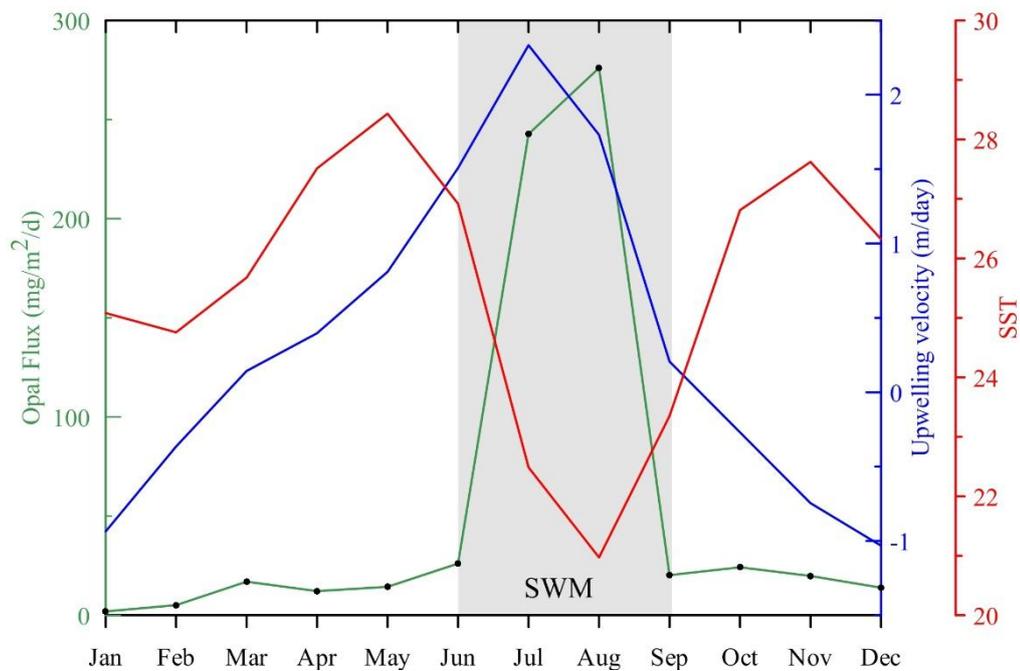


Figure 2: Location of our sediment core SS4018 in the western Arabian Sea. Also shown are the sites discussed in the manuscript. Bottom figures shows the seasonal changes in Wind speed, Precipitation and SST during southwest (SWM) and northeast monsoon (NEM). ECMWF-ERA-Interim data (Berrisford et al., 2011) used and the image obtained using Climate Reanalyzer (<http://cci-reanalyzer.org>), Climate Change Institute, University of Maine, USA.

