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Examining the salinity changes at different depths in the Indian Ocean prior to summer monsoon season and its connection to monsoon arrival in India: A case study

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ABSTRACT

The Indian Ocean interacts intricately with the atmosphere, and its features, such as sea surface temperature and salinity. The Indian Ocean can influence the monsoon's onset, intensity, and duration. This study examines the fluctuation of the salinity in the Indian Ocean throughout the onset phase over the Indian Peninsula, with a focus on the Kerala coast. The study makes use of daily averaged reanalysis data from 1992 to 2017 from the Ocean Reanalysis System 5 (ORAS) of the European Centre for Medium-Range Weather Forecasts (ECMWF). Considerable variations in salinity have been seen in the Indian Ocean prior to the onset of the monsoon. Higher salinity levels are found in the top subsurface layers of the western Indian Ocean, namely the Arabian Sea, whereas lower salinity concentrations are found in the equivalent layers of the eastern Indian Ocean, which include the Bay of Bengal. The salinity gradient between the Arabian Sea and Bay of Bengal decreases with depth due to the inflow of freshwater into Bay of Bengal through river discharge. The peak salinity is localized in a specific region, adjacent to the Somalia and Kenya coastlines, within depths ranging from 20 to 80 meters from March to the first week of May. Subsequently, this region of heightened salinity, extends to depths ranging from 50 to 90 meters. During the pre-monsoon months of the early onset year, intense evaporation leads to immense moisture in the atmosphere. Conversely, moisture is low during normal onset and late onset years, with wind-driven moisture transport towards the Kerala coast.

Keywords: Indian Ocean, Summer Monsoon, Sea Surface Temperature, Salinity, Kerala Coast

INTRODUCTION

The Indian Summer Monsoon is a crucial meteorological phenomenon that profoundly shapes India's climate and agricultural productivity (Gadgil and Rupa Kumar, 2006). It describes the precipitation that falls across the Indian subcontinent as a result of the seasonal reversal of winds, which usually occurs from June to September (Goswami et al., 1999; Krishnan et al., 2013). According to the Indian meteorological calendar, the onset of the Indian Summer Monsoon over southern India, also known as Monsoon Onset over Kerala, signifies the beginning of the rainy season (Ananthakrishnan and Soman, 1988). The onset of the Indian monsoon is accompanied by significant transformations in atmospheric circulation patterns. This dramatic shift includes major changes in wind patterns, pressure systems, and overall atmospheric flow across the region (Ananthakrishnan et al., 1983). The Southwest Monsoon Current, which flows generally eastward in the northern Indian Ocean throughout the summer, circles around Sri Lanka and enters the Bay of Bengal after traveling eastward south of India (Vinayachandran et al., 1999). The onset dates of the monsoon over Kerala, show a strong positive correlation with how often the zonal index at 500 hPa level occurs in the region between 160°E-45°W and 35°N-70°S (Bhatla and Chattopadhyay, 2003). Small changes in the commencement date, can have a significant impact on particularly sensitive areas even if the monsoon season's total average rainfall is normal (Raju et al., 2007). Bhatla et al. (2016a) examined changes in surface meteorological fields and approximated surface heat fluxes associated with the onset of the summer monsoon seasons based on 50-year data collected over India from 1957 to 2006. There are some impact of Madden Julian Oscillation on onset of Indian Summer Monsoon studied by Bhatla et al. (2017). The annual fluctuation of sea surface salinity anomalies moves earlier than that of sea surface temperature anomalies in similar places because of changes in wind stress and freshwater flow (Yuan et al., 2018). Some studies have also been carried out by modelling to simulate the onset of monsoon over India (Bhatla et el., 2015, 2016b, 2019). Fasullo and Webster (2003) utilized vertically integrated moisture transport, while Taniguchi et al. (2010) observed a strong link between rapid wind speed increases and the sudden start of the rainy season. Wang et al. (2009) suggested a straightforward definition based solely on the 850 hPa wind field. The factors affecting salinity changes with depth in the Indian Ocean during monsoon season, are complex and vary across different oceanic regions (Skliris et al., 2014). To create an extended time series of Indian Summer Monsoon onset dates, using a consistent and objective method, researchers have investigated defining the onset through algorithms using pre-satellite era variables such as precipitation, moisture transport, and wind (Ordoñez et al., 2016).

