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Message from President OSI

Dear OSI members and friends,

It gives me immense pleasure to bring out the first issue of Ocean Digest for the first quarter of2021. As you all know, the newly elected Governing Council of Ocean Society of India (OSI) has assumed their role in further propelling OSI activities since December 2020. I thank our past President and GC members for their contributions to OSI. As the incoming President, my goal is to promote and strengthen ocean society activities in India. Many new members have joined OSI, and I welcome them all and invite others to join OSI. A corporate membership scheme has also been formulated to bring various organisations to be a part of OSI in the future. OSI is now in Social Media too.As part of its aim to establish linkage with other professional bodies recently, OSI inked an MoU with the Indian Meteorological Society (IMS) for more collaboration to benefit the atmospheric and ocean community to work in unison since both communities'are working to understand the fluids on the Earth with varied density.

OSICON-21, the seventh biennial conference of OSICON series, will be held during 12-14 August 2021 at NCPOR, Goa. OSI proposes to introduce a Fellowship program for its distinguished/outstanding life members. Also, OSIis pleased to announce 'Dr. D. Srinivasan Endowment Award 2021' in the fond remembrance of Dr. D. Srinivasan, former Director-NPOL, DRDO, a veteran Oceanographer and father of Indian underwater acoustics. P.G. Dissertation Awardsfor the academic year 2019-20 for meritorious students for 7 themes was finalized. The winners will get their awards during OSICON-21.

In the coming years, there will be many Ocean-related activities initiated by the Government of India, including Deep Ocean Mission and BlueEconomy. A draft policy framework on India's Blue Economy is available in https://moes.gov.in/writereaddata/files/BlueEconomyPolicy.pdf. OSI members can go through the same and provide suggestions /feedback. United Nations has proclaimed a Decade of Ocean Science (UN-DOS) for sustainable Development (2021-2030) to support a new cooperative framework to ensure that Global ocean science provides greater benefits for ocean ecosystems and broader society. OSI aims to play a significant role in contributing innovative ideas and suggestions for implementing UN-DOS.

This quarterly newsletter of the OSI (Ocean Digest) presents articles on thetectonic stability of the Mumbai city, the significance of reliable wind in tropical cyclone prediction, the importance of internal tides in mixing ocean interior in the Bay of Bengal, and the mechanisms that are responsible for the occurrence of core oxygen minimum zone in the Arabian sea. I am sure the readers will enjoy reading the same. I look forward to more such research abstracts in plain language from members, which will help students, teachers and researchers.

With all your support and guidance, OSI strides to provide a forum to disseminate knowledge across all the disciplines of Ocean Science & Technology.

(M. Ravichandran)

Tectonic stability of the Mumbai City: A Geophysical Investigation in the Mid-Thane Creek

* *article based on Jacob, J., Pitchika, V.K., Dubey, K.M. et al. Tectonic appraisal of the Mid-Thane Creek of Mumbai, India: An integrated geophysical approach. J Earth Syst Sci* ***129,*** *207 (2020).*
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Abstract

The Thane Creek, a prominent water body incising the main land of the Mumbai City, serves as navigational channel with peripheries accommodating many engineering and infra-structural constructions. For assuring a robust and durable basement for these infra-structural projections, a detailed subsurface scanning is inevitable to locate the week zones buried in the creek. Though, the structural mapping of several lineaments/faults along the Panvel flexure and Mumbai coast is performed, location of their marine counterparts has not been updated. Concerns for updating the structural map of the Mumbai city is essential, as many of the lineaments/faults marked on the land might have extended inside the Thane Creek. An integrated geophysical survey, comprising marine magnetic, high resolution shallow seismic and single-beam bathymetry was conducted to assess the subsurface tectonics of the Mid Thane Creek(MTC) of Mumbai. The results of the survey reveal that bathymetry of the MTC is highly fluctuating due to the periodic dredging to maintain the navigational channel, with maximum depth up to 6.4 m and a minimum of -1.6 m. Spectral analysis of the magnetic data of MTC reveals that the thickness of the Deccan flood basalt where lineaments/faults are inferred is estimated as ~500m. The most prominent lineament interpreted from the seismic and magnetic data, in the central region of MTC is inferred as marine analogue of the Alibagh-Uran fault passing through the mainland of Alibagh and Uran close to Mumbai city.

1. Introduction

The Thane Creek serves as a water link between main land Mumbai and Navi Mumbai. The rapid urbanization of Mumbai city has immense impact on the Thane Creek, expanding the industrialization on the peripheries of the creek. The basic necessity to assure durable and sustainable foundation for the constructions and engineering structures primarily includes estimation of terrain stability. Several prominent faults and lineaments which are mapped in the vicinity of the Thane Creek might have extended towards the continental shelf, traversing the Thane creek. Identifying and mapping these probable weak zones is crucial for effective planning of civil engineering projects in and around the Thane Creek. Hence a detailed tectonic evaluation of the Thane Creek is performed by integrating the geophysical techniques, including single beam bathymetry, high resolution shallow seismic and magnetic surveys.

2. Locating the Mid-Thane Creek

The Thane Creek, fringing eastern flank of the Mumbai city is connected to the Ulhas River in the north. The Panvel creek merges at the middle stream of the Thane creek where the Butcher and Elephanta is lands are the prominent landmarks. The final stage of the Creek at southern extremity opens into the Arabian Sea.The survey area is located in the middle stream of the Thane Creek (Figure1). We refer the study area as the Mid-Thane Creek (MTC), which is limited by the Trombay hills in the northwest, and islands of the Butcher, Elephanta, Nhava-Sheva in the south. The eastern extreme of the study area extends up to the mouth of the Panvel Creek, while the Sewri fort and the Mumbai port limit the western end.

