Continental Shelf Research 236 (2022) 104678

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Influence of dynamic stability on chlorophyll distribution along the eastern Arabian Sea

Vishnu Narayanan Nampoothiri S[a,b,*], Y.V.B. Sarma[a], K. Rasheed[a], G.V.M. Gupta[a]

[a] Centre for Marine Living Resources and Ecology, Ministry of Earth Sciences, Kochi, Kerala, India

[b] School of Marine Sciences, Cochin University of Science and Technology, Kochi, 682016, India

ARTICLE INFO

Keywords:
Dynamic stability
Chlorophyll
Deep chlorophyll maximum
Deep stability maximum
Eastern Arabian Sea

ABSTRACT

Dynamic stability (Brunt-Vaisala frequency) has marked control on the formation of deep chlorophyll maximum (DCM) layers when it occurs in shallow euphotic zone. In this work, the monthly timeseries hydrographic data collected during December 2017 to January 2019 were used to investigate the relationship between vertical structure of dynamic stability and chlorophyll concentration. Generally, on an annual scale it was found that in terms of dynamic stability of the waters, the northern region was always unstable or neutrally stable while the southern region was relatively stable. During winter, the entire coastal region presented unstable to neutrally stable (N^2~0–5 cph) conditions while in the offshore it was observed highly stable layers starting from the surface to 100 m depth in the south and unstable waters in the north up to 100 m. Consequently, very significant DCM extends from south to north with gradual rise from about 50 m at south to surface that eventually merged with high productive waters of winter bloom in the offshore along north. During summer, the stability concentration with $N^2 > 15$ cph is shallow (<20 m) near the coast while it deepened to more than 50 m with about an order of magnitude less (<5 cph) in the offshore. This has resulted in high chlorophyll concentration (>5 mg/m^3) at shallow regions near the coast while it was absent in the offshore where Deep Stability Maximum (DSM) deepened to sub-thermocline region. The mean structures of dynamic stability and chlorophyll profiles during summer and winter indicated that DCM is associated with the DSM, which was further confirmed by statistical correlation. Vertical structure of dynamic stability apparently controlled the depth of the DCM and its chlorophyll concentration though it is not tightly coupled. It may be due to influence of light and nutrients that may have stronger control on productivity. This study was useful to assess the phytoplankton biomass and productivity potential of the eastern Arabian Sea using basin scale approach.

1. Introduction

The Brunt-Vaisala frequency (BVF), also known as buoyancy frequency or dynamic stability, represented by N^2 gives a better measure of the stability of oceanic water column thus a value of >5 cycle per hour (cph) indicates stable stratification, 0–5 cph neutral stratification and <0 cph unstable stratification (Pond and Pickard, 1983). In the tropical north Indian Ocean, the existence of deep chlorophyll maxima (DCM) has been reported in the Arabian Sea mediated by nutrient turnover and nutrient regeneration in the subsurface corresponding to the depth of the thermocline (Banse, 1994; Bhattathiri et al., 1996). Earlier, the DCM was related to the mixed layer dynamics but Pingree et al. (1978) showed that the phytoplankton tend to settle in the stable zone of the seasonal thermocline rather than in the surface mixed layer. Further, the studies of Fasham et al. (1985) and Catalano et al. (1997) indicated the potential role of water column vertical stability in controlling the phytoplankton distribution in the upper ocean. Turbulent mixing in the near surface and in the deep water leads to low stratification and results in instability. Low mean turbulence production and relatively high stability over a spawning season might favour DCM (Husby and Nelson, 1982). Banse (1987) observed DCM formation in the pycnocline along the eastern Arabian Sea during summer monsoon where it traps diffusive flux of nutrients into the depleted upper layers. Bhattathiri et al. (1996) observed DCM formation at 40–60 m during inter-monsoon period in the eastern Arabian Sea. This DCM formation also depends on the depth of thermocline or varies with the presence of seasonal thermocline which was reported by Sarma and Aswanikumar (1991). Agusti and Duarte (1998) reported that there was DCM associated with the thermocline

* Corresponding author. Centre for Marine Living Resources and Ecology, Ministry of Earth Sciences, Kochi, Kerala, India.
E-mail address: vish4well@gmail.com (V.N. Nampoothiri S).

https://doi.org/10.1016/j.csr.2022.104678
Received 5 April 2021; Received in revised form 8 February 2022; Accepted 10 February 2022
Available online 12 February 2022

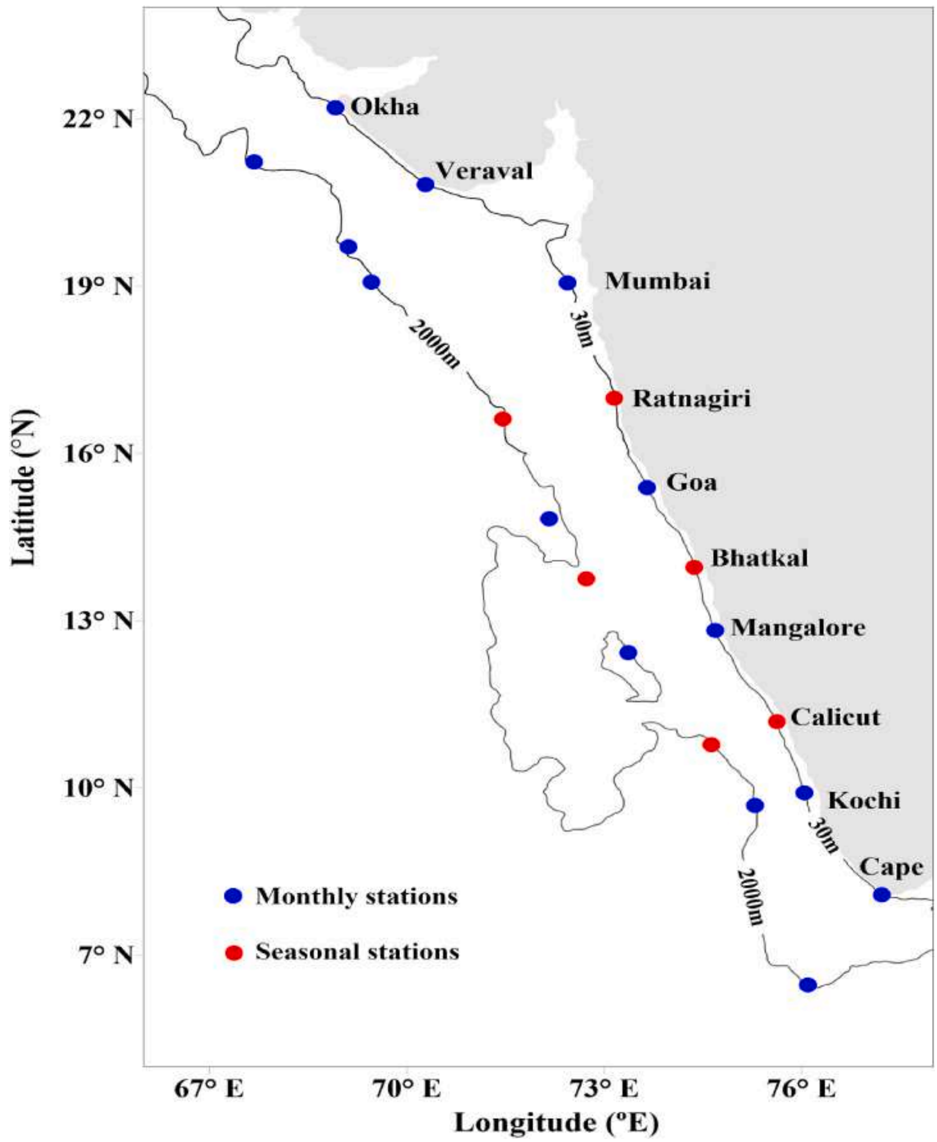

Fig. 1. Study area and sampling stations along the eastern Arabian Sea.

