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Observed Inter-annual Variability of Upwelling Characteristics during 2016-2017: A Study using Princeton Ocean Model

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ABSTRACT

Oceanographic observations carried out during 2016 and 2017 onboard *INS Sagardhwani* in the Southeastern Arabian Sea are used to study the inter-annual variability of the upwelling. In 2016, the strong upwelling signatures are noticed in the observations (SST < 27°C and strong up-slopping of isotherms) as well as in the satellite derived sea level anomaly data. Whereas in 2017 the low sea level in June (-2 cm) are weakened during the mid of July (+3 cm) along the southern track (8 °N and 9 °N). This decrease in the strength in 2017 can be attributed to two major reasons. One is the presence of an anti-cyclonic eddy along the coast (8.5 °N, 76.5 °E) weakens the upwelling processes and second is the weak northerly component of the wind compared to 2016. In addition, Lakshadweep low is less prominent and situated towards the southern side (around 7°N) of its usual region of occurrence in 2017. The inter-annual variability of upwelling during July 2016 and 2017 is investigated using the 3D ocean model Princeton Ocean Model. Experiments with model in different combinations of forcing reveals that the alongshore wind component is the major parameter influencing the upwelling characteristics during these periods.

Keywords: Upwelling; POM model; Arabian sea; Wind direction; Ocean model

1. INTRODUCTION

The oceanic region in the Southeastern Arabian sea (SEAS) is influenced by monsoon conditions where the wind changes its direction semiannually with transition periods in-between. The unique wind and current system during summer causes upwelling off the southwest coast of India while sinking during winter, despite northeasterly winds. The periods of upwelling is characterised by shoaling of mixed layer towards the coast, resulting in shallow layers in the coastal regions (<5 m) and many times the thermocline starts from the surface. Another manifestation of the onset of upwelling is the fall in the sea level[1,2].

In the past there have been many studies on upwelling in the SEAS as part of the IIOE and other cruises by[3-7]. Based on the hydrographic data, it is found that upwelling takes place during the summer monsoon season, i.e. from May to October[3]. However, the initiation of upwelling first occur off the southern tip of India much prior to the onset of summer monsoon over Kerala[4,8] and then slowly progress towards north with the advancement of the monsoon. The localisation of cold water suggests a relation to the coastline orientation and (or) wind field. Muraleedharan and Prasannakumar[9] made a comparison study between the coastal and open ocean upwelling in the Arabian Sea. Shankar[10], *et al.* explored the influence of alongshore winds on the coastal upwelling between 8 °N and 15 °N. Many studies have related the coastline orientation and the upwelling-favourable winds[11]. In the Arabian Sea, the Western Ghats guide the monsoon winds to follow the west coast of India, i.e. to northwesterly or even northerly, which are then favourable for eastern boundary upwelling.

Based on FAO-UNDO project data sets Johannessen[8], *et al.* gave a detailed account of the seasonal variations in the upwelling and watermasses characteristics in this region. Later, Johannessen[12], *et al.* explained the variability in the hydrographic properties off the southwest coast of India utilised the data collected during June-August 1987. Utilising the available time series data[13], the mixed layer variability during the pre-monsoon and monsoon seasons at selected locations in the coastal and deep water of the AS are documented. Some other studies focused on the undercurrent observed during the summer monsoon season[12,14-16] and its importance in the coastal circulation. Rao[17], *et al.* made some attempt to simulate the coastal upwelling off the west coast of India using the Princeton Ocean Model. However, even today, a thorough understanding of this phenomenon is not yet accomplished. Strength of this study is the availability of in-situ data collected systematically for verifying model results.

In this paper, the monthly spatial data collected from surveys during July 2016 and 2017 onboard *INS Sagradhwani* in the Southeastern Arabian Sea are utilised to document and explain the upwelling off the southwest coast of India. The variability of upwelling characteristics are simulated using the 3-D Princeton Ocean Model (POM).

