

Response of the low-level jet to precession and its implications for proxies of the Indian monsoon

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Key Points:

- Upwelling in the Arabian Sea in modern climate is closely linked to the strength of the low-level jet and the South Asian summer monsoon.
- On longer timescales, along with the strength of the jet, the location as well as the width of the jet change.
- This affects the intensity and spatial extent of upwelling and has implications for the interpretation of proxies of upwelling.

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Abstract

The long-term variations in the South Asian monsoon have been inferred based on the variations in the ocean productivity along the western coast of the Arabian Sea. The variations in ocean productivity were previously thought to be primarily influenced by the intensity of upwelling. Here, using idealized precession experiments in fully coupled climate models, we have shown that the area as well as the region of maximum upwelling change with precession. When summer occurs at perihelion (stronger summer insolation and monsoon precipitation) the area of upwelling is narrow. In contrast, during summer at aphelion (weaker summer insolation and monsoon precipitation), upwelling occurs over a broader region. This is due to the effect of convective heating over northeastern Africa and the western equatorial Indian ocean on the width and meridional location of the low-level jet. Therefore, the upwelling inferred from proxies does not necessarily indicate the Indian summer monsoon strength.

Plain Language Summary

Modern observations suggest that the upwelling along the eastern coast of the Arabian Sea is primarily controlled by the strength of the low-level jet (LLJ). The strength of the LLJ and the Indian summer monsoon rainfall are also positively correlated. Hence, proxies of upwelling have been used to infer the variations in the monsoon of the distant past. We find, however, that factors other than the strength of the LLJ also affect upwelling. Variations in Earth's orbit alter the latitudinal location and width of the LLJ. This affects the area over which upwelling occurs and shifts the region of maximum upwelling. During periods of weaker summer insolation, the LLJ is broader and further south. This leads to an increase in the spatial extent of the upwelling. Therefore, the ocean productivity in the Arabian Sea is higher during such periods. This explains the large lag (~ 9 kyrs) with respect to the local summer insolation as observed in these proxies. Thus, we conclude that the proxies of upwelling capture multiple signals resulting from changes in the location, width, and strength of the LLJ and hence are not appropriate for deducing the long-term variations in monsoon rainfall.

1 Introduction

The low-level jet (LLJ) in the Arabian Sea is a prominent feature of the Indian summer monsoon (Findlater, 1969, 1974; Halpern & Woiceshyn, 2001; Rajendran et al., 2012). The jet carries moisture from the Indian Ocean onto the Indian subcontinent. Thus, the strength of the LLJ is positively correlated with the Indian summer monsoon rainfall in the modern climate (Joseph & Sijikumar, 2004; Chakraborty et al., 2002, 2009). The coastal upwelling induced by the LLJ is proportional to the strength of the LLJ, and therefore, stronger monsoons produce larger upwelling (Murtugudde et al., 2007). This relation has been used to reconstruct the strength of the past monsoons. Regions of upwelling are also regions of higher ocean productivity. Therefore, by measuring the productivity in these regions as archived in the sediment cores, upwelling can be inferred.

Evidence from such reconstructions indicates that the strength of upwelling lags local summer insolation by about 9 kyrs (S. Clemens et al., 1991; Reichert et al., 1998; S. C. Clemens & Prell, 2003; S. C. Clemens et al., 2010; Caley et al., 2011). Whether this can be interpreted as a lag in the South Asian monsoon has been a subject of debate (Gebregiorgis et al., 2020; Zhang et al., 2020) because terrestrial proxies of monsoon suggest that monsoon rainfall is nearly in phase with local insolation (Zhang et al., 2019). Therefore, the proxies of upwelling in the Arabian Sea are thought to represent the strength of the LLJ instead (Gupta et al., 2005). Thus, indicating that the relationship between LLJ and the monsoon rainfall may be different in different climate regimes. This view is supported by recent studies where it was shown that it is the net energy flux into the atmosphere and water vapor, and not the monsoon winds that account for vari-

ability of South Asian monsoon on centennial and longer timescales (Jalihal, Srinivasan, & Chakraborty, 2019; Jalihal et al., 2020).