with concentration reaching up to 50 fold greater than those in surface waters of the central Atlantic Ocean. The correlation between the DCM and the depth of the strongest thermocline accounted for 87.2% of the total variance (Agusti and Duarte, 1998). The DCM tends to be shallower than the depth of thermocline and the depth of maximum vertical stability when they are deeper than 60 m. Fennel and Boss (2003) studied the subsurface maxima of phytoplankton and chlorophyll and described that vertical separation of maxima of biomass and chlorophyll by about 50–80 m during stratified conditions. They used a mathematical framework to describe the phytoplankton, chlorophyll and nutrients to identify their vertical maxima and their model predicted a DCM below the particle maximum. The study by Murty et al. (2000) showed that in the Bay of Bengal, the profile of water stability shows two maxima, one in the halocline and in the other in the deep seasonal thermocline or pycnocline. The depth of seasonal thermocline coincided with the depth of deep stability maximum (DSM) and the DCM was located above the depth of DSM above the seasonal thermocline. Jurado et al. (2012) found that larger values of stability occur just below the MLD, and close to the surface in the northeast Atlantic region. The chlorophyll *a* concentration in the DCM layer tended to decline as the depth at which the Brunt-Vaisala frequency was highest. The vertical stability in the upper 100 m water column can be closely approximated by the vertical distribution of temperature but not in salinity, as salinity variation is generally small or nearly constant with depth. Seawater mixing is important because it affects the nutrient distribution, heat transfer and can impact climate. The stability (stratification), resulting from integration of solar radiation, precipitation and many physical processes (upwelling, low wind and divergence) strongly affects the nutrient and light in upper ocean. In warm areas, cloud cover may lead to enhanced nutrient flux into upper part of pycnocline but not to mixed layer (Banse, 1987). Prasanna Kumar et al., (2010) described the profile of static stability parameter in the northern part of central Bay of Bengal and reported that during spring inter-monsoon and the winter season, the upper 60 m of the water column was least stable compared to the rest of the seasons. Spring and fall inter-monsoons represent warm and stratified waters with low production in the eastern Arabian Sea (Kumar et al., 2000). Banse (1994) studied the nutrient return to euphotic zone is more efficient due to advection during upwelling and convection from overturn of water column by cooling. According to Husby and Nelson (1982), stability in the upper layers of the ocean is determined by a balance between the net downward heat flux across the air-sea interface and the turbulent mixing process associated with the wind stirring and convective cooling. In the Arabian Sea, upwelling along southwest coast of India commences in the south in deeper layers and reaches the surface

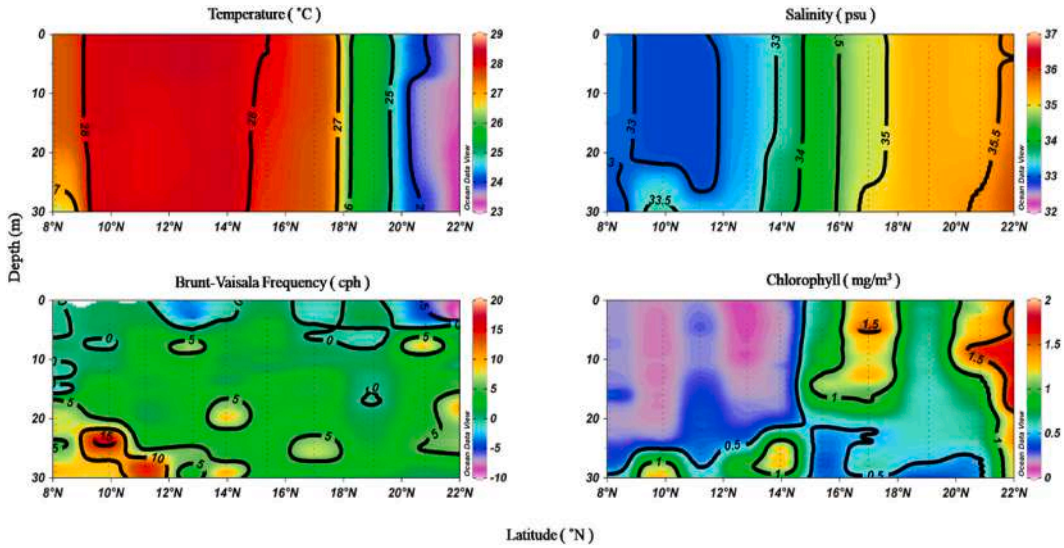

Fig. 2. Hydrographical parameters along with Brunt-vaisala frequency and chlorophyll during winter along 30 m depth contour.

during May which continue to occur till June and upwelling gradually extend towards north (Sharma, 1978). McCreary et al. (1993), Shankar and Shetye (1997) stated that upwelling was reported first in the SEAS and propagates towards north. Cold and dry north-easterly winds in the North eastern Arabian Sea during winter leading to a process known as winter cooling and thereby deepened mixed layer and increased chlorophyll concentration (Madhupratap et al., 1996; Shankar et al., 2016). This cold dense waters in the NEAS lead to convective mixing during winter (Prasanna Kumar et al., 2004). Banse (1994) reported that winter cooling in the north deepens mixed layer which erodes pycnocline and enhances nutrient supply. The analysis by Midhun shah et al. (2020) along the NEAS gives indications to the possible strengthening of SCM in the scenario of warming and enhanced stratification and shows the influence of vertical density on SCM.

There are limited studies carried out along the west coast of India which examined the relation between vertical stability of the water column and the chlorophyll distribution using the in-situ data. In this paper, we attempt to examine the role of vertical stability in determining the chlorophyll distribution of the eastern Arabian Sea using large set of time series monthly in-situ shipborne observations. Further, the seasonal processes like upwelling and convective mixing were examined in modifying the vertical stability, and modulating the chlorophyll concentration. Finally, we analyse in this article the Brunt-Vaisala frequency versus fluorescence (chlorophyll) to test the above hypothesis during winter and summer periods along the 30 m and 2000 m isobaths (coast and offshore regions respectively). This study on stability can have a direct impact on the phytoplankton biomass and productivity pattern in the water column.

2. Data and methods

2.1. Study area

Eastern Arabian Sea undergoes seasonal reversal of winds in association with the monsoons, resulting changes in the upper layer circulation pattern during summer monsoon (SM) and winter monsoon (WM). The general circulation along the west coast of India is southward during summer monsoon and northward during winter monsoon which are termed as the west India coastal current (WICC) (Shetye et al., 1990). The coastal current driven by the pressure gradient (McCreary et al., 1993) during winter monsoon (November to February), results in the intrusion of less saline Bay of Bengal water to the SEAS. Winter cooling is observed in the NEAS during winter (November to February) monsoon and coastal upwelling during summer (July to October) monsoon (Narayanan Nampoothiri et al., 2022). Coastal upwelling regulates the major ecosystem dynamics of the SEAS with increased production potential (Madhupratap et al., 2001; Smitha et al., 2008) as a result of the enhanced nutrient pumping. In general, upwelling is present, albeit discontinuously, all along the west coast of India during summer and winter cooling along the north during winter. Apart from the upwelling and winter cooling processes, the density gradient due to the mixing of water masses and freshwater runoff also play lead role in structuring the stability patterns and thereby influencing the chlorophyll distribution. Study area map and station details are given in Fig. 1.

2.2. In-situ data and analysis

The study was carried out based on ten repeated observations onboard *FORV Sagar Sampada and ORV Sagar Kanya* during December 2017 to January 2019 along 30 m and 2000m depth contour in the eastern Arabian sea as a part of ongoing Marine Ecosystem Dynamics of Eastern Arabian Sea (MEDAS) project. Seven transects off Cape, Kochi, Mangalore, Goa, Mumbai, Veraval, and Okha were sampled at 30–45 days interval and additional three transects (Calicut, Bhatkal and Ratnagiri) were considered for seasonal sampling for a better resolution (Fig. 1). Depth contour along 30 m and 2000 m were considered to understand the coastal and offshore distribution of hydrography, stability and chlorophyll. EAS has been categorized into three regions *viz.* south (~6–13°N - SEAS), centre (~13–17°N - CEAS), and north (~19–22°N - NEAS).

The water temperature, salinity and chlorophyll (fluorescence) were measured using a Seabird CTD (SBE 911 Plus) profiler. Water samples were collected using a Niskin samplers attached to the CTD Rosette. Fluorescence sensor was calibrated before deployment during winter sampling whereas new sensor were used during summer.

The dynamic stability (Brunt-Vaisala frequency) was computed as

$$N = \sqrt{-\frac{g}{\rho} \times \frac{d\rho}{dz}} \tag{1}$$

where ‘g’ is the gravitational acceleration (9.8 m/s^2) and ‘ρ’ is the sea water density (1025 kg/m^3) and ‘dρ/dz’ is the vertical gradient of density (Pond and Pickard, 1983). If the water is more stratified, N is higher and if less stratified, N is lower. Thus a value of >5 cph indicates stable stratification, 0–5 cph neutral stratification and <0 cph unstable stratification.

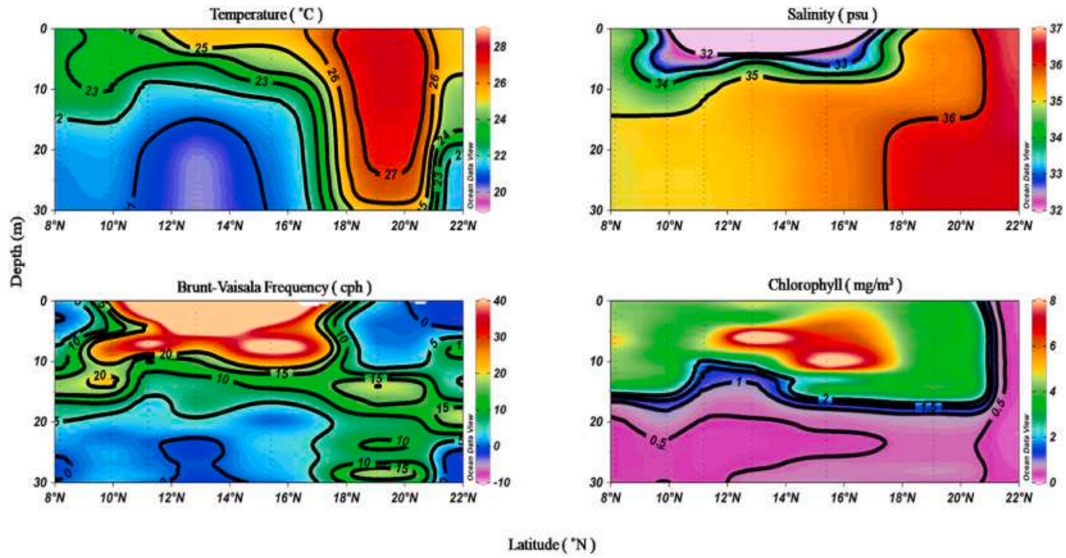

Fig. 3. Hydrographical parameters along with Brunt-Vaisala frequency and chlorophyll during summer along 30 m depth contour.

