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Subsurface ocean characteristics and their impact on Indian monsoon advancement: A case study

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सार – भारतीय प्रायद्वीप पर मॉनसूनप्रणाली भारतीय महासागर और वायुमंडलीय स्थितियों के बीच जटिल तालमेल से काफी प्रभावित होता है। यह अनुसंधान इस बात की जांच करता है कि मॉनसूनकि उन्नति चरण के दौरान हिंद महासागर में संभावित तापमान और लवणता का स्तर कैसे बदलता है। इन प्रतिरूप का विश्लेषण करने के लिए, हम हिंद महासागर (IO) पर संभावित तापमान, लवणता और हवा के दैनिक और मासिक औसत की जांच करते हैं। यह अध्ययन विशेष रूप से शिनाख्त करता है कि समुद्री सतह के नीचे के तापमान और लवणता सहित समुद्री विशेषताएं, मॉनसून के मौसम के समय, सामर्थ्य और अवधि को कैसे प्रभावित करती हैं। मॉनसून के आगे बढ़ने से पहले, हिंद महासागर में संभावित तापमान और लवणता वितरण में उल्लेखनीय बदलाव देखे गए। देर से आगे बढ़ने वाले वर्ष (2002) के दौरान, MAM के दौरान केरल तट से सटे ऊपरी सतह (5-25 मीटर गहराई) में कम लवणता (34 PSU से नीचे) देखी गई, जबकि जल्दी आगे बढ़ने वाले वर्ष (2005) में, उसी क्षेत्र में उच्च लवणता (34.5 PSU से ऊपर) देखी गई। दोनों वर्षों में 20 मीटर की गहराई तक उच्चतम संभावित तापमान देखा गया है, लेकिन धीमी गति से आगे बढ़ने वाले वर्ष की तुलना में तेजी से आगे बढ़ने वाले वर्ष में थोड़ा बाद में। क्षेत्र R1 (अरब सागर) में उच्चतम लवणता (36.3 PSU) 2002 के मार्च, अप्रैल, मई और जून के दौरान 50 से 80 मीटर की गहराई के बीच देखी गई, जबकि 2005 में उच्चतम लवणता (36.3 PSU) अधिक गहराई (55 से 90 मीटर) पर देखी गई। 2002 के दौरान, बंगाल की खाड़ी (BoB) में, लवणता 2005 की तुलना में अधिक तेजी से कम हुई। अरब सागरऔर बंगाल की खाड़ीके बीच तापमान और लवणता में अंतर तेजी से आगे बढ़ने वाले वर्षों में अधिक देखा गया है, जो 2002 की तुलना में 2005 में अधिक वाष्पीकरण दर्शाता है, और हवा पूरे भारत में नमी पहुंचाने में महत्वपूर्ण भूमिका निभाती है।

ABSTRACT. The monsoon system over the Indian Peninsula is significantly influenced by the complex interplay between the Indian Ocean and atmospheric conditions. This research investigates how potential temperature and salinity levels in the Indian Ocean vary during the monsoon's advancement phase. To analyze these patterns, we examine daily and monthly averages of potential temperature, salinity and wind over the Indian Ocean (IO). The study specifically explores how oceanic characteristics, including sea subsurface temperature and salinity, affect monsoon season timing, strength, and duration of the monsoon. Before monsoon advancement, the Indian Ocean exhibits notable variations in potential temperature and salinity distribution. During the late advancement year (2002), low salinity (below 34 PSU) was observed in the upper subsurface (5-25m depth) adjoining the Kerala coast during MAM, while in the early advancement year (2005), high salinity (above 34.5 PSU) was observed in the same region. The highest potential temperature has been observed up to 20 meters depth in both years, but slightly later in the fast advancement year than in the slow advancement year. The highest salinity (36.3 PSU) in the region R1 (Arabian Sea) has been observed between 50 to 80 meters depth during March, April, May and June of 2002, while in 2005 highest salinity (36.3 PSU) was observed at a larger depth (55 to 90m). During 2002, in the Bay of Bengal (BoB), salinity decreased more rapidly than in 2005. The contrast in temperature and salinity between AS and BoB has been observed to be higher in fast advancement years, showing greater evaporation in 2005 than in 2002, and wind plays a crucial role in transporting moisture all over India.

Key words – Indian ocean, Summer monsoon, Potential temperature, Salinity.

1. Introduction

The Indian Summer Monsoon (ISM) is a large-scale atmospheric phenomenon that profoundly impacts the socio-economic fabric of the Indian subcontinent and surrounding regions (Gadgil, 2003). This intricate system, driven by the temperature and pressure gradients between the Indian Ocean and the Asian landmass, brings significant rainfall to the region during the summer months. However, the onset, progression and intensity of the ISM exhibit considerable interannual and intraseasonal variability, which can have far-reaching consequences for various sectors, including agriculture, water resources, and disaster management (Krishnan *et al*., 2019).