555



**Figure 3. 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, 2000 and Opal flux from Haake et al., 2003.**

560

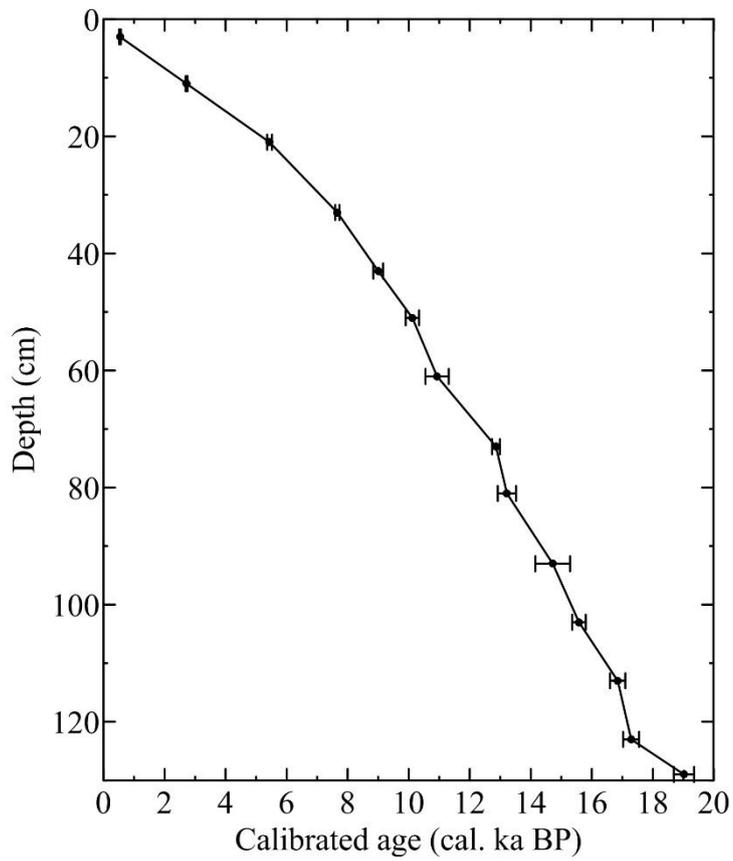
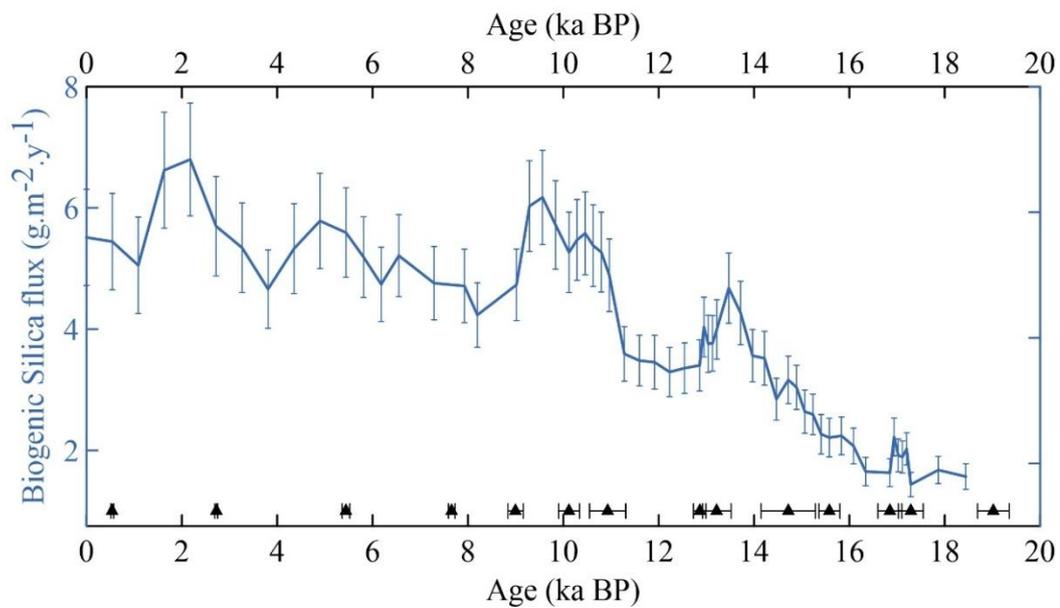


