

Response of Ocean Eddies to Monsoon Winds Over the Western Arabian Sea

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ABSTRACT

Western Arabian Sea is one of the key regions in terms of momentum transfer which transfers kinetic energy to ocean eddies and also air-sea interaction process. The present study focused on interaction between eddies and seasonal monsoon winds over western Arabian Sea. Satellite derived wind fields, ocean surface currents (SODA, ORSA4) are used to study the kinetic energy changes along these observations we also collected Argo profiles at three eddy regions namely Socotra Eddy, Great Whirl and Southern Gyre for Brunt Vaisala frequency and Turner Angle calculations during southwest monsoon of 2015 and 2017 to check the stability of the water column. Lowest current induced kinetic energy was observed at Socotra Eddy, but at Great whirl its value is high and it was found to be fully driven by wind and showed positive feedback to the wind forcing, where Southern Gyre is under the influence of both wind and Equatorial current.

INTRODUCTION

In fluid dynamics, an eddy is the swirling of a fluid and the reverse current created when the fluid is in a turbulent flow regime. The moving fluid creates a space devoid of downstream-flowing fluid on the downstream side of the object. Fluid behind the obstacle flows into the void creating a swirl of fluid on each edge of the obstacle, followed by a short reverse flow of fluid behind the obstacle flowing upstream, toward the back of the obstacle. In oceans the main forcing to generate the eddies are to be winds. The main reason for the formation of eddies and how it responds to the winds was important to know in order to predict its size and circulation area size.

Eddy processes are of primary importance for the dynamics of intense western boundary currents, through the exchange of momentum and energy via instability and/or rectification processes, and also influence the dynamics of the Southern Ocean. The eddy contribution to the meridional transport of heat and fresh water is small in many regions but cannot be ignored on the global scale. Long lived, propagating eddies such as Agulhas rings determine a major part of the inter-basin exchange between Indian and South Atlantic Oceans. The decaying rings provide a source of warm salty water important for the global thermohaline circulation (de Ruijter et al., 1999). Along the Somali Current

(SC) three major anticyclonic circulations: the Socotra Eddy (SE), the Great Whirl (GW), and the Southern Gyre (SG), are present (Beal and Donohue, 2013; Akuatzevi et al., 2016). The GW is an almost-closed anticyclonic eddy, extending up to 1000 m deep with average speeds of 10 cm/s (Beal and Donohue, 2013; Wiggert et al., 2000). Another smaller warm core eddy that often forms to the northeast of the GW during South West monsoon is the SE (Jensen, 1991). Akuatzevi et al. (2016) analysed SC eddy interactions through hindcast simulations of the ocean/sea-ice model configuration ORCA025 as described in Barnier et al. (2006) and suggest potential formation mechanisms for the SE, such as anticyclonic vorticity shedding of the GW, advection of GW-induced flanking cyclones, induction by the mean current along the northern edge of the GW, or independent development as a coherent mesoscale eddy (Akuatzevi et al., 2016). The SG is generated by the clockwise directional change of the EACC as it interacts with the western boundary of the Indian Ocean from 10S to 2N (Shankar et al., 2002; Akuatzevi et al., 2016). Hence there is importance of Study of how the Ocean Eddies respond to winds especially during monsoon season over of Western Arabian Sea.

DATA AND METHODOLOGY

Data Sets used in this study are as follows. SODA v2.2.4 (Ocean data assimilation model),

ECMWF Ocean Reanalysis System 4 (ORAS4) & AVISO Topex/Poseidon monthly data sets were used with temporal resolution of 5 years for the U-V current components of the Ocean to calculate the Kinetic Energy. Cross-Calibrated Multi-Platform (CCMP) Monthly V02.0 data set were used for U, V components of the wind. The temporal resolution of all these data were kept same. Argo data sets were used to calculate the physical parameters with temporal resolution of one day for five years. The SODA data sets consist of Meridional 0.5 degree, Horizontal 0.5-degree resolution. The plots are with the same resolution as that of original data. Similarly, ORAS-4 data sets consist of Meridional 1 degree, Horizontal 1-degree resolution. AVISO data sets consist of Meridional 1/3-degree, Horizontal 1/3-degree resolution. The plots are with the same resolution as that of original data.