The variations in precipitation over the Bay of Bengal are, however, linked to those in LLJ on precession timescales (Jalihal, Bosmans, et al., 2019; Jalihal et al., 2020). The LLJ extends into the Bay of Bengal and modulates the surface latent heat flux there. These fluctuations in the surface latent heat flux are large enough to counter the changes induced by insolation. Hence, precipitation over the Bay of Bengal is out-of-phase with local summer insolation. This has also been documented in proxy reconstructions (Gebregiorgis et al., 2018; McGrath et al., 2021), and it has been found to be consistent with the proxies of upwelling in the Arabian Sea (Gebregiorgis et al., 2018). Thus, the orbital-scale variations in LLJ is linked to oceanic precipitation and not to the terrestrial precipitation within the South Asian monsoon domain.

The variations in the LLJ on intraseasonal and interannual timescales has been studied extensively (Chen & van Loon, 1987; Arpe et al., 1998; Halpern & Woiceshyn, 2001; Fasullo & Webster, 2002; Joseph & Sijikumar, 2004; Jain et al., 2021). Several studies have also highlighted that LLJ location and intensity are changing and are likely to change further due to global warming (Rajendran et al., 2012; Sandeep & Ajayamohan, 2015; Decastro et al., 2016; Preethi et al., 2017; Sandeep et al., 2018). A comprehensive study of LLJ variations on the orbital timescale is, however, missing. An understanding of the long-term variations in LLJ and the factors that drive it is necessary for the correct interpretation of the proxies. In this article, using fully coupled general circulations models, we have unraveled the factors that affect upwelling on the orbital timescale.

2 Data and Methods

We have used NCEP reanalysis over the period 1948–2017 to understand the connection between upwelling and precipitation at the interannual timescales. Upwelling is calculated based on the curl of windstress. GPCP monthly precipitation data is used to evaluate precipitation over India. Reconstructions of upwelling from the Arabian Sea give an estimate of the upwelling on longer timescales. We have used several foraminifer assemblages from the cores RC27-61 (S. C. Clemens & Prell, 2003), MD04-2861 (Caley et al., 2011), and GeoB3004-1 (Schmiedl & Leuschner, 2005). The productivity estimates from the NIOP cores 455, 464, and 497 (Reichart et al., 1998) were also used. Furthermore, denitrification in the oxygen minimum zone also represents upwelling (Reichart et al., 1998; Altabet et al., 2002). Hence, we have used $\delta^{15}\text{N}$ from the cores RC27-14 and RC27-23 (Altabet et al., 2002). These are compared with the $\delta^{18}\text{O}_{\text{sw}}$ ($\delta^{18}\text{O}$ of seawater; see methods in Jalihal, Srinivasan, and Chakraborty (2019) for a detailed description) from a sediment core near the mouth of Ganga-Brahmaputra in the northern part of the Bay of Bengal (Kudrass et al., 2001). Since this region is influenced by the runoff from over land, this proxy captures the amount of terrestrial monsoon rainfall. All the proxies are interpolated to an equally spaced interval of 500 years, following which a bandpass filter is applied to extract the precession modes (18 - 24 kyrs).

We have carried out time slice orbital experiments in the high resolution, fully coupled CESM 1.2.0 (Neale et al., 2010; Hurrell et al., 2013). The model consists of the CAM 5 (Community Atmospheric Model) for the atmospheric component and Parallel Ocean Program (POP) for the ocean model. CAM has a resolution of $0.9^\circ \times 1.2^\circ$, whereas the POP has a resolution of about 0.25° near the equator. The model was run with orbital configurations corresponding to the minimum and maximum precession (P_{min} and P_{max}), following the experimental setup used by Bosmans et al. (2015). In the precession minimum (P_{min}) orbital configuration, the boreal summer solstice occurs near the perihelion, whereas in the Precession maximum (P_{max}), it occurs at aphelion. The eccentricity is set close to the highest values that occurred in the last million years. This produces a difference in summer insolation (Jun-Jul-Aug) between P_{min} and P_{max} , over India of

about 80 Wm⁻² (Berger, 1978; Bosmans et al., 2015, 2018; Jaliha, Bosmans, et al., 2019). Each simulation is run for 100 years. The first 50 years of the simulation are discarded as spin-up, and only the last 50 years are considered for the study. All the other boundary conditions are kept constant at their pre-industrial values. The model has a decent representation of the climatological Indian summer monsoon and reproduces the seasonal cycle quite well (Supplementary figures 1 and 2). To validate our results, we have used data from the P_{min} and P_{max} simulations from another high-resolution model: EC-Earth (Bosmans et al., 2015).