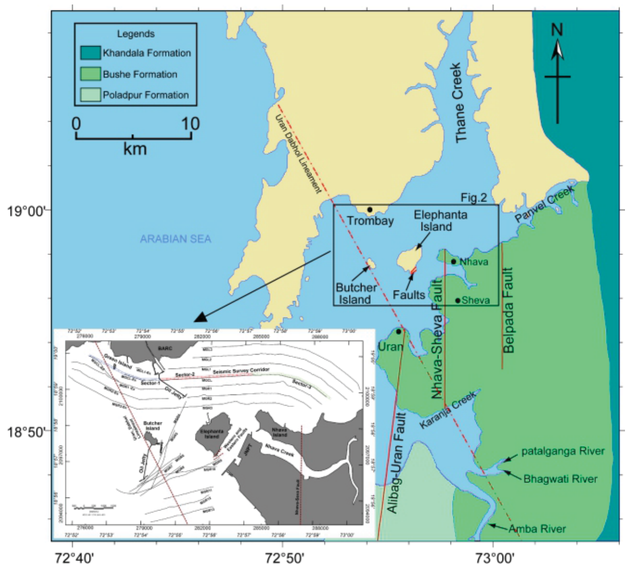

Figure 1.The detailed tectonic map of the Thane Creek superimposed with lineaments and faults (digitized from Ghodke 1978, Dessai et al, 1990; Dessai and Bertrand (1995); Mohan et al, 2007; Samanth*et al.*, 2017). Geologic formations are represented in different colors. The study region is demarcated by black rectangular box. Details of the survey is shown in the inset picture. Central corridor of the MTC is represented by blue, red and green regions for sectors-1, 2 and 3, respectively with 7 seismic track lines with 20m spacing. The surveyed magnetic tracks are represented by black lines synchronized with the single beam bathymetry track lines.

3. DataAcquisition

The initial planning of the geophysical survey is performed using existing bathymetry records from the National Hydrographic Office (NHO).Water level in the creek is highly fluctuating with tidal variations, recording highest water depth of ~6.4 m in the proximity of the Trombay channel and the lowest of ~1.6 m in the intertidal zone fringing the western flank of the creek. The challenge of maintaining

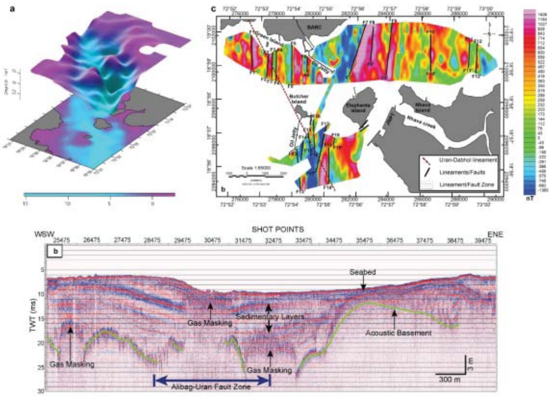

Figure 2**. (a)** 3D bathymetry map of the Mid-Thane Creek (MTC) derived from integrating the single beam eco-sounding data with the bathymetry charts from National Hydrographic Office of India. (**b)** High resolution shallow seismic sections across the Sector-2 (central region of the MTC) with identified off-shore extension of the Alibagh-Uran Fault/Lineament zone. (c) Interpreted lineaments/faults superimposed on the RTP map of the MTC. Black lines represent the possible location of lineaments/faults

optimal water depth to venture the survey boat in the MTC is achieved by dividing the survey areas into Sector 1(western part of the survey area), Sector 2 (Central region of the survey area), and Sector 3 (easternpart of the survey area). Hence, the surveys in Sectors 1 and 3 were exclusively conducted during the high tide to maintain the optimum water depth. The data acquired using Atlas Deso-30 dual channel (33/210 kHzfrequency) and the Bathy-500 MF (210 kHz frequency) echo-sounders were processed using the HYPACK® software. Further, the data were reduced to chart datum and gridded at 10m interval (Figure 2a). The high resolution shallow seismic data were acquired using the SPARKER system, exclusively along 7 track lines with 20m track spacing and the data were processed using the SeisSpace®ProMAX® of Landmark Solutions. The final depth conversions are achieved by considering the P-wave velocities of 1500 m/s for water column and 1583 m/s for shallow sedimentary layers (Krishna et al. 1989) (Figure 2b). The magnetic data were acquired till south of the Elephanta Island along 7 track lines at 500m track spacing using Geometrics G-882 Cesium Vapor marine magnetometer. The magnetic anomaly map (Figure 2c) of the MTC is generated by subtracting the IGRF value (International Geomagnetic Reference Field) from the total magnetic intensity (TMI) of the earth's magnetic field and gridded at an interval of 125m.Reduction to Pole (RTP) technique is applied to TMI with inclination of 27.6° and declination of -0.4°.

4. Tectonic Fabrics of the Mid-Thane Creek

4.1 Identifying the Faults/Lineaments

Several derivative methods have been applied to the RTP magnetic anomalies to identify contacts and depths of lineaments/faults. Solutions derived from the Tilt Derivative and Euler deconvolution methods are super imposed on the horizontal derivative map. Better precision for the lineaments/faults location is achieved by choosing the location where solutions derived from all the three derivative methods coincides in a linear fashion. A set of 19 probable lineaments/faults are identified in the MTC, which are coherent with the proximal location and NE-SW trend of the Alibagh-Uran fault zone identified on land. Hence, we consider the interpreted lineaments/fault zone of the MTC as the marine extension of the Alibagh-Uran fault zone (Figures 2c) which is ~25m wide at Alibagh and widens up to ~200m at Uran (Desai and Bertrand, 1995). However, the marine analogue of the Alibagh-Uran fault zone is ~900m (between F7 and F8) wide at the northern side, while on the southern extreme of the Thane creek, the width ranges from ~581 m (between F17 and F19) to ~710m (between F17 and F18)encompassing the East and West faults of the Elephanta Island identified by Samant et al. (2017).