Argo profile data was taken up to 1 300m depth and all the physical parameters were plotted in Ocean Data View display software. Physical parameter includes Temperature, Salinity, Neutral Density, Brunt-Vaisala Frequency and Turners angle.

Kinetic Energy calculated over the western Arabian Sea using both Ocean Currents (zonal and meridional) and Wind speed (Zonal and meridional) based on the following formula

$$K.E = \frac{1}{2}(u^2 + v^2) \text{ ----- (1)}$$

Here K.E = Kinetic Energy

U= Zonal component (m/s); V= Meridional component (m/s)

Brunt Vaisala frequency (N) is measure of Stability of Water parcel. The higher the frequency the lower the static stability of water parcel and it tends to become turbulent.

$$N = \sqrt{\frac{g}{\rho} \frac{d\rho}{dz}} \text{ ----- (2)}$$

Here N is Brunt Vaisala frequency (cycles/hr); g – gravity (m/s²); ρ - seawater density (kg/m³)

dρ/dz – density gradient of water column

Turner Angle (T_u) for the measure of stability to diffusive convection and salt fingering.

$$T_u = \tan^{-1} \left(\frac{\alpha \partial z T + \beta \partial z S}{\alpha \partial z T - \beta \partial z S} \right) = \tan^{-1} \left(\frac{R_\rho + 1}{R_\rho - 1} \right) \text{ -- (3)}$$

Here T_u = turner angle; α = Expansion Coefficient of Temperature; β = Expansion Coefficient of Salinity; R_ρ = which is defined as the ratio of the change in density due to temperature over the change in density due to salinity

$$R_\rho = \frac{\alpha \partial z T}{\beta \partial z S} \text{ ----- (4)}$$

Neutral Density is calculated -----

$$\nabla \gamma^n = b\rho(\beta \nabla S - \alpha \nabla \theta) + R \text{ ----- (5)}$$

S = salinity (psu); θ = Potential Temperature (°C); α = Thermal Expansion coefficient; β = Salinity contraction coefficient; b = Integrating Factor; R = Residue number which is not zero; ∇γⁿ = Neutral Density.

RESULTS

Monthly Mean and Seasonal wind speed were measured to be > 12m/s (Figure1) at the area of study which we intended to conduct the study. Initially the wind direction was towards the NE direction but later on it's changed during JJAS month (Figure1). The change was found to be from NE to E direction exactly at 62°E longitude. But the average seasonal wind direction was remained towards North-East. Besides that, wind speed also increased from June to July month and later on decreased till the September and the range was found to be in between the range of 9-10 m/s.

Two Eddy circulation pattern observed among all the data sets, two being significant among those to be considered for studies at 4-10°N, 50-56°E in SODA (Figure 2) 1°N, 49°E in ORAS4 (Figure 2) respectively. Also, there is another circulation pattern observed one of them being not that distinct in terms of circulation pattern. These two major circulation patterns believed to be Great Whirl and Southern Gyre respectively according to (Shankar et al., 2002; Akuetevi et al., 2016). On an average the velocity of surface current of these two eddies was found to be to be > 0.85 m/s. The movement of the Great Whirl was observed towards North from 6°N, 52°E to 8°N,52°E (Figure 2). During this transition the size of the Eddy gradually grew and shrunk towards the end of the September month. There was no strong circulation pattern observed at Socotra Eddy region which was also part of the study region. Besides this there is change the direction of flow of coastal water current from south west to North east (Figure 2). Due to unavailability of similar resolution data of all there are some feature hindered due to averaging the monthly means.