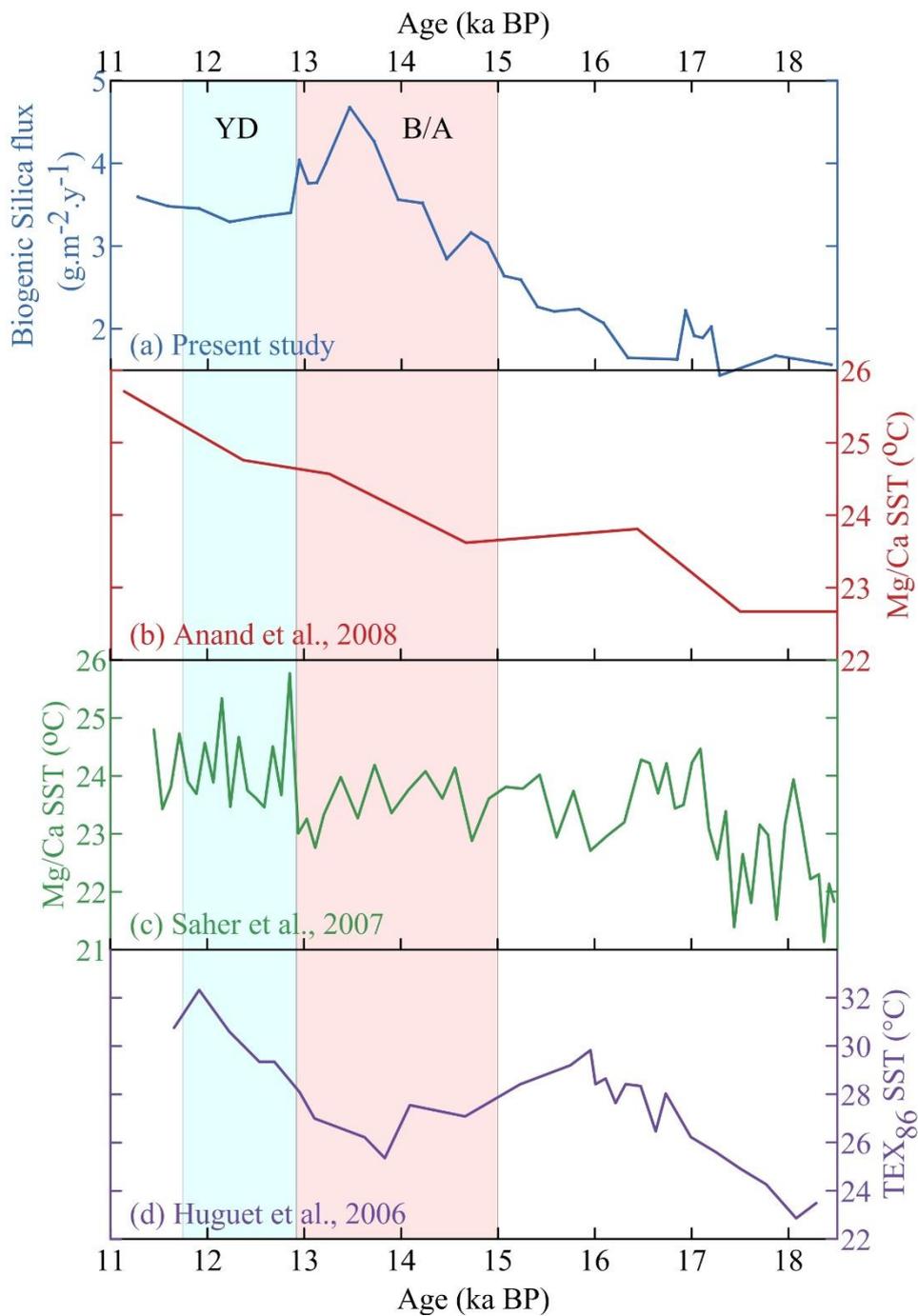
Figure 43: Age depth model of the sediment core SS-4018 (adopted from Tiwari et al., 2010). The error bars marks one sigma uncertainty in calibrated age.



565

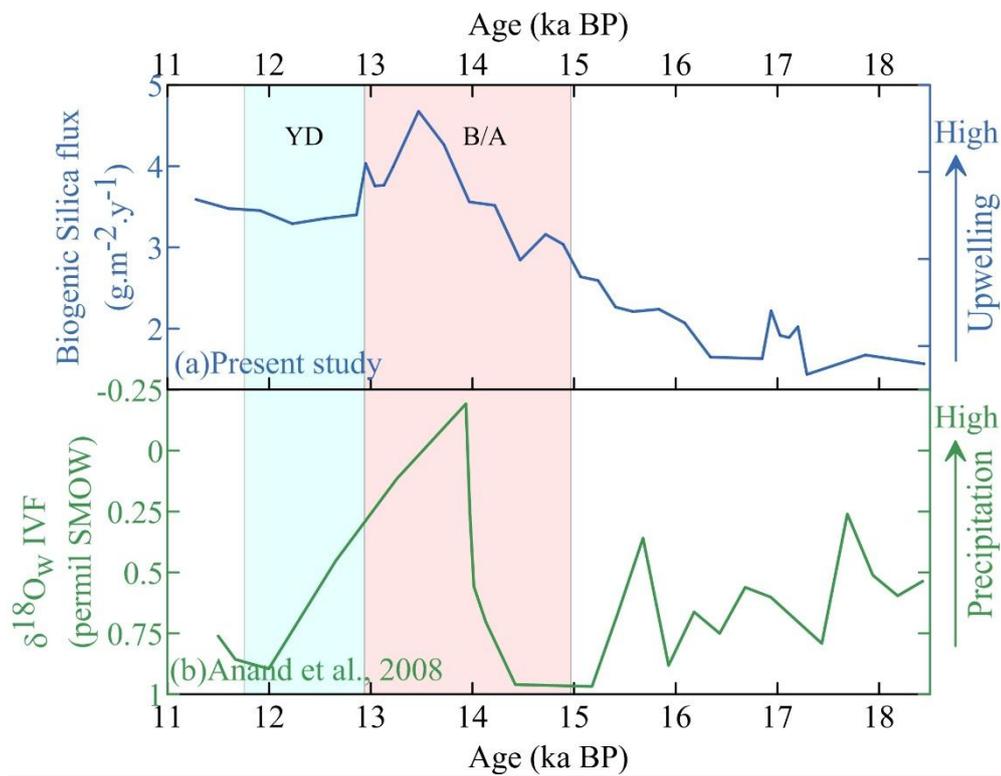
Figure 54: Temporal variation of Biogenic silica flux with two sigma uncertainty in sediment core SS4018. Filled triangles at the bottom of the plot marks the age-control points with one sigma ~~uncertainty~~ uncertainty.