4.2 Depth of the Faults/Lineaments

Depth to the source is estimated using several depth estimating techniques, mainly Standard Euler Deconvolution (Thomson 1982; Reid et al. 1990; Stavrev 1997; Barbosa et al. 1999), tilt derivative (Miller and Singh 1994; Verduzo et al. 2004), analytic signal (Nabighian 1972) and source parameter imaging (Thurston and Smith 1997). The depth estimated for the zero contours from the derivative methods, representing structure index N=0, indicates the solutions derived for contacts. Detailed depth solutions estimated from different methods are shown in figure 2c. All the derivative methods provide a range of depth solutions from 50m to 600m, but the density of the solutions decreases with increasing depths. However, the lineaments/faults may have deeper extension beyond the maximum depth recorded, as the total magnetic anomaly of the MTC is influenced by highly magnetized layers of flood basalt with varying thickness emplaced in different depths. Hence, differentiating the weak magnetized anomalies associated with the lineaments/faults from the highly magnetized basalt flow is difficult. Also, the magnetic anomaly is biased by the thickness and depth of emplacement of the basalt flow layers.

4.3 Thickness of the basaltic flow layer

Estimating the thickness of the magnetic source body includes delimiting the top and bottom boundary of the source. Performing the spectral analysis (Spector and Grant, 1970; Bhattacharyya and Leu, 1975; 1977; Okubo et al.,1985) by considering 18 windows of 2000x2000 m with an overlap of 500m in the MTC provided depths to top and bottom of magnetic flow layer.The thickness of the magnetic layer in the western, central, eastern and southern flanks of the MTC is estimated as ~478m, ~498m, ~477m and ~566m respectively. The average thickness of the magnetic layer in the MTC is estimated to be ~504m with maximum thickness at the southern sector of the creek and minimum thickness in the western sector of the MTC (Figure 3). From various geological analyses (e.g.,Cox and Hawkesworth 1985; Beane et al., 1986; Devey and Lightfoot 1986; Subbarao et al., 1994; Jerram and Widdowson 2005), the Deccan continental flood basalt is classified into three major subgroups, the oldest Kalsubai of ~2000m thick, comparatively younger Lonavala of ~525m thick and youngest Wai of ~1100m thick. The subgroups are further divided into twelve formations based on the flow type, rock structure and the chemical composition (Najafi et al.

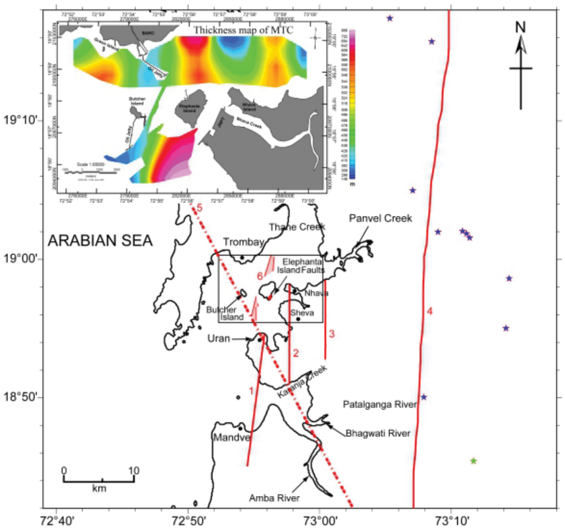

Figure 3. Blue star represents earthquake hypocenters less than 15 km and green star represents hypocenters greater than 15 km (Mohan *et al.*, 2007). 1- Alibagh-Uran Fault, 2- Nahava-Sheva Fault, 3- Belpada Fault, 4- Panvel Flexure, 5- Uran-Dabhol Lineament (Ghodke 1978, Dessai et al, 1990; Dessai and Bertrand,1995; Samanth*et al.*, 2017). Inset picture represents the thickness of the flow basalt in the MTC derived from the 'depth to the top' and 'depth to the base' from spectral

1981; Mahoney et al. 1982; Cox and Hawkesworth 1985; Beane et al. 1986; Devey and Lightfoot 1986; Bodas et al. 1988; Khadri et al. 1999). The probable four main formations in the Mumbai region includes the youngest Khandala formation (thickness of ~140m) representing the oldest formation from the Lonavala subgroup. The older Kalsubai sub-group comprises the Bhismashankar, Thakurvadi and Neral formations(140m, 650m and 100m thick respectively) (Chenet et al. 2008). Considering proximal location of the MTC near Mumbai, one could expect the occurrence of all or the combination of any of the four formations corresponding to each basalt flow, representing the overall thickness of the basalt flow in MTC.

5. Implication of Lineaments/Faults on seismicity of the Mumbai coast

Analyzing the earthquake records from 1998 to 2005 along the Mumbai and the Panvel flexure zone (Mohan et al. 2007; Raghu Kanth and Iyengar, 2007; Gupta et al. 1998, Nandy 1995) about 27 seismic events were recorded in the vicinity of the Panvel flexure zone between magnitude 2.5 and 2.9 Mw. Depending on the depth, the epicenters are categorized into near surface (<2 km), shallow (2-15 km) and deep (>15 km).The set of lineaments/faults identified in the present study are not exceeding ~600m of depth, hence categorized as near surface weak zones embedded in the basaltic layers. An average of 14 earthquake events of magnitude greater than 3.0 Mw were recorded at a depth of 5 km closer to the Panvel, with 3.6 Mw as the highest magnitude recorded. Though some of these hypocenters contributed to the historical earthquakes (e.g.: Chandra et al. 1977; Bansal and Gupta, 1998) the Bombay earthquake of 1618 with intensity IX), none of these hypocenters are located within boundary of the MTC (Figure 3).The seismic section of the MCT do not indicate presence of faulting or dislocation of the sedimentary strata, rather the region displays several gas masking zones which coincides with the extended location of the Alibagh-Uran fault zone. We infer that the Alibagh-Uran fault embedded in the deep-seated flood basalt may act as the weak zone favoring the gas to seep through, forming the gas mask zones. It is worth to note that no seismic and magnetic signature of the previously identified Uran-Dabhol lineament which traverses the MTC is observed from the MTC data. Summarizing Mohan et al. (2007) and Widdowson and Mitchell (1999), the shallow and deep crustal earthquakes are driven by reactivation of basement faults. However, near surface earthquakes occur within the Deccan Traps due to failure of the faults flanking the Panvel Flexure zone, mainly due to the regional tectonics and isostatic adjustments. Though Subrahmanyan (2001) reported seismic activity of 3.6 Mw on 31st May, 1998 with epicenter located in the Panvel creek, the MTC of Mumbai did not record any seismicity. For more details of this article, please refer Jacob et al. (2020).