Our study focuses on analyzing the year-to-year changes in salinity throughout various depths of the Indian Ocean, exploring both the patterns and underlying reasons for these variations. We also examined how these salinity changes influence the timing of the monsoon's arrival in India. Understanding these salinity fluctuations prior to the monsoon season is crucial, as it provides valuable insights for scientists and policymakers in their decision-making processes related to water usage and resource management strategies.

DATA AND METHODOLOGY

The Monsoon Onset over Kerala dates, were obtained from Roman-Stork et al. (2020). Years 2000, 2001 and 2003 (1st June, 26th May, and 13th June respectively) have been selected for this study due to large departure from normal onset within four years. Our salinity analysis relies on data from the Estimating the Circulation and Climate of the Ocean (ECCO) project, specifically Version 4 Release 4 (V4r4). This dataset provides daily mean ocean salinity estimates interpolated to a regular 0.5-degree grid. The ECCO project reconstructs three-dimensional, time-varying Ocean, sea-ice, and surface atmospheric conditions. Initial and boundary conditions are derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ORAS5 Interim reanalysis. This data is provided daily (every 24 hours) with a 1° x 1° latitude/longitude horizontal grid and 50 vertical levels. We've used the daily salinity data to calculate monthly salinity averages at various depth levels (5, 25, 55, and 75 meters).

Raju et al. (2005) have categorized onset in India into three parts (early onset, normal onset, and late onset). This study examines the spatial patterns of monthly salinity changes across the Indian Ocean, encompassing the area from 30°E to 110°E and 30°S to 25°N. Within this broad region, we find large variation in salinity near Somalia's coast and its adjoining eastern part of the Indian Ocean. The southwest monsoonal wind cross this broad region before entering in India. There are some issues in analyzing this due to the broad region, therefore, we divided this broader region into two sub-regions R1 (40°E-60°E, 9°S-9°N) and R2 (60°E-80°E, 9°S-9°N), and focus on these smaller sub-regions, each measuring 20° by 18°. For these two sub-regions, we conducted a more detailed analysis of daily salinity variations from the surface down to 400 meters depth, below 400 meters depth salinity variation was found similar in every years. We designated Early onset years, Late onset years and Normal onset years are those when onset falls within ±2 days of its mean date (June 1st) (Table 1).

RESULTS AND DISCUSSION

The spatial distribution of salinity at different depths in the Indian Ocean during March, April and May (MAM) of three different years (2001, 2000 and 2003) is depicted in (Figures1) and 2) for the pre-onset, onset and post-onset of monsoon over India. The distribution of salinity for 5 and 25 meters depths, shows a very distinct pattern with minimum salinity in the northern Bay of Bengal, while maximum salinity in the north Arabian Sea and southern Tropical Indian Ocean. Salinity decreased gradually southward from the head of the Arabian Sea. In contrast, from the head of the Bay of Bengal, it increased gradually towards the equator. While having the same latitude band, Arabian Sea and Bay of Bengal, show contrasting salinity characteristics on opposite features due addition of fresh water in the Bay of Bengal (Rao and Shivakumar, 2003; Rao, 2015). During MAM in 2001, salter water was observed near the northern coast of Somalia which becomes less salter towards the south. A large area of high salinity (35.6 PSU) has been observed near the east of Kenya, elongated in an east-west direction which gently decreased towards east at the uppermost sub surface (Figure 1a). At 25 meters depth during MAM, more or less same distribution of salinity has been observed as 5 meters depth, the salinity decreased more gradually toward the east at 25 meters depth as compared to 5 meters depth (Figure 1d).

Near the Kerala coast, high salinity was observed during MAM in 2001 at 55 meters depth, which decreases rapidly towards south while moderately decreasing westward (Figure 2a). At the lower subsurface (75 m), high salinity is observed near the Kerala coast during MAM 2001. Contrast between Arabian Sea and Bay of Bengal become lessen and also salter water has been observed near Indonesia as compared to the upper subsurface (Figure 2d). During MAM 2000 at 5 meters depth, small area of high salinity (35.6 PSU) elongated in east-west direction, has been observed east of Kenya coast and east of north Somalia coast. Low salinity has been observed near the Kerala coast (Figure 1b). At 25 meters depth during MAM 2000 more or less same distribution of salinity has been observed as 5 meters depth with smaller area of high salinity over east of Kenya coast. (Figure 2b**)** shows high salinity near the Kerala coast which decreased gradually southward and salter water has transported towards Indonesia at 55 meters depth during MAM 2000. Salinity near Kerala coast has been increased at the lower sub surface (75 meters), which has gradually decreased towards south west direction while rapidly towards southward, and the amount of salt water in Bay of Bengal and near Indonesia has been increased (Figure 2e).