Strength of correlation between DSM and DCM in open ocean stations (2000m depth contour) was tested using Pearson's correlation coefficient (r) in IBMSPSS Statistics 25 and regression analysis (R^2) in Microsoft Excel.

3. Results and discussion

In the first part, we present seasonal variability of hydrography, stability and chlorophyll along the coastal (30m) waters, and the corresponding properties along the offshore (2000m) are presented in the second part. Time series monthly variations of stability and chlorophyll along the coastal and offshore waters of EAS were discussed in the third section as a basin scale approach. In the final section, the relationship between DSM and DCM were examined through statistical analysis.

3.1. Analysis of seasonal variability along the coastal waters of eastern Arabian Sea

3.1.1. Winter monsoon

January–February represents peak winter conditions in the Arabian Sea, particularly in the northern Arabian Sea. The vertical sections of temperature, salinity, Brunt-Vaisala frequency and chlorophyll (Fig. 2) shows the presence of warm, low saline and low dense waters in the south-eastern Arabian Sea (SEAS). During this period, the sea surface temperature (SST) was higher (29 °C) in the southern Arabian Sea between off Cape and off Goa but rapidly falls towards north with a steep change around off Mumbai (19°N) to 26 °C and then progressively decreased further north to 24 °C off Okha. The low SST off Okha in the NEAS was due to winter cooling and associated convective mixing. The surface salinity also exhibited visible extremities along the coast with lowest salinity (<33.0) in the south and highest in the north (>35.5). The intrusion of low salinity waters from the Bay of Bengal (BoB) was clearly noticeable up to Goa in the upper 30 m water column. It is expected that BoB waters advect nutrients into the region along west coast of India over the shelf region to enhance chlorophyll concentration (Prasanna Kumar et al., 2004; Sarma et al., 2012). In the northern parts, prevalence of Arabian Sea High Salinity Water (36–36.7) is noticeable. The strong temperature and salinity gradients along the coast in the eastern Arabian Sea (EAS) sequenced similar gradient in surface density.

The upper 10 m remained unstable to neutrally stable (0–5 cph) due to the presence of low salinity BoB waters and became relatively stable (>5 cph) at subsurface along SEAS. The high chlorophyll concentration along the coastal waters of SEAS matches well with high stability. The subsurface below 20 m was strongly stable and this characteristic feature progressively moved surfacewards towards north up to Mumbai. The NEAS has unstable (<0 cph) condition up to 30 m which stimulated winter cooling processes. High chlorophyll values (1.5–3 mg/m^3) were noticed off Okha in the NEAS due to winter cooling and mixing that is prevalent throughout the winter period with low temperature (24 °C) north of 19°N. Earlier Kumar and Prasad (1996) reported winter blooms to occur in the NEAS. The high unstable condition was noticed off Okha is the result of deeper mixed layer depth (MLD) forced by intense evaporative cooling at the surface (Kumar and Prasad, 1996).

3.1.2. Summer monsoon

A thin ribbon of low SST (24–26 °C) was observed hugging the coast from Kochi to Ratnagiri (Fig. 3). The low temperature waters in the shelf region all along the coast indicate the prevailing upwelling conditions (Gopalakrishna et al., 2008; Shah et al., 2019; Shafeeque et al., 2021). This condition, however, is interrupted by a strong vertical thermal front of about 200 km wide was noticed around 18°N extending from surface to bottom except near Okha where the subsurface waters below 15 m depth were relatively cool. Within this thermal front, the temperature was >26 °C. Freshwater inflow in this upwelling region is clearly evident from the salinity plot. Moderate salinity values (~35.0) observed off Cape due to intense upwelling and the occurrence of low saline water (32–33) was due to fresh water plumes existed from Kochi to Ratnagiri whereas at north, Arabian sea high saline water mass (ASHSW) is dominant. This one-time event has generated highly stable conditions in that region. Upper water column near to the coast is found to be stable during southwest monsoon period in the SEAS except off Cape and Northern Arabian Sea. In SEAS, from Kochi to Ratnagiri, due to heavy rainfall and fresh water inflow, there is stable condition with a value of 7.5 cph within the stratified column. But both coastal and offshore waters of NEAS and also southern tip off Cape transect has a neutrally stable upper column (0 to −2.5 cph) near coast. The advection of ASHSW creates unstable condition from Okha to Ratnagiri developing a vertical unstable front extending up to 20 m depth along the coast (Fig. 3). As like other parameters described above, chlorophyll showed a high value (2–8 mg/m^3) from Cape to Goa thereafter a comparatively low value (2–3 mg/m^3) along Ratnagiri and north of it oligotrophic waters separate a northern high chlorophyll region from the south. Low stability in the NEAS favours the vertical motion of bottom waters and entrainment that helps pump nutrients into euphotic zone (Narvekar et al., 2017) that increasing productivity. This high chlorophyll observed in the SEAS is matching with the stability maximum (Fig. 3).

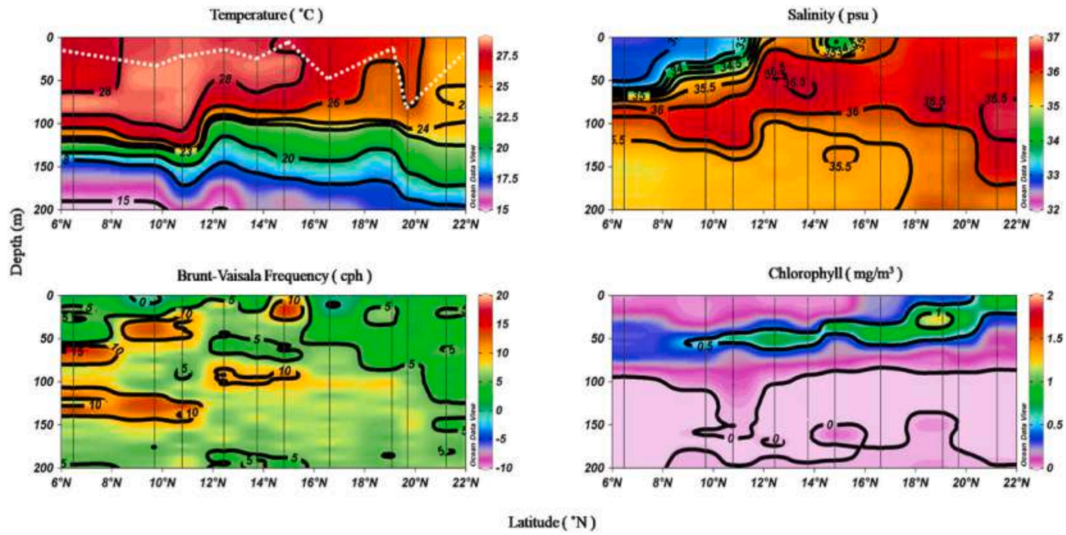

Fig. 4. Hydrographical parameters along with Brunt-Vaisala frequency and chlorophyll during winter along 2000m depth contour. Mixed Layer Depth (MLD) is represented as white dotted lines.

Off Mumbai, chlorophyll is high (2–3 mg/m^3) due to the mixing of different water masses (coastal water and ASHSW) creating a subsurface stable layer which favours the existence of chlorophyll. From the above observations, NEAS has low to moderate chlorophyll and stability concentration while coastal waters of SEAS has high stability and high chlorophyll concentration during summer. This indicates the direct relation between the water column stability and chlorophyll. Generally, along the coastal stations, stability mainly depends on coastal upwelling, freshwater inflow and mixing of different water masses.