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Parametric Wind Field and its Application for Tropical Cyclones in a Changing Climate

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Tropical cyclones are extreme weather events and considered as one among the natural disasters that results in widespread catastrophe, loss to life and property along coastal regions during landfall. Approximately about 90 tropical cyclones form over the global ocean basins annually (Knapp et al. 2010). Enormous destruction by tropical cyclones are experienced in coastal areas associated with very strong winds posing imminent danger to property and infrastructure facilities, in addition to secondary hazards such as extreme water levels caused by storm surges and extreme wind-waves. Hazards associated with cyclonic winds are usually quantified using statistical measures of cyclone frequency and intensity by generating wind speed maps with return periods (Fang and Lin, 2013). Prior studies have reported onseveral prospective methods such as the Extreme Value Analysis estimated from in situ observations (Elsner et al. 2008) for specific locations; Monte-Carlo method (Huang et al. 2001) applicable for smaller regions, and basin-scale stochastic simulations (Emanuel et al. 2006) for larger areas. Therefore, it is imperative to formulate reliable estimates of tropical cyclone wind field that can be simulated using either numerical or parametric methods. Numerical models such as WRF (Weather Research and Forecasting) is quite popular (Skamarock et al. 2005) and widely used to generate wind fields both in nowcast and forecast modes.This model has the capability to simulate multiple parameters of the atmospheric column at user defined vertical levels, and widely used in operational weather centers. The India Meteorological Department (IMD) under the Ministry of Earth Sciences, Government of India is the nodal agency related to meteorology and allied subjects. IMD is also involved in warning of severe weather related phenomena such as tropical cyclones, heavy rains, norwesters, dust-storms, snow, cold and heat waves that directly impacts the life and property in addition to services offered to sectors such as agriculture, irrigation, shipping, aviation, offshore oil explorations etc. More details and information are available in the website: https://mausam.imd.gov.in/. Specialized bulletins and warnings during tropical cyclone activity are also issued by IMD and disseminated to State Government officials for necessary preparedness action.

In addition to numerical weather models such as WRF, wind field generation using parametric models have also gained popularity in recent years as they provided satisfactory modeling accuracy using limited tropical cyclone parameters as input. Advantage using a parametric modelis the ease to estimate wind fields with no high demand on computational resources. The key parameter required by parametric models are the best-track storm datasets that are available from sources such as India Meteorological Department (IMD) and Joint

Typhoon Warning Center (JTWC). Relevant cyclone parameters for the North Indian Ocean region are documented in the best-track records of IMD, whereas the compiled information of best-tracks for the global oceans are available in JTWC (Knapp et al. 2010). JTWC maintains the archives of best-track cyclone data for different regions in the global ocean basins such as Southern hemisphere, North Indian Ocean, and western North Pacific Ocean covering the period from 1945 until present. Archived data of best-track cyclone parameters are available and stored in zipped folders from 1945 until present. In addition, to the text files archived in zipped folders, additional KML files are also made available from 1977 until present that can be used to display the geographical data in an Earth browser such as Google Earth.

Parametric models have a definite advantage primarily attributed due to its efficiency, simplistic nature, and low computational power and can provide reliable quality of wind fields surrounding the cyclone track within a considerable radial distance (inner core) from the eye of the storm. However, it has limitations in representing realistic winds radially from the outer core of the cyclonic center. There are different forms of parametric wind models such as: (i) Rankine vortex model (Phadke et al. 2003) wherein wind fields are represented using the solid body rotation surrounded by circulation having zero vorticity; (ii) Holland model with pressure wind profile of Myers (1957) and with extension of the surface pressure field by Schloemer (1954); (iii) Young and Sobey(1981) model which is a modified version of Schloemer (1954) for the outer region of the radial profile; (iv) SLOSH (Storm Surge model for Sea, Lake and Overland surges) model that use parametric wind formulation by Houston and Powell (1994); (v) Emanuel (2004) model based on physical environmental parameters that governs the structure of tropical cyclones; (vi) Emanuel and Rotunno (2011) model which is an improved version of Emanuel model (2004) better representing the inner core convective regions with a constant Richardson number not valid for the outer storm area. The efficacy of these parametric models are documented in the study by Ruiz-Salcines et al. (2019). One can find popular parametric cyclone wind models such as Jelesnianski (1966), Holland (1980), Knaff et al. (2007) being widely used to hindcast the wind fields during tropical cyclone events (Dube et al., 1985).