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2. DATA AND MODEL

To oceanographic surveys were carried out onboard *INS Sagardhwani* during 18-24 July 2016 and 18-27 July 2017 off the southwest coast of India (Fig. 1) to study the thermohaline variability. During 2016, the survey is carried out along five transects, each separated by 60 Nm, and extended to offshore up to 73.25 °E. During 2017, the survey is carried out along twelve transects in which first three are in the Gulf of Mannar and rest in the South Eastern Arabian Sea (SEAS) extending from 8 and 15 °N latitude, each separated by 60 Nm, and extended to an offshore distance of 60 Nm from the 30 m depth contour. Vertical profiles of temperature and salinity are collected from all the stations using portable CTD system (accuracy +0.05 °C, 0.01 psu) at every 15 Nm intervals. The hydrographic data is supplemented with satellite derived winds for the corresponding observational period and monthly climatology winds. The sea level anomaly (SLA) data corresponding to the observational period (http: //las.aviso.oceanobs. com) are analysed to study the surface signatures of upwelling.

The Princeton Ocean Model, POM[18] with realistic bottom topography[19] is utilised to study the influence of wind on the variability of the upwelling during 2016 and 2017. The model domain extends from 60 °E – 95 °E and 10 °S to 30 °N. More details of the model are given in[17,20]. There are 211 x 241 (60 °E – 95 °E and 10 °S to 30 °N) grid points in the horizontal computational plane and 26 levels in the vertical. Resolution in the zonal and meridional direction is 1/6°. In the vertical, a terrain following sigma coordinate is used with fine resolution of 0.5 and 15 m respectively near the surface and the bottom, while a relatively coarse grid of about 30 m is used at the mid-depths. The horizontal time differencing is an explicit scheme, whereas the vertical time differencing is an implicit scheme. It uses a mode splitting technique with barotropic (20 s) and baroclinic (800 s) mode. The initial fields of temperature and salinity are obtained from the monthly climatology data of World Ocean Atlas 2009. After 20 year of diagnostic run, a steady-state velocity field and surface elevation that are dynamically consistent with temperature and salinity are established. This velocity and elevation along with temperature and salinity are used as initial conditions for the model simulations in the prognostic mode. In the simulation, mechanical forcing is done using the daily ASCAT wind data and thermal forcing using daily net heat flux and solar radiation data for the study period.

In addition to that, current data is taken from the ocean surface current analysis real-time (OSCAR) which is a blended data set of observation and model (http://podac.jpl.nasa.gov, Dataset: Ocean Circulation) available at 0.33° x 0.33° resolution. The wind data is from ASCAT (www.remss.com/missions/ascat) which is available at 0.25° x 0.25° grid interval. Net heat flux and solar radiation from Tropflux[21] is used.

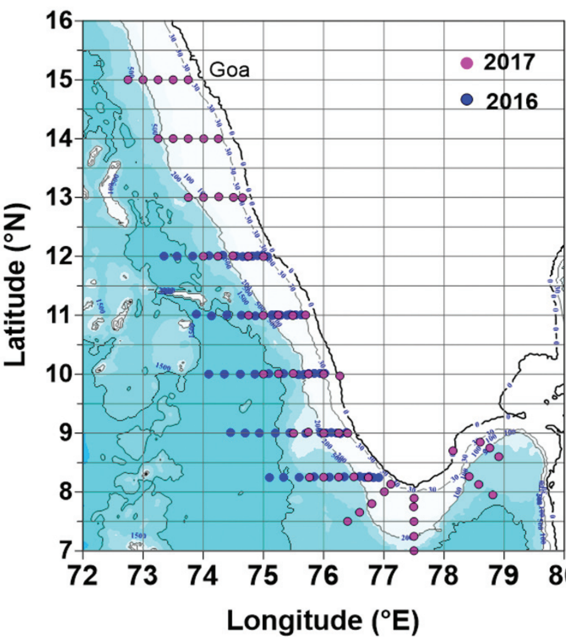

Figure 1. Surface parameters during July 2016 and 2017 (a) wind (b) SST with current overlaid.