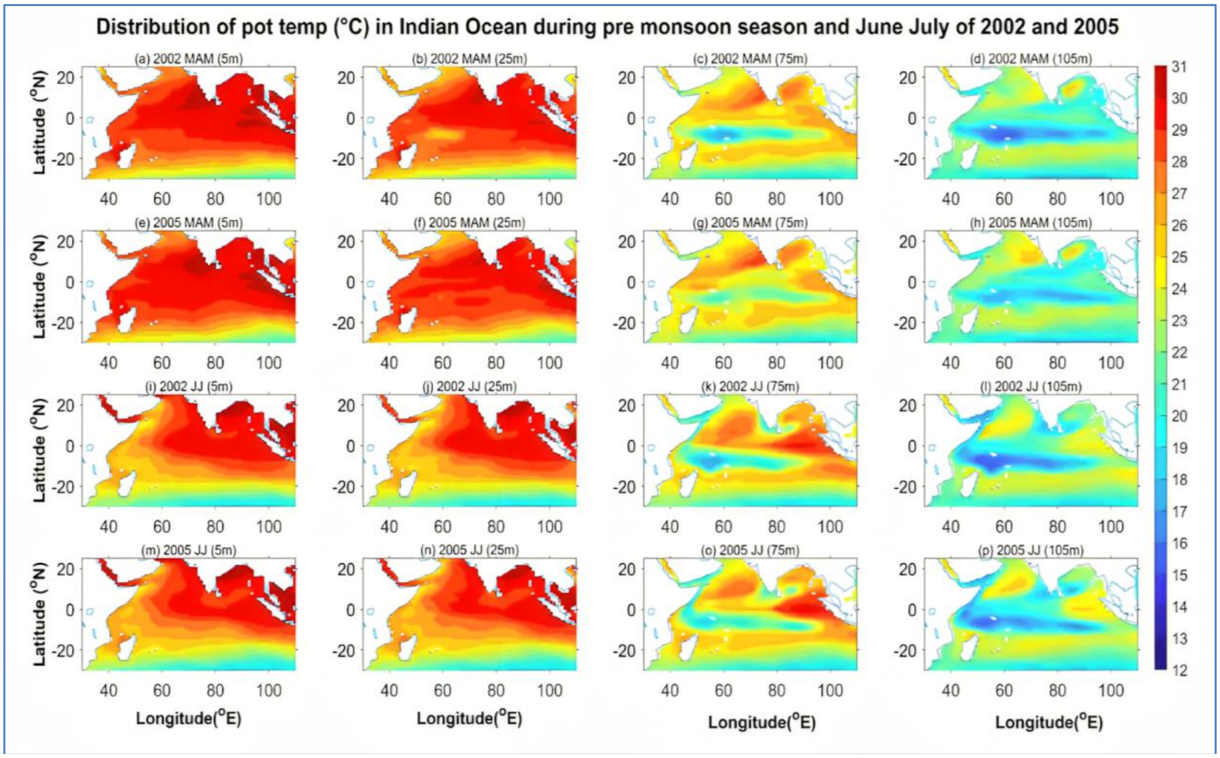
The life cycle of the MJO (30-60 days) aligns well with ISM's average lead time of 41 days (Singh *et al*., 2017). Extensive research has already explored various phases of the monsoon, including its onset, active and break periods, and withdrawal (Bhatla *et al*., 2004, 2016; Raju *et al*., 2007, 2014). Research by Joseph and Pillai (1988) found that low-frequency oscillations with 30-40 day periods are connected to the monsoon's onset and progression. According to Saha and Saha (1980), the northward migration of the inter-tropical convergence zone (ITCZ) plays a more fundamental role in defining the monsoon's northern limit than rainfall-based criteria typically used to determine ISM's onset and progression. Research by Dey and Kumar (1982) analyzed the time taken for the summer monsoon to progress from southern to northwestern India from 1967-1978. Later, Krishnamurthy and Shukla (2008) distinguished between eastward and northward propagation patterns and examined how these movements relate to convection during the Indian Summer Monsoon. While the influence of surface oceanic parameters, such as sea surface temperature (SST), on the ISM has been extensively studied (Shukla, 1987; Vecchi & Harrison, 2002), there is growing recognition of the pivotal role played by subsurface oceanic characteristics in modulating the monsoon system (Shenoi *et al*., 2002; Felton *et al*., 2014). Among these subsurface features, salinity, potential temperature, mixed layer depth, and barrier layer thickness in the Indian Ocean have garnered considerable attention from the scientific community. Subsurface salinity distributions in the Indian Ocean can influence the density stratification and vertical mixing processes, thereby impacting the heat and moisture exchange between the ocean and atmosphere (Shenoi *et al*., 2005; Nyadjro *et al*., 2011). In the Bay of Bengal, pronounced salt-based stratification exists in the uppermost ocean layer (Rao and Sivakumar**,** 2003**;** Thadathil *et al***.,** 2007**;** Girishkumar *et al***.,** 2011**),** typically linked with an intermediate "barrier layer" – defined as the region between the mixed layer bottom and the thermocline upper boundary **(**Rao and Sivakumar**,** 2003**;** Thadathil *et al***.,** 2007; Mignot *et al*., 2009; Agarwal *et al*., 2012). Anomalies in salinity patterns can alter the atmospheric stability and convection, potentially affecting the onset and strength of the ISM. Furthermore, the salinity structure in the Indian Ocean is closely linked to the Indian Ocean Dipole (IOD) phenomenon, which is known to modulate the monsoon rainfall patterns (Saji *et al*., 1999; Webster *et al*., 1999). Similarly, the subsurface potential temperature profiles in the Indian Ocean play a crucial role in governing the ocean-atmosphere heat fluxes and atmospheric convection (Hareesh Kumar *et al*., 2017; Kido & Tozuka, 2017). Positive potential temperature anomalies can enhance atmospheric instability, favouring stronger monsoon rainfall, while negative anomalies can suppress convection and weaken the monsoon system.

By investigating the complex interplay between these subsurface oceanic parameters and their interactions with atmospheric processes, researchers aim to improve the understanding and predictability of the ISM advancement system. This knowledge can contribute to more effective monsoon forecasting, risk management strategies, and sustainable resource planning in the region. The remainder of the paper is organized as follows: Section 2 describes the data and methodology used in this study; Section 3 presents the results and discussion; and Section 4 provides the conclusions.

2. Data and methodology

The number of days for the advancement of monsoon over India was obtained from Khole (2009). We selected 2002 and 2005 for our study due to their significant deviations from typical monsoon progression (41 days) (Singh *et al*., 2017), with periods of 78 (+37 days) and 25 (-16 days) days, respectively. The oceanographic analysis employs salinity and potential temperature data from ECCO (Estimating the Circulation and Climate of the Ocean) V4r4n, interpolated 0.5-degree grid resolution (Qu and Melnichenko, 2023). While the raw data is collected daily, our analysis focuses on monthly averaged potential temperature and salinity values at specific depths of 5, 25, 75, and 105 meters. Further, our analysis centers on 5 distinct sub-regions R1 (55° E - 75° E, 8° N - 20° N, *i.e*., AS), R2 (80° E - 90° E, 8° N - 20° N, *i.e*., BoB), R3 (50° E - 65° E, 2° S - 8° N), R4 (65° E - 80° E, 2° S - 8° N) and R5 (80° E -95° E, 2° S - 8° N) within this larger study area (Shee *et al*., 2023).