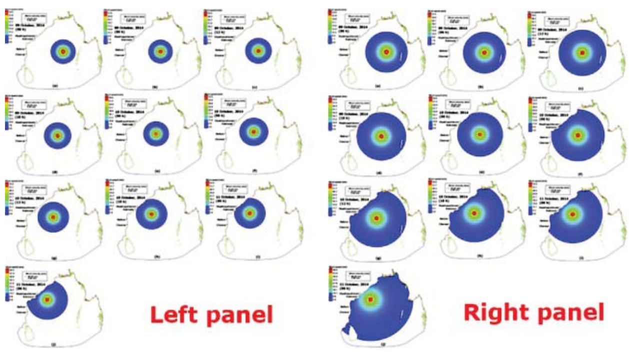

Figure 1: Wind field envelope for *Hudhud* cyclone using (a) Left panel – original Jelesnianski and Taylor wind formula, (b) Right panel – modified Jelesnianski and Taylor wind formula using the 3/5 power law (source: Murty et al. (2016))

Impact of changing climate over the global oceans had witnessed changes in both the intensity of frequency of extreme events like tropical cyclones. In context to Bay of Bengal region, the past decade also noticed increased intensity of tropical cyclones. Another notable feature is increasing size of severe cyclones that has a direct bearing on the risk and vulnerability along coastal regions during landfall. Increased size of tropical cyclones and associated strong winds pose direct threat in terms of storm surge and inundation having greater exposure of the coastal area. An interesting recent numerical study of coastal hydrodynamics by Murty et al. (2016) using a coupled wave-hydrodynamic model for Hudhud cyclone postulates the importance in modifying the existing parametric wind formulation for tropical cyclones in a changing climate. The study proposed a 3/5 power-law that was applied to the existing Jelesnianskiand Taylor wind formula leading to better wind field considering the cyclone size. The modified formula considered the correction for radial distance of exponential wind decay. Study of storm surge for the Phailin (2013) event using this modified formula has resulted in an excellent match with the observed data. Further, several sensitivity experiments conducted for six very severe cyclones that formed over Bay of Bengal decipher an optimum value of 0.6 for the coefficient of radial wind decay (Murty et al. 2016).An inter-comparison between the wind fields generated using the parametric wind formulation of Jelesnianski and Taylor with existing and modified formulae are shown in Figure 1 for the Hudhud cyclone that made landfall in Andhra Pradesh coast during October 2014. These findings (Murty et al. 2016) are very important and points out that models that use parametric wind formulation as forcing function needs proper correction for storm surge and coastal inundation studies associated with tropical cyclones in a changing climate.

Details pertaining to the validation exercise for maximum significant wave between coupled wave-hydrodynamic model against wave rider buoy observation off Visakhapatnam and storm surge validated against tide gauge observation near Bheemunipatnam and Visakhapatnam are available in Murty et al. (2016). As mentioned earlier, the parametric wind formula have inherent limitation in treating regions beyond the outer core area of tropical cyclones. To bring in more clarity to this issue and an extension of the previous study by Murty et al. (2016), improved cyclonic wind fields in the Bay of Bengal region and its application to storm surge and wind-wave computations was reported in a very recent study (Murty et al. 2020) that also considers the quality of the outer core wind fields. A blending technique was employed using a combination of both parametric wind formula and global atmospheric model product. The objective was to improve quality of surface wind fields in both the inner and outer domains of tropical cyclones using smoothing algorithm and superposition technique. Improved wind field is a blended product comprising of Holland model and ECMWF winds. The methodology proposed by Pan et al. (2016) and Shao et al. (2018) were adopted in preparing the blended wind field with the best-track data from IMD as the input. The ECMWF global wind fields were considered as the background field that provide a better representation for the outer core area and it is blended with Holland parametric wind formula for the inner core region of the cyclone. In order to overcome the deficiencies in the generated wind field by parametric and global atmospheric models, the following blending procedure was used from the two different models: (i) Firstly, it is important to determine the relative shift in the location of cyclone center between Holland winds and the

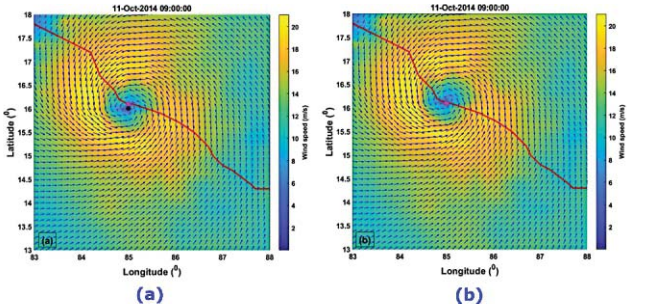

Figure 2: Relative shift in the eye of Hudhud cyclone with ECMWF winds (a) before the shift cyclone eye as per ECMWF data, (b) after the shift. Track of Hudhud cyclone is shown with the red solid line (source: Murty et al. (2020))

global ECMWF wind field. The best-track IMD data is considered as actual and used as the reference in this context. The Figure 2 show the relative shift in the center of cyclone eye for Hudhud cyclone on October 11, 2014 0900 UTC with ECMWF data (Figure 2a) and the correction in shift using the IMD best-fit track data.

As seen in Figure 2(b), (ii) the next step is to translate the cyclone center from ECMWF winds to match with the best-track IMD data following the procedure of Pan et al. (2016). As seen, there is an exact match with the IMD best-track data following the superposition technique by Pan et al. (2016); (iii) the third step is the blending procedure merging the new center shift of ECMWF winds with the parametric winds to obtain the blended winds. An optimized distance is to be followed in order to conduct the superposition of the datasets. One can expect discontinuities in the wind field when the superposition technique is used. Therefore, it demands a smooth transition between the parametric wind formula and the global ECMWF wind field. The proposed methodology by Shao et al. (2018) can be used in this context. The final blended product that can be used for operational needs are shown in Figure 3. It represents the parametric, ECMWF, and blended wind fields corresponding to October 11, 2014 0900 UTC for the Hudhud cyclone event.