The average seasonal kinetic energy was calculated and found to be > 70 cm²/sec² (Figure 3). The calculation was done using CCMP wind component hence, no circulation kind of pattern was observed, and instead it showed the strength and the spatial stretch of the wind forcing. Near Somali Coast (Socotra eddy region) during July month the Kinetic Energy was found to be very intense. The Kinetic Energy undergone a change by increasing June to July and later on decreasing

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till September throughout the Monsoon season, this might be because of the decrease in wind speed. The areas of high kinetic energy showed possibility of strong Air-Sea interaction in terms

moment transfer. As the wind speed increased from June to July and later on decreased till September (Figure 1) the kinetic energy responded accordingly (Figure 2)

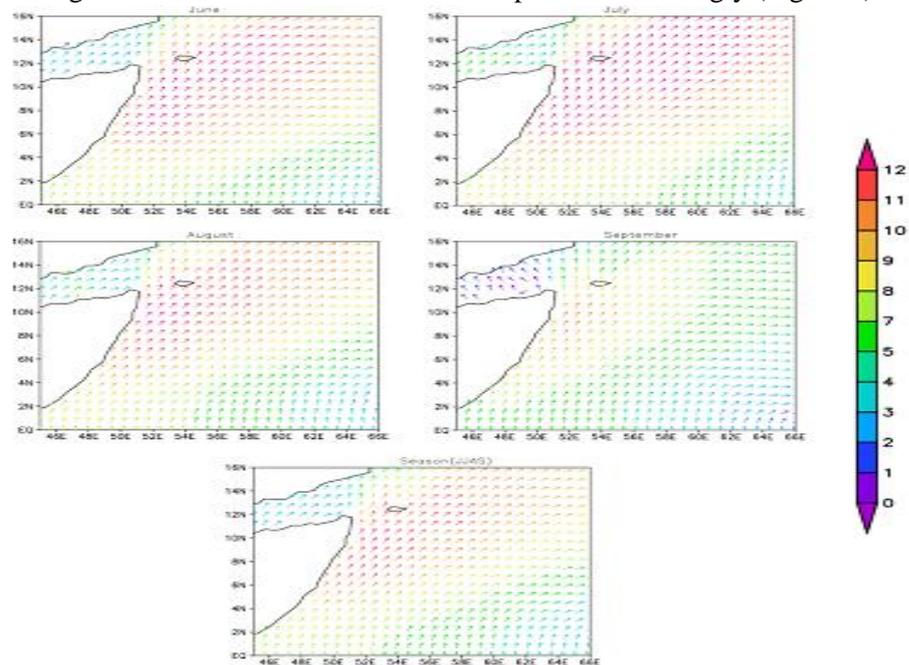


Figure1. Monthly mean wind speed over the Western Arabian Sea using CCMP winds.