Within these five sub-regions, we perform an in-depth examination of daily salinity patterns, analyzing variations from surface waters (5 meters) to deep waters (200 meters). Atmospheric circulation patterns over the



Figs. 1(a-p). Distribution of potential temperature (° C) in the Indian Ocean at different depth levels (5 m, 25 m, 75 m, and 105 m) during the pre-monsoon season and in June and July of 2002 and 2005

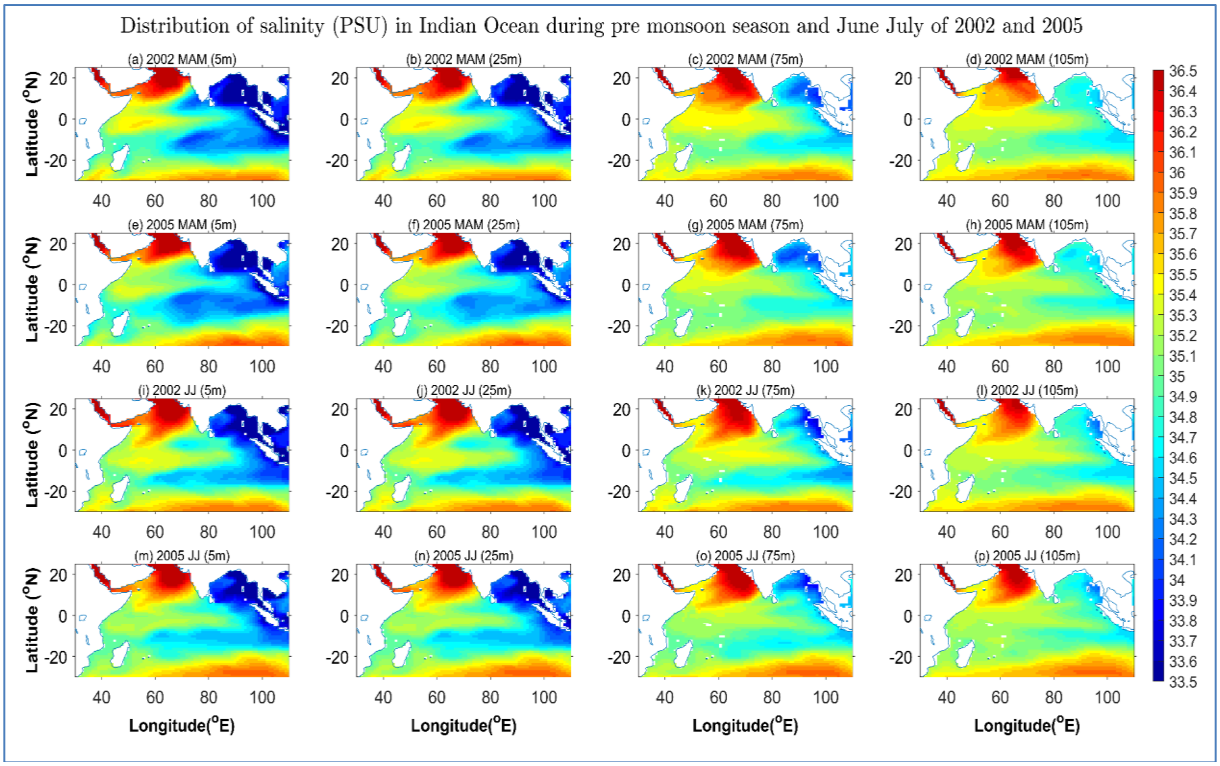
Indian Ocean are characterized using ERA5 reanalysis data from ECMWF, specifically examining monthly zonal and meridional wind components at the 850 hPa pressure level (Gunwani *et al*., 2021).

3. Results and discussion

3.1. *Profile of potential temperature at Various Depths during pre-monsoon season, June and July*

Distribution of potential temperature in IO at different depths (5, 25, 75 and 105 m) has been shown in Fig. 1 during the pre-monsoon season and June & July of 2002 (slow advancement year) and 2005 (fast advancement year). During the pre-monsoon season in both years, at the uppermost subsurface (5 m), higher temperatures (>30 °C) were observed near the western coast of India, most of the AS, and near Indonesia, but the distribution of higher temperatures was larger in 2005 than in 2002, and lower temperatures (27 °C) were observed in the head of the AS in both years (Chatterjee *et al*., 2012), Fig. 1(a & e). As the depth increased (25 m), temperature decreased slightly all over IO but in northeast of Madagascar, temperature decreased dramatically up to 5 °C in 2002 while in 2005 higher temperature were observed and uniformly high temperature has been observed in BoB (Qu *et al*., 2005), Fig. 1(b & f). At 75 meters depth, the temperature contrast between AS and BoB was observed to be higher in 2005 than in 2002 during the pre-monsoon season. At 105 meters, the higher temperature was observed in BoB than in AS in the year 2002, and the reverse pattern of temperature was observed in 2005.

During June and July at the uppermost subsurface (5 m) in 2002 higher temperatures (>30 °C) were observed in the head of BoB than in 2005 while near the Somalia coast and north of Madagascar lower temperatures (26 °C) were observed in 2002 and decreased slowly towards east while in 2005 comparatively higher temperature (27 °C) were observed and decreased more rapidly towards east, it may be due to lesser insolation in 2002 (Li *et al*., 2018), Fig. 1(i & m). At 25 meters depth, a higher temperature was still observed in the head of BoB during 2002 than in 2005, and also near the western Indian coastal region in AS higher temperature was observed in 2002 compared to the year 2005 but the temperature decreased more rapidly in 2002 than 2005 towards the Somalia coast, Fig. 1(j & n). Fig. 1(k & o) shows the dramatically low temperature (17 °C) near the north of Madagascar and the southern coastal region of India at 75 meters. North of the equator, comparatively higher temperatures were observed during June and July in 2002 than in 2005. At 105 meters depth, temperature contrast between AS and BoB was higher in 2005 than in 2002 Fig. 1(l & q).