As seen from Figures 3a and 3b for regions near cyclone eye, the magnitude of parametric winds are higher compared to ECMWF winds, whereas in the outer core area the magnitude of ECMWF winds were higher. The final blended product is shown in Figure 3c which is a combination of Figures 3a and 3b (Murty et al. 2020). This blending procedure is followed for the entire duration of cyclone until it attains the landfall. The corresponding radial profiles obtained from parametric, ECMWF, and blended product extending from center of cyclone to the outer core regions are shown in Figure 3d. It is very clear that the blended product almost follows the parametric winds for the inner core and ECMWF profiles for the outer core region. To demonstrate the efficacy of the blended product validation exercise were performed against in situ observations with buoys and anemometer records in the Bay of Bengal for the computed storm surge and significant wave heights (Murty et al. 2020). Both the significant wave height and storm surge computations were carried out using coupled wave-hydrodynamic model (SWAN+ADCIRC). For more information about coupled wave-hydrodynamic models, one can refer to the studies by Bhaskaran et al. (2007, 2013a, 2013b); Funakoshi et al. (2008); Dietrich et al. (2011, 2012); Nayak et al. (2013);Nayak and Bhaskaran (2014);Murty et al. (2014, 2016). Recent study by Murty et al. (2020)

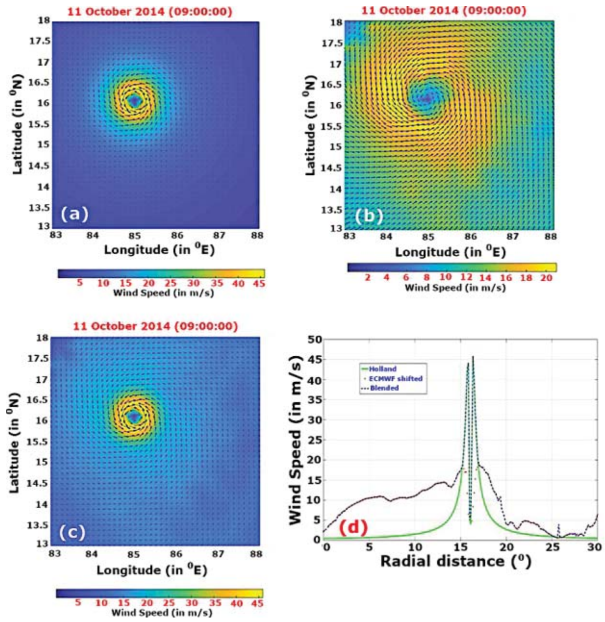

Figure 3: Representation of (a) parametric winds, (b) corresponding ECMWF winds with center shift, (c) blended wind field profile, (d)radial profiles of parametric, ECMWF and blended winds (source: Murty et al. (2020))

performed a detailed validation of the blended wind product with moored buoy observations BD08, BD09, and BD10 located in the central Bay of Bengal for the Titli cyclone that developed during October, 2018 shown in Figure 4. It is clear that the blended wind product performed better and closely matched with observations at the three buoy locations.

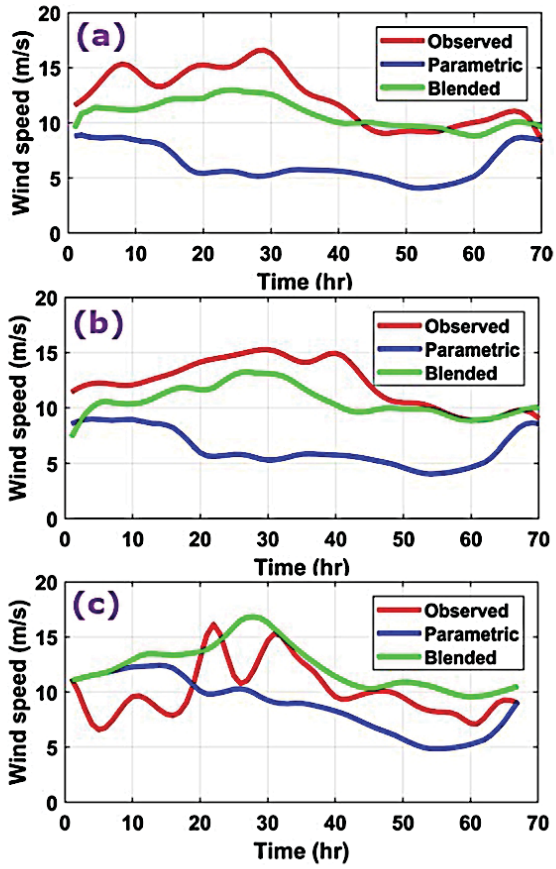

Figure 4: Wind speed validation for parametric and blended product against buoy records BD08, BD09, and BD10 during October 2018 Titli cyclone (source: Murty et al. (2020))

The study clearly indicates that the blended wind product showed reasonably good agreement with the observations. Instances of mismatch could be attributed to forecast errors in the ECMWF winds and parametric wind formulation and collective constraints in both the wind fields. As mentioned earlier, in a changing climate more detailed studies are warranted on tropical cyclone size and its structure. Keeping in view the limitation of using parametric wind formulation, the described methodology on blended winds has wide practical application in better simulating storm surge and wind-wave characteristics.

The article provides an insight on the importance of parametric wind formulation and blended wind product that can provide reliable estimates of storm surge and extreme wind-waves during tropical cyclone activity and importance of climate change that can modulate tropical cyclone characteristics. There are many unforeseen challenges that can improve the forecast accuracy of parametric wind models such as the number of parameters being considered in tropical cyclone forecast. More research is warranted on the four quadrant radii of additional specified wind speed or increasing the radii at eight or more directional bins instead of the four quadrant for specified wind speed remains a challenge. Also, the effect of tropical cyclone translation speed on the asymmetric nature of wind field on synthetic vortex remains an area of interest. Better methods such as developing composite wind field by leveraging all wind parameters rather than only considering the largest wind speeds at four quadrant radii using appropriate weighting coefficients is an area that can be further explored. Also, a recent study by Krien et al. (2018) have reported on improving parametric cyclonic extreme wind fields using recent satellite remote sensing data. Interestingly, the study (Krien et al. 2018) demonstrated that Cyclone Global Navigation System mission of NASA together with ASCAT (Advanced Scatterometer) were able to capture major part of tropical cyclone structure thereby providing an opportunity to verify the output of parametric wind models. It looks quite promising, the reason being it is very difficult to validate parametric wind models with ground truth observations during tropical cyclone activity. It is anticipated that more research work is required in estimating reliable wind field during tropical cyclone activity having wide practical applications and socio-economic implications.

