

# Increase in Paleoproductivity Driven by Strengthening of Indian Summer Monsoon During Past ~14kyrs: Evidenced by Biogenic Silica Accumulation Rates at Southeastern Arabian Sea

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**Abstract:** We analysed the BSi (Biogenic Silica) contents of the marine core SK-313/1 from the southeastern Arabian Sea which is dated up to ~14.5 kyr BP. Results show that the maximum and minimum BSi contents are 2.5 and 0.5%, respectively. This is because of the low supply of silica skeleton and the high dissolution and dilution of terrigenous materials. The BSi mass accumulation rates indicate a trend of reduced paleoproductivity during the late Glacial period and increase during the Holocene, with global climatic shifts. Insolation changes at low latitudes, which regulate temperatures, may affect nutrient availability and, consequently productivity variations on a glacial–interglacial timescale. Notably, millennial events like the Younger Dryas (YD) periods, exhibited lower paleoproductivity, in contrast to the Bølling/Allerød (B-A) period and the middle Holocene, which displayed elevated levels of paleoproductivity. These millennial-scale fluctuations in siliceous productivity may be due to the changes in nutrient supply caused by the Indian summer monsoon (ISM). The period of increased paleoproductivity could be influenced by intensified chemical weathering and a boosted nutrient supply, which are consequences of the strengthened ISM during periods of relatively higher temperature.

**Keywords:** Biogenic Silica; Arabian Sea; Younger Dryer; Paleoproductivity; ISM.

## Introduction

The production of biogenic silica (BSi) on the ocean surface by phytoplankton communities and subsequent silica export into marine sediments plays an essential part in the global silicon cycle. The accumulation of biogenic silica in marine sediments is closely tied to the productivity of siliceous organisms, such as diatoms, in the surface ocean. Diatoms, found in nutrient-rich waters, can be analysed in sedimentary records to determine productivity periods, reflecting

changes in nutrient availability, upwelling intensity, and oceanic productivity (Doering et al., 2016). Among phytoplankton in the modern ocean, diatoms are responsible for ~45 % of the global primary production (DeMaster, 2003; Benoiston et al., 2017). Silicic acid ( $\text{H}_4\text{SiO}_4$ ) or dissolved Silica (DSi) is a bio-limiting nutrient in the marine environment (Broecker and Peng, 1982; Dugdale et al., 1995). Most of the surface waters of the world ocean are deficient in silica (Hurd, 1973), which increases (45-50%) the dissolution of produced silica in the top ~100 m depth (Nelson et al., 1995).

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Globally, the average burial flux is around 20% of the opal rain rate and about 12% of opal production, with roughly 10% of the silica content being buried in deep sediments. Opal accumulation in marine sediments is influenced by factors such as bathymetry, advection, surface layer temperature, aggregation formation, sink, selective grazing, and the physical properties of BSi (Treguer et al., 1995).

During the summer monsoon through fluvial discharge and coastal upwelling water is enriched with nutrients that trigger the phytoplankton growth in the Arabian Sea. Intense upwelling in the western Arabian Sea is more productive compared with the north and eastern parts (Van der Weijden et al., 1999). Ramaswamy and Nair (1994) trap study reports that diatom opal fluxes were increased when nutrient-rich upwelled waters were advected near the surface. Whereas, the eastern Arabian Sea contributes 6 to 14 g m<sup>-2</sup> yr<sup>-1</sup> (Ramaswamy and Gaye, 2006). Most of the produced BSi was dissolved within a few cm of the surface water. After that, more than 84 % of the opal was re-mineralised at the sediment-water interface (Ramaswamy and Nair, 1994) and turned to silicic acid, which then diffused back into the overlying water. Eventually, it returns to the euphotic zone and supports a fresh diatom population. The southeastern Arabian Sea (SEAS) situated within the intense Indian monsoon activity region, experiences paleoproductivity in its surface waters influenced by both global climate variations and vigorous monsoon dynamics (Thamban et al., 2001). The accumulation of biogenic silica (BSi) in marine sediments is a direct indicator of diatom productivity. During periods of intensified monsoon strength, the increased upwelling leads to higher nutrient concentrations in the euphotic zone, fostering diatom blooms. The resultant increase in diatom productivity leads to a higher deposition of BSi in the sediments. Conversely, when the monsoon activity is weaker, there is less upwelling and a decreased supply of nutrients, which leads to a decrease in diatom production and, therefore, a reduction in the accumulation of biogenic silica (BSi). Furthermore, the BSi MAR findings suggest that the Holocene historical productivity was primarily governed by the influx of terrigenous substances, according to Pattan et al. (2019). Consequently, a thorough examination of paleoproductivity is essential for comprehending paleoclimate development in low-latitude areas and its interaction with worldwide climate transformation.