Figs. 2(a-p). Distribution of salinity (PSU) during the pre-monsoon season and June-July of 2002 and 2005 in IO at different depth levels (5m, 25m, 75m, and 105m)

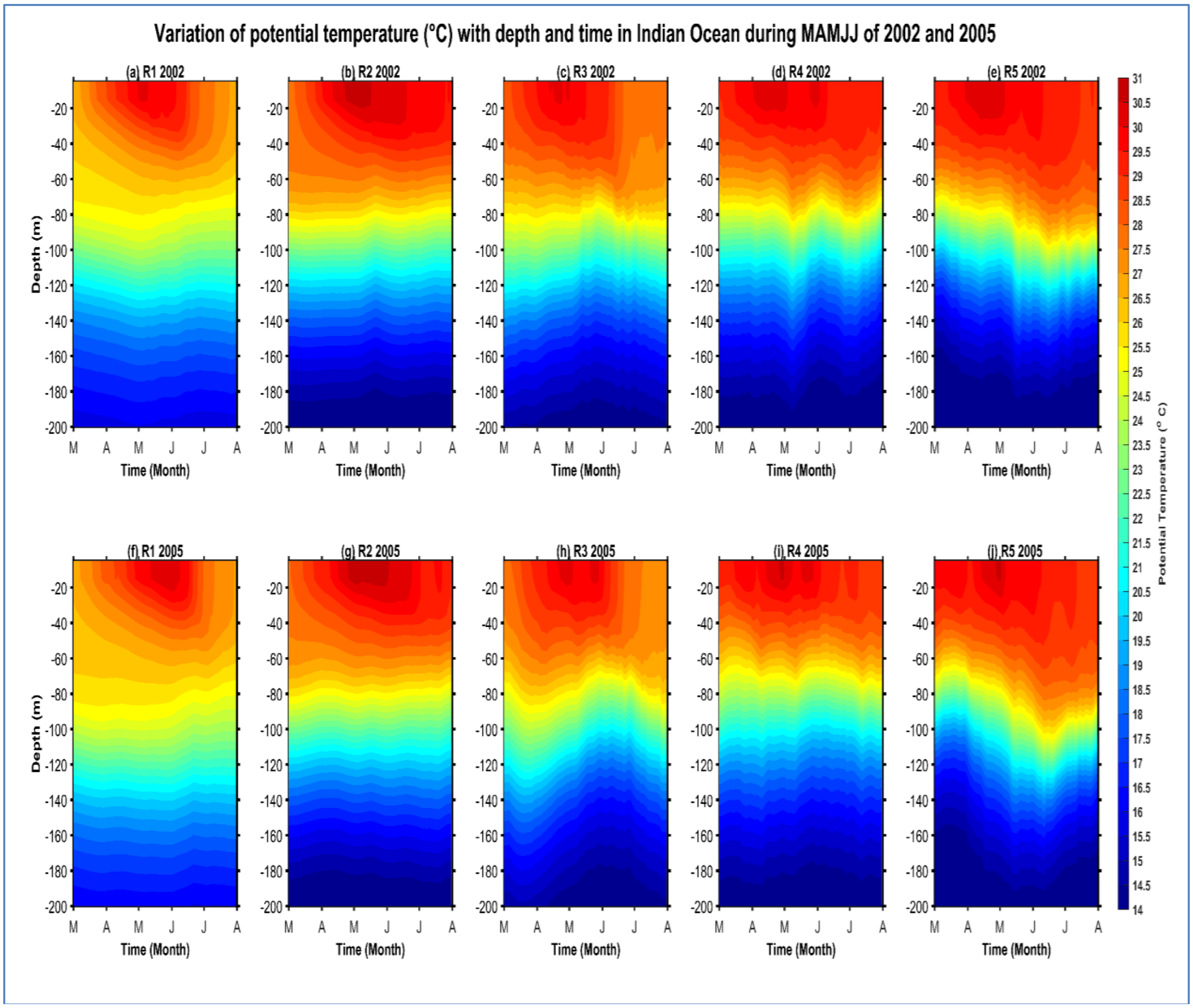
3.2. *Profile of salinity at Various Depths during pre-monsoon season, June and July*

The spatial distribution of salinity in IO has been depicted in Fig. 2 at different depths. The salinity contradiction between the head of AS and the head of BoB has been observed to be higher in upper sub-surfaces while moderate in lower sub-surfaces. BoB received more fresh water than AS, hence the salinity of BoB is much less than that of AS while having the same latitude (Rao and Shivakumar, 2003; Rao, 2015).'

At the upper subsurface (5 meters), during pre-monsoon in 2002 low salinity (<30 PSU) was observed in BoB along with the Kerala coast and Indonesia region while high salinity in the head of AS and moderate near north of Madagascar (Fig. 2a). At the same depth (5 meters) in 2005, slightly higher salinity has been observed near the eastern coast of India and also Kerala coast region (34.5 PSU) but slightly lesser near north of Madagascar than in 2002 (Fig. 2e). At 25 meters depth in both years, salinity has increased slightly all over IO Fig. 2(b & f). During the pre-monsoon season at 75 meters depth salinity has increased in both regions (AS and BoB); hence, the salinity contrast between both regions has more or less the same in 2002 (Fig. 2c). Salinity in the BoB did not increase in 2005 as it did in 2002, but in the AS, salinity increased more in 2005 than in 2002; hence, the salinity contrast between both regions was higher in 2005 (Fig. 2g). As the depth increased, salinity in the BoB increased in both years while decreasing in AS, but the salinity contrast in 2005 was observed to be higher than in 2002 during pre-monsoon at 105 meters depth may be due to higher evaporation in 2005 (Yu, 2007). At 5 meters depth, salinity in AS was observed to be higher in 2002 (slow advancement year) than in 2005 (fast advancement year), while more or less the same salinity was observed in 2002 as in 2005 during June and July Fig. 2(i & m). At the next sub-surface (25 m), salinity has slightly increased in IO in both years Fig. 2(j & n). At 75 meters depth, higher (lower) salinity has been observed in AS (BoB) during 2005 than in 2002; hence, the salinity contrast between AS and BoB is higher in 2005 than in 2002 Fig. 2(k & o). The salinity has decreased at 105 meters depth in both years, but the salinity contrast between AS and BoB was higher in 2005 Fig. 2(l & q).