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Internal Tides in the Bay of Bengal and the Mixing in the Interior Ocean

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The restless waves coming to the shore and breaking on the beaches always fascinate us. These wind generated waves, that are seen on the surface of the ocean, usually have a height of a few meters and wavelengths of a few tens to hundreds of meters. Can you imagine huge waves with a height of a skyscraper and wavelengths of about a hundred kilometer in the ocean? Yes, there are such monstrous waves that exist in the ocean but not on the ocean surface. They are hidden beneath the sea surface. These underwater waves are known as internal waves. Internal waves exist in most of the oceanic region but to see them, you may need an aerial picture of the sea, probably from a satellite/spacecraft orbiting the earth, that gives the variation in the surface height/roughness or need to monitor the variation of temperature over the water column by the moored instruments in the ocean. These internal waves also break in the interior ocean like the surface waves do in the shore. Breaking of these internal waves are the main source of energy for the mixing of the interior ocean and thus play a crucial role in controlling the climate (MacKinnon et al., 2017). In addition, they also play an important role in biological productivity by regulating the nutrient distribution and sediment suspension in the ocean. Identification and prediction of such waves are also important for the safe conduct of submarine navigation and off-shore industries.

Do such subsurface waves exist in our surrounding seas ?

Presence of these huge underwater waves with a height of a few tens of meters are reported all along the Indian coastal waters in the Bay of Bengal and Andaman Sea in previous studies but we did not know exactly where they get formed and what is the fate of these waves. Recently, a series of studies were carried out to track these waves from their generation source to their destination in the coastal regions in the Bay of Bengal (Jithin et al. 2017, Jithin et al. 2019, Jithin et al. 2020a, 2020b and Jithin et al. 2020c). Data from satellites orbiting around the Earth, instruments moored in the coastal and deeper parts of the Bay of Bengal and simulations from a very high resolution mathematical model were used in these studies. The subsurface velocity measurements collected using an instrument called *'Acoustic Doppler Current Profilers (ADCP)'* moored at the bottom of the sea about 30-50 km away from the coast detected fluctuations in the velocity of ocean currents induced by the underwater internal waves all along the coastal waters in the east coast of India with relatively larger variation in the currents in the northern parts compared to the southern parts of the coast. One of the important features observed in the ADCP data is that most of these internal waves occur with a periodicity of about 12 hours- the same periodicity in which water level changes on beaches due to tides.

How these internal waves are related to tides ?

Tides are the periodic change in water level caused by gravitational pull of moon and sun and their rotational effects. In addition to periodic water level variation that we observe on the coast, they also result in horizontal movement of water in the ocean, called tidal currents. When the tidal currents flow over the rough oceanic bottom, such as ridges, seamounts or other steep areas, they result in up and down motion of water with constant density in the interior ocean (Egbert and Ray, 2000). These disturbances propagate away as waves through the interior of the ocean. The internal waves due to tidal flow are generally termed as internal tides. Thus, energy for the generation of internal tides is essentially provided by the earth-moon gravitational forcing (tidal energy).

Where do these internal waves get generated in the Bay of Bengal?

Since internal tides are generated by the tidal flow, they are generally found to be strong (weak) when the earth, moon and sun align in the same line (perpendicular), which is called spring tide (neap tide). This usually occurs once in every 15 days. If these internal waves are generated by the local tidal activity, their variability will be the same as the variability of local tidal variability. Interestingly, observations from the ADCPs suggest that the spring-neap variability of internal tides along the east coast of India are not in phase with the variability of local tides. In fact, strong internal tides/waves are observed when the tides are weak (neap phase). This observation contradicts the previous understanding that the source of internal waves along the east coast of India is the steep bathymetric regions in the continental margins called continental slope (Jithin et al., 2017, 2019).

Further analysis by Jithin et al. (2019) using the numerical simulations revealed that the internal tides observed along the coastal waters of the east coast of India are not generated at the steep continental slopes as previously believed. Instead, these waves originated from an underwater mountain range, called Andaman-Nicobar Ridge, which are located about 1000-1500 km away from the east coast of India. The Andaman-Nicobar Ridge is a submerged mountain range, which was formed due to the subduction of the Indian plate below the Eurasian plate. Some parts of this ridge are raised above the ocean surface, which is a landmass popularly known as the Andaman-Nicobar Islands. The periodic flow of water over the Andaman-Nicobar ridge due to tides generates internal waves with an amplitude of about 50 m and more. The internal waves generated over the ridge travel both westward and eastward. The waves that radiate into the west, travel freely across the Bay of Bengal about 1000-1500 km and finally reach the Indian coasts. These waves are very slow, often travel with a speed of about 8-10 km/hour. Therefore, once generated at the Andaman-Nicobar ridge, these waves reach the Indian coasts in about 5-7 days. Due to this delay in the arrival of internal tide from the remote location, large internal waves are seen along the east coast of India in the neap phase (weak tides) of the local tidal activity. Major sources of these internal waves, their propagation and dissipation are illustrated in Fig. 1.