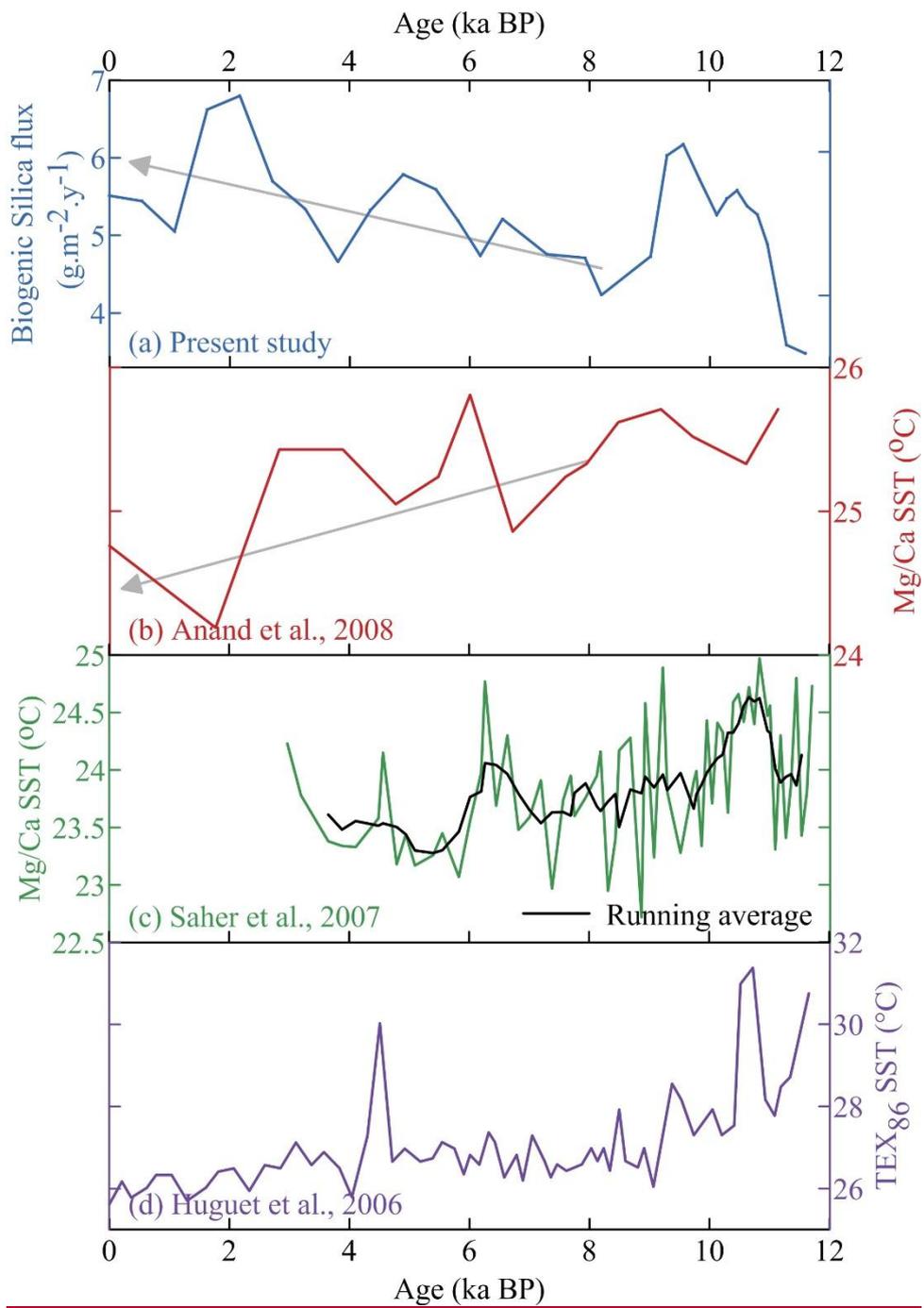


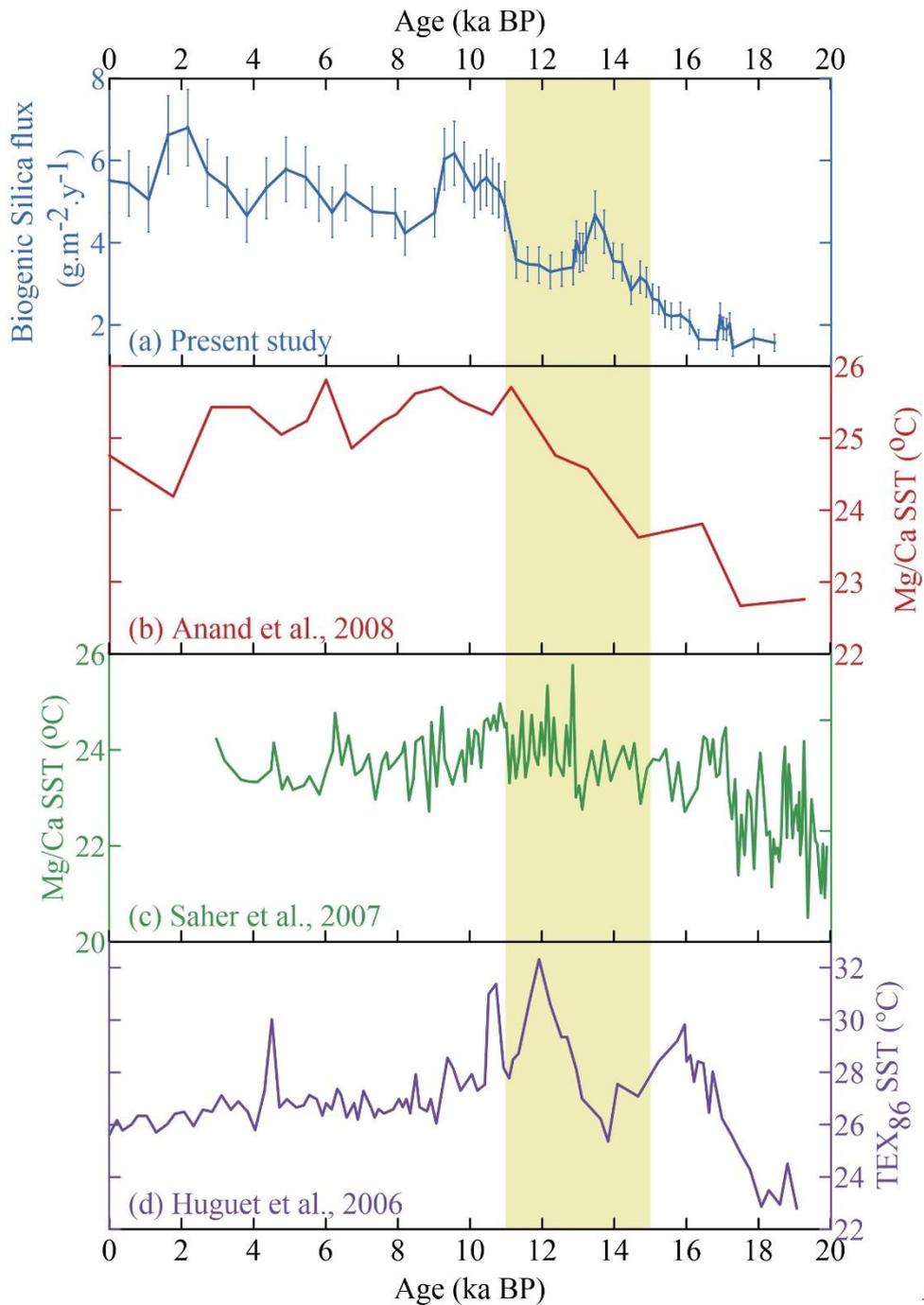
**Figure 6. Comparison of biogenic silica flux with SST records from western Arabian Sea for pre-Holocene time (18.5-11.7 ka BP). a) Biogenic silica flux, b) Mg/Ca based SST from NIOP-905 core (Anand et al., 2008), c) Mg/Ca based SST from NIOP-929 core (Saher et al., 2007), d) TEX<sub>86</sub> SST from NIOP-905 core (Huguet et al., 2006).**