3.2. Analysis of seasonal variability along the offshore waters of eastern Arabian Sea

3.2.1. Winter monsoon

Along 2000m, the meridional variation of hydrography shows that higher temperature (28 °C) was observed up to 100 m water column in the SEAS while moving towards north, temperature reduces to 24°C due to mixing and convection, causing unstable condition. Similar to the coast, the intrusion of BoB waters were seen along 2000 m isobath also with typical low salinity (33) in SEAS up to Kochi. This low salinity water apparently traps relatively higher salinity water along the subsurface depths. Mixing of water mass as reported by Kumar and Prasad (1999) can alter the water column stability. Convection of high salinity water during winter advects at surface 18°N and intrudes as subsurface high salinity water towards south and also towards coast at certain locations (Fig. 4). Consequently, we noticed unstable conditions in the upper 50 m water column followed by relatively stable conditions below, in the SEAS. In contrast, neutral to near neutral stability (0-5cph) was noticed extending up to 80 m depth in NEAS. Maximum stability layers were deeper in NEAS due to convective mixing thereby restricting stable water to depths deeper than 80 m when compared to SEAS where maximum stability was shallower (30 m) due to less wind action and intrusion of BoB waters (Fig. 4). Coincident with stable and unstable conditions, winter shows a well-defined and intense DCM all along 2000 m isobath with increasing concentration of chlorophyll in DCM towards north. Prasad (2004) found that MLD in the Arabian Sea during this period were more than 80 m by convective vertical mixing. Similar comparison between wind mixing, mixed layer depth (MLD) variations and stability was reported by Narvekar and Kumar (2006) in the BoB.

In general, throughout the eastern Arabian Sea, neutrally stable to unstable waters were present (−2 to 3 cph) except off Kochi and at a few sporadically distributed pockets in the offshore. In the northern most region off Okha, a large pool of unstable waters were evident which may

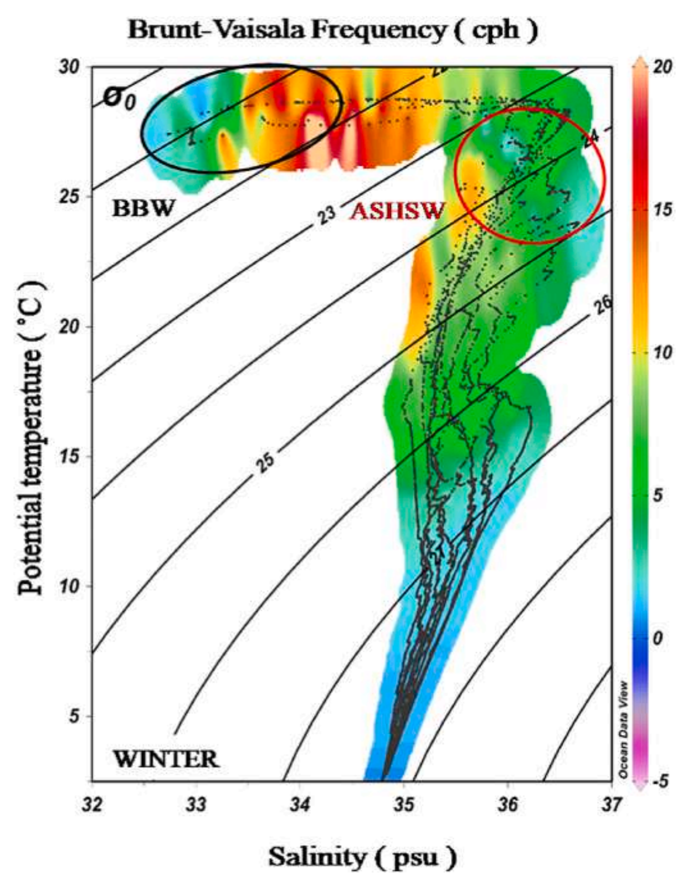

Fig. 5. T-S diagram showing the role of water mass in the vertical stability during winter monsoon where Bay of Bengal water mass (BBW) is highly stable (black circle) and Arabian Sea High Saline Water mass (ASHSW) is unstable (red circle). Colour scale represents Brunt-Vaisala frequency.

be due to the evaporative cooling leading to convective mixing in that region driven by prevailing cold and dry north-easterly winds during this season (Kumar and Prasad, 1996). The chlorophyll concentration was also high (>1.5 mg/m^3) off Okha with a rapid decrease towards south turning the region south of Mumbai and in the offshore to nearly oligotrophic. In the present study, we noticed stability maximum

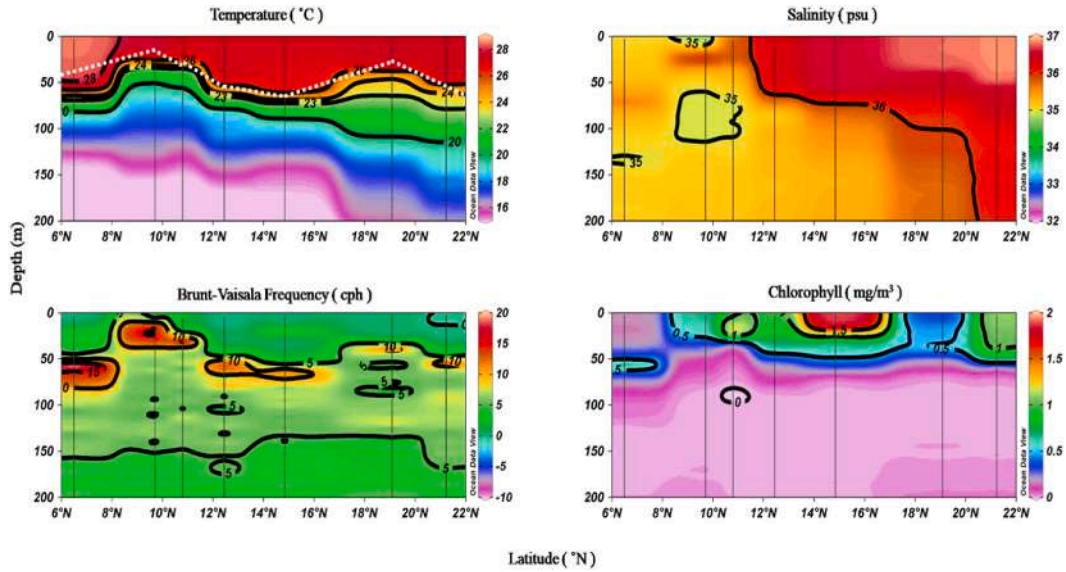

Fig. 6. Hydrographical parameters along with Brunt-vaisala frequency during summer along 2000m depth contour. Mixed Layer Depth (MLD) is represented as white dotted lines.

occurred just below the MLD which agrees with observations of Murty et al. (2000) in BoB. As seen in the previous sections, a barrier layer forms due to the intrusion of low saline BoB waters in the south. This barrier layer coincided with the stability and chlorophyll maximum in the subsurface. During winter monsoon, due to intrusion of low saline BoB water mass, SEAS remains stable while due to combined effect of winter cooling and due to presence of ASHSW, NEAS remains unstable (Fig. 5).

3.2.2. Summer monsoon

Temperature profiles shows shallowing of D24 and D26 isotherms off Kochi and Mumbai to 50 m whereas other locations isotherms remains linear at 75 m. The movement of ASHSW (salinity>35.5 psu) southwards is well evident from salinity plot and this mixing of water mass in the offshore regions can lead to shallowing of isotherms and MLD (Fig. 6). The surface waters were neutrally stable (0–5 cph) along 2000 m isobath during summer in the offshore region. However, noticed a high stable water (10 cph) in an isolated pocket at surface waters off Kochi. This high stable water appears may be due to offshore extent of upwelling (Smitha et al., 2014) in the region. MLD was found to be shallower off Kochi and Mumbai (30 m), where the stability is also shallower compared to other regions (Fig. 6). This is due to the intense offshore transport of coastal waters along Kochi (Vishnu et al., 2020), whereas varying wind and currents along Mumbai. In the offshore waters along 2000m isobath, there is no evidence of DCM in summer except near Cape (Fig. 6). The DCM off Cape during summer was located around 80 m depth coinciding with pocket of high DSM. North off Cape, there is no DCM but there is a broad chlorophyll concentration extending from surface to high stable layer (40–50 m) all along the 2000m isobath with multiple pockets of relatively high and low concentrations. There is a stretch of highly stable water exist all along the offshore stations in the 50–160 m depth. The DSM was observed to be along 50 m and high chlorophyll concentration (>0.5 mg/m^3) was observed just above this layer. Relation between stability and chlorophyll is captured well in the offshore stations. Chlorophyll is maximum (2 mg/m^3) around Mangalore and Goa transects where there is mixing of water masses. Along the Offshore stations, it can be seen that DCM mainly depend on the DSM layer. During summer monsoon, due to shallowing of isotherms and isopycnals due to the upwelling process (Hareesh Kumar and Anand, 2016) there is a well-defined DSM coinciding with the MLD and thermocline all along the EAS which is missing during the winter. Freshwater influences from the hinterland during summer monsoon also add to the high stability when compared to winter monsoon (Figs. 6 and 7).