3.3. *Vertical distribution of potential temperature and salinity with time in different region of the IO during the MAMJJ Period*

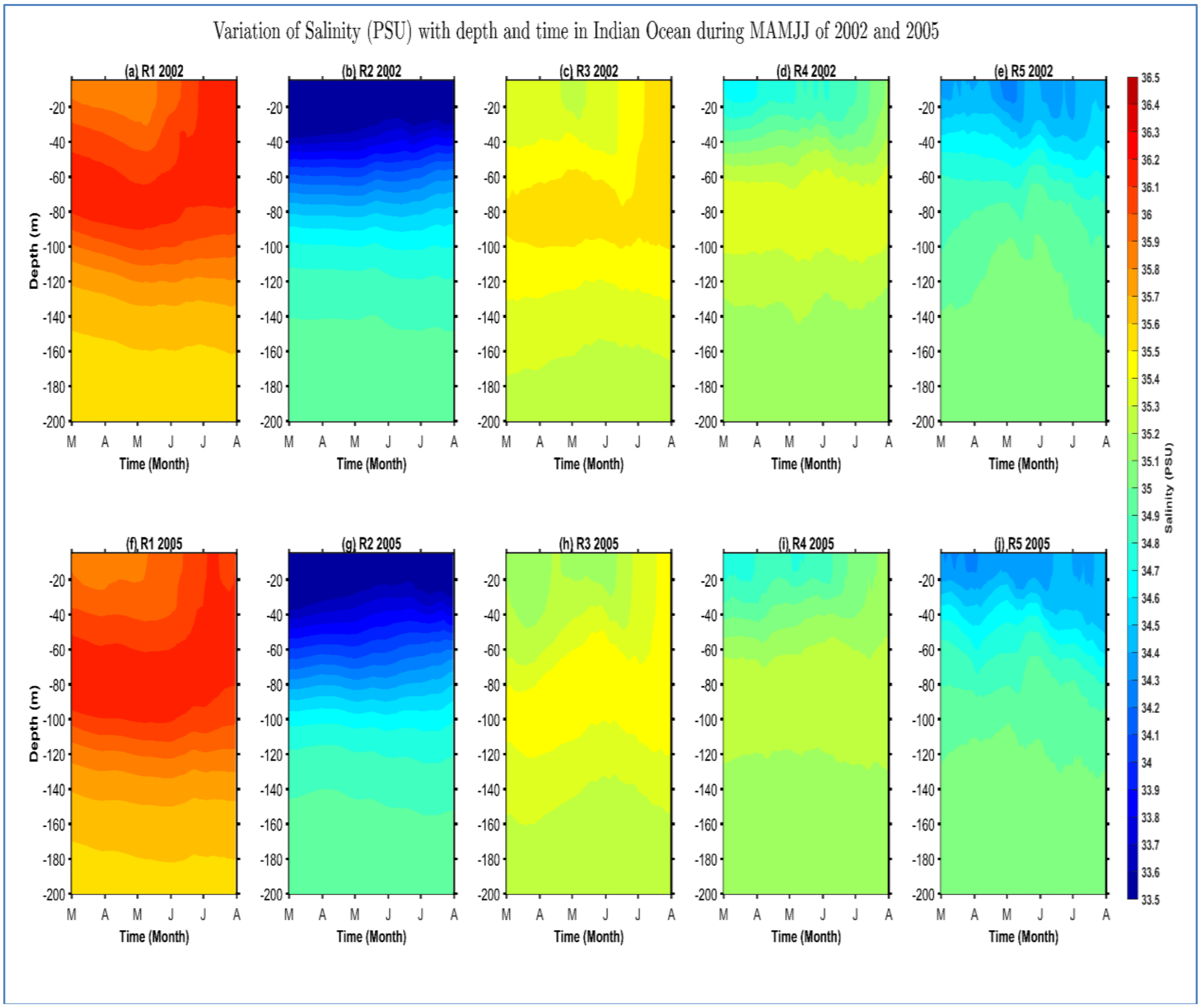
Variation of potential temperature during March, April, May, June, and July (MAMJJ) has been shown in Fig. 3. The Upper row shows the variation of potential



Figs. 3(a-j). Vertical distribution of potential temperature (º C) in the different regions of IO during MAMJJ of 2002 and 2005

temperature during MAMJJ 2002 across five different regions, while the lower row shows the variation of potential temperature during MAMJJ 2005. During 2002, temperature increased with time in the upper sub-surface of AS (R1). From the beginning of March, the temperature increased with time, and in the first week of April, the highest temperature (31 °C) was observed up to 20 meters. After that, the temperature decreased with time until the end of July. Between 60 to 80 meters depth, mild temperature (26 °C) was observed from the beginning of May to the end of July. During March to April, the same temperature was observed between 50 to 80 meters depth, with a linear increase of depth with time showing a linear increase of temperature with depth in AS (Fig. 3a). In the same region during 2005, the highest temperature (31 °C) was observed from the second week of May to the first week of July, and a mild temperature (26 °C) was observed between 70 to 85 meters depth at the beginning of March. While at the end of July, the same temperature was observed between 60 to 70 meters depth. This shows the temperature was increased with time during MAMJJ 2005 in AS (Fig. 3f). In the BoB, more or less the same temperature distribution was observed during MAMJJ of both years below 60 meters depth. The highest temperature (31 °C) was observed in the upper sub-surface of BoB from mid-April to mid-June 2002 up to 30 meters in depth, while in 2005, the highest temperature (31 °C) was observed until the last week of June Fig. 3(b & g). In the sub-region R3, temperature gradually decreased with depth but increased with time in both years, and the highest temperature was observed in the last two weeks of May 2002, while in 2005, the highest temperature was observed in the last weeks of May and June Fig. 3(c & h).

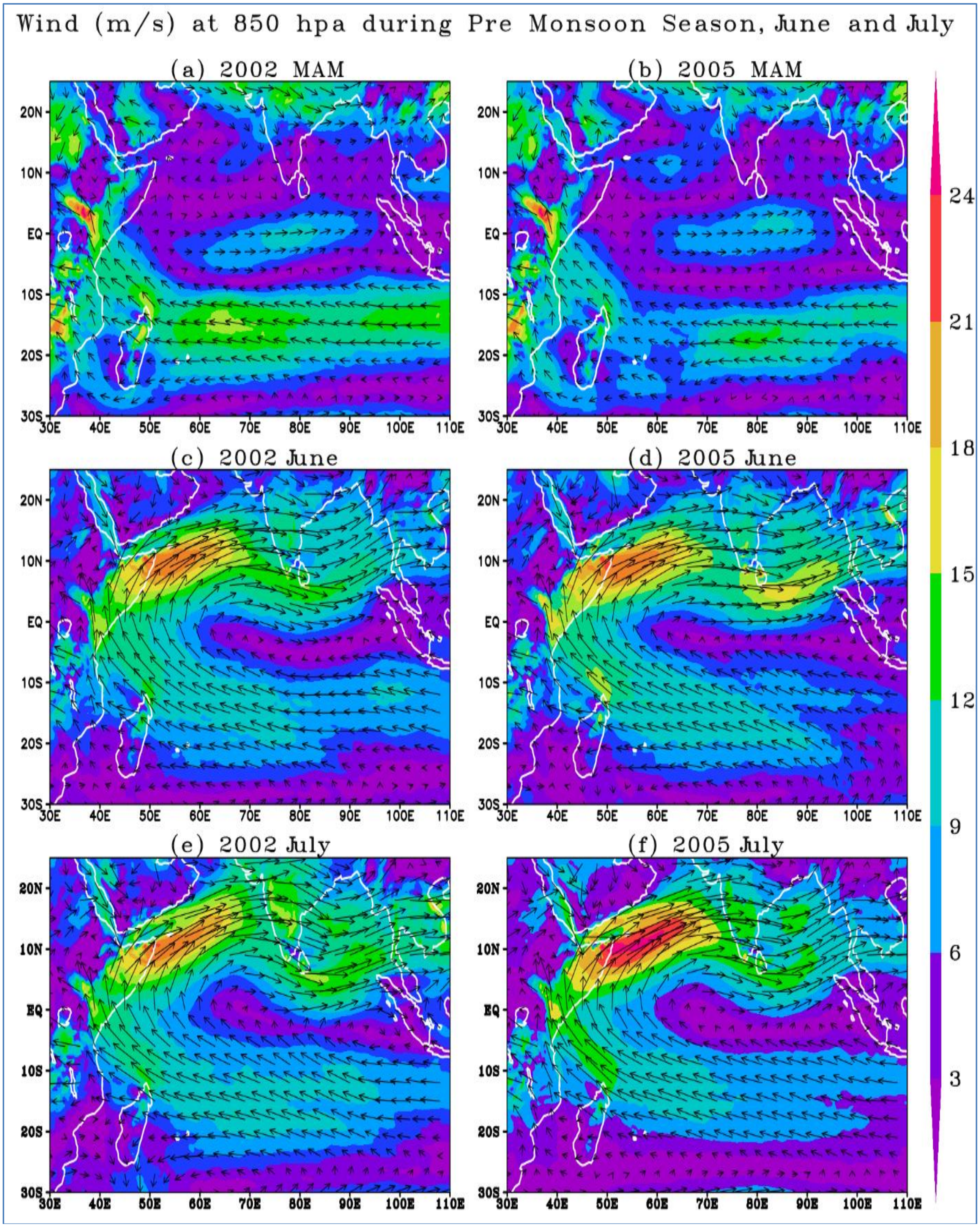
The potential temperature was observed to be higher in the upper subsurface of sub-region R4 during MAMJJ 2002, with the highest temperature (30.5 °C) throughout



Figs. 4(a-j). Vertical distribution of salinity (PSU) in the different regions of IO during MAMJJ of 2002 and 2005

April and the last week of May up to 20 meters depth (Fig. 3d), while for the same region and same duration, higher temperature (31 °C) was observed in 2005, and temperature decreased in the upper subsurface during July 2005. Moderate temperature (26 °C) was observed between 60 to 70 meters in depth throughout MAMJJ in 2005, while the same temperature was observed between 70 to 80 meters in depth in 2002. This shows that temperature decreased more rapidly in 2005 than in 2002 (Fig. 3i). The higher temperature was observed in the upper subsurface up to 40 meters depth during MAMJJ in both years, and slightly decreased in the last two weeks of July. In both years, temperature decreased gradually up to 40 meters depth; after that, it decreased rapidly in both study years Fig. 3(e & j).

In the five different regions of the IO including AS and BoB, variations of salinity with depth and time (from 5 meters depth to 200 meters) during MAMJJ months of the years 2002 and 2005 are depicted in Fig. 4. In the upper subsurface of AS, low salinity (35.85 PSU) was observed from mid-March to mid-May, after which it gradually increased with both time and depth, reaching 36.2 PSU by the end of August. At a depth of 75 meters, high salinity (36.2 PSU) was observed in March, followed by a slight decrease over time; however, by July, the same salinity (36.2 PSU) was observed again. Below 100 meters depth, salinity has decreased continuously down to 200 meters depth (Fig. 4a). In 2005, low salinity (35.85 PSU) was observed in the upper sub-surface of AS at the end of March. After that, it increased very gradually over time but more rapidly with depth. Maximum salinity (36.2 PSU) in AS was observed between 65 and 85 meters depth from March to mid-June, after which salinity decreased continuously with depth (Fig. 4f). In the BoB, during both years, low salinity was observed in the upper



Figs. 5(a-f). Distribution of wind during pre-monsoon season, June and July of 2002 and 2005 over IO at 850hPa sub-surface up to 50 meters depth. Salinity was increased rapidly (gradually) with time in 2005 (2002). After mid-June 2005, salinity decreased rapidly Fig. 4(b & g).

Fig. 4(c & h) shows the variation of salinity in region R3. Low salinity was observed in the upper subsurface from March to May 2002, after which it gradually increased until the end of July. Salinity increased gradually with depth to 80 meters in April and May. Below 80 meters, salinity decreased gradually with depth (Fig. 4c). Extremely low salinity was observed in the upper sub-surfaces of region R3 in 2005 until the end of June, after which it increased very gradually. At a depth of 75 meters, salinity increased over time from March to May, but in June 2005, it decreased abruptly until the end of the month. Below 80 meters, salinity decreased gradually with depth (Fig. 4h). In 2002, high salinity was observed at depths of 60 to 100 meters from March to July, while low salinity was observed from the upper subsurface down to 50 meters until mid-July. Below 100 meters, salinity gradually decreased (Fig. 4d). The salinity of the upper sub-surface in region R4 in 2005 was observed to be more or less the same as in 2002, but between 60 and 100 meters depth, it was much lower in 2005 than in 2002 (Fig. 4i). In the region R5, a similar pattern and comparable amount of salinity were observed in both years up to 130 meters. Beyond that depth, high salinity was observed during March, April, and May of 2005, whereas in 2002, high salinity was observed in mid-May at a depth of 130 meters Fig. 4(e & j).

3.3. *Wind patterns at the 850 hPa level over the IO during the pre-monsoon season, June and July.*

Special distribution of wind at 850 hPa over IO is depicted in Fig. 5. The intensity of the wind is represented by the shading and length of arrows, while the arrowheads indicate the direction of the wind. During a pre-monsoon season in both years, a north-easterly wind was observed over the AS (moderate to high in 2005), while over a south-westerly wind was observed over BoB (Sankar *et al*., 2011) Fig. 5(a & b). In June of both years, intense south-westerly winds were observed along the Somalia coast, while strong westerly winds covered the entire Indian peninsula. Additionally, very strong winds were observed south of Sri Lanka in 2005 Fig. 5(c & d). The wind intensity and direction over Somalia in July 2002 were similar to those in June, but the intensity over India and BoB was much higher in July than in June (Fig. 5e). Very intense south-westerly (nearly westerly) winds were observed near the Somalia coast during July 2005, extending to the western coast of India. This intense wind helps the monsoon to cover the entire Indian region earlier (Fig. 5f).

4. Conclusions

This study highlights significant potential temperature and salinity variations in the IO during pre-monsoon periods and the first two months of the monsoon season, comparing the western IO (WIO) and eastern IO (EIO) regions. The AS in the WIO exhibits peak salinity levels in its upper subsurface waters. Conversely, the BoB in the EIO shows markedly lower salinity concentrations in its upper subsurface layers, primarily due to freshwater influx from river systems (Rao and Shivakumar, 2003; Rao, 2015). In the year of fast advancement of monsoon (2005), monsoon reached Kerala on 05th June (as per IMD report). During the pre-monsoon season of 2005, the highest temperature (>30 °C) was localized in AS (near the western coast of India) while in June and July, the highest temperature (>30 °C) was localized eastern coast of India (including the head of BoB) and the same pattern of temperature has also shown 2002. In all five regions, temperature is higher in 2005 than in 2002, which shows greater evaporation in 2005, causing high moisture in the atmosphere. During the late onset year, the highest temperature (30.5 °C) was observed in AS during the first week of May up to 20 meter, while in BoB 31 °C was observed from mid-April to mid-June whereas the highest temperature (31 °C) in R2 (BoB) was observed from last week of April to mid-May. In 2005, the highest temperature (30.5 °C) in AS was observed from mid-May to first week of June, below 20 meters, whereas in the BoB 30.5 °C was observed from mid-April to mid-June, and highest temperature, 31 °C was observed in May, and after mid-June temperature decreased gradually in both years. The highest temperature in BoB for long time create a low pressure in BoB, which helps to transport the moisture towards the BoB., Salinity in region R1 (AS) is slightly higher than R3 (near Somalia coast along with some eastern part) and R4 (near Kerala coast along with some western part) (between 60 to 80 meters depth) during MAMJJ 2002 while on same depth and period in 2005 salinity is much higher in R1 than R3 and R4 it may be due to low degree of evaporation in R3 and R4 during 2005 and wind in June and July of 2005 has more intensified than June and July of 2002 which may also help monsoon to cover all over India earlier. In 2002, the highest salinity (36.1PSU) was observed between 50 to 80 meters depth, in May, it decreased to 60 to 85 meters depth. After which it expanded and reached to uppermost subsurface to 80 meters in July. Whereas in 2005, the same salinity was observed between 55 to 95 meters depth in AS, and expanded to the uppermost subsurface to 80 meters in July. In R2, salinity increased more rapidly in 2002 than in 2005, which also created a contrast between AS and BoB. Again, the high salinity in 2005 shows greater evaporation in 2005 than in 2002. In July 2005, the wind was much higher than in 2002, which helped to transport the moisture earlier to the entire Indian region.

Data Availability

The weather data supporting the findings of this study is available upon request, and the datasets will be shared accordingly.

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Conflicts of Interest

The authors declare no conflict of interest.

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R. Bhatla: Conceptualization, Methodology, Supervision, Writing - Review & Editing.

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Reference.

Agarwal, N., Sharma, R., Parekh, A., Basu, S., Sarkar, A. and Agarwal, V. K., 2012, "Argo observations of barrier layer in the tropical Indian Ocean", *Advances in Space Research*, **50**, 5, 642-654.

Bhatla, R., Mohanty, U. C., Raju, P. V. S., and Madan, O.P., 2004, "A study on dynamic and thermodynamic aspects of breaks in the summer monsoon over India", *International journal of climatology*, **24**,3, 341-360.

Bhatla, R., Raju, P. V. S., Mall, R. K. and Bist, S., 2016, "Study of surface fluxes during onset of summer monsoon over India", *International Journal of Climatology*, **36,** 4.

Chatterjee, A., Shankar, D., Shenoi, S. S. C., Reddy, G. V., Michael, G. S., Ravichandran, M., and Sanjeevan, V. N., 2012, "A new atlas of temperature and salinity for the North Indian Ocean", *Journal of Earth System Science*, **121**, 559-593.

Dey, B., and Kumar, O. B., 1982, "An apparent relationship between Eurasian spring snow cover and the advance period of the Indian summer monsoon", *Journal of Applied Meteorology*, **21**, 12, 1929-1932.

Felton, C. S., Subrahmanyam, B., Murty, V. S. N., and Shriver, J. F., 2014, "Forced subsurface warming over the Atlantic western boundary currents and the associated impacts on the development of hurricanes", *Journal of Geophysical Research: Oceans*, **119,** 9, 5935-5957.

Gadgil, S., 2003, "The Indian monsoon and its variability", *Annual Review of Earth and Planetary Sciences*, **31,** 1, 429-467.