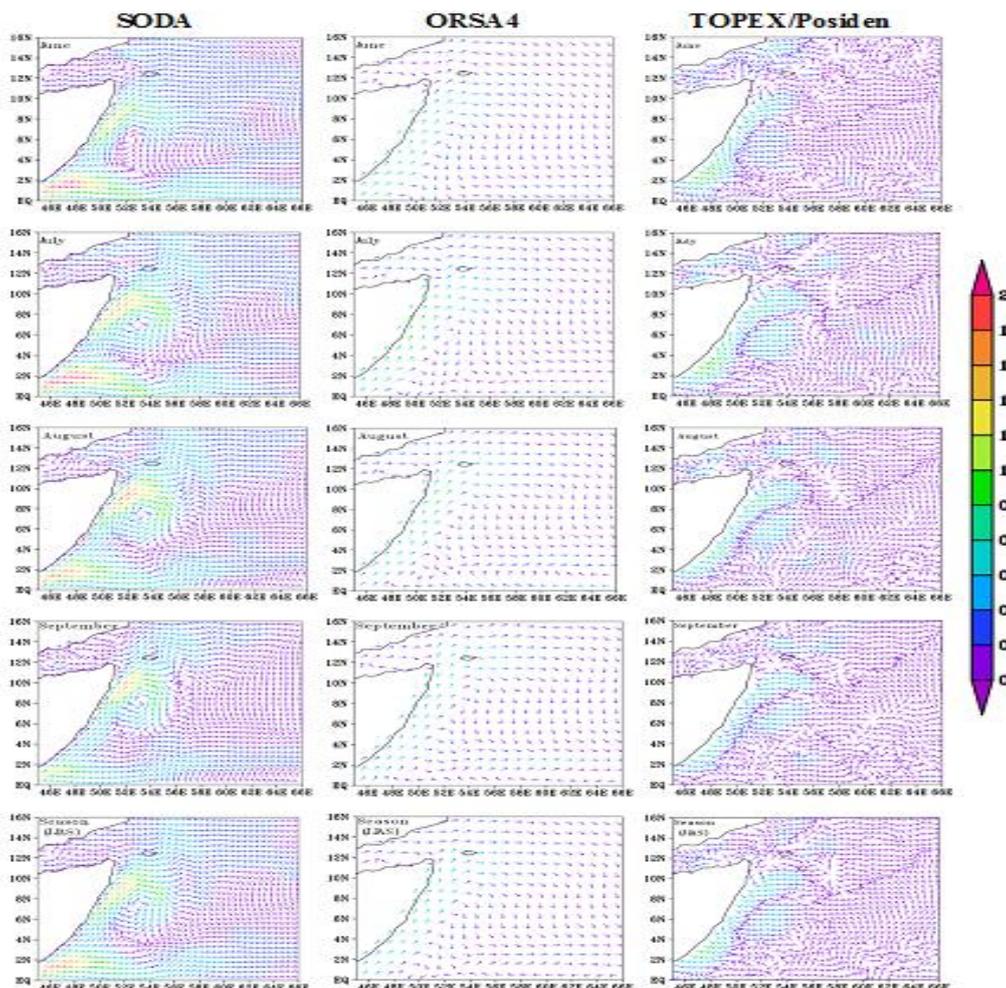


Figure2. Monthly mean surface circulation over the western Arabian Sea using SODA, ORSA4 and TOPEX data

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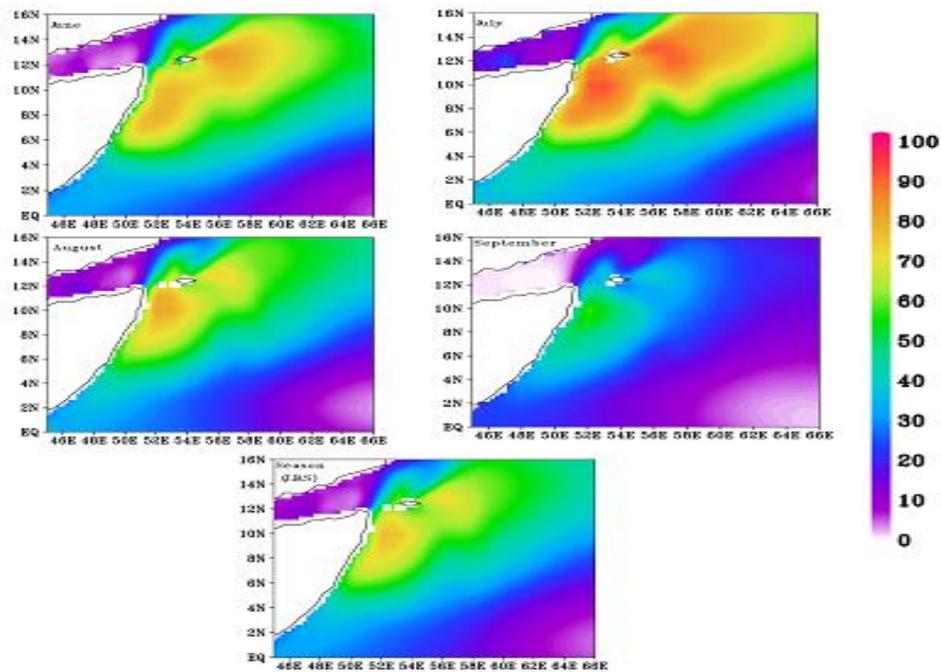