3. RESULTS AND DISCUSSION

3.1 Surface Parameters in the SEAS

During the southwest monsoon period, northwesterly winds are expected along west of India due to the orographic effect of the Western Ghats. It is observed that the effect of topography on wind produce complex circulation pattern[21]. Winds are north-westerly during 2016 following the climatological pattern. Winds are considerably stronger during 2017 and more westerly than in 2016. South of 10 °N, 2017 is having more northerly component than that of 2016 (Fig. 2(a)). Following the trend of the wind, the surface temperature is much cooler along the coastal regions north of 10°N in

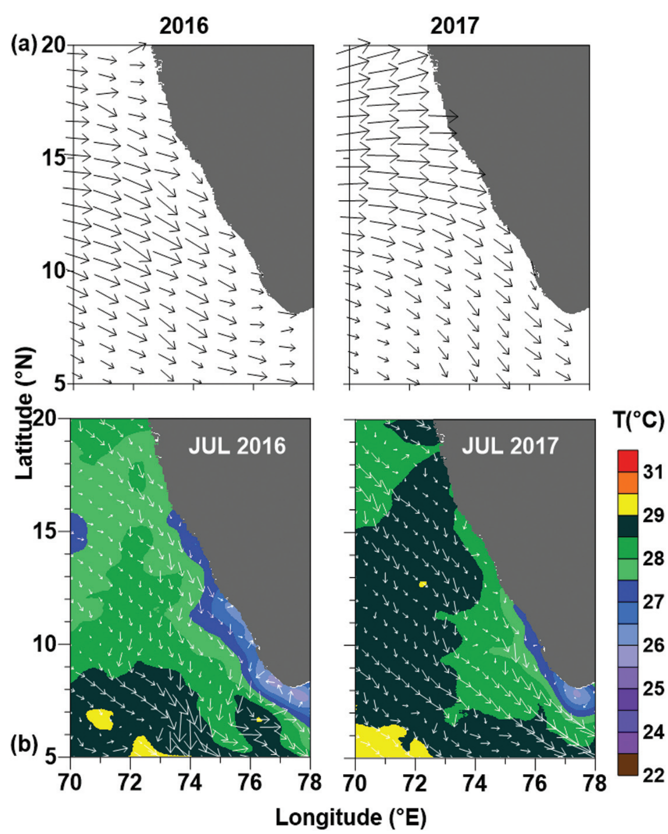

Figure 2. Surface parameters during July 2016 and 2017 (a) wind (b) SST with current overlaid.

2016. The SST during 2017 shows a trend of upwelling in the southern SEAS with a limited spread to offshore compared to that of 2016. The influence of the wind in the upwelling can be clearly identified from the SST distribution during 2017 with the spread of cool water much lesser towards north of 10°N. Based on the analysis this variability can be attributed to the weaker northerly component of the wind north of 10°N in 2017. The circulation in the SEAS followed SW monsoon seasonal pattern, with southward flowing surface current (Fig. 2(b)). An anticyclonic eddy is noticed in the southern region of the study area during July 2016. This eddy is centered at 76 °E and 8 °N. This eddy is absent during July, 2017.

3.2 Spatio-temporal Variability of Temperature and Salinity in the SEAS

The vertical sections of temperature (Fig. 3(a)) and salinity (Fig. 3(b)) corresponding to both the years (2016 and 2017) shows up-slopping of isolines towards the coast in the upper 100 m and down-slopping below this depth. In general, the offshore waters are warmer and less saline compared to the coastal waters especially in the topmost layers. In the offshore region, upsloping is evident at the subsurface level (75 m) at 9 °N, whereas it is less extent towards the offshore along 10 °N. The isotherms surfaces very near to the coast at 9 °N in and cool the near surface layers by 3 °C to that of offshore (27 °C in offshore to 24 °C at the coast). During 2017, the upwelling is comparatively weaker to that of 2016. The surface layers at the coast are only having a cooling of 1.5 °C - 2 °C to that of offshore (25 °C at the coast and 27 °C in offshore). It is reported that there is a cooling of 2.5 °C in the surface layers off Kochi during 1987 compared to offshore due to upwelling[8]. During the initial phase of upwelling the temperature difference is about 0.52 °C at the surface and 1.6 °C in the thermocline in the near shore between 2016 and 2017. In close proximity to the coast, the water column along 9°N is cooler (1.2 °C / 1.32 °C at the surface and 0.5 °C / 0.7 °C in the thermocline during 2016/2017, respectively) than across 10 °N, suggesting early onset of upweling at the south. In contrary, in the offshore, the water column is slightly warmer along 9 °N than 10 °N (0.46 °C at the surface during 2016 and 0.53 °C during 2017). During 2016, doming of isothermal lines are seen along 75.5 °E in the 9 °N transect indicating the presence of the cyclonic eddy in that region. In the case of salinity, both years properly indicate the similar trend with lesser saline (34.5 psu - 35 psu) waters at the surface. The salinity along the 10 °N is much less compared to that of 9 °N. The vertical variations are primarily confined to the top 150 m depths level (Fig. 3(b)). During summer monsoon season massive freshwater discharges from two local rivers (Periyar and Muvatupuzha) typically occur along the south west coast of India[22]. This result in considerable dilution of surface waters especially very close to the coast, as evident from salinity (< 34 psu). This low saline water is detected only in the upper few meters (<10 m). As the freshwater discharge is mostly confined close to the coast, salinity increased towards the offshore region. Even though the trend remained same, the salinity is seen higher during 2017 compared to 2016.