Table 1. Categorization of onset years of summer monsoon over India.

Category	Years
Early onset	1994,1999,2001,2004,2006,2007 and 2009
Normal onset	1993,1998,2000,2008,2010,2011 and 2013
Late onset	1992,1995,1996,1997,2002,2003,2004,2005,2012,2014,2015 and 2016

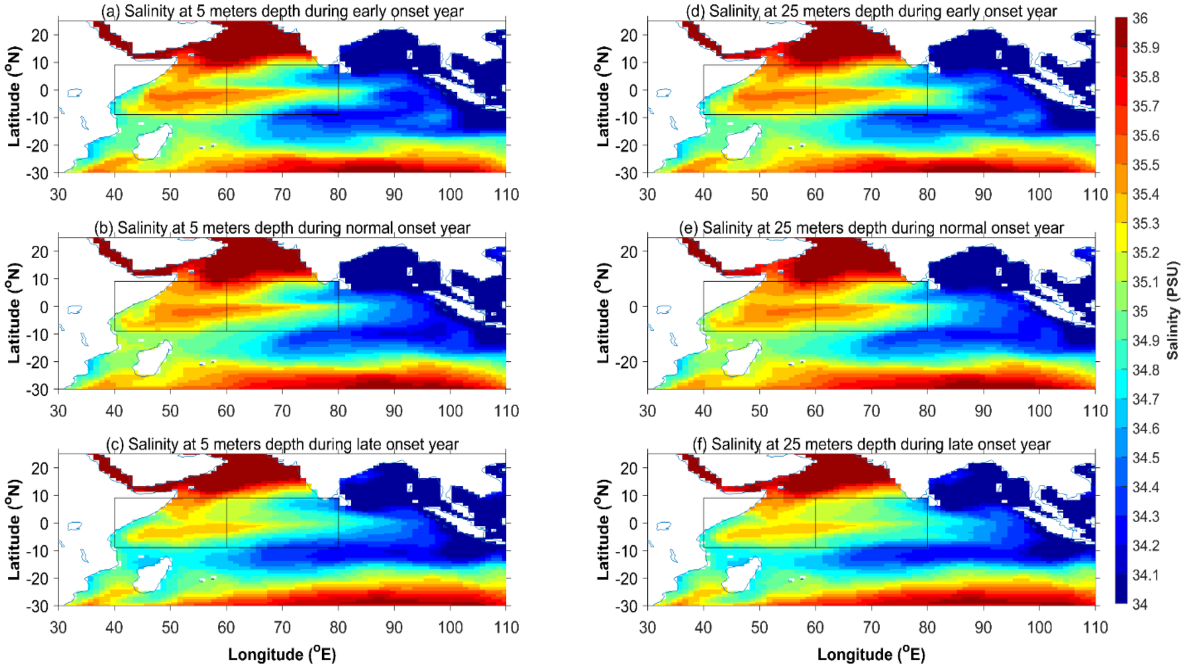

Figure 1. The salinity distribution in Indian Ocean during pre-monsoon season (2001, 2000 and 2003) at 5 and 25 meters depth levels.

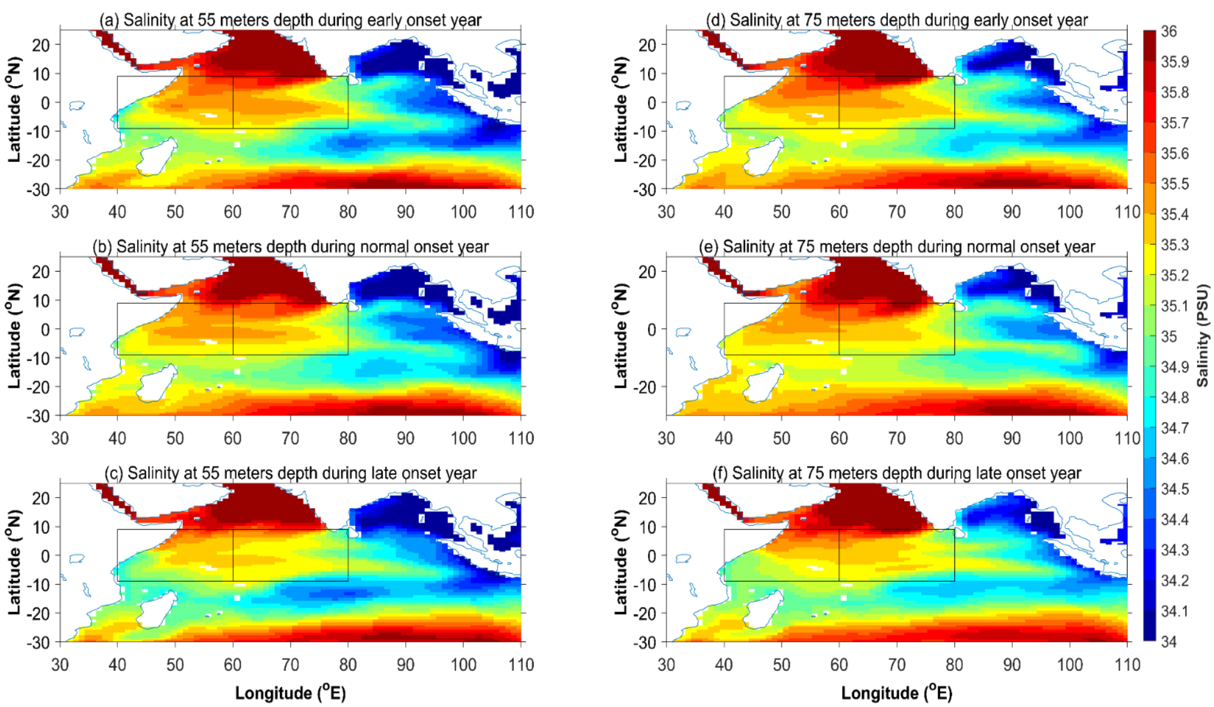

Figure 2. The salinity distribution in Indian Ocean during pre-monsoon season (2001, 2000 and 2003) at 55 and 75 meters depth levels.

During MAM 2003, high salinity (35.5 PSU) has been observed near the northeast coast of Somalia and east of Kenya coast which has elongated in E-W direction below the equator. Near the Kerala coast, low salinity (34.5 PSU) has been observed (Figure 1c). At 25 meters depth, distribution of salinity has been observed almost same as 5 meters depth with eastward transported of salt water.

Near Somalia and Kenya coast, high salinity has been observed which has decreased gently southward and eastward towards Indonesia at 55 meters depth (Figure 2c). The salinity near the Kerala coast and Indonesia has increased at 75 meters depth during MAM 2003 and the contrast between Arabian Sea and BoB has been decreased (Figure 2f).

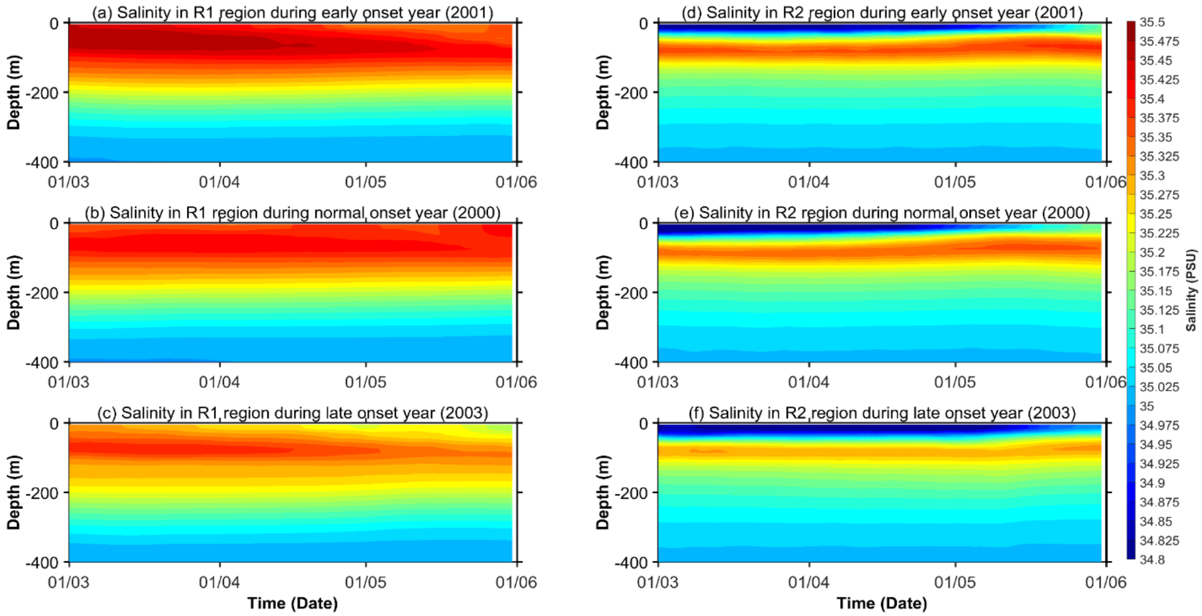

Figure 3. The distribution of salinity with depth in two different sub regions, R1 and R2, during March, April and May (2001, 2000 and 2003).

Figure 3 shows the distribution of salinity with depth in two sub regions R1 (Figure 3 a-c) and R2 (Figure 3 d-f) during MAM in 2000, 2001, and 2003, salinity varies rapidly with depth while gently with time. A high salinity (35.5 PSU) has been observed between 20 to 80 meters depth from the beginning of March to mid-April due to immense evaporation after that salinity diminished gradually till May at the same depth in R1. In the beginning of March high salinity was observed in the uppermost sub-surface, which decreased gently till the last week of May. Below 100 meters depth, salinity lessens gradually (Figure 3a). In 2000, during MAM, high salinity was observed in the upper sub-surface (up to 100 meters depth) and after that decreased rapidly with depth (Figure 3b). During MAM 2003, high salinity (35.425 PSU) was observed from 50 to 80 meter depth till mid-April due to low evaporation, further lessen gently with time and in the upper sub surfaces, salinity has decreased continuously from the beginning of March to the end of May (Figure 3c).

During MAM 2001 in R2, low salinity has been observed within the upper sub surfaces throughout the period with a gently increase in the last week of May while the high salinity (35.375 PSU) has been observed throughout March and April between 70 to 90 meter depth after that moderately increased from mid-May to end between 50 to 90 meter depth, and below 90 meter depth, salinity decreased with depth (Figure 3d). Distribution of salinity with depth during MAM 2000 in R2 (Figure 3e) has been observed more or less same as 2001 for same period with slightly lessen amount (35.350 PSU). Low salinity has been observed within upper sub surfaces of R2 during MAM and below 50 meter depth, salinity increased with depth and high salinity (35.300 PSU) has been observed between 70 to 100 meter depth in last week of May below that, salinity decreased gently with depth (Figure 3f).

CONCLUSIONS

The current research effectively illustrates the substantial modifications observed in salinity during pre-monsoon season in western Indian Ocean and eastern Indian Ocean. The highest salinity has been observed in the upper sub-surfaces of the top of the western Indian Ocean (Arabian Sea). In contrast, the lowest salinity has been observed in the upper sub-surfaces of the top of the eastern Indian Ocean (Bay of Bengal) due to the addition of fresh water in Bay of Bengal by river discharge (Rao and Shivakumar, 2003; Rao, 2015) and the contrast in salinity between Arabian Sea and Bay of Bengal decreased with depth. In the early onset year, the highest salinity was observed in R1 (near Somalia and Kenya coast) between 20 to 80 meter depth level due to a high degree of evaporation during March and mid-April, while during May, salinity decreased gradually and sifted eastward due to wind stress. During normal-onset (late onset), average (below average) salinity between 50 to 80 meter (60 to 80m) has been observed in R1 due to less evaporation and is sifted eastward also. In R2, the highest salinity has been observed between 70 to 90 meters in depth from the beginning of March to the first week of May, and then after, the region of highest salinity has been increased to 50 to 90 meter depth. Intense evaporation during pre-monsoon season causes large amount of moisture in the atmosphere and large amount of moisture may lead the early onset over India, while in normal onset and late onset years, moisture in the atmosphere was low and wind stress transported the moist air toward the Kerala coast.

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Author Credit Statement

All authors contributed to the study conception and design. Data collection was performed by Dinesh K Yadav. The data analysis and plotting were done by Dinesh K Yadav and Archana Maurya. B. Mandal and Dinesh K Yadav wrote the first draft. R Bhatla supervised the work and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The daily salinity data is available on the given link.
https://podaac.jpl.nasa.gov/dataset/ECCO_L4_TEMP_SALINITY_05DEG_DAILY_V4R4

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copy right norms.

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