The Ekman upwelling was evaluated as the curl of wind stress over the surface of the ocean:

$$W_e = \text{curl} \left(\frac{\tau}{\rho f} \right) \quad (1)$$

Where, W_e is the upwelling averaged over the Ekman layer, ρ is the density of sea water (taken to be 1025 kg m⁻³), f is the Coriolis parameter, τ is the wind stress on the surface of the ocean. τ is given by:

$$\tau = \rho_a * C_d * W S_{sfc} \quad (2)$$

ρ_a is the density of air (taken to be 1 kg m⁻³), $W S_{sfc}$ is the surface wind speed (10 m wind speed is used from NCEP and wind speed at 0.995 sigma for model data). C_d is the drag coefficient and is given by Large and Pond (1981):

$$C_d = 0.0013 \quad W S_{sfc} \leq 11 \text{ m s}^{-1} \quad (3)$$

$$C_d = 10^{-3}(0.49 + 0.065 * W S_{sfc}) \quad W S_{sfc} > 11 \text{ m s}^{-1} \quad (4)$$

3 Results

3.1 Impact of precession on the relation between the Arabian Sea upwelling and South Asian monsoon

Fig. 1 depicts the correlation between the Indian summer monsoon rainfall (ISMR) and upwelling in the surrounding oceans at interannual timescales based on NCEP data. It shows that ISMR is positively correlated with upwelling in the northwestern Arabian Sea along the coast. At the precession mode, the reconstructions of upwelling within this region are, however, negatively correlated with the proxies of the Indian monsoon. This correlation is not spatially uniform. There are differences in the correlation as we move north. Near the horn of Africa, it is positively correlated, but changes sign further north. Thus, suggesting a complex relation between ISMR and upwelling on precession timescales (~ 23 kyrs).

Orbital forcing modulates both the ISMR as well as the LLJ (Jaliha, Bosmans, et al., 2019; McGrath et al., 2021). Therefore, we have examined the relation between ISMR and upwelling due to variations in Earth's orbit (Fig. 2). We find that the relation between ISMR and upwelling is different under different climates (Fig. 2). During periods of high local summer insolation and climatological monsoon (P_{min}), the correlation between interannual variations in ISMR and upwelling is negligible. In contrast, during periods of weaker summer insolation and climatological monsoon (P_{max}), the correlation between interannual variations in ISMR and upwelling is stronger. Thus, underscoring that the relationship between ISMR and upwelling as seen in modern observations should not be extended for all climates.

The orbital configuration of P_{max} resembles the modern orbital configuration, albeit with higher eccentricity. The pattern of the correlation between ISMR and upwelling