3.3 Variability in the Surface Characteristics

To see the variability in the characteristics of upwelling in the surface, the hovmoller diagram of SST from Satellite data is plotted (Fig. 4(a)). Along 9 °N, SST values during 2016 showed a trend of lowing temperature from 20th June onwards and it peaked by August. The same can be seen along 10 °N also but with lower amplitude. But during 2017, in both 9 °N and 10 °N the upwelling phase can only be detected during 15

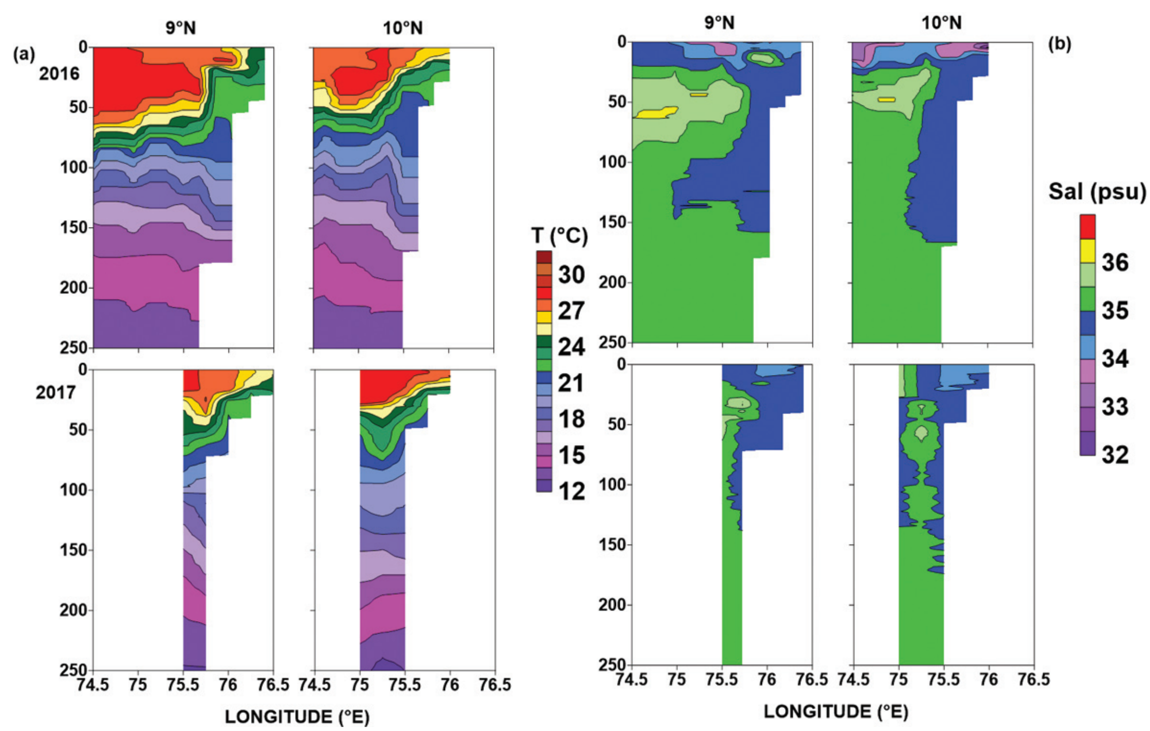

Figure 3. Vertical sections along 9°N & 10°N during July 2016 and 2017 (a) Temperature and (b) Salinity.