Variations in paleoproductivity along the continental margins of the Southeast Arabian Sea have been thoroughly examined to decipher historical shifts in

monsoon-driven upwelling (Kessarkar et al., 2013), overall productivity (Banakar et al., 2005; Naik et al., 2017; Pattan et al., 2019), and the intensity of the oxygen minimum zone (OMZ) in this area (Joshi et al., 2021). Most of these previous studies have been based on OC and CaCO<sub>3</sub> contents and their accumulation rate (Bhusan et al., 2001; Pattan et al., 2003), clay mineralogy (Rao et al., 2010; Das et al., 2013), trace element geochemistry (Pattan et al., 2019; Kessarkar et al., 2022), and foraminiferal diversity (Saraswat et al., 2013). To understand the past changes in the monsoon-induced upwelling intensity of the region, biogenic silica content and its mass accumulation rate can be used as a better proxy (Ragueneau et al., 2000). Diatoms respond more to upwelling water than foraminifera and produce silica only during nutrient-rich periods, which is important for reconstructing past upwelling strength in the Arabian Sea. To understand the implications of climate warming on marine ecosystems and biological carbon pumps, it is essential to examine past biogenic silica accumulation (Ragueneau et al., 2000). This study aims to understand the upwelling strength and productivity variation in the geological past of the SEAS by using BSi as a proxy.

## Materials and Methods

### Study Area

The southeastern margin of the Arabian, i.e., the southwestern continental margin of Indian sub-continent is the area selected for the study. The present study area contains several small and moderate rivers that originate from these regions and drain their detritus into the Arabian Sea. The width of the continental shelf in this area is 60 km off Cochin (Rao and Wagle, 1997). The monsoon winds enhance upwelling and bring cold and nutrient-rich subsurface waters to the surface off the western continental margin of peninsular India (Shetye, 1984; Naqvi et al., 2009). During the summer monsoon, fluvial runoff to the southeastern Arabian Sea and upwelling providing the nutrients for the diatom production are high ( $672 \times 10^3 \text{ l}^{-1}$ ) in the surface water of SEAS, which leads to higher opal flux ranges between 3 and 28 g m<sup>-2</sup> yr<sup>-1</sup> (Ramaswamy and Gaye, 2006). The sedimentary opal levels in the Arabian Sea significantly surpass those found in the Bay of Bengal (Kolla and Kidd, 1982). In the Arabian Sea sediments, opal preservation may be enhanced by a combination of factors, including opal particle quality and bulk accumulation rates. The two regions have

different patterns for opal fluxes, with 84% of the opal flux occurring during the SW monsoon season in the Arabian Sea, and moderate fluxes throughout the year in the Bay of Bengal. In Western Arabian Sea, Opal fluxes are normally about  $40 \text{ mg m}^{-2} \text{ day}^{-1}$  but increase to over  $100 \text{ mg m}^{-2} \text{ day}^{-1}$  during August-September (Nair et al., 1989). Opal percentage increases during peak flux periods especially during the late South-West monsoon (summer monsoon) period due to a diatom bloom.

### Sample Collection

A 4.82-m long gravity core SK-313/1 (location:  $10^{\circ}30.11'' \text{ N}$ ,  $72^{\circ}22.50'' \text{ E}$ ; water depth: 513 m) was collected from the continental slope of the SEAS during the ORV SagarKanya cruise 313 during 2014 (Figure 1). The samples for the BSi analysis were taken at 2 cm interval.

### AMS $^{14}\text{C}$ Analysis

The age model for core SK-313/1 was developed using accelerator mass spectrometry (AMS) radiocarbon age data from planktonic foraminifera at the Rafter Radiocarbon Laboratory in New Zealand. The radiocarbon ages were corrected for local reservoir ages of  $138 \pm 68 \text{ yr}$  for the eastern Arabian Sea (Southon et al., 2002). We then calibrated all  $^{14}\text{C}$  dates into calendar ages using CALIB 7.1 software (Stuiver and Reimer, 1993).

### Biogenic Silica Analysis

Biogenic silica was extracted from the bulk sediment by leaching with  $2\text{M Na}_2\text{CO}_3$  at  $85^{\circ}\text{C}$  for 5 h following the technique of Mortlock & Froelich, (1989). The precision of the data based on duplicate analyses was