Girishkumar, M. S., Ravichandran, M., McPhaden, M. J., and Rao, R. R. 2011, "Intraseasonal variability in barrier layer thickness in the south central Bay of Bengal", *Journal of Geophysical Research: Oceans*, **116,** C3.

Gunwani, P., Sati, A. P., Mohan, M., and Gupta, M., 2021, "Assessment of physical parameterization schemes in WRF over national capital region of India", *Meteorology and Atmospheric Physics*, **133**, 2, 399-418.

Hareesh Kumar, P. V., Kumar, B. P., Matthew, J., and Vialard, J., 2017, "Processes of vertical heat redistribution by ENSO events in the equatorial Indian Ocean", *Journal of Geophysical Research: Oceans*, **122,** 7, 5956-5979.

Joseph, P. V., and Pillai, P. V., 1988, "40-Day Mode of Equatorial Trough For Long· Range Forecasting Of Indian Summer Monsoon ONSET", *Current Science*, **57,** 17, 951-954.

Khole, M., 2009, "Meteorological conditions associated with very sluggish advance of Indian summer monsoon in 2002", *Mausam*, **60,** 1, 51-60.

Kido, S., and Tozuka, T., 2017, "Salinity variations associated with interannual variability of the tropical Indian Ocean in the CMIP5 models", *Climate Dynamics*, **48,** 7-8, 2361-2375.

Krishnamurthy, V., and Shukla, J. J. C. D., 2008, "Seasonal persistence and propagation of intraseasonal patterns over the Indian monsoon region", *Climate Dynamics*, **30**, 4, 353-369.

Krishnan, R., Sabin, T. P., Ayantika, D. C., Kitoh, A., Sugi, M., Murakami, H., and Krishnan, R., 2019, "Towards Indian monsoon drought and flood risk assessments for agriculture and hydrological impacts" *Current Science*, **116,** 4, 538-554.

Li, Z., Chen, M. T., Lin, D. C., Shi, X., Liu, S., Wang, H., and Hendrizan, M., 2018, "Evidence of solar insolation and internal forcing of sea surface temperature changes in the eastern tropical Indian Ocean during the Holocene", *Quaternary international*, **490**, 1-9.

Mignot, J., Montégut, C. D. B., and Tomczak, M., 2009, "On the permeability of barrier layers", *Ocean Science Discussions*, **6,** 1, 799.

Nyadjro, E. S., Subrahmanyam, B., and Murty, V. S. N., 2011, "On the occurrence of the Arabian Sea mini warm pool in the northern Indian Ocean", *Journal of Geophysical Research: Oceans*, **116,** C5.

Qu, T., and Melnichenko, O., 2023, "Steric changes associated with the fast sea level rise in the upper South Indian Ocean", *Geophysical Research Letters*, **50,** 4, e2022GL100635.

Qu, T., Du, Y., Strachan, J., Meyers, G., and Slingo, J., 2005, "Sea Surface Temperatureand Its Variability", *Oceanography*, **18,** 4, 50.

Raju, P. V. S., and Bhatla, R., 2014, "Evolution of withdrawal features of the southwest monsoon over India", *International journal of climatology*, **34,** 6.

Raju, P. V. S., Mohanty, U. C., and Bhatla, R., 2007, "Interannual variability of onset of the summer monsoon over India and its prediction", *Natural Hazards*, **42**, 287-300.

Rao, R. R., 2015, "Observed variability of near-surface salinity field on seasonal and interannual time scales and its impact on the evolution of sea surface temperature of the tropical Indian Ocean", *The International Journal of Ocean and Climate Systems*, **6,** 2, 87-111.

Rao, R. R., and Sivakumar, R., 2003, "Seasonal variability of sea surface salinity and salt budget of the mixed layer of the north Indian Ocean", *Journal of Geophysical Research: Oceans*, **108,** C1, 9-1.

Saha, S., and Saha, K., 1980, "A hypothesis on onset, advance and withdrawal of the Indian summer monsoon", *pure and applied geophysics*, **118**, 1066-1075.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., and Yamagata, T. 1999, "A dipole mode in the tropical Indian Ocean", *Nature*, **401,** 6751, 360-363.

Sankar, S., Kumar, M. R., and Reason, C. (2011). On the relative roles of El Nino and Indian Ocean Dipole events on the Monsoon Onset over Kerala. *Theoretical and applied climatology*, **103**, 359-374.

Shee, A., Sil, S., and Gangopadhyay, A., 2023, "Recent changes in the upper oceanic water masses over the Indian Ocean using Argo data", *Scientific Reports*, **13,** 1, 20252.

Shenoi, S. S. C., Shankar, D., and Michael, G. S., 2005, "On the effects of local and remote forcing on the unusual upwelling along the east coast of India during the summer monsoon of 2005", *Deep Sea Research Part I: Oceanographic Research Papers*, **52,** 12, 2312-2325.

Shenoi, S. S. C., Shankar, D., and Shetye, S. R., 2002, "Differences in heat budgets of the near-surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon", *Journal of Geophysical Research: Oceans*, **107**, C6, 5-1.

Shukla, J., 1987, "Long-term forecasting of monsoons" *Monsoon*, 523-548.

Singh, M., Bhatla, R., and Pattanaik, D. R., 2017, "An apparent relationship between Madden–Julian Oscillation and the advance of Indian summer monsoon", *International Journal of Climatology*, **37,** 4, 1951-1960.

Thadathil, P., Muraleedharan, P. M., Rao, R. R., Somayajulu, Y. K., Reddy, G. V., and Revichandran, C., 2007, "Observed seasonal variability of barrier layer in the Bay of Bengal", *Journal of Geophysical Research: Oceans*, **112,** C2.

Vecchi, G. A., and Harrison, D. E., 2002, "Monsoon breaks and subseasonal sea surface temperature variability in the Bay of Bengal", *Journal of Climate*, **15,** 12, 1485-1493.

Webster, P. J., Moore, A. M., Loschnigg, J. P., and Leben, R. R., 1999, "Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98", *Nature*, **401,** 6751, 356-360.

Yu, L., 2007, "Global variations in oceanic evaporation (1958–2005): The role of the changing wind speed". *Journal of climate*, **20,** 21, 5376-539.