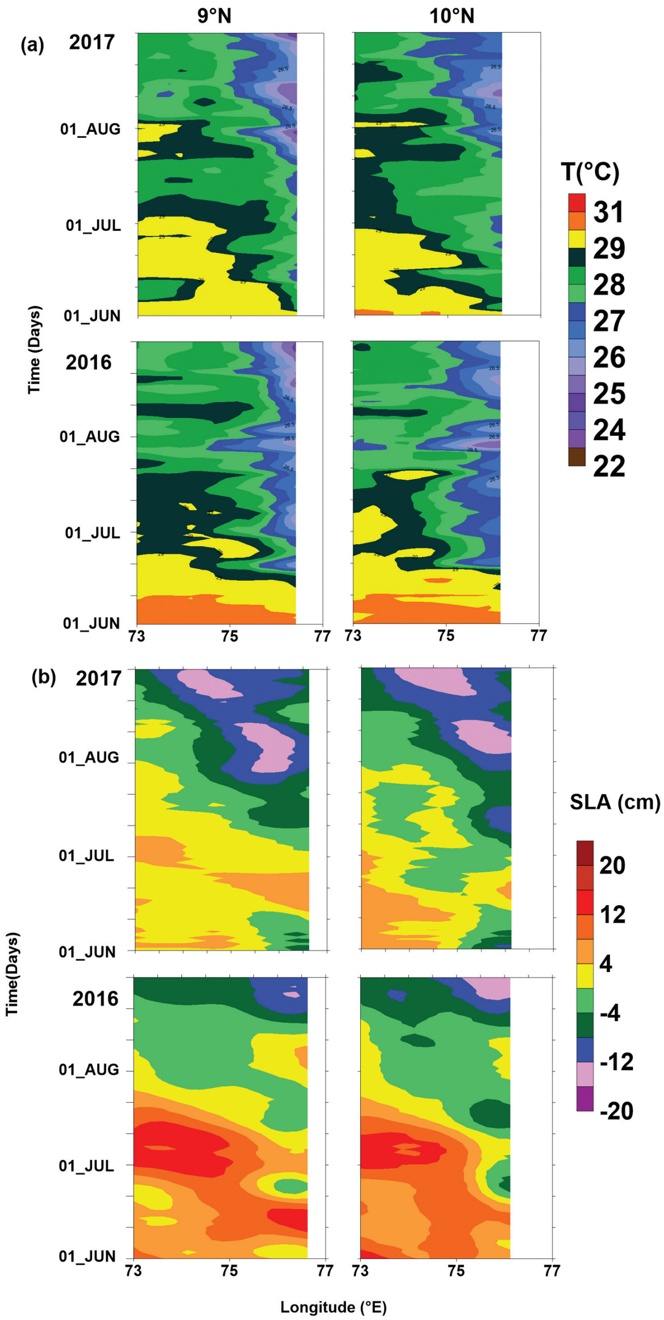

Figure 4. Hovmoller plots along 9°N and 10°N during 2016 and 2017 (a) SST and (b) SLA.

July only and that too in a very feeble manner. But it peaked very fast and also has a higher spread towards offshore than that of 2016.

The sea level anomaly (SLA) which is noticed during these two year (Fig. 4(b)) also has more similar to that of SST pattern. During 2016, the upwelling (low in sea level) can be seen by 15th June 2016 along 9 °N as well as 10 °N. During the last week of June, the cool upwelled water disappears along 9 °N which again appears by 1st July. This pattern is also well seen in the SLA for the period. A high (4cm during last week of July) is sandwiched between two lows on either side (< -4 cm, 15th June to last week of July and 1st July). In the case of 2017, the sea level is high till 10th July, from where it started decreasing. In the SST also the low temperature water is seen only towards the mid of July and there onwards the low continues till August in both cases.

3.4 Modelling of the SEAS for July 2016 and 2017

To see the variability and its dynamics, the Princeton Ocean Model, POM[14] is run for the same period using realistic bottom topography[15]. The model is forced by daily ASCAT wind stress, INCOIS net heat flux and solar radiation data for 2016 and 2017.