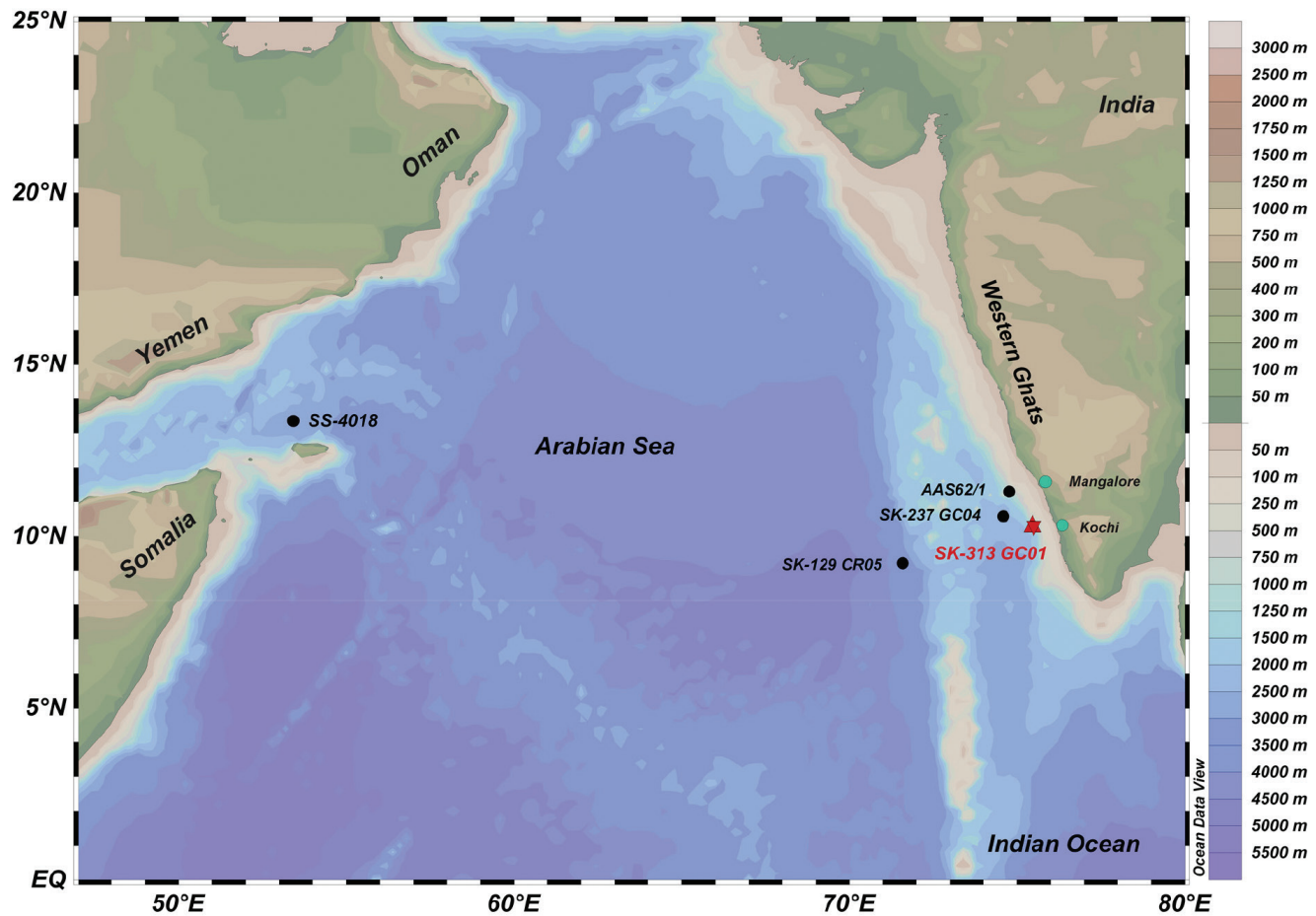


Figure 1: Location map of core SK313 GC01 (filled star), off Cochin, southeastern Arabian Sea. The other sites discussed in the paper are also shown: SK129-129 CR05 (Pattan et al., 2003), SK-237 GC04 (Saraswat et al., 2013), AAS62/2 (Kesserkar et al., 2013) and SS-4018 (Balaji et al., 2018). Map drawn with Ocean Data View.

$\pm 5\%$ . The BSi MAR (MAR,  $\text{g cm}^{-2} \text{ kyr}^{-1}$ ), a measure for productivity proxies, is computed using the linear sedimentation rates (LSR,  $\text{cm}^{-2} \text{ kyr}^{-1}$ ) and the dry bulk density ( $\rho$ ,  $\text{g cm}^{-3}$ ), with the formula:  $\text{MAR} = \text{X} \times \rho \times \text{LSR}$  as delineated by Schoepfer et al., 2015.

## Results

### Chronology and Sedimentation Rate

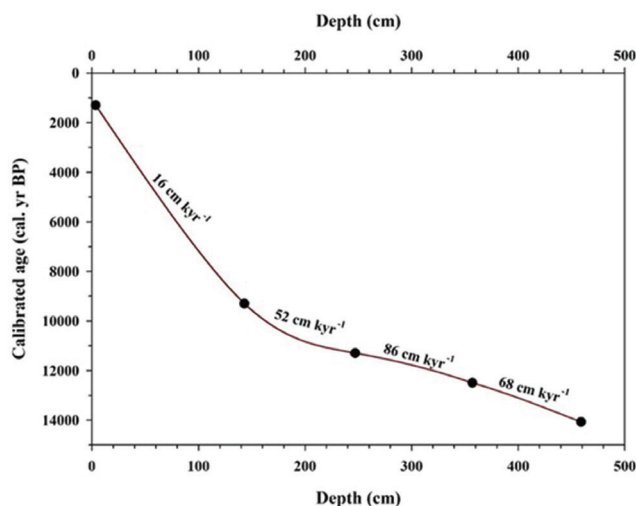
Ages throughout the core were determined through linear interpolation among the dated sediment strata, as illustrated in Figure 2. This core exhibits a finer resolution, ranging from 22 to 136 years, surpassing the resolution of prior research conducted in the SEAS. The resolution of the core is based on climatic intervals like B–A ( $\sim 14.5 - 12.9$ kyrs.), Younger Dryers ( $\sim 12.9 - 11.7$ kyrs.), early Holocene ( $\sim 11.7$ kyrs.), and mid to Late Holocene (8–5kyrs.). Correspondingly, the sedimentation rates ranged between 15.4 and 24.8  $\text{cm kyr}^{-1}$  during the Holocene period and were relatively lower than the late glacial period ( $\sim 31.16 \text{ cm kyr}^{-1}$ ). The analysis of core SK-313/1 indicates that the resolution and sedimentation rates during the Holocene periods are approximately consistent, averaging around  $\sim 16 \text{ cm kyr}^{-1}$ . However, the late glacial period (B–A and YD) contains a relatively high sedimentation rate of  $\sim 68\text{--}86 \text{ cm kyr}^{-1}$ .