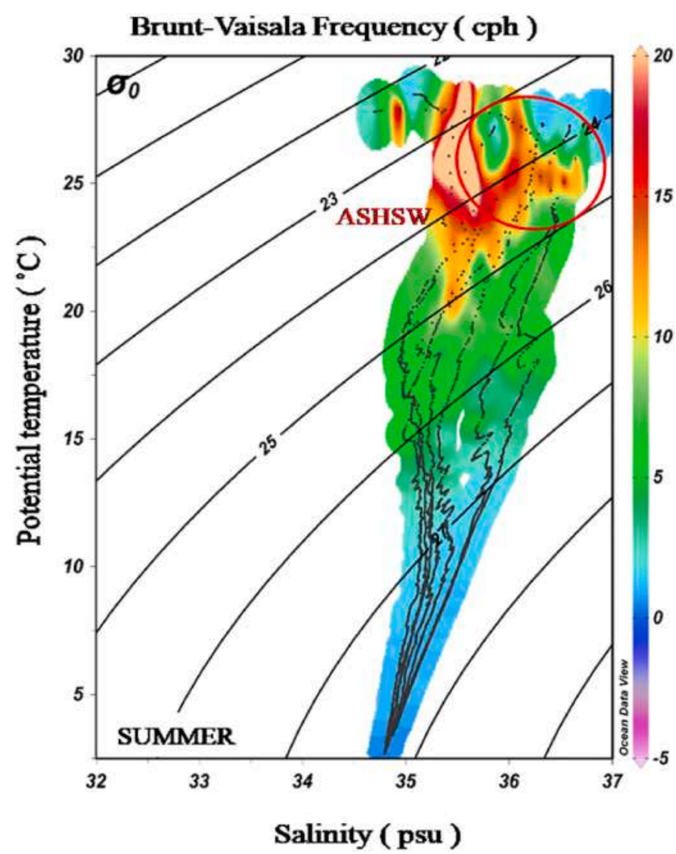

Fig. 7. T-S diagram showing the role of water mass in the vertical stability during summer monsoon. The Arabian Sea High Saline Water mass (ASHSW) is marked in red circle.

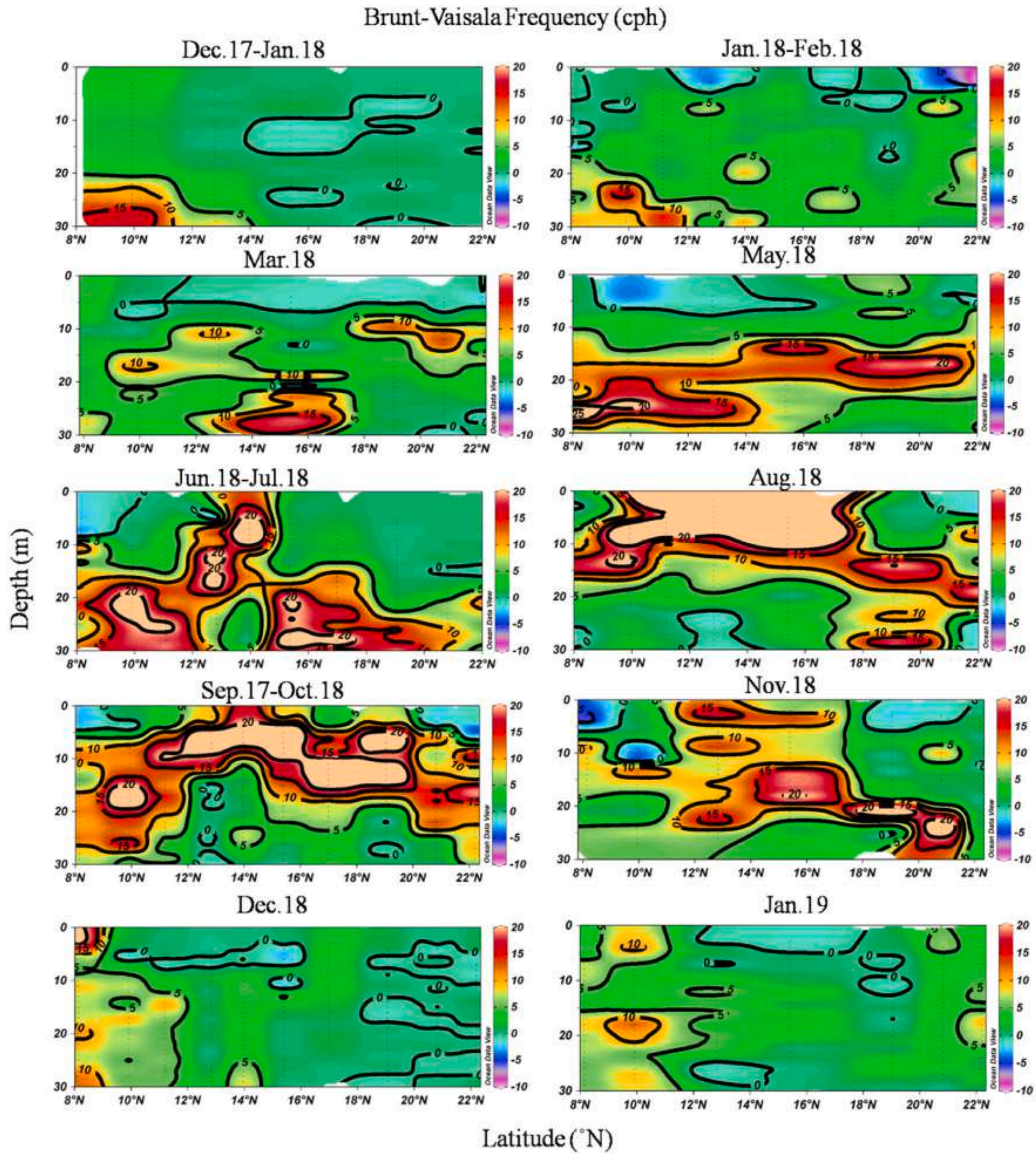

Fig. 8. Time series stability (cph) pattern along the coastal (30 m) waters of eastern Arabian Sea.

3.3. Analysis of monthly basin scale variability of stability and chlorophyll along the coastal region

During winter, the vertical structure of stability appeared to be strongly stable in SEAS, the conditions gradually changed towards the NEAS where the unstable conditions prevail. This change in stability conditions is apparently the results of prevailing thermohaline conditions during winter. The intrusion of warmer BoB waters in the southern regions up to 12°N makes the coastal waters stable. Unstable condition was observed generally throughout the EAS during February except for high stability observed at certain pockets like bottom waters off Kochi. During April–May, the surface waters along the EAS remains unstable whereas subsurface to bottom waters are stable. Unstable waters in the surface may be attributed to the high solar insolation during the season. June to September, due to the effect of upwelling there is stable surface waters along Kochi to Goa regions but water remains unstable in the southern tip off Cape region and the surface waters of NEAS (Fig. 8). Upwelling in SEAS and density gradients due to the southward movement of ASHSW in the EAS can alter the stability pattern during this period. October represents unstable characteristics with withdrawal of upwelling process observed all along the EAS, but the surface waters of Kochi, subsurface waters of Central eastern Arabian Sea (CEAS) and bottom waters of NEAS represents stable conditions. Influence of freshwater makes surface waters of Kochi stable whereas subsurface upwelling makes bottom waters stable in the CEAS and NEAS (Fig. 3).

There is low chlorophyll (0–0.4 mg/m^3) concentration in the surface waters off Cape transect whereas subsurface waters of the region and further northern transects have high chlorophyll (0.6–1.0 mg/m^3) during December. Maximum concentration were along surface off Goa (1.0 mg/m^3) where there is very less fluctuation in the vertical density profile. Due to winter cooling in the NEAS during February to March, there is high chlorophyll concentration in the north (Fig. 9). During April to May, the bottom waters along the EAS and surface waters off Kochi have high concentration (1.50 mg/m^3). June represents onset of summer monsoon and there is high chlorophyll (2.0 mg/m^3) in the Cape region where the upwelling process is initiated first, apart from this, subsurface