The simulated SST reveals the presence of upwelling in both years as seen in the satellite SST (Fig. 5(a)). The cooling during 2017 is much low compared to that of 2016. In the Hovmoller plots (Fig. 5(b)) also, it is visible that onset of upwelling is delayed during 2017. The surface cool water is noticed only after 15th July in 2017 where as it is much earlier in 2016. This is noticed in the observations also (Fig. 4(a)). The model could also simulate the southward flow of WICC during this period. The presence of low salinity waters are noticed in the coastal region matching with the observation (Fig. not presented). From the observed SSS field it is very clear that, the salinity of the water increase towards northern part as well as to offshore of the study region, the model could simulate the trend in a very significant manner. As such, the model could simulate much of the surface parameters well and comparable with the observations.

The depth-space section of model simulated temperature and salinity (Fig. not presented)) along transects 9° and 10°N also indicated the upsloping of isotherms towards the coast suggesting the occurrence of upwelling. The upwelling is mostly confined to the upper 50 m - 60 m. The coastal waters we cool by about 2 °C during 2016 and 1.5 °C during 2017. This is in good agreement with that of observation (3 °C and 2 °C during 2016 and 2017 respectively). The salinity also follows the trend of increase towards the offshore, even though the model could not capture the presence of very low saline water at the coast due to the non-inclusion of Periyar/Moovattupuzha Rivers in the model.

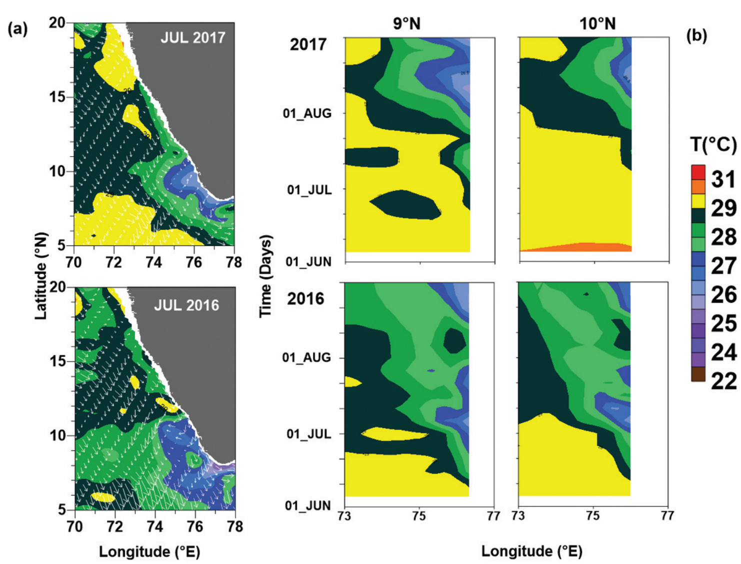

Figure 5. (a) Simulated SST with current overlaid and (b) Hovmoller plots of SST during 2016 and 2017.

3.5 Model Experiments to Identify the Role of Wind in the Upwelling

It is obvious from the observation as well as the model that, there is variability in the upwelling pattern during 2016 and 2017. To study the dynamics, the POM model has been utilised and various experiments are done with different model setup. To see the effect of wind over the upwelling during these two phase the model is run with

(a) Actual wind
(b) Constant wind
(c) Wind from north east
(d) Wind from north
(e) Wind parallel to the coast.

In the case where the wind is constant, the upwelling is noticed higher during 2016 as well as 2017 (Figs. 6(a) - 6(e), all figures are of 15 July). The wind speed when given constant simulated a cyclonic eddy during 2016 as well as 2017 in the southwest coast of India with different dimensions and strength. When the wind is from northeast (345° north taken as 0°) and when it is parallel to the coast (335°), the strength of upwelling seems have no much difference. In both the cases the upwelling found to be very high than that of normal case. When the wind is from true north, then also there is a significant improvement in the upwelling seen in the southwest coast of India. This clearly shows that, the upwelling is much dependent on the northerly component of wind. During 2017, the wind is more westerly than that of 2016 (Fig. 2) and hence the upwelling is found to be weak during this year compared to that of 2016.