### BSi Content

The BSi values of core (SK-313/1) range between 1 % and 2.5% with an average value of 1.5 % as shown in Figure 3. The core shows low BSi content ( $\sim 1.4$  %) during the late glacial to early Holocene interval (14.3–8 kyr BP). Relatively high BSi content was observed during the B–A event ( $\sim 14.4 - 12.9$  kyr BP) and late Holocene intervals, while low BSi % was mostly observed during YD and early Holocene. The fluctuation amplitudes during these intervals varied by up to 0.5%.

### BSi Mass Accumulation Rate

Utilising the BSi values, the MAR for the core was computed as depicted in Figure 3, revealing that the BSi MAR fluctuated within the range of 11 to 57  $\text{g cm}^{-2} \text{ kyr}^{-1}$  (Figure 3a). Relatively highest BSi accumulation occurred at  $\sim 14.3$  and 9.3 kyr BP and the stepwise decreasing trend was noted. While the BSi MAR fluctuated ( $57\text{--}23 \text{ g cm}^{-2} \text{ kyr}^{-1}$  with an average of  $41 \text{ g cm}^{-2} \text{ kyr}^{-1}$ ) more distinctly during the late glacial to early Holocene. A slightly increasing trend with the



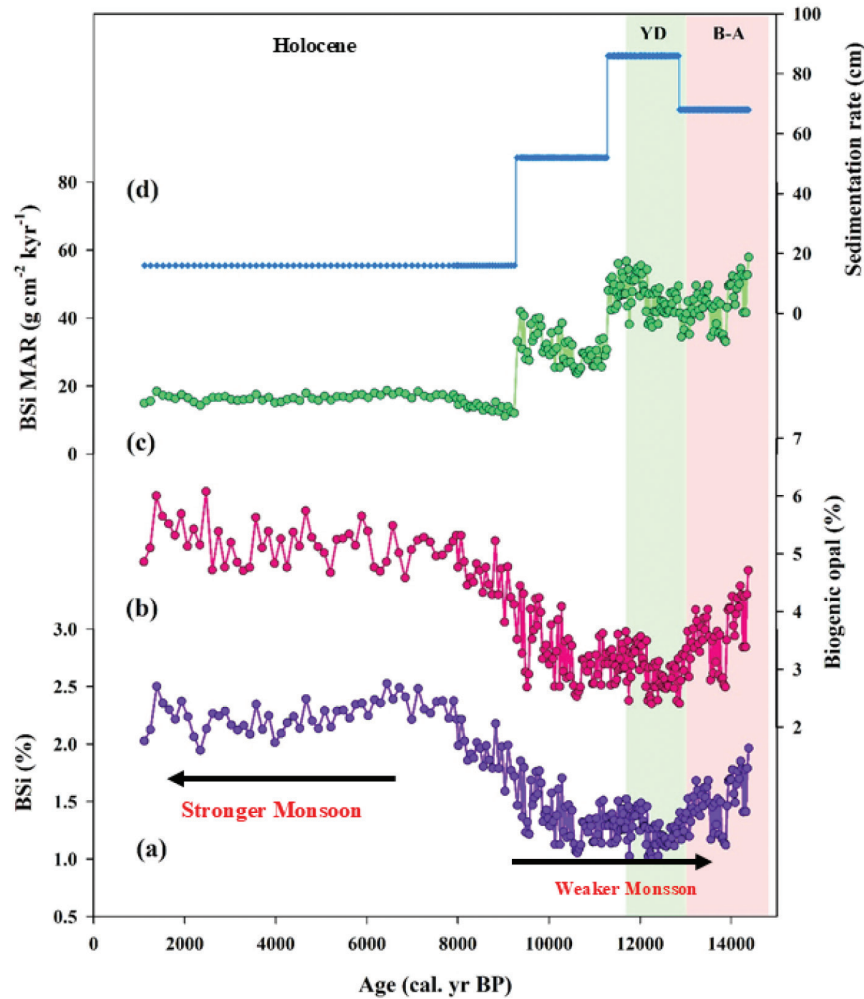
**Figure 2: Age-depth model of the Core SK-313 GC01.**  
The error bars mark  $1\sigma$  uncertainty in calibrated age.