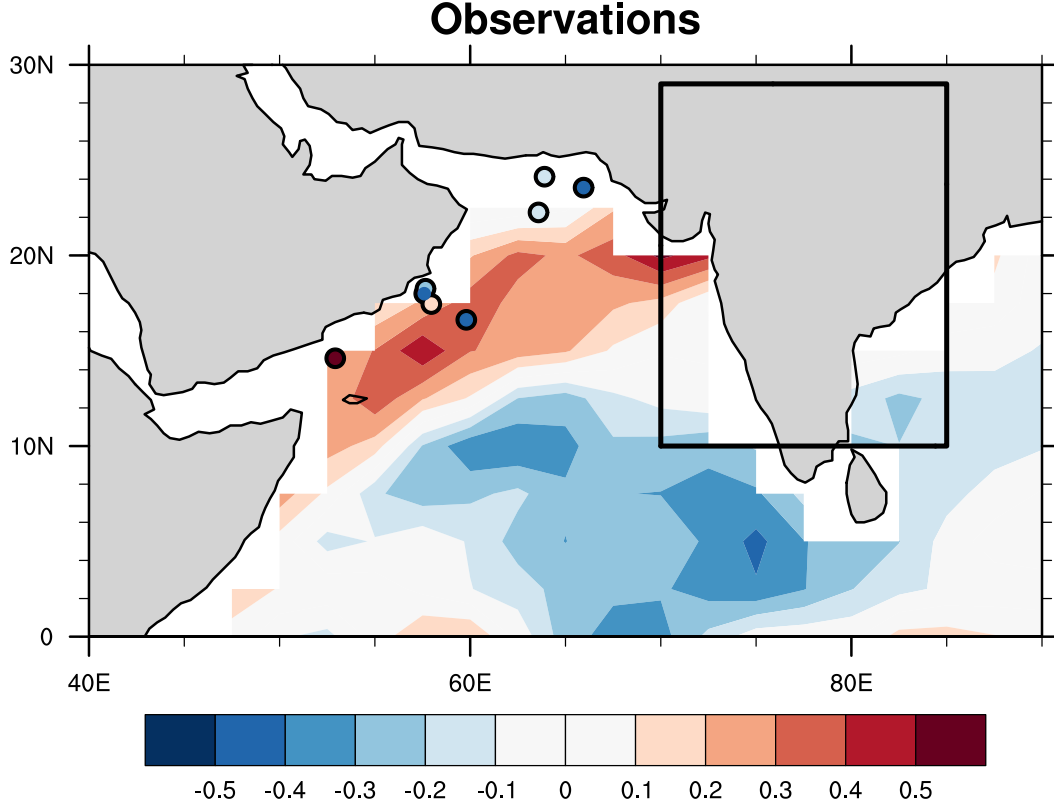


Figure 1. The spatial map of correlation between Jun-Jul-Aug (JJA) averaged rainfall over India and Ekman upwelling everywhere. The inset black box represents the region over which area-averaged precipitation was evaluated (10-29N; 70-85E; land only grids). NCEP-reanalysis 1 dataset was used to evaluate the curl of wind stress, and Global Precipitation Climatology Project (GPCP) dataset was used for precipitation. The filled circles show the correlation between the proxy of the Indian monsoon, $\delta^{18}\text{O}_{\text{sw}}$ (Kudrass et al., 2001), with the proxies of upwelling in the Arabian Sea (Reichart et al., 1998; Altabet et al., 2002; S. C. Clemens & Prell, 2003; Schmiedl & Leuschner, 2005; Caley et al., 2011). These proxies were bandpass filtered for the precession modes (18–24 kyrs). The filled circles represent the location of the upwelling proxies. The color with which the circles are filled corresponds to the correlation of the proxy with that of the Indian monsoon proxy.

is, also, the same (Fig. 1 & Fig. 2b). The interannual variations in the latitude and strength of the LLJ is related to those in the gradient of surface pressure over the Arabian Sea (Tomas & Webster, 1997; Webster et al., 2003; Sandeep & Ajayamohan, 2015; Chakraborty & Agrawal, 2017). At the precession timescales, additional factors influence the location and strength of the LLJ (Jalihal, Bosmans, et al., 2019). Precipitation over northeastern Africa and the west equatorial Indian Ocean increase on account of higher summer insolation in P_{min} compared to P_{max} . The convective heating over these two regions drives a Matsuno-Gill-like response of the lower tropospheric winds (Jalihal, Bosmans, et al., 2019; Pausata et al., 2021). The ensuing Kelvin wave produces an anomalous easterly that leads to narrowing of the LLJ and also causes its maxima to shift northward (Jalihal, Bosmans, et al., 2019; Pausata et al., 2021). In the current study, we find a similar dependence at the interannual timescales as well in P_{min} . The interannual variations in precipitation over northeastern Africa and the west equatorial Indian Ocean have a greater impact on the LLJ, and hence on the upwelling in P_{min} (Supplementary Fig. 3a). In P_{max} ,