570

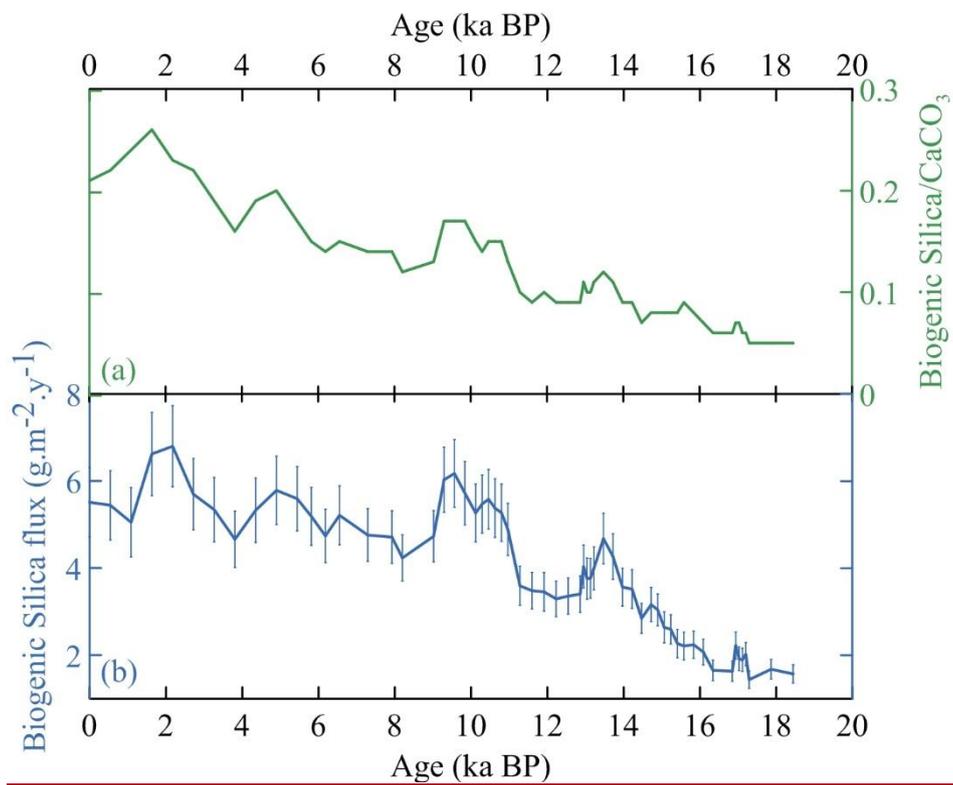


**Figure 7. Comparison of biogenic silica flux with rainfall record from eastern Arabian Sea for pre-Holocene time (18.5-11.7 ka BP). (a) Biogenic silica flux (present study), (b)  $\delta^{18}\text{O}_w$  IVF (Anand et al., 2008).**