relatively lowest MAR (11 to 18  $\text{g cm}^{-2} \text{ kyr}^{-1}$ ) occurred in the mid to late Holocene period (Figure 3b). This range is consistent with ( $0.03$  to  $0.013 \text{ g cm}^{-2} \text{ kyr}^{-1}$ ) the core SK-129/CR-05 in the SEAS (Pattan et al., 2003). The BSi MAR over the past ca.  $\sim 14.5$  kyr also decreased during the late glacial and increased after the early Holocene (Figure 3b). Due to the higher sedimentation rate the mass accumulation rate of the core varied.

## Discussion

### Late Glacial

The deposition of BSi on the seabed is predominantly governed by the biological productivity in the overlying waters, the dissolution rate throughout the water column and at the seabed, and the dilution due to terrigenous materials. Balaji et al. (2018) suggest that the low BSi flux during 18.5–15 kyr BP indicated weak upwelling in the Somali upwelling region. The present study found a similar BSi MAR variation pattern, with a higher MAR during the late glacial period than in the higher sedimentation rate ( $52\text{--}68 \text{ cm kyr}^{-1}$ ), unlike the productivity-related causes in the above-mentioned studies. The core SK-313 GC01 recorded the B–A event was observed in the proxies with high BSi content (1.1 to 1.9 %) and BSi flux ( $13$  to  $57 \text{ g cm}^{-2} \text{ kyr}^{-1}$ ). From 14.3 to 12.9 kyr BP, there is a stepwise decline in both proxies. This is correlated with the higher freshwater influx into the SEAS and leads to lower  $\delta^{18}\text{O}$  and sea surface salinity (Kessarkar et al., 2013). Previous studies have documented the high biogenic silica (BSi) content and its flux in regions of high productivity, and



**Figure 3:** Temporal variation of the (a) biogenic silica content in the core SK-313 GC01. (b) Biogenic opal content, (c) Biogenic silica mass accumulation rate (MAR), and (d) linear sedimentation rate. Pale Pink bar indicates the Bølling-Allerød period and Pale Green bar indicates the Younger Dryas (YD) event.

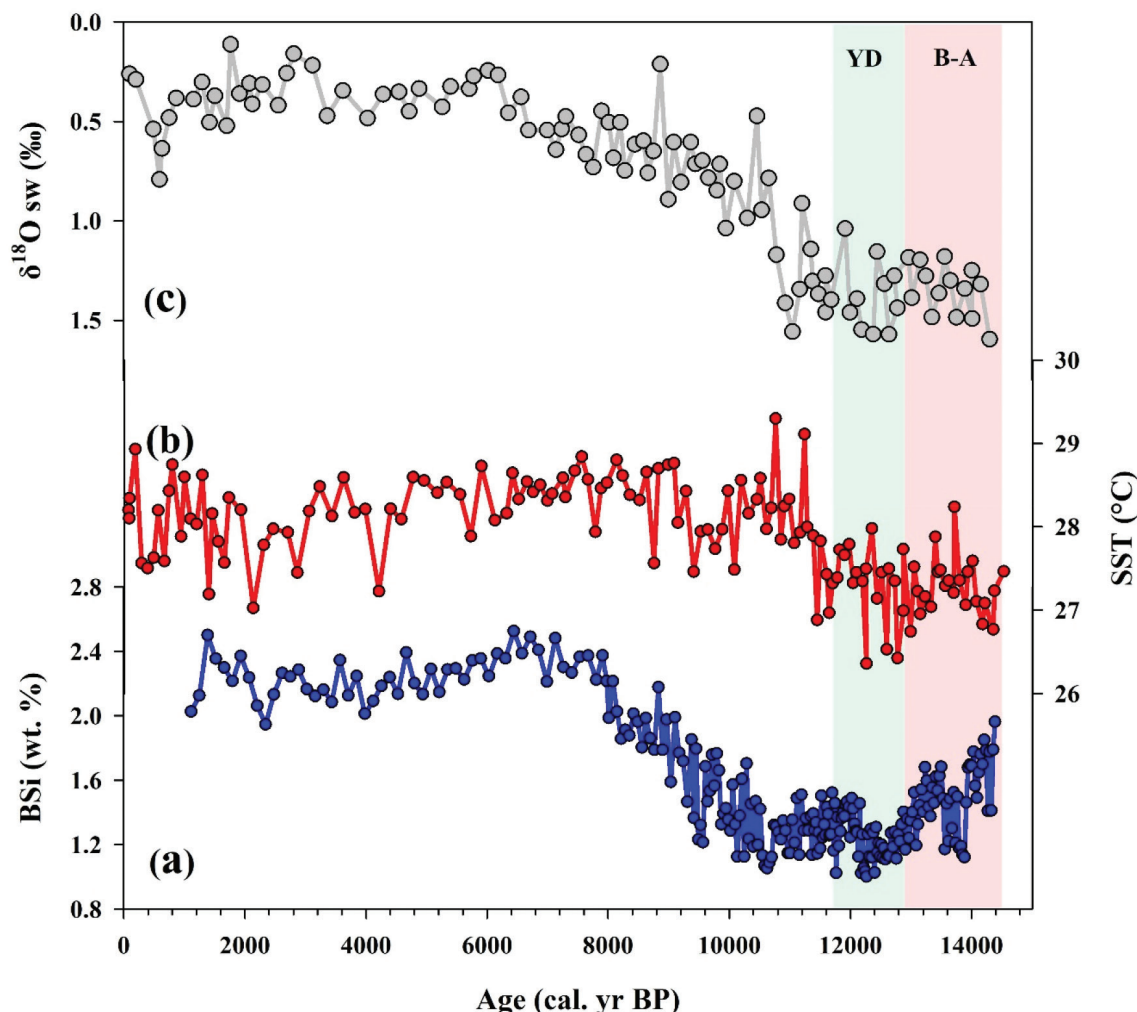
variations over time in this flux have served as a proxy for reconstructing changes in productivity (Balaji et al., 2018). Our study reveals that the BSi content and BSi MAR in the YD period gradually decreased from the B-A to the early Holocene period (Fig. 3a, b). The trends in the BSi and OC contents are generally compared well. The *G. bulloides* population census data could be used as a proxy for the southwest monsoon and the upwelling intensity (Saraswat et al., 2013). During the YD event *G. bulloides* count was relatively low compared to the B-A periods (Siva chandiran et al., 2018). This suggests that SW monsoon-induced upwelling intensity was very low during the YD interval.