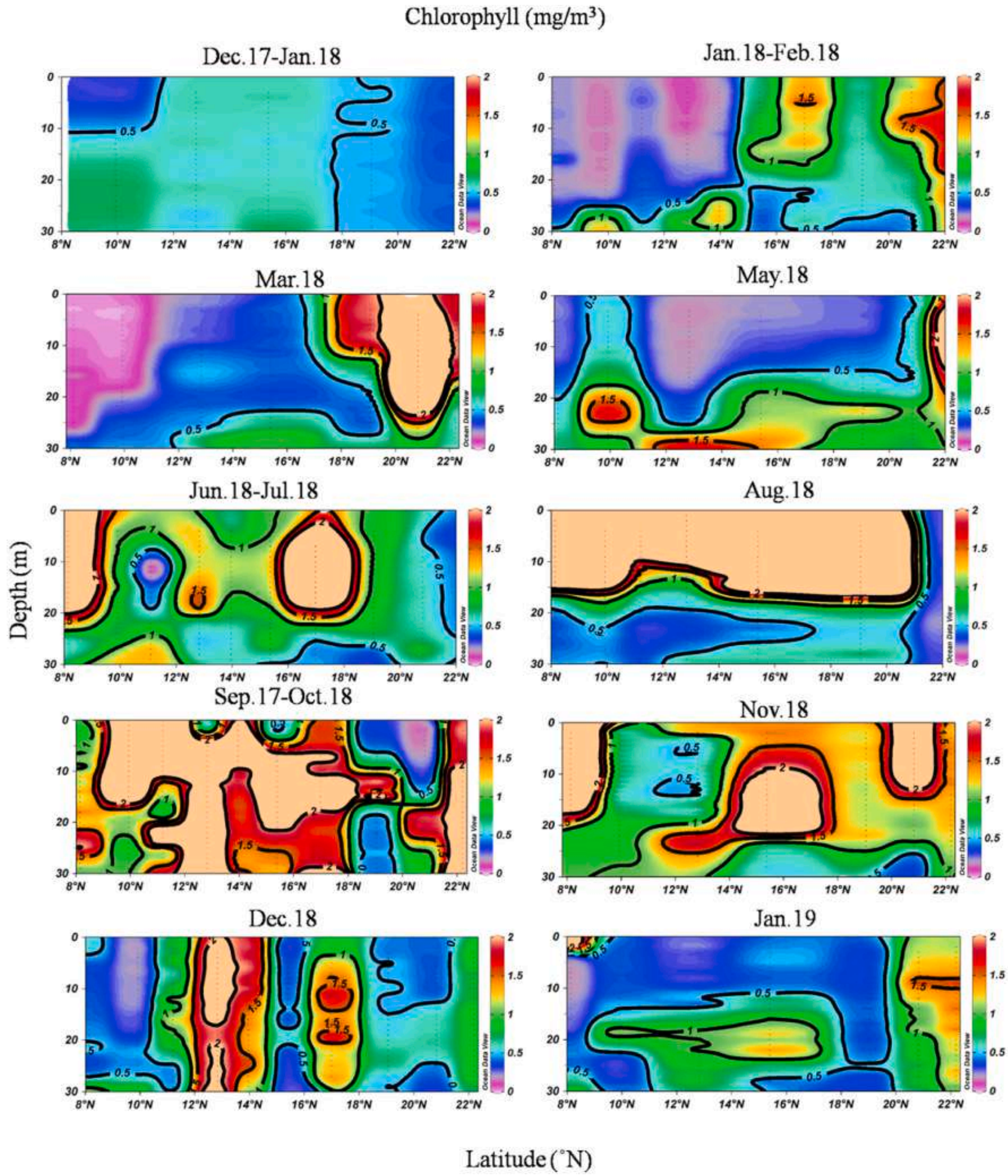

Fig. 9. Time series chlorophyll (mg/m^3) pattern along the coastal (30 m) waters of eastern Arabian Sea.

Ratnagiri region also shows high values due to sharp density gradient. Due to intense upwelling and freshwater inflow along the EAS, the chlorophyll concentration sharply increases during August and September. During October, high chla observed due to the effect of upwelling conditions off Cape and off Okha, subsurface upwelling off Goa and Ratnagiri. Again winter conditions show high chlorophyll concentration along Central EAS and NEAS due to density gradients.

3.4. Analysis of monthly basin scale variability of stability and chlorophyll along the offshore region

Winter months shows a well-defined DSM layer along SEAS whereas water remains unstable in the NEAS due to convective mixing. During March to May, the surface water column remains unstable along EAS but there is the presence of DSM in the subsurface waters of SEAS. June to September due to shallowing of isotherms and mixed layer, an intense DSM below the MLD is observed all along the EAS (Fig. 10). Density gradients generated due to mixing of water masses also makes subsurface waters stable. Month of October represents neutral stability all along the EAS but again, during winter monsoon, stable waters are restricted to SEAS when compared to the NEAS where convective mixing dominates. Generally, when compared to coastal region, offshore regions represent a well-defined DSM which is concentrated below the MLD (Fig. 10).

Compared to the coast, offshore regions represent a well-defined DCM (~50 m) formation stretching all along the EAS during winter. This high concentration layer (1.0 mg/m^3) becomes shallower on reaching NEAS due to convective mixing (Fig. 11). During April to May, there is well defined DCM at around 80 m depth with maximum concentration (05-1.0 mg/m^3) in the NEAS. Month of June represents a

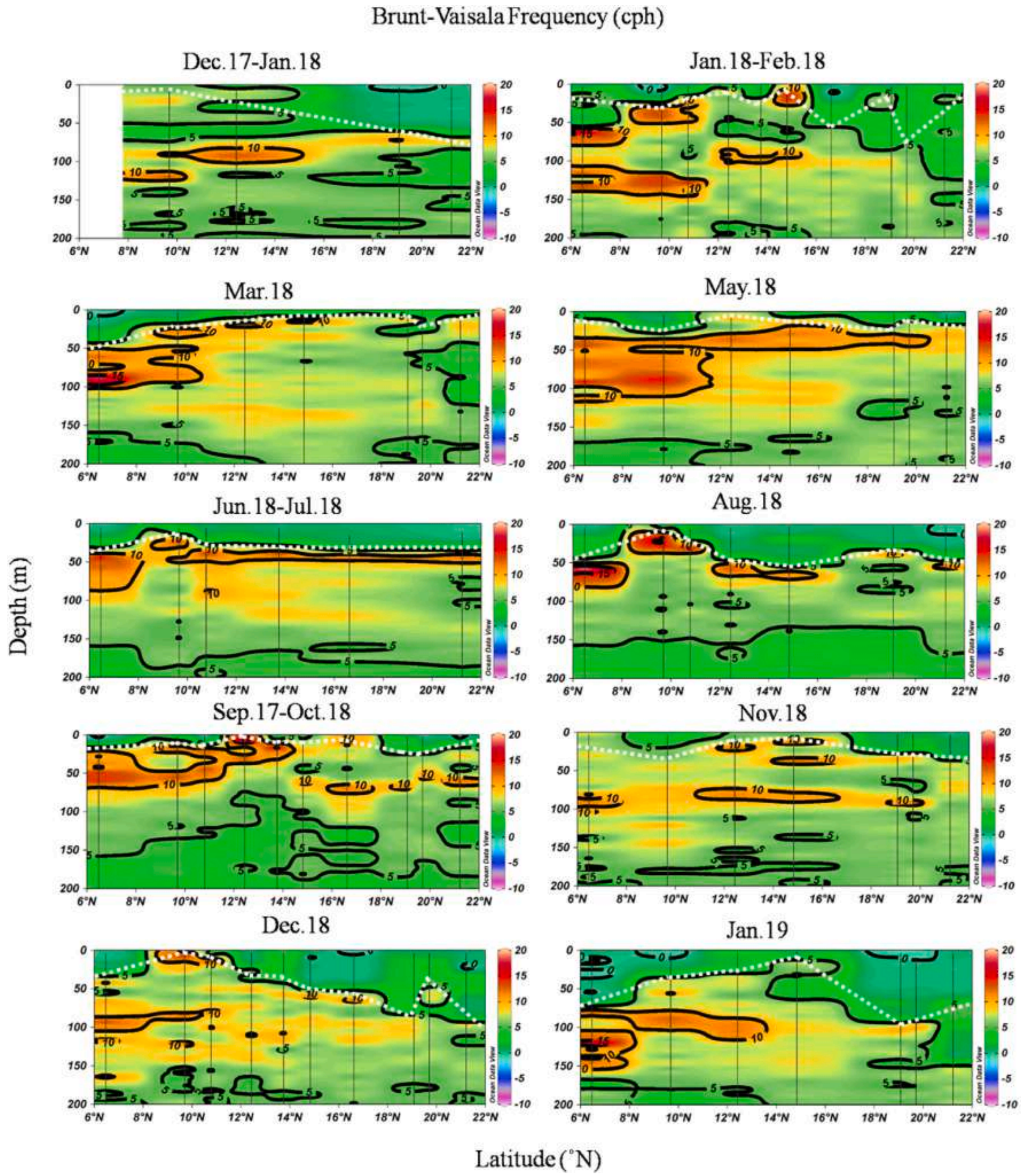

Fig. 10. Time series stability (cph) pattern along the offshore (2000m) waters of eastern Arabian Sea. Mixed Layer Depth (MLD) is represented as white dotted lines.

shallowing of DCM in the south with the prevailing upwelling process. July to September, there is high concentration (~1.75 mg/m^3) of chlorophyll which is now at the surface due to freshwater inflow stretching from Kochi to Ratnagiri. During October, due to downwelling, the high concentration at surface deepens to 20–50 m and then to 80 m by November. Again during December and January, DCM layer is about 50 m along the EAS with high concentration (0.5–1 mg/m^3) at surface waters of north due to convective mixing. Off Cape and Kochi regions also shows high concentration of DCM due to sharp density gradients formed due to intrusion of BoB waters at 50 m isobath.