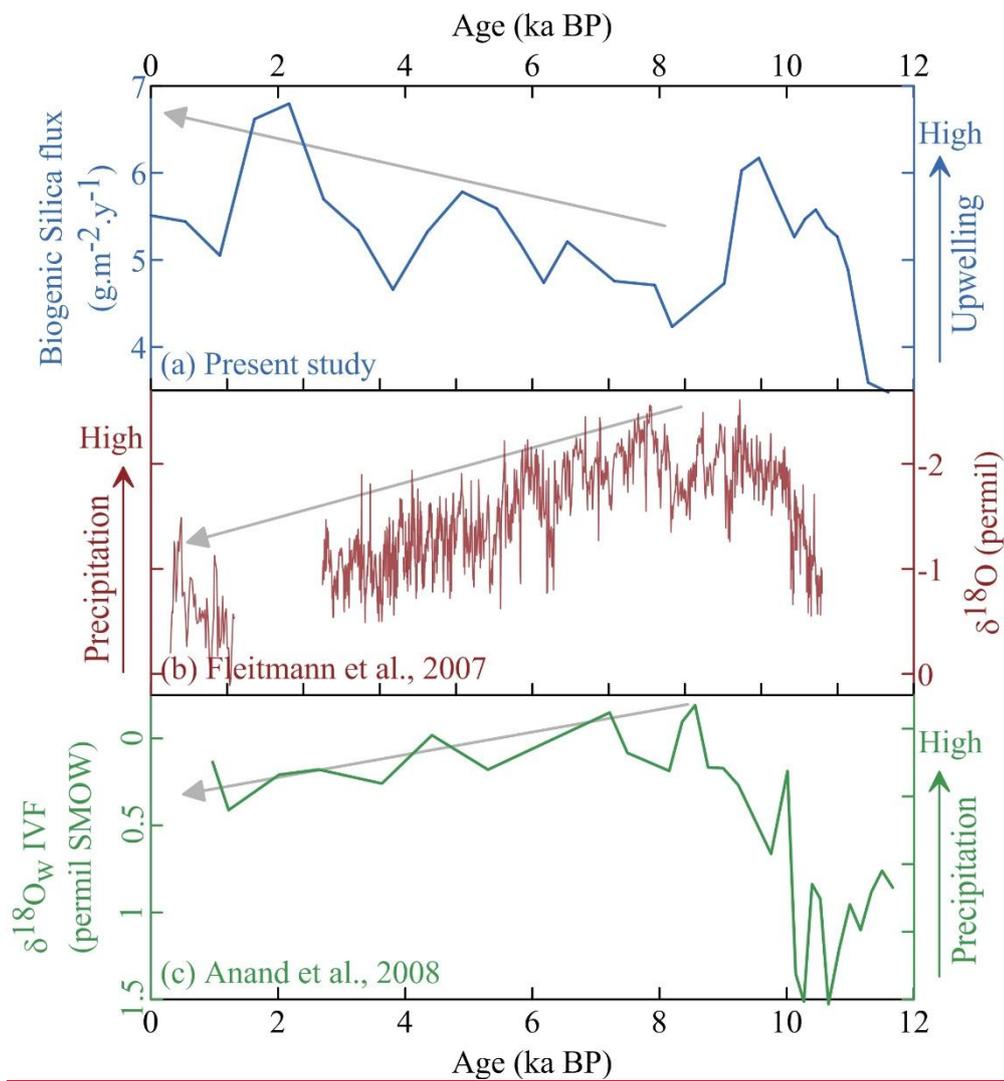




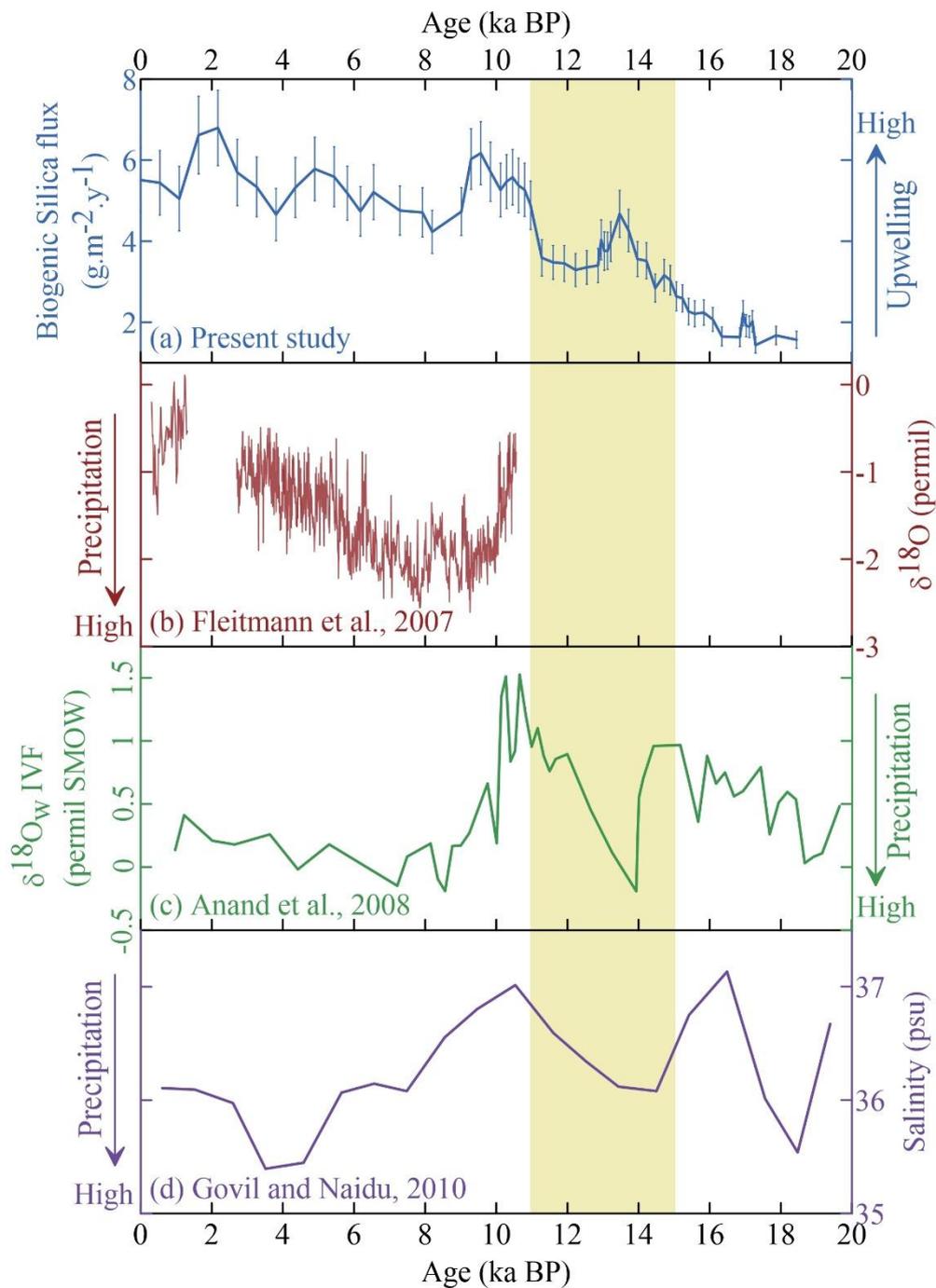
**Figure 85:** Comparison of Somali upwelling with western Arabian Sea SST records. a) Biogenic silica flux, b) Mg/Ca based SST from NIOP-905 core (Anand et al., 2008), c) Mg/Ca based SST from NIOP-929 core (Saher et al., 2007), d)  $TEX_{86}$  SST from NIOP-905 core (Huguet et al., 2006). **Red arrow indicate the trend of proxy records during the last 8 ka. Shaded region marks the Deglacial Period (DP).**



**Figure 9: 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.**



585



**Figure 106:** Comparison of Somali upwelling with southwest monsoon rainfall records during Holocene. (a) Biogenic silica flux (present study), (b) Oman speleothem record, (c)  $\delta^{18}\text{O}_w$  IVF data from sediment core SK-17 eastern Arabian Sea. Grey arrow indicate the trend of proxy record during the last 8 ka.

(d) Salinity record of sediment core AAS9/21. Shaded region marks the Deglacial Period (DP).

Age (ky)	B. Si (%)	$\sigma$ B.Si	B.Si flux (g/m <sup>2</sup> /y)	$\sigma$ B.Si flux	Age (ky)	B. Si (%)	$\sigma$ B.Si	B.Si flux (g/m <sup>2</sup> /y)	$\sigma$ 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 1: Biogenic silica concentration and flux data.