#### Holocene

During the early Holocene ~11.7 kyr BP, BSi % was increased (0.5 %) than the YD interval. However,

compared to the mid to late Holocene, the beginning of the early Holocene stage recorded low productivity with decreased BSi MAR. The BSi content in the middle of the early Holocene (~10.5 kyr BP) shows a rapid enrichment that is simultaneous with an increase in the BSiMAR (Figure 4). These results indicate a rise in paleoproductivity off the southeastern coast. The peak diatom production aligns well with the periods of intensified upwelling during the seasonal monsoon in the Southeast Asian Seas (Naidu et al., 1992). These findings indicate that the production of diatoms and the intensity of upwelling are influenced by the amount of solar radiation throughout the summer in the northern hemisphere (Clemens et al., 1991; Romero et al., 2012).

During the period spanning 10.2 to 6 thousand years before the present (kyr BP), the BSi content peaked at 2.5%, a figure that aligns closely with the BSi content



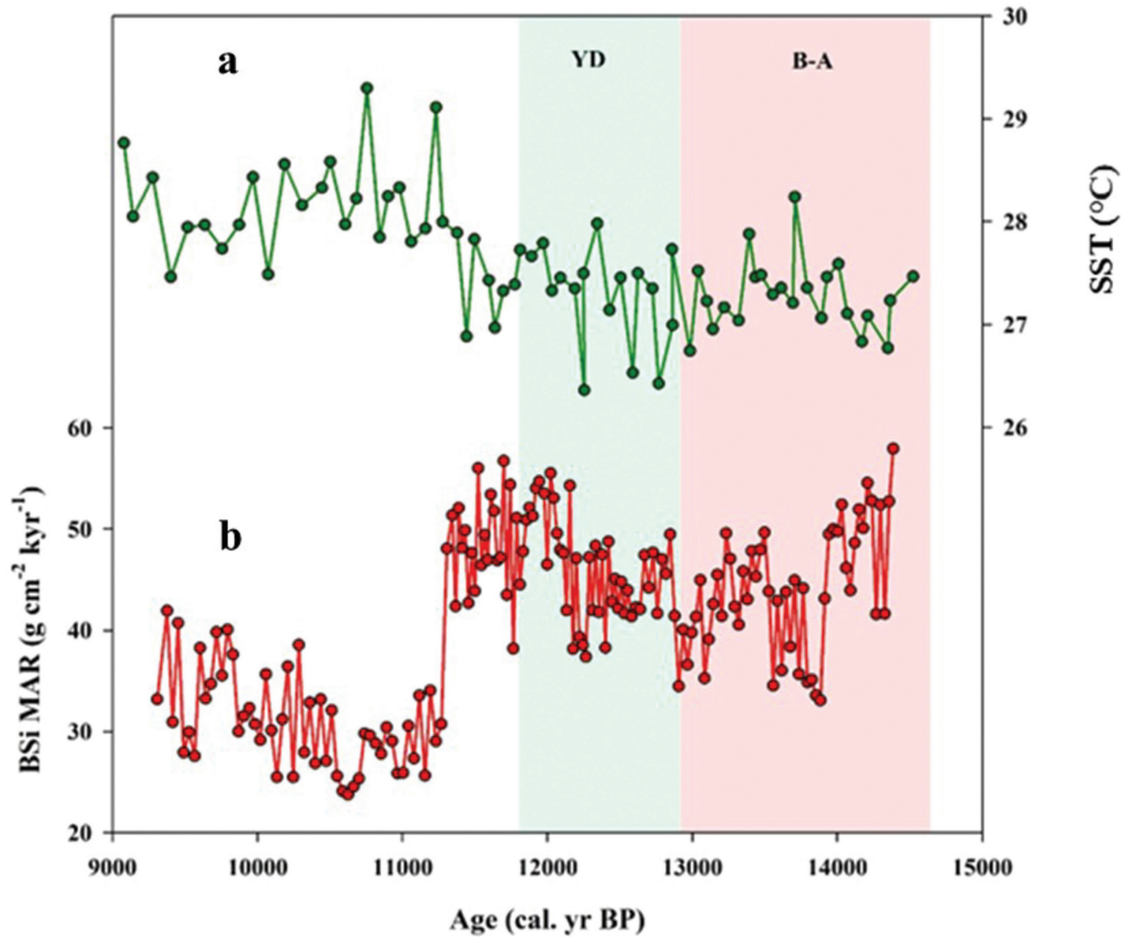
**Figure 4:** A comparison of the southeastern Arabian Sea upwelling with southwest monsoon records during the late glacial – Holocene period. White colour represent Holocene period, Pale green colour represent Younger Dryas period, and Pale pink colour represented Bolling-Allerod period. (a) The biogenic silica % (present study), (b) Sea surface temperature and (c)  $\delta^{18}\text{O}_{\text{sw}}$  of southeastern Arabian Sea (Saraswat et al., 2013).