In the hovmoller diagrams also similar trend is noticed (Fig. 7). In the actual scenario, the upwelling during 2017 started late and its signal in the surface layers is noticed only during 15th of July. Whereas during 2016, upwelling showed its surface signals well before July (Jun 15th).

Also when the wind is modulated towards the northerly direction during 2017, it is very interesting to notice that the onset of upwelling is advanced by about 20-25 days with a comparably higher spread towards the offshore. Here also it is evident that the northward wind stress is playing a major role in the upwelling of the southwest coast of India. During the year 2016, the trend is similar.

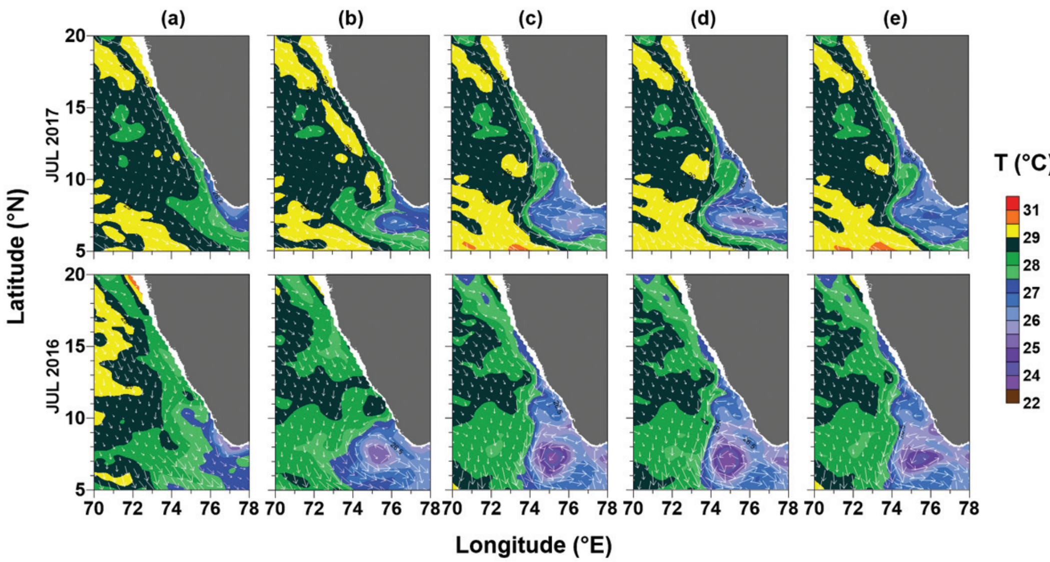

Figure 6. Simulated SST with current overlaid for different model runs for 2016 and 2017 (a) Actual wind, (b) Constant wind speed, (c) Wind from North-east direction, (d) Wind from North, and (e) Wind parallel to coast.

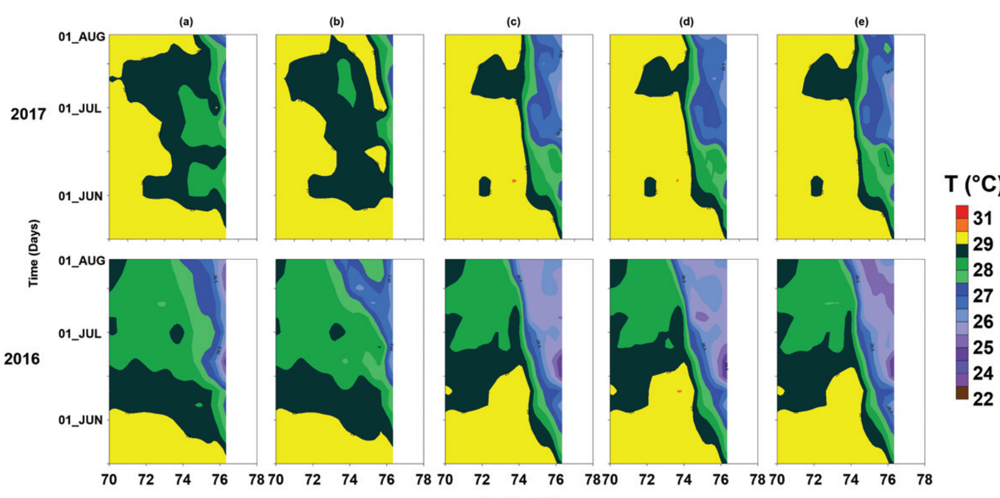

Figure 7. Hovmoller plots of simulated SST along 9 °N for different model runs for 2016 and 2017 (a) Actual wind, (b) Constant wind speed, (c) Wind from North-east direction, (d) Wind from North, and (e) Wind parallel to coast.