Strength of correlation between DSM and DCM was tested using Pearson's correlation coefficient (r) and regression analysis (R^2). For the EAS as a whole, DCM was correlated with DSM ($r = 0.535$, $p < 0.05$; $R^2 = 0.276$). During the WM, strong correlation was noted in the SEAS ($r = 0.808$, $p < 0.05$; $R^2 = 0.654$) and CEAS ($r = 0.980$, $p < 0.05$; $R^2 = 0.960$) but not in the NEAS ($p > 0.05$; $R^2 = 0.122$). During the SM, strong correlation was noted in the SEAS ($r = 0.724$, $p < 0.05$; $R^2 = 0.524$) but not in the CEAS ($p > 0.05$; $R^2 = 0.510$) and NEAS ($p > 0.05$; $R^2 = 0.140$). During inter-monsoon seasons (SIM and FIM), correlation between DSM and DCM was found to be strong across entire EAS ($r = 0.948$, $p < 0.05$; $R^2 = 0.898$). In general, DSM and DCM were tightly coupled more or less throughout the year in the SEAS ($r = 0.845$, $p < 0.05$; $R^2 = 0.713$) and CEAS ($r = 0.907$, $p < 0.05$; $R^2 = 0.822$), while in the NEAS significant correlation was noted only during inter monsoon seasons ($r = 0.919$, $p < 0.05$; $R^2 = 0.845$) (Fig. 12).

4. Conclusion

Seasonal variations both in coastal and offshore waters are visible from fundamental hydrographic parameters such as temperature and salinity as well as chlorophyll concentration. The close relationship between the distribution of chlorophyll and the stability of the water

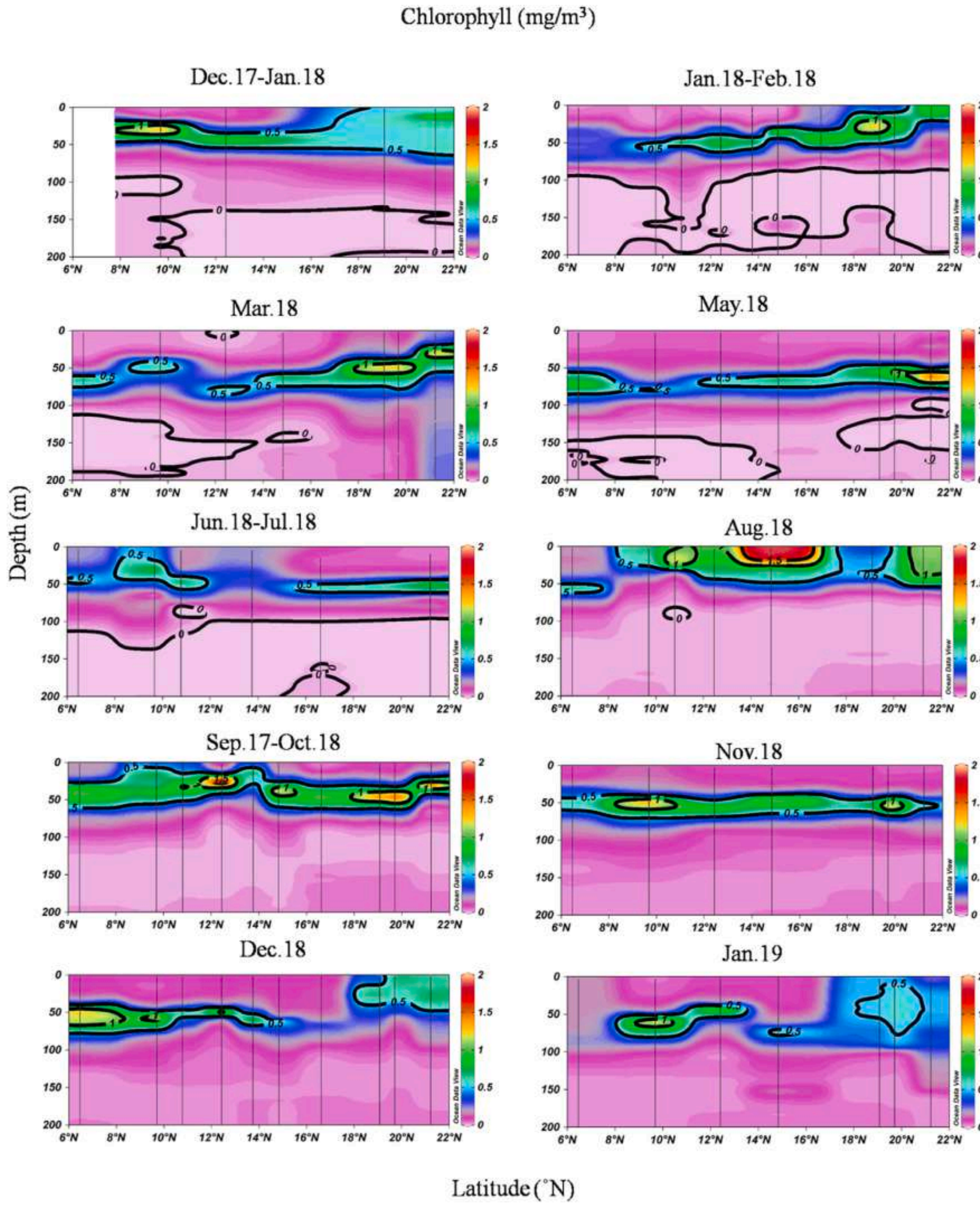

Fig. 11. Time series chlorophyll (mg/m^3) pattern along the offshore (2000m) waters of eastern Arabian Sea.

column emerges from the observations, where the depth of maximum induced chlorophyll corresponds to that of maximum vertical stability. In general, south has a comparatively high stability while north has a neutrally stable or unstable water column both during summer and winter. Moreover, the concentration of chlorophyll in the offshore waters mainly depends on vertical movement of high stable layer due to convective mixing and mixing of water masses while in the coastal regions depends upon factors like winter cooling, freshwater influence and upwelling. The changes in vertical stratification generate significant changes in chlorophyll vis-à-vis productivity patterns all along the coast. Peaks in the DCM may coincide with peaks in phytoplankton abundance and primary productivity.

From the observations, stability can be used to identify the high chlorophyll or DCM layer and thus DSM becomes a proxy to DCM or regions of high productivity. Dynamic stability serves as adequate parameter to assess the potential productivity patterns in the oceans. This can have a direct impact on identifying the potential foraging grounds for marine organisms.

Funding

Ministry of Earth Sciences (MoES), India.

Declaration of competing interest

The authors declare that they have no known competing financial

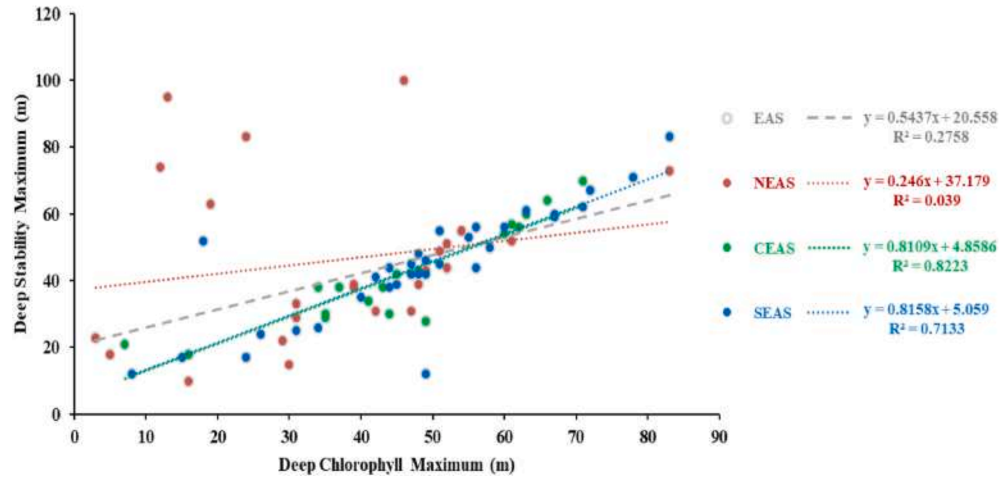

Fig. 12. Scatter plot of DSM and DCM in the SEAS, CEAS and NEAS.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors are thankful to the Secretary, Ministry of Earth Sciences, India and the Director, CMLRE for their interest and support. This study was carried out as part of the Marine Ecosystem Dynamics of eastern Arabian Sea (MEDAS) Program funded by the Ministry of Earth Sciences (MoES), Government of India, New Delhi and implemented by the Centre for Marine Living Resources and Ecology (CMLRE), Kochi. The authors acknowledge Vessel Management Cell and all fellow participants of FORV Sagar Sampada and ORV Sagar Kanya for their support and help rendered during sampling onboard. The authors wish to thank Dr. Usha V. Parameswaran and Mr. Arun V. S. for the help rendered in statistical analysis. The authors are grateful to the Editor and anonymous reviewers whose comments greatly improved the manuscript. This is CMLRE contribution number 150.

References

Agusti, S., Duarte, C.M., 1998. Phytoplankton chlorophyll a distribution and water column stability in the central Atlantic Ocean. Oceanol. Acta 22, 193–203.