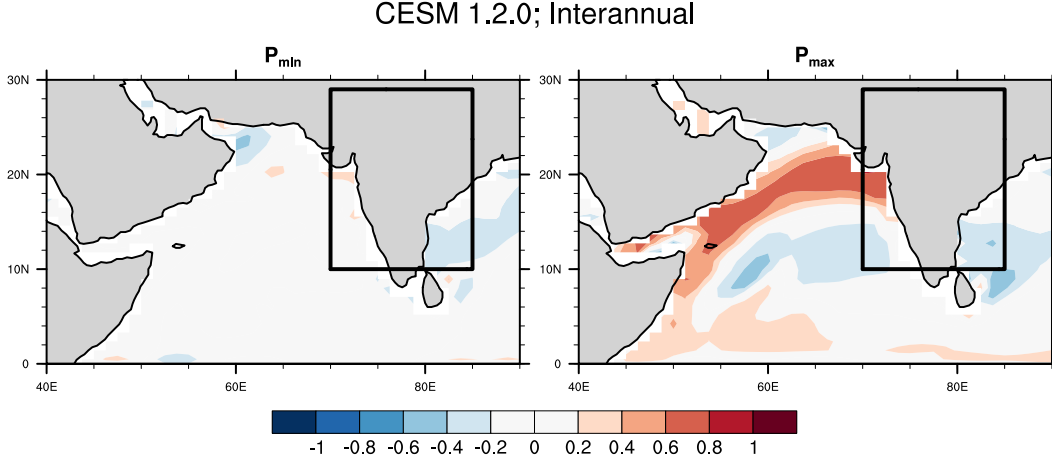


Figure 2. The spatial map of correlation between the Jun-Jul-Aug (JJA) mean Indian monsoon rainfall (Precipitation over the domain 10° - 29° N; 70° - 85° E; land only grids) with Ekman upwelling over grids everywhere. (a) is for the P_{\min} simulation, whereas, (b) is for the P_{\max} simulation. The last 50 years of the simulation were used to generate the correlation maps.

precipitation over these two regions is weaker. Therefore, they do not influence the upwelling in P_{\max} at the interannual timescales (Supplementary Fig. 3b).

3.2 Change in area of upwelling

The proxies used to detect upwelling, in general, record the integrated effect of several years. Therefore, we have examined the climatology in our simulations. A change in precession leads to meridional shifts in the LLJ (Fig. 3a&b). In P_{\min} , the LLJ is parallel to the coast of Oman and is located in the northern Arabian Sea. The climatological summer monsoon is stronger in this experiment. On the other hand, summer insolation and ISMR are weaker in P_{\max} . The LLJ is further south as compared to its location in P_{\min} . Along with this southward shift, the strength of the LLJ also changes. The maximum velocity is higher in P_{\max} and is located near the horn of Africa. There is a change in the width of the LLJ as well. The LLJ is broader in P_{\max} and is narrower in P_{\min} (Fig. 3 a & b). Thus, suggesting that the orbital scale variability of the LLJ consists of fluctuations in the strength, meridional location, and width, whereas, its interannual fluctuations are primarily due to changes in its strength (Supplementary figure 4). The variations in the strength, magnitude, and location of the LLJ on precession timescales are due to the additional influence of convective heating over northeastern Africa and the west equatorial Indian Ocean (Jalihal, Bosmans, et al., 2019; Pausata et al., 2021).

Since upwelling is determined by the curl of wind stress, any changes in the location, width, or strength of the LLJ would have an impact on upwelling. Therefore, we have compared the curl of wind stress from the two experiments to understand the impact of the changes in the LLJ (Fig. 4). In P_{\min} (stronger summer insolation), upwelling is concentrated along the eastern coast of the Arabian Sea and extends all the way into the northern parts of the Arabian Sea. In P_{\max} , the intensity of upwelling increases along the horn of Africa. The region of largest upwelling is, however, concentrated at 15° N. The upwelled water gets advected along with the nutrients to the northern Arabian Sea (Caley et al., 2011). Therefore, most of the proxies would capture a stronger signal in climates with P_{\max} -like orbital configurations. Furthermore, the area over which upwelling occurs in the northern Arabian Sea more than doubles in P_{\max} . This explains why most of the proxies suggest a large lag with respect to the local summer insolation. Such changes