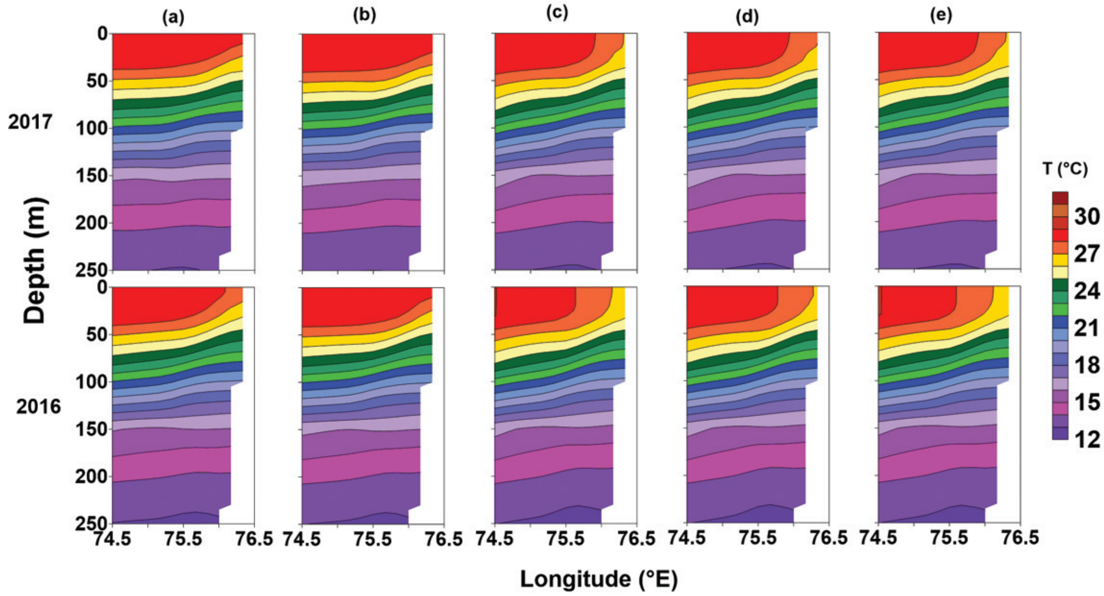

Figure 8. Vertical sections along 9 °N during July 2016 and 2017 (a) Actual wind, (b) Constant wind speed, (c) Wind from North-east direction, (d) Wind from North, and (e) Wind parallel to coast.

In the simulated results with actual wind, along the transect 9 °N, the intensity of upwelling is less during 2017 compared to 2016 (Fig. 8). Coastal temperature is 1 °C cooler during 2016. With constant wind, even though the upwelling trend is seen in both the years, the surface water is warmer. The entire scenario changed, when the wind direction is given north-east, parallel to coast or from north. The intensity increased and the coast is cool by around 1 °C - 1.5 °C in all these cases. This also signifies the importance of the northerly component in the upwelling dynamics.

4. SUMMARY AND CONCLUSION

Upwelling is observed along the west coast in SEAS in both the years 2016 and 2017 with a higher spread in 2016 compared to that in the latter. Wind component in SEAS plays a major role in the upwelling during the south west monsoon. Stronger northerly wind components are observed in 2016 which is attributed to the variation in upwelling. POM model is utilised to study the effect of wind on the upwelling during the south west monsoon. POM model could simulate well the actual dynamics of ocean for the study region during the south west monsoon. Model run is carried out for various wind conditions. Maximum upwelling is noticed when winds are in 345° or parallel to the coast which confirmed that predominant northerly wind components in 2016 causes the increased up-slopping of the low temperature water along the south west coast when compared to 2017.

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In the current study, he has initiated the idea and guided the work.