Banse, K., 1987. Clouds, deep-chlorophyll maxima and nutrient supply to the mixed layer of the stratifed water bodies. J. Plankton Res. 9, 1031–1036.

Banse, K., 1994. On the coupling of hydrography, phytoplankton, zooplankton, and settling organic particles o!shore in the Arabian Sea. Proc. Indiana Acad. Sci. 103, 125–161.

Bhattathiri, P.M.A., Pant, A., Sawant, S., Gauns, M., Matondkar, S.G.P., Mohanraju, R., 1996. Phyto-plankton production and chlorophyll distribution in the eastern and central Arabian Sea in 1994-1995. Curr. Sci. 71, 857–862.

Catalano, G., Povero, P., Fabiano, M., Benedetti, F., Goffart, A., 1997. Nutrient utilisation and particulate organic matter changes during summer in the upper mixed layer (Ross Sea, Antarctica). Deep Sea Res. Oceanogr. Res. Pap. 44 (1), 97–112.

Fasham, M.J.R., Platt, T., Irwin, B., Jones, K., 1985. Factors affecting the spatial pattern of the deep chlorophyll maximum in the region of the Azores front. Prog. Oceanogr. 14, 129–165.

Fennel, K., Boss, E., 2003. Subsurface maxima of phytoplankton and chlorophyll: steady state solutions from a simple model. Limnol. Oceanogr. 48 (4), 1521–1534.

Gopalakrishna, V.V., Rao, R.R., Nisha, K., Girishkumar, M.S., Pankajakshan, T., Ravichandran, M., Rajesh, S., 2008. Observed anomalous upwelling in the Lakshadweep Sea during the summer monsoon season of 2005. J. Geophys. Res.: Oceans 113 (C5).

Hareesh Kumar, P.V., Anand, P., 2016. Coastal upwelling off the southwest coast of India: observations and simulations. Int. J. Digital Earth 9 (12), 1256–1274.

Husby, D.M., Nelson, C.S., 1982. Turbulence and vertical stability in the California current. CALCOFI (Calif. Coop. Ocean. Fish. Investig.) Rep. XXIII, 1–17.

Jurado, E., Van Der Woerd, H.J., Dijkstra, H.A., 2012. Microstructure measurements along a quasi-meridional transect in the northeastern Atlantic Ocean. J. Geophys. Res. 117, C04016. https://doi.org/10.1029/2011JC007137.

Kumar, S.P., Prasad, T.G., 1999. Formation and spreading of Arabian Sea high-salinity water mass. J. Geophys. Res.: Oceans 104 (C1), 1455–1464.

Kumar, S.P., Prasad, T.G., 1996. Winter cooling in the northern Arabian sea. Curr. Sci. 834–841.

Kumar, S.P., Madhupratap, M., Kumar, M.D., Gauns, M., Muraleedharan, P.M., Sarma, V. V.S.S., De Souza, S.N., 2000. Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea. J. Earth Syst. Sci. 109 (4), 433–441.

Madhupratap, M., Kumar, S.P., Bhattathiri, P.M.A., Kumar, M.D., Raghukumar, S., Nair, K.K.C., Ramaiah, N., 1996. Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. Nature 384 (6609), 549–552.

Madhupratap, M., Nair, K.N.V., Gopalakrishnan, T.C., Haridas, P., Nair, K.K.C., Venugopal, P., Gauns, M., 2001. Arabian Sea oceanography and fisheries of the west coast of India. Curr. Sci. 81 (4), 355–361.

McCreary Jr., J.P., Kundu, P.K., Molinari, R.L., 1993. A numerical investigation of dynamics, thermodynamics and mixed-layer processes in the Indian Ocean. Prog. Oceanogr. 31 (3), 181–244.

Midhun shah, H., Smitha, B.R., Hatha, A.M., Sudhakar, M., 2020. Subsurface chlorophyll maxima in the North Eastern Arabian sea: simulation on impact of warming. Ecol. Indicat. 110, 105858.

Murty, V.S.N., Gupta, G.V.M., Sarma, V.V., Rao, B.P., Jyothi, D., Shastri, P.N.M., Supraveena, Y., 2000. Effect of vertical stability and circulation on the depth of the chlorophyll maximum in the Bay of Bengal during May–June, 1996. Deep-Sea Res. Part I Oceanogr. Res. Pap. 47 (5), 859–873.

Narvekar, J., Kumar, S.P., 2006. Seasonal variability of the mixed layer in the central Bay of Bengal and associated changes in nutrients and chlorophyll. Deep Sea Res. Oceanogr. Res. Pap. 53 (5), 820–835.

Narayanan Nampoothiri, S., Ramu, C., Rasheed, K., Sarma, Y.V.B., Gupta, G.V.M., 2022. Observational evidence on the coastal upwelling along the northwest coast of India during summer monsoon. Environ. Monit. Assess. 194 (1), 1–16.

Narvekar, J., D'Mello, J.R., PrasannaKumar, S., Banerjee, P., Sharma, V., Shenai-Tirodkar, andP., 2017. Winter-timevariability of the eastern Arabian sea: acomparison between 2003 and 2013. Geophys. Res. Lett. 44, 6269–6277. https://doi.org/10.1002/2017GL072965.

Pingree, R.D., Holligan, P.M., Mardell, G.T., 1978. The effects of vertical stability on phytoplankton distributions in the summer on the northwest European Shelf. Deep Sea Res. 25 (11), 1011–1028.

Pond, S., Pickard, G.L., 1983. Introductory Dynamic Oceanography. Pergamon Press, New York, p. 240.

Prasad, T.G., 2004. A comparison of mixed-layer dynamics between the Arabian Sea and Bay of Bengal: one-dimensional model results. J. Geophys. Res.: Oceans 109 (C3).

Prasanna Kumar, S., Narvekar, J., Kumar, A., Shaji, C., Anand, P., Sabu, P., Nair, K.K.C., 2004. Intrusion of the Bay of Bengal water into the Arabian Sea during winter monsoon and associated chemical and biological response. Geophys. Res. Lett. 31 (15).

Prasanna Kumar, S., Nuncio, S.M., Narvekar, J., Ramaiah, N., Sardesai, S., Gauns, M., Fernades, V., Paul, J.T., Jyothibabu, R., Jayaraj, K.R., 2010. In: Seasonal cycle of physical forcing and biological response in the Bay of Bengal, 39, pp. 388–405, 3.

Sarma, V.V., Aswanikumar, V., 1991. Subsurface chlorophyll maxima in the north-western Bay of Bengal. J. Plankton Res. 13 (2), 339–352.

Sarma, Y.V.B., Al Azri, A., Smith, S.L., 2012. Inter-annual variability of chlorophyll-a in the Arabian sea and its gulfs. Int. J. Mar. Sci. 2 (1).

Shafeeque, M., Balchand, A.N., Shah, P., George, G., Smitha, B.R., Varghese, E., Joseph, A.K., Sathyendranath, S., Platt, T., 2021. Spatio-temporal variability of chlorophyll-*a* in response to coastal upwelling and mesoscale eddies in the South Eastern Arabian Sea. Int. J. Rem. Sens. 42 (13), 4836–4863.

Shah, P., Sajeev, R., Thara, K.J., George, G., Shafeeque, M., Akash, S., Platt, T., 2019. A holistic approach to upwelling and downwelling along the south-west coast of India. Mar. Geodes. 42 (1), 64–84.

Shankar, D., Shetye, S.R., 1997. On the dynamics of the Lakshadweep high and low in the southeastern Arabian Sea. J. Geophys. Res.: Oceans 102 (C6), 12551–12562.

Shankar, D., Remya, R., Vinayachandran, P.N., Chatterjee, A., Behera, A., 2016. Inhibition of mixed-layer deepening during winter in the northeastern Arabian sea by the west India coastal current. Clim. Dynam. 47 (3–4), 1049–1072.
Sharma, G.S., 1978. Upwelling off the southwest coast of India. Indian J. Mar. Sci. 7 (4), 209–218.
Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Sundar, D., Michael, G.S., Almedia, A.M., 1990. Hydrography and circulation off the West coast of India during the southwest monsoon 1987. J. Mar. Res. 48, 359–378.
Smitha, A., Joseph, K.A., Jayaram, C., Balchand, A.N., 2014. Upwelling in the southeastern Arabian Sea as evidenced by Ekman mass transport using wind observations from OCEANSAT–II Scatterometer. Indian J. Geo-Mar. Sci. 43 (1), 111–116.
Smitha, B.R., Sanjeevan, V.N., Vimalkumar, K.G., Revichandran, C., 2008. On the upwelling off the southern tip and along the west coast of India. J. Coast Res. 24, 95–102.
Vishnu, N.N.S., Sachin, T.S., Rasheed, K., 2020. Dynamics and forcing mechanisms of upwelling along the south eastern Arabian sea during south west monsoon. Regional Stud. Mar. Sci. 40, 101519. https://doi.org/10.1016/j.rsma.2020.101519.