CESM 1.2.0; Climatology

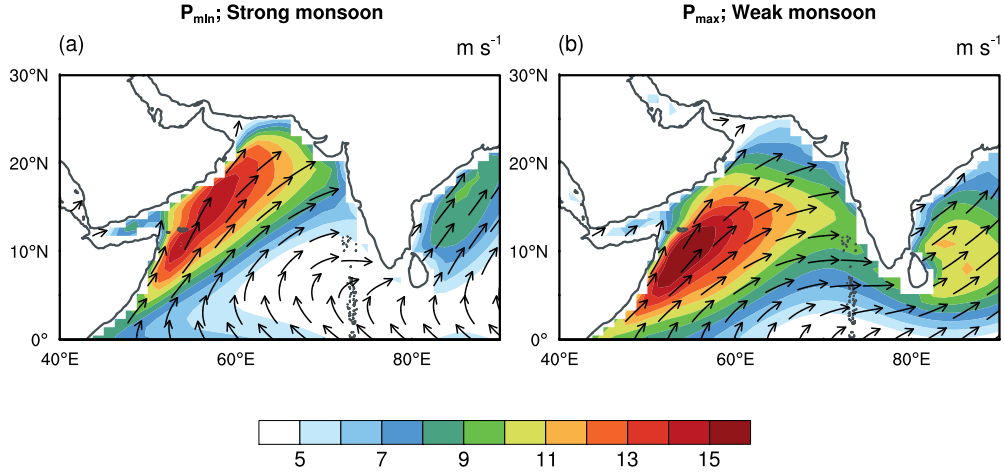


Figure 3. The Jun-Jul-Aug averaged climatological surface wind speed in shading for (a) P_{\min} (strong monsoon) and (b) P_{\max} (weak monsoon). The unit vectors indicate the direction of surface winds.

in the area of upwelling are not observed on interannual timescales (Supplementary Fig. 5). These results are consistent in P_{\min} and P_{\max} simulations using another fully coupled model- EC-Earth (Supplementary Fig. 6).

CESM 1.2.0; Climatology

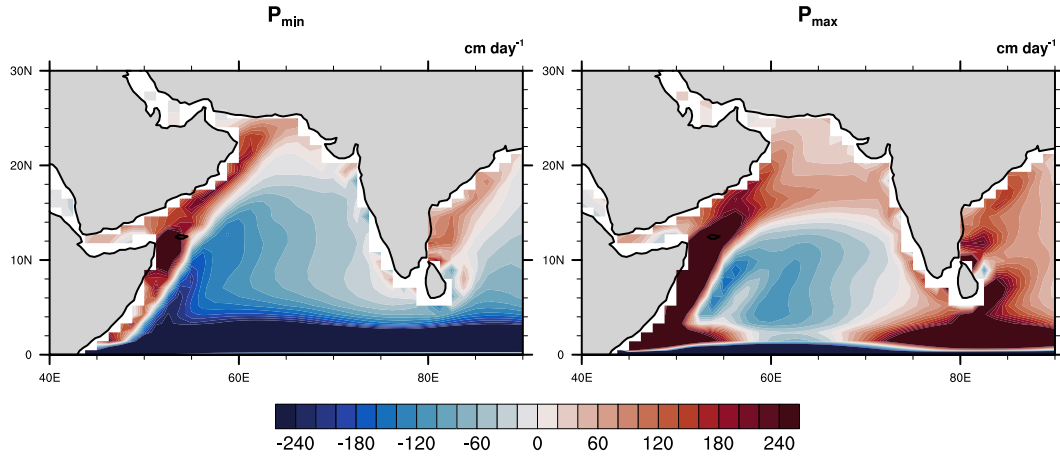


Figure 4. The Jun-Jul-Aug averaged climatological Ekman upwelling in shading for the climate for (a) P_{\min} (strong monsoon) and (b) P_{\max} (weak monsoon).

4 Discussion and conclusions

Terrestrial and marine reconstructions of the South Asian monsoon are inconsistent in terms of phase (Wang et al., 2014; Gebregiorgis et al., 2020; Cheng et al., 2021; McGrath et al., 2021). This is primarily due to the different responses of precipitation over land and ocean to changes in precession (Jalihal, Bosmans, et al., 2019). This phase

difference between India and the Bay of Bengal has been explored in detail (Battisti et al., 2014; Jaliha, Bosmans, et al., 2019; Jaliha et al., 2020). The connection between the precipitation over the Bay of Bengal and winds in the Arabian Sea were established both in the proxies (Gebregiorgis et al., 2018) and the models (Jaliha, Bosmans, et al., 2019). A comprehensive mechanism for the cause of lag in the proxies from the Arabian Sea was still missing. Furthermore, the differences in the sign of the correlation between the Indian monsoon rainfall and upwelling at interannual and precession modes were not explained in the previous studies.

In this study, we have demonstrated that along with the changes in wind speed of the low-level jet, the changes in the width of the jet, and its meridional location has an influence on upwelling in the Arabian Sea. On interannual timescales, the changes in the wind speed governs upwelling. At the precession timescales, the variations in the width and latitude of the jet also play a crucial role. These are influenced by convective heating in the west equatorial Indian Ocean and northeastern Africa (Jaliha, Srinivasan, & Chakraborty, 2019). These convective heat sources are a result of precessional forcing. The changes in the strength, width, and latitude of the low-level jet are such that the curl of wind stress is stronger during climates with weaker summer insolation. Moreover, the spatial extent of upwelling is substantially larger. Thus, proxies register enhanced productivity (upwelling) in such climates even though the summer monsoon is weaker. Two high-resolution fully coupled climate models show consistent results, further enhancing confidence in our results. Thus, upwelling-based proxies do not represent the variability of the South Asian monsoon at the precession mode. This also explains the large lag observed between upwelling and other terrestrial proxies of the monsoon. These proxies were previously thought to represent the South Asian monsoon and were found to have a large lag with respect to the terrestrial proxies, sparking-off a long-standing debate (Wang et al., 2014; Caley et al., 2011; Zhang et al., 2019; Gebregiorgis et al., 2020; Zhang et al., 2020). Our results show that upwelling-based proxies in the Arabian sea are not linked to Indian monsoon rainfall at precession timescales.

Proxy reconstructions are based on the relation between physical processes observed in the modern climate. Our results underscore that additional factors can impact the interpretation of some of the proxies on longer timescales. For example, since the region of upwelling expands and shrinks out-of-phase with the strength of the Indian monsoon on precession timescales, the upwelling signal captured by the proxy in many cases is out-of-phase with the Indian monsoon.

Acknowledgments

The NCEP reanalysis data was obtained from <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>. The GPCP precipitation data is publicly available at <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>. The $\delta^{18}\text{O}$ from the sediment core in North Bay of Bengal (Kudrass et al., 2001) was obtained from <https://doi.pangaea.de/10.1594/PANGAEA.735053>. Data from the cores RC27-14 and RC27-23 (Altabet et al., 2002) can be accessed from <https://www.ncdc.noaa.gov/paleo-search/study/2617>. The data from NIOP497, NIOP464, and NIOP455 cores (Reichart et al., 1998) is available from <https://www.ncdc.noaa.gov/paleo-search/study/2557>. The data from the core RC27-61 (S. C. Clemens & Prell, 2003) can be accessed from <https://www.ncdc.noaa.gov/paleo-search/study/5882>. We are thankful to T. Caley for providing the data from the core MD04-2861 (Caley et al., 2011). Data from the core GeoB3004-1 is available at <https://doi.pangaea.de/10.1594/PANGAEA.738202>. The EC-Earth data used here can be accessed from <https://zenodo.org/record/4912315#.YL91DC0RpJl>. The servers hosting our CESM simulation data at the institute have been turned off in accordance with the lockdown guidelines. Hence, as of now, we were not able to deposit the data in any repository. However, we confirm that the relevant data will be made available through a suitable data repository at the earliest possible.

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