What happens to the internal tides when they approach the Indian coast from Andaman-Nicobar ridges? It is observed that these waves are reflected back to the deep ocean when they encounter steep continental slopes along the east coast of India (Jithin et al. 2019). Therefore, steep continental slopes act as barriers to the incoming underwater waves and they prevent them from entering into the shallow coastal regions from the deep Bay of Bengal. In some areas, continental slope is not very steep and in such areas, incoming underwater waves enter into coastal regions and eventually break as they reach shallow regions. Therefore bathymetric steepness plays an important role in the variability of internal waves along the east coast of India. For example, internal tides in the coastal regions off Gopalpur is found to be very energetic due to the relatively gentle bathymetric slope in the offshore areas whereas the internal tide activity is

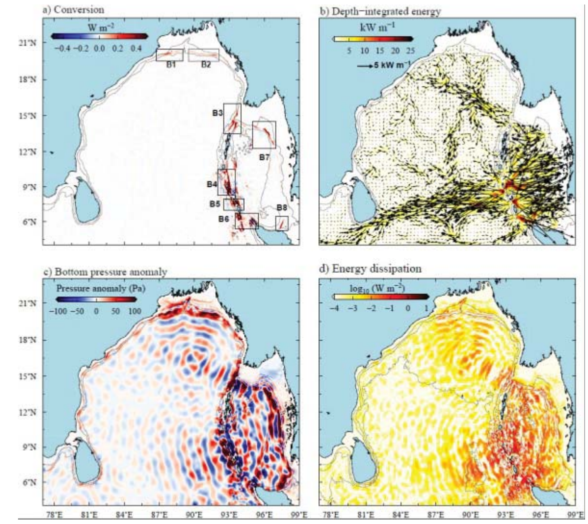

Figure 1: (a) Major sites of internal tide generation (B1-B8) in the Bay of Bengal and Andaman Sea (b) Depth-integrated energy during the neap phase of the barotropic tides in the Bay of Bengal (c) Bottom pressure fluctuation due to the internal tide propagation (d) Rate of dissipation of internal tide energy in the Bay of Bengal

relatively weak in coastal regions in the northern parts of Visakhapatnam due to very steep continental slopes (Jithin et al., 2019).

Why do these large waves not cause damages like the tsunami waves in the coastal region? The internal waves are baroclinic in nature and hence exist only in the regions where there is density stratification in the ocean water, i.e. the interface between low-density water in the upper and high-density water interior ocean. As these waves approach the coastal areas, they start to feel the bottom of the ocean and due to this drag, they become unstable and break before they reach the shore. In fact, this wave dissipation releases a large amount of energy, which erodes the stratification in the ocean and mixes up the ocean water.

Focusing of internal waves in the central part of the Bay of Bengal

Mirrors or lenses with a curvature can focus light into the focal point region. Can the internal waves be focused into a focal point? Yes, it is possible and the same phenomenon has been reported in the Bay of Bengal by Jithin et al. (2020). Only difference is that here instead of reflection, the internal tides generated at the source regions aligned in the arc-shaped northern Bay of Bengal converge into the focal regions in the north-central Bay of Bengal, which is located about 450 km away from their sources. Amplitude of the underwater waves are generally large near their generation sites and their amplitude gradually decreases away from the source. Due to the focusing of internal waves as described above, amplitudes of these waves are large even hundreds of kilometers away from their source in the Bay of Bengal.

Do internal tides play any role in keeping the interior ocean warm?

Internal waves in the ocean mix the water vertically in the ocean, which is essential for the distribution of heat from the top to bottom. The observations of vertical structure of temperature measured by several ocean observing platforms revealed that the bottom waters in the Andaman Sea are about 1-2 °C warmer than the water at same depth in the adjacent basin Bay of Bengal (Jithin and Francis 2020)! Andaman-Nicobar ridge, which separates

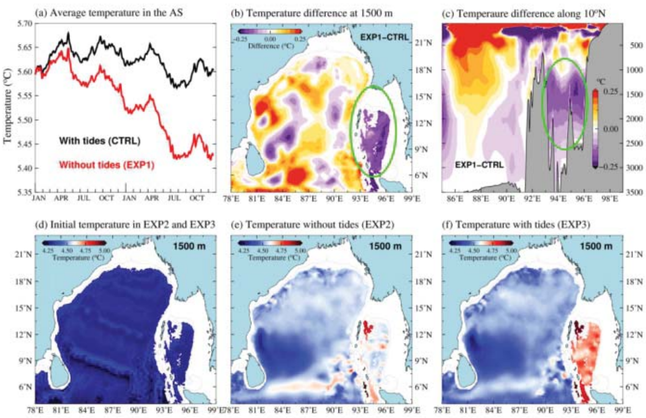

Figure 2. (a) Evolution of average temperature at 1500 m in the AS with (CTRL) and without tidal forcing (EXP1) for a 2-year period (2013–2014). (b) Temperature difference between the model simulations without and with tidal forcing at a depth of 1500 m (EXP1-CTRL) after 2 year (December 2014). (c) Temperature difference between the model simulations without and with tidal forcing along 10°N (EXP1-CTRL) after 2 years. Green circle represents AS, where the temperature cooling occurs when the tidal forcing is stopped. (d) Temperature distribution at 1500 m in the initial conditions (01 January 2013) of EXP2 and EXP3. (e) Temperature at 1500 m after 2 years of model simulation with tidal forcing (EXP2). (f) Temperature at 1500 m after 2 years of model simulation without tidal forcing (EXP3). Souce : Jithin and Francis (2020)

the two basins, restricts the water exchange between these two regions at the bottom levels. The observed temperature difference between these two basins was mainly attributed to the enclosed nature of the Andaman Sea. Analysis of observations and simulations from very high-resolution models shows that internal tide activity in the Andaman Sea is very strong compared to the Bay of Bengal, which leads to a higher vertical mixing of the water column (Jithin and Francis, 2020) in the formar basin. Experiments conