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Variability of Hydrographic Properties in the Alleppey Terrace Region: Insights from July 2023 Observations

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ABSTRACT

This study examines how ocean conditions change during the peak summer monsoon in the South Eastern Arabian Sea (SEAS), particularly around the Alleppey Terrace (AT). To understand these variations, we conducted detailed field observations along seven transects at 15 Nm intervals in the AT region. The results show that the AT's underwater topography plays a crucial role in shaping coastal upwelling, eddy movements, and ocean circulation. Upwelled waters extend offshore approximately 160 km in the southern part, 50 km near the AT region, and up to 100 km further north. Cyclonic eddies dominate the southern part of the AT and the continental slope region, while anticyclonic eddies prevail in the western side of the AT and the extended shelf region of the AT. Undercurrents were commonly observed between 100-130 m, with shallower undercurrents (~30 m) in the northern transect near the coast. Poleward undercurrents exhibited maximum velocity in the southern transect, flowing along the continental slope region. Data from Acoustic Doppler Current Profilers (ADCP) provide valuable insights into circulation patterns and their influence on thermo-haline and biogeochemical properties. Chlorophyll distributions highlight strong coastal upwelling, with peak concentrations varying by depth and eddy activity. These findings enhance understanding of SEAS dynamics during the monsoon period, contributing valuable insights into coastal upwelling, eddy formation, and biogeochemical interactions.

Keywords: Alleppey terrace; Coastal currents; Southwest monsoon; Upwelling; Eddies

1. INTRODUCTION

The South Eastern Arabian Sea (SEAS) is a highly dynamic region in the northern Indian Ocean, characterized by a wide range of oceanographic processes, such as upwelling, down welling, the Arabian Sea warm pool, and mud banks. These processes, along with quasi-seasonal eddies and water mass exchange between the Arabian Sea and the Bay of Bengal, create a complex oceanographic environment. The seasonal monsoonal variations further influence the SEAS, with significant impacts on the hydrography and circulation in the region.

Bottom topography plays a crucial role in shaping these oceanographic processes in the SEAS, which is distinct from other regions of the eastern Arabian Sea. For example, the continental slope in the eastern Arabian Sea varies considerably in width, extending over 300 km off the Mumbai coast in the north, but narrowing to about 50 km off Trivandrum in the south. Additionally, the bathymetry of the SEAS is characterized by several notable topographical features, including the Laccadive Island chain, the Alleppey-Trivandrum-Terrace Complex (ATTC), and the Wadge Bank. One of the key geomorphological structures is the Alleppey Terrace (Alleppey Platform), a bathymetric high located around 70 km off the Quilon coast, Kerala. This terrace covers an area of approximately 55 km by 55 km and lies at a depth of around 400 mtr. It exhibits a distinct bathymetric gradient, being steeper on the western side and more gradual on the eastern side .[1,2]

The unique combination of complex bottom topography and seasonal monsoonal cycles creates distinctive oceanographic conditions in the SEAS, making it a focal point for research in the northern Indian Ocean. Coastal currents in the SEAS, during the summer monsoon, generally flow equatorward with a strong poleward undercurrent beneath them. Upwelling along the southwest coast of India starts in the subsurface layers around February or March, reaching the surface by May or June. It peaks during July and August before weakening in September. The upwelling begins along the southwest coast and gradually spreads northward, with its intensity diminishing as it moves further north[9].

The West India Coastal Current (WICC) plays a significant role in the distribution of upwelled water, usually extending about 150 km from the coast[4]. While the WICC flows equatorward, an undercurrent flows poleward below it, causing downwelling beneath the upper 100 mtr where upwelling typically occurs. The dynamics of upwelling in the region have been the subject of debate. Initially, it was considered a wind-driven or[5] current induced upwelling[4], but later studies suggested that remote forcing from the Bay of Bengal might trigger the upwelling, while wind forcing plays a lesser role[7]. However, more recent studies have found that alongshore wind stress in the SEAS, along with remote forcing from the south of Sri Lanka, are critical factors in the upwelling process[8].

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In this study, dedicated field observations in and around the Alleppey Terrace investigate how this bathymetric feature influences upwelling intensity and local circulation patterns. The survey entailed high-resolution measurements with station intervals of roughly 15 nautical miles across the Alleppey Terrace area. This data will allow us to accurately determine the offshore extent of coastal upwelling and investigate the water column characteristics in the region during the summer monsoon. Objectives of the present study are:

- To gain a comprehensive understanding of the prevailing oceanographic characteristics in and around the Alleppey Terrace region
- To assess the biogeochemical processes in the region.

2. METHODOLOGY

To meet the aforementioned objective, INS Sagardhwani conducted a survey over the Alleppey Terrace region in the South Eastern Arabian Sea (Fig. 1) employing state-of-the-art oceanographic instruments (Table 1). CTD casts were performed up to a depth of 500 m along seven transects spanning from 8.25 °N to 9.75 °N. Stations along each transect were spaced at 15 Nm intervals, with station depths ranging from approximately 30 m near shore to over 2000 m at the farthest offshore stations.

Table 1. Details of the various instruments operated during the survey onboard INS Sagardhwani in July 2023

Instrument	Parameters measured	No. of stations
Online SBE 19 plus V2 CTD with optional Eco FLNTU sensor	Conductivity-temperature-depth – pH – turbidity - fluorescence	41
Acoustic doppler current profiler (RDI – 150 kHz)	Subsurface current at every 4m depth level	Along track
Automatic weather station (AWS)	Air temp, humidity, solar radiation, air pressure, Wind speed, wind direction, rain fall	Along track continuous
Wave height meter (TSK)	Wave height and period	Along track
Single beam echo sounder	Depth	Along track
X band radar (WAMOS II)	Surface wave characteristics and currents	Along track

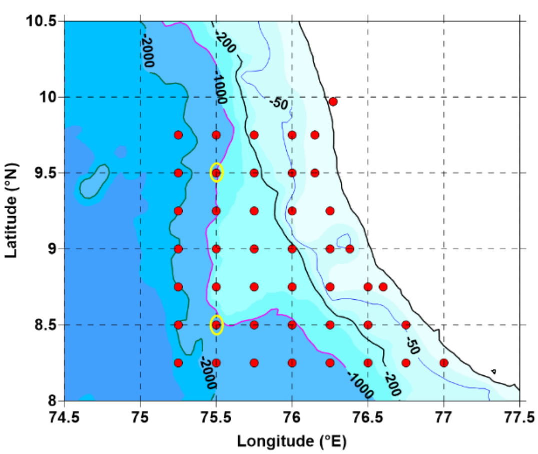


Figure 1. Bathymetry and station location in the Alleppey Terrace region in the SEAS. The spacing between the stations is 15 Nm.

3. RESULTS AND DISCUSSION

During the survey period, relatively rough sea surface conditions were observed in the region. South-westerly winds with speeds ranging from 8 to 30 knots were blowing over the area, contributing to significant wave heights ranging from 1.4 to 2.2 mtr. Subsurface currents in the region ranged from 0.3 to 0.8 m/s, predominantly flowing south-eastward.

To decipher the variabilities in the thermo-haline properties in the AT region vertical profiles of three selected transects representing the south of AT region (along 8.25 °N), centre of the AT region (along 8.75 °N), and North of AT (Along 9.5 °N) are presented in Fig. 2 and Fig. 3. The vertical sections of temperature clearly show the upsloping of isotherms towards the coastal region, indicating distinct thermal fronts in all transects and suggesting strong upwelling in the area. However, it showed remarkable variabilities in the study region.

The surface temperature along 8.25 °N exhibits a difference of approximately 4.5 °C between the coastal station (24.50 °C) and the farthest offshore station (28.90 °C) (Fig. 2(a)). The cooling rate is estimated to be around 0.08 °C per nautical mile (NM) in the shelf region and 0.016 °C per NM in the deep ocean region. Below 100 m depth, the thermal structure reveals the downsloping of isotherms towards the coast, a typical signature of poleward undercurrents. ADCP current measurements along this transect substantiate the presence of a poleward current extending offshore beyond the continental shelf. Additionally, cyclonic and anti-cyclonic structures observed in the thermal structure are well discernible in the current structure as well (Fig. 4). Shallow mixed layers (<5m) are observed near the shore region, deepening towards the offshore area. Salinity structure shows variation ranging from 34 to 35.8 practical salinity units (psu), with the presence of Arabian Sea high salinity water mass (ASHSW) (salinity > 35.4 psu) observed along the offshore region between 20 m and 60 m depth (Fig. 3(a)).

Vertical sections along 8.75 °N also showed the signature of upwelling, with very shallow (<5m) MLDs in the nearshore region. SST along this transect shows the highest cooling rate among all transects in the Alleppey Terrace region, with cooling towards offshore at approximately 0.1°C per Nm in the shelf region and ~0.057 °C per Nm in the deep water region (Fig. 2(b)). The thermal structure displays cyclonic eddy structures in the upper 120m of the slope region and an anticyclonic eddy patterns in the extended shelf region. ASHSW is observed in two distinct pockets, separated near the cyclonic eddy. A narrow band of ASHSW (with a core depth of ~50m) is found on the western side of the cyclonic eddy, while well-defined ASHSW pockets (with a core depth of ~30m) appear in the anticyclone region (Fig. 3(b)). ADCP current structures capture these signatures, with a poleward undercurrent observed below 80 m to 120 m, extending from the extended Alleppey Terrace topography to the eastern side.

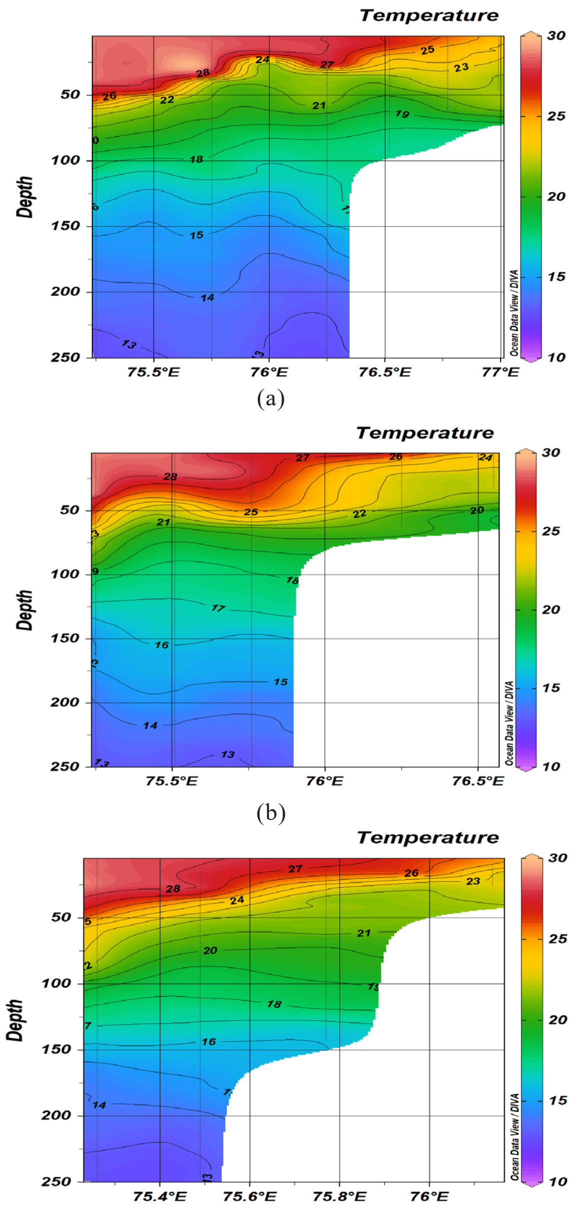
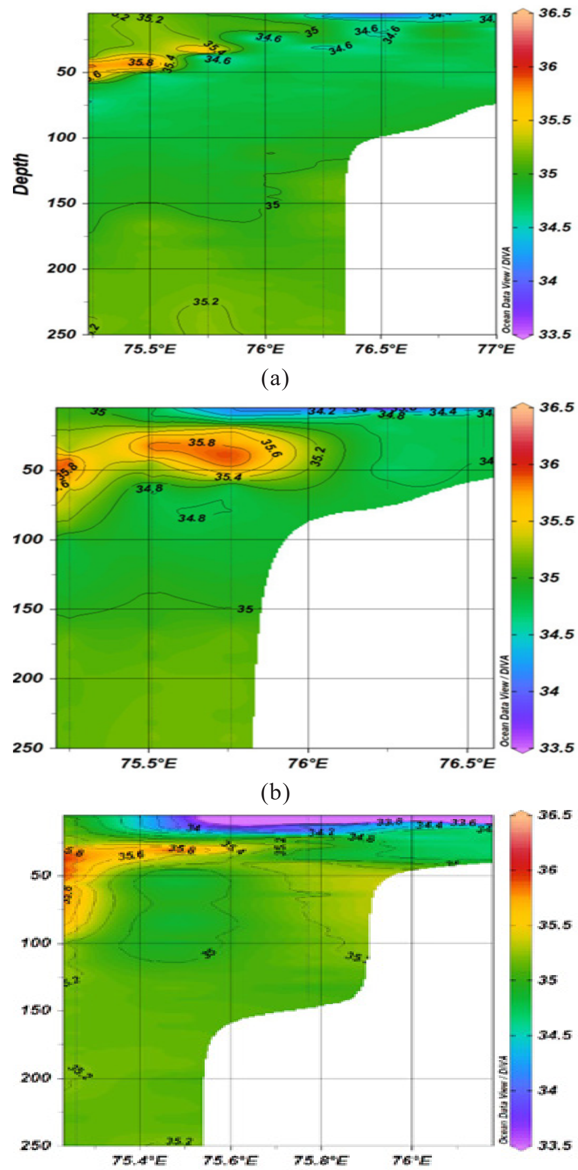


Figure 2. Vertical section of temperature (a) along 8.25 °N; (b) along 8.75 °N; and (c) along 9.5 °N in the AT region during July 2023.



(c)

Figure 3. Vertical section of salinity (a) along 8.25 °N; (b) along 8.75 °N; and (c) along 9.5 °N in the AT region during July 2023.

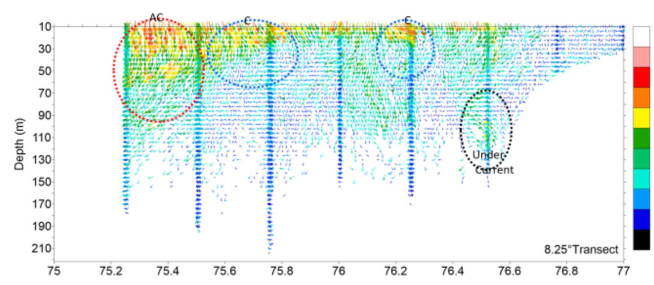
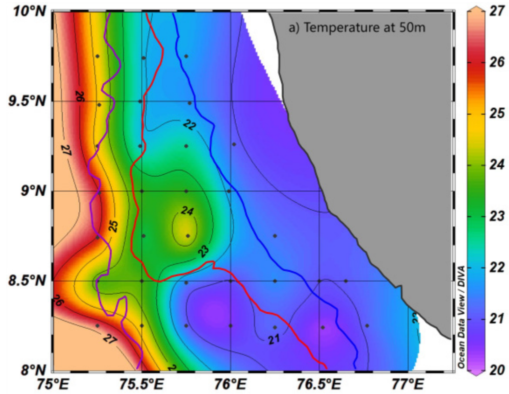


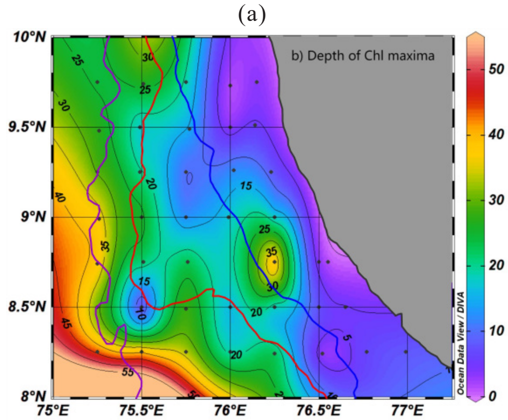
Figure 4. Depth – Space section of ADCP currents along 8.25 °N. Anticyclonic, cyclonic, and undercurrent signatures in the plot are demarcated.

Transects along 9.5 °N (Fig 2c) and 9.75 °N represents the zonal sections north of the AT region. Hydrographic sections along this transect showed similar properties, but the upwelling intensity is notably stronger in the transect along 9.75 °N. Surface temperature is ranged from 27.04 °C (nearshore) to 28.57 °C (offshore) and from 25.83 °C (nearshore) to 28.19 °C (offshore) along the 9.5 °N and 9.75 °N respectively. The cooling rates towards offshore are estimated to be 0.026 °C per nautical mile (Nm) in the shelf region and 0.03 °C per Nm in the slope region along 9.5 °N. Along 9.75 °N, the cooling rates are 0.06 °C per Nm in the shelf region and 0.03 °C per Nm in the slope region. Both transects display steady upsloping of isotherms towards the coast, indicating strong upwelling, but no cyclonic or anticyclonic eddy structures are evident.

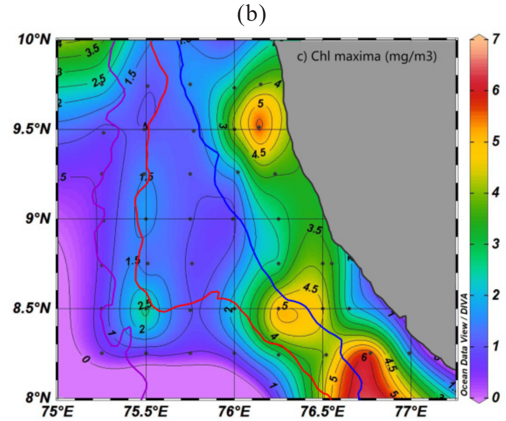
Poleward undercurrents are observed below 30 m depth in both transects, with Acoustic Doppler Current Profiler (ADCP) data clearly showing the circulation pattern of the West India Coastal Current (WICC) and the poleward undercurrent. The salinity in these transects is notably low, with transect 9.75 °N exhibiting the lowest salinity among all the study regions.



(a)



(b)



(c)

Figure 5. Horizontal distribution of (a) temperature (°C) at 50 m depth; (b) Depth of Chlorophyll maxima (m); and c) Chlorophyll maxima (mg/m³) in the AT region. Bathymetry contours of 200 m (blue), 1000 m (red) and 2000 m (violet) are overlaid to understand the bottom topography.

The Arabian Sea High Salinity Water (ASHSW) is found between 80 m and 30 m in both transects, but it is absent in the continental shelf region, suggesting that these water masses do not protrude toward the coastal region due to the strong inflow of the West India Coastal Current (WICC) (Maheswaran, 2004).

To study the offshore extend of the upwelled water and the variability of upwelling in the AT region, horizontal distribution of temperature, the depth of chlorophyll maxima and the chlorophyll maxima are presented in the Fig. 5. Generally, colder waters are observed in the nearshore region, but this area is characterized by both cyclonic and anticyclonic eddies. The western side of the AT region experiences anticyclonic eddies, while multiple cyclonic eddies are observed to the south of the AT region. However, over the AT region itself, anticyclonic eddies are observed in the extended flat region. North of the AT region, there are no eddy signatures, but distinct thermal fronts are noticeable.

The 22 °C isotherm in Fig. 5(a) is considered as marking the offshore extent of upwelling. Notably, upwelled waters extend approximately 160 km offshore in the southern part, while in the AT region, the upwelling spreads only up to 50 km offshore, and further north, it extends up to 100 km. The distribution of depth of chlorophyll maxima (Fig. 5(b)) and the chlorophyll maxima (Fig. 5c) further confirms the presence of upwelling and eddy signatures. Strong coastal upwelling is indicated by chlorophyll maxima occurring at shallow depths (0–10 mtr) nearshore and at cyclonic eddy locations. In anticyclonic eddy regions and the deep ocean, chlorophyll maxima occur at greater depths, typically between 30 mtr and 50 mtr.

4. CONCLUSION

The observed variability of hydrographic properties during the peak summer monsoon in and around the Alleppey Terrace (AT) in the South Eastern Arabian Sea (SEAS) were investigated in this paper. Seven transects were specifically planned to collect CTD observations, covering both the northern and southern parts of the AT region and its boundaries. Coastal upwelling is a major oceanic process in the SEAS, typically starting in the subsurface layer during April/May and reaching the surface in June, with peak intensity occurring in mid-July[9-10].

The study revealed a strong upwelling in the region, with cooler waters observed in the coastal regions of the southern transect, while the northern transect exhibited relatively warmer waters. This suggests that upwelling generally begins in the southern part and expands northward as the season progresses. Despite the generally strong upwelling, there was significant variability in intensity around the AT region. Offshore, upwelled waters extended up to 160 km in the southern part but were less extensive around the AT region, showing stronger upwelling north of the AT. These patterns were reflected in chlorophyll distribution, which serves as a marker for biological productivity associated with upwelling. Eddies played a key role in influencing circulation patterns. Cyclonic eddies were observed along the western edge of the AT, while anticyclonic eddies were prevalent in the extended shelf regions. Undercurrents, typically observed at depths of 100-130 mtr, were particularly strong in the southern transect and along the continental slope. The poleward undercurrents, which are part of the larger West India Coastal Current (WICC), reached maximum velocity in the southern transect, demonstrating significant flow dynamics along the slope. Acoustic Doppler Current Profiler (ADCP) data further clarified circulation patterns and the influence of currents on thermohaline and biogeochemical properties

The offshore extent of upwelled waters in the south-eastern Arabian Sea is influenced by complex interactions between wind patterns, ocean currents, remote forcing, and coastal topography[8,11]. Research shows that upwelling typically occurs within 200 ± 50 km of the coast, driven by southwest monsoonal winds and coastal dynamics[4,12]. However, in the Alleppey Terrace (AT) region, surface winds remain steady and constant during the study period. The topography of the AT plays a crucial role in influencing local ocean circulation. As the West India Coastal Current (WICC) flows equatorward during the summer monsoon, it encounters the AT's varying topography, which acts as a physical barrier that alters current flow and generates eddies. These eddies and redirected currents contribute to variability in temperature, salinity, and the intensity of upwelling. The impact of the AT on local hydrography and circulation, however, requires further investigation through numerical modeling and long-term ocean observation programs.

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