recorded in the western Arabian Sea, which ranged between 9.7% and 11.8% from 10.9 to 6.5 kyr BP. Since the mid-Holocene, elevated global temperatures have fostered an increase in nutrient production, enhancing diatom proliferation in the Arabian Sea. Concurrently, the accelerated weathering and transport of terrigenous materials (Cao et al., 2015; Liu et al., 2021) have resulted in a greater influx of terrigenous nutrients. This, combined with swift deposition dynamics, has culminated in a marked rise in biogenic silica (BSi) concentrations. The current core (SK-313/1) exhibits a decline in BSi concentration from the late Holocene. These declines reflect that the diatom paleoproductivity was lower during the late Holocene on SEAS (Figure 5 and Figure 6). Pattan et al., (2003) documented that

the western Arabian Sea had a higher biogenic opal accumulation rate ( $0.03\text{--}0.13 \text{ g cm}^{-2}\text{kyr}^{-1}$ ) than the SEAS, indicating greater productivity in the former.

#### **Paleoproductivity Evolution in the SEAS since the Late Glacial**

On a millennial scale, the surface productivity in the SEAS exhibits multiple high-low cycles. Notably, higher productivity occurred during the B-A period and the mid-Holocene, while lower productivity was observed during the YD and early Holocene periods (Figure 5). These patterns are consistent with studies suggesting that climate variability is a primary driver of past productivity fluctuations in the region (Pattan et al., 2019). The Indian Summer Monsoon (ISM)



**Figure 5:** A comparison of the southeastern Arabian Sea upwelling with the sea surface temperature record. White colour represent Holocene period, Pale green colour represent Younger Dryas period, and Pale pink colour represented Bolling-Allerod period. (a) The biogenic silica mass accumulation rate (MAR) of the present study, (b) The Mg/Ca based SST from the core SK-237 GC04 (Saraswat et al., 2013).

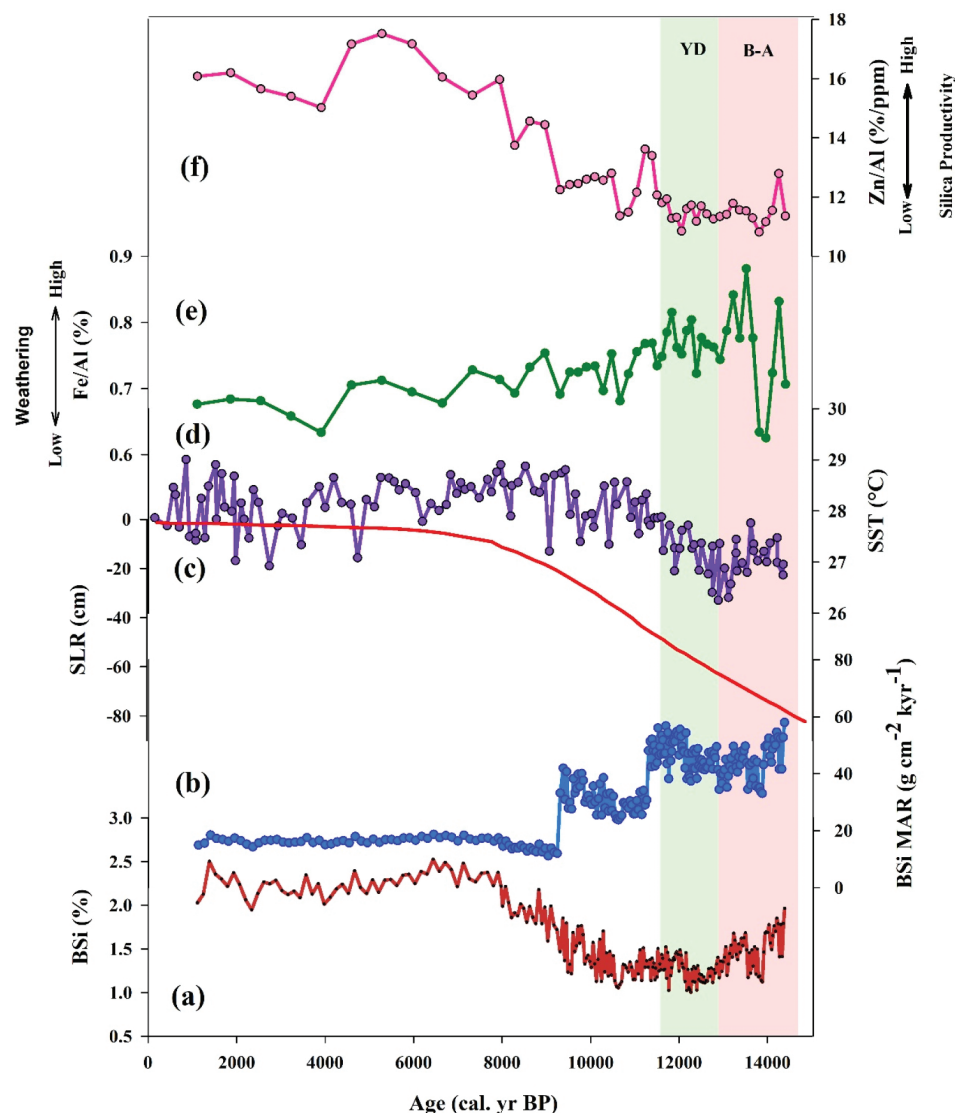
significantly influences the region's climate, with increased freshwater input during the early Holocene leading to stratification in the surface water column (Saraswat et al., 2013). The productivity trends observed in this study correspond closely with the historical evolution of the ISM, as indicated by SEAS  $\delta^{18}\text{O}$  records (Kessarkar et al., 2013; Pattan et al., 2019), underscoring the role of the ISM in controlling surface productivity.

Additionally, the intensification of the summer monsoon during the mid-Holocene provided nutrients and optimal temperatures for silica production, leading to an increase in BSi flux. When comparing the BSi flux with the Greenland ice core  $\delta^{18}\text{O}$  record, we observe that periods of enhanced paleoproductivity since the late glacial period correspond to intervals of heavier seawater  $\delta^{18}\text{O}$  (Liu et al., 2021). This correlation suggests a strong link between BSi enrichment in the

SEAS and large-scale climate changes, reflecting a regional response to global climatic shifts (Figure 6).

## Conclusions

Our analysis of BSi contents in core SK-313/1 from the Southeastern Arabian Sea (SEAS) since ~14.5 kyr BP reveals distinct changes in paleoproductivity. The low BSi levels observed are primarily attributed to a reduced influx of silica skeletons and enhanced dissolution, along with dilution by terrigenous materials. The variability in BSi mass accumulation rates (MAR) reflects shifts in paleoproductivity across different timescales. Specifically, we observed lower paleoproductivity during the late glacial period, followed by increased productivity throughout the Holocene. These changes in productivity appear to be closely linked with global climatic temperature trends, particularly driven by



**Figure 6:** A comparison of the southeastern Arabian Sea biogenic silica productivity with southwest monsoon proxies. White colour represent Holocene period, pale green colour represent Younger Dryas periods, and Pale red colour represented Bolling-Allerød period. (a) Biogenic silica content (b) BSi MAR of the core SK-313 GC01, (c) Sea level rise (SLR) of the eastern Arabian Sea, (d) Sea surface temperature (SST) of the SEAS (Saraswat et al., 2013), (e) Fe/Al ratio of the present core as an indicator for the continental weathering and (f) Zn/Al ratio of the same core indicator for silica productivity.

insolation changes at low latitudes. Furthermore, millennial-scale events, such as the Younger Dryas, are marked by reduced paleoproductivity, while periods like the Bolling-Allerød and the mid-Holocene show increased productivity, which may correspond with enhanced chemical weathering and nutrient availability driven by a stronger Indian Summer Monsoon during warmer phases. SEAS often lack high-resolution temporal records which are crucial for understanding the short-term climatic and oceanographic variations. Our study provides the millennial time scale biogenic

silica sedimentary record which helps to enhance the understanding of past climate conditions and the monsoonal activity in the SEAS.

### Contribution

Arunkarthik Palanisamy: Manipulation of data, conceptualisation, methodology, data analysis, mapping, writing the original draft. Yoganandan Veeran: supervision, critical review. Sivachandiran Alagudurai: critical review. Monisha Balasubramanian: editing.

### Declaration of Competing Interest

The authors declare there is no competing interest.

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