Figure3. Monthly mean kinetic energy (cm^2/sec^2) during southwest monsoon over the western Arabian Sea using CCMP winds.

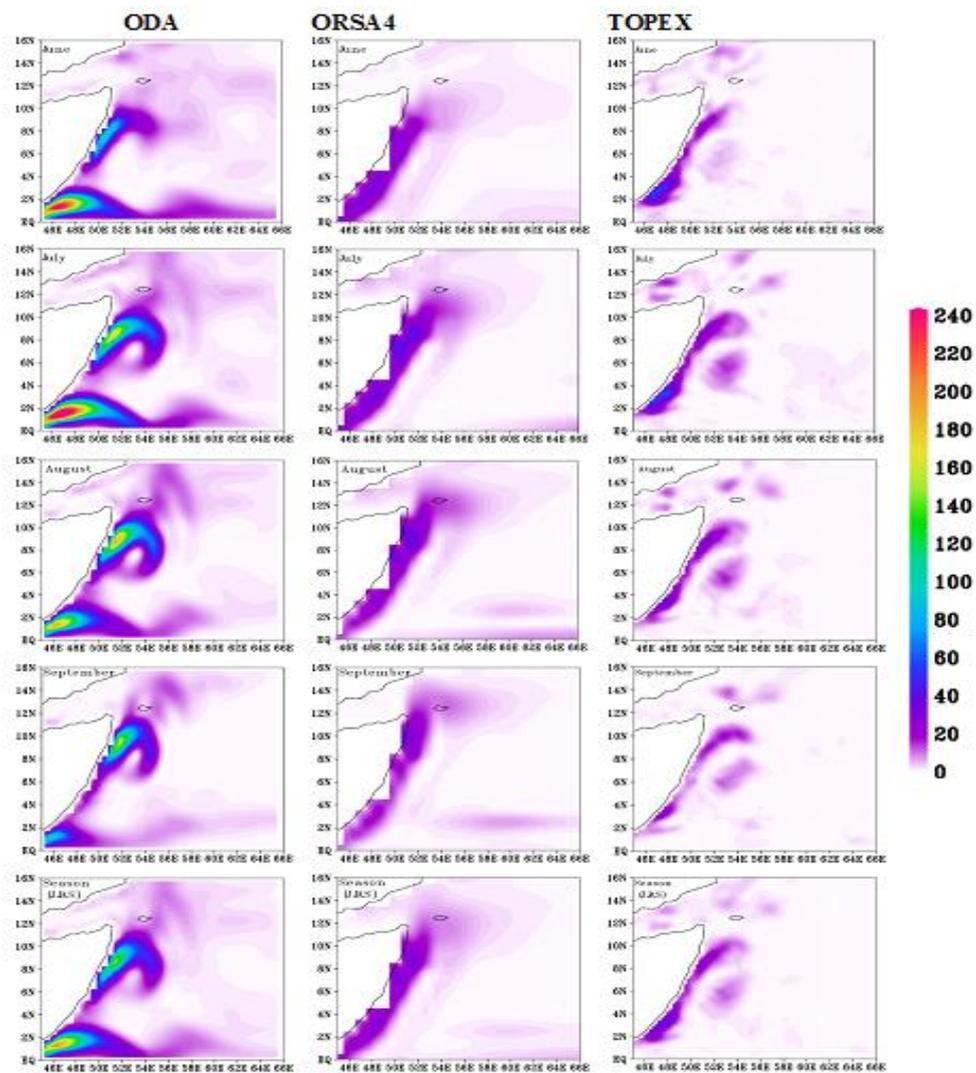


Figure4. Monthly mean kinetic energy during southwest monsoon over the western Arabian Sea using SODA, ORSA4, TOPEX data respectively in cm^2/sec^2

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The Kinetic Energy Field measured using ocean current unlike the wind of Great Whirl and Southern Gyre was found to be in between the range of 160-180 cm^2/sec^2 . The region of Socotra Eddy didn't show signatures of significant Kinetic energy field and was weak compared to other two Eddies. Southern Gyre showed greater Kinetic Energy Field compared to the Great while, it might be possibly due to the forcing of equatorial current which adds the kinetic energy to the circulation. Surprisingly Kinetic Energy of Southern Gyre goes on increasing during JJAS, in contrast it decreases in Southern Gyre during the same season. In addition to this significant kinetic energy fields were found to stretch along the coast of the African continent

signifies the linear movement of high velocity ocean water which leads to Socotra eddy region (Figure 4).

High Brunt-Vaisala Frequency and Turner angle shows the instability at the surface water. This indicates very weak stratification of ocean water at surface and subject to salt marshing and double diffusion. The vertical salinity profile solidifies the argument that salinity decreased due to mixing of water at surface, which is mainly caused due to wind forcing. Turner angle measured to be >90 indicates that Socotra Eddy is statistically unstable, i.e. weak stratification (Figure 5). Turner angle is $45 < T_u < 90$ at surface, this is unstable to salt fingering.

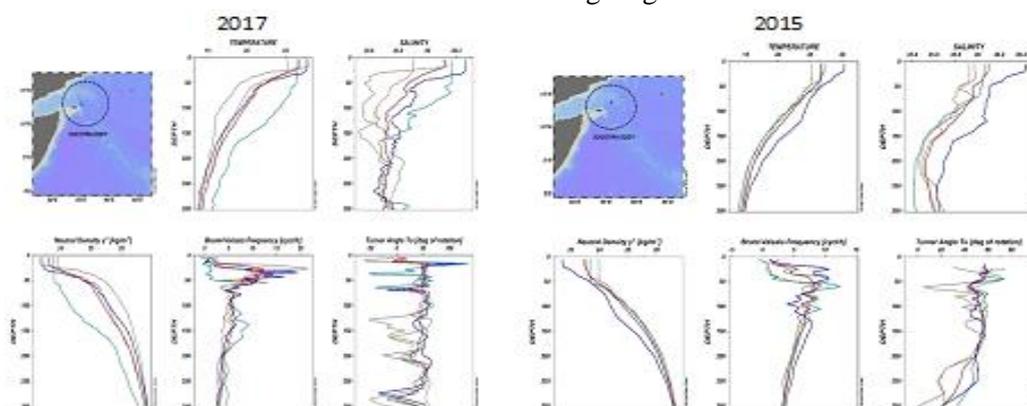


Figure5. Vertical profiles of Ocean Parameters (Temperature, Salinity, Neutral Density, Brunt-Vaisala Frequency & Turner Angle) of 'Socotra Eddy' 2017 Left Panel & 2015 Right Panel.

This was suspected to be the cause of salinity profile response in that fashion. Very low Kinetic Energy of current induced (Fig 1) solidifies the fact that it's stable at depths but not at surface because of the wind forcing (Fig 1.). The lack of strong kinetic energy field even though there is the strong wind shows that it's hindering its circulation movement. Even though the Air-Sea interaction was strong in terms of momentum transfer but it could not able to generate any distinct circulation pattern. Surprisingly the circulation movement of Argo was limited to a trajectory of having small

diameter opposite to our predictions, even though there is strong wind pattern observed which should have effect the hull of the Argo and would cause it to circulate on a trajectory with bigger diameter. The lack of bigger circulation movement even though presence of strong wind confirms the obstruction of circulation of Socotra Eddy. The stable oceanographic parameters such as temperature at the depth shows that there is no instability at deeper depths and confirms the cause of wind itself only in hindering the movement of the Socotra Eddy.

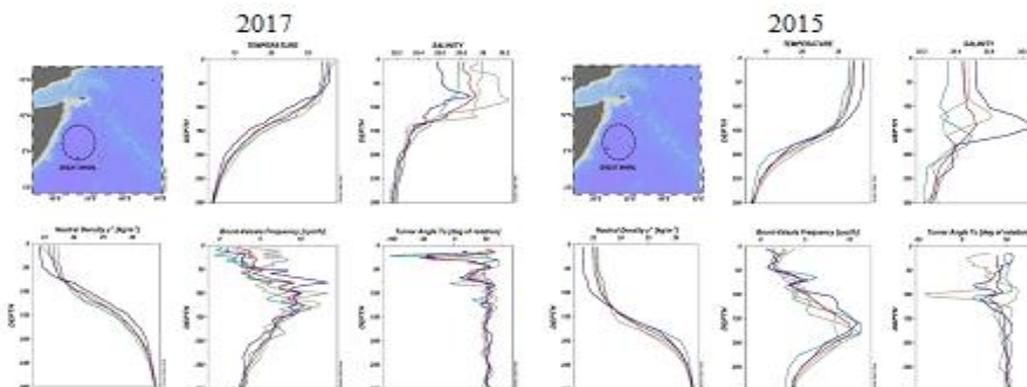


Figure6. Vertical profiles of Ocean Parameters (Temperature, Salinity, Neutral Density, Brunt-Vaisala Frequency & Turner Angle) of 'Great Whirl' 2017 Left Panel & 2015 Right Panel.

Great Whirl was found to received, highest wind pressure which is the place of highest Air-Sea interaction region during JJAS. Gradual increment of Brunt-Vaisala frequency till the depth of 110 m shows that the ocean water became instable gradually from top to 110m gradually (Figure 6). It signifies that the impact of wind forcing is less compared to the current forcing.

This means it's not much forced by the wind and didn't affected much due to wind. The instability of water at depth instead of the surface showed

that there was strong mixing at depth around 110m. This mixed result signifies the effect of both wind and ocean currents predominantly ocean currents. Southern Gyre was found to be weakly stratified (Figure 7) at the surface but unlike Socotra eddy it also showed static instability at depths. This signifies the forcing of both wind and ocean currents. Since the two years panels are not in accordance hence could not conclude for this eddy. Due to unavailability of enough Argo data strong conclusion was not possible.

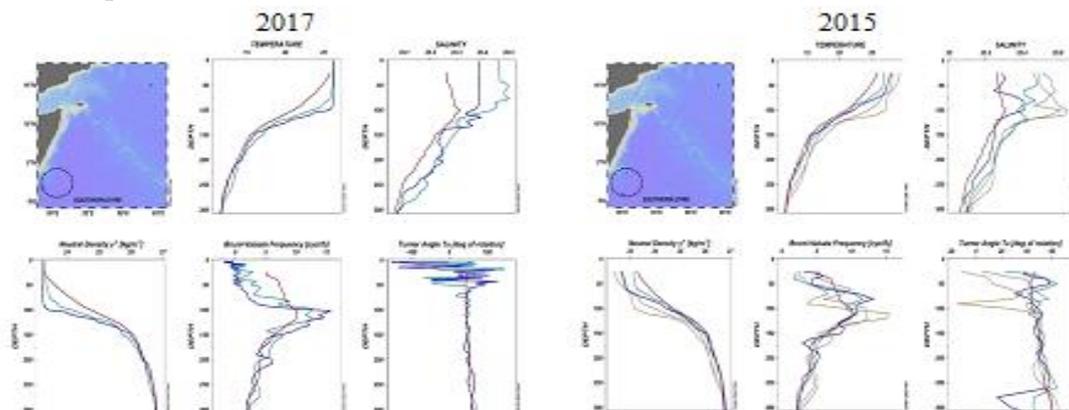


Figure7. Vertical profiles of Ocean Parameters (Temperature, Salinity, Neutral Density, Brunt-Vaisala Frequency & Turner Angle) of 'Sothern Gyre' 2017 Left Panel & 2015 Right Panel.

DISCUSSIONS

In this study it was found that the primary triggering mechanism of formation of Eddy over western Arabian Sea was monsoon winds. The currents formed by the monsoon wind triggers the formation of the Eddies.

But Socotra Eddy showed some surprising result in this study. The study showed that Socotra Eddy is being subdued by the winds. Instead of growing and forming in to bigger size it's shrinking and not showing prominent circulation pattern. This is evident from the Kinetic Energy Field computed by using current data (Figure 1). Even though there is presence of strong wind induced Kinetic Energy field, current induced Kinetic Energy field was almost absent, by being the area of high Air-Sea interaction.

Surprisingly the circulation movement of Argo was limited to a trajectory of having small radius opposite to our predictions, even though there is strong wind pattern observed which should have effect the hull of the Argo and would cause it to circulate on a trajectory having bigger radius. This confirms that there is effect of wind which is both circulating and hindering the movement itself. The lack of bigger circulation movement even though presence of strong wind confirms the obstruction of circulation of Socotra

Eddy in both Argo movement and ocean current (Figure 3).

Besides that, normal trend of oceanographic parameters such as temperature at the depth shows that there is no instability at deeper depths (Figure 5). In addition to that Turners angle vertical profile (Figure 5) solidifies the fact that it's stable at depths but not at surface because of the wind forcing (Figure 1). Besides this the movement of Argo floats and their vertical profiles confirms that there is strong interaction but the wind is acting as negative forcing in case of Socotra eddy. Instead of providing enough momentum while in maximum Kinetic Energy area of JJAS season it's not having any significant Kinetic Energy and circulation pattern. Instead of forming a circulation it's just showing Static instability which is confirmed from the results of Brunt-Vaisala frequency plots at surface and quite stable at the depths (Figure 5). The more the Brunt-Vaisala frequency the more instable it is. All these combined to confirm that Socotra Eddy is affected mostly and losing its energy due to wind forcing only.

Comparing all the SODA, ORAS and TOPEX data it can be concluded that the wind is not the only force acting in the Western Arabian sea (Figure 2).

The Great Whirl region was found to be having strong circulation pattern and high current induced Kinetic Energy field. The Kinetic Energy computed using CCMP wind data confirms this argument that it's responding well to the wind (Figure 1). Here wind is not obstructing unlike in the case of Socotra Eddy. Besides that, gradual increment and sudden drop of Brunt-Vaisala frequency in Great Whirl till the depth of 110 confirms that it's becoming unstable gradually till the depth of 110. This is because the mixing is happening uniformly till the depth hence static stability lost (Figure 6).

Southern Gyre was formed and driven both by the wind and equatorial current. Similar to Great whirl it didn't show any negative feedback to the wind, instead responded positively to the wind forcing during Monsson season. Nothing well defined results were found in case of Southern Gyre because its spatial extent was beyond the study area and lack of data availability.

CONCLUSIONS

The wind is the only factor of formation of circulation in Socotra Eddy. The size of circulation radius does not grow because of negative forcing of wind on to Socotra Eddy. Being in the region of highest kinetic energy field of wind it's having lowest kinetic energy of currents. This is mainly because wind obstructs the motion of the Socotra Eddy. The Great Whirl showed positive response towards wind forcing during JJAS. The gradual increment and sudden drop of Brunt-Vaisala confirms this. Whereas southern eddy is both in response of wind and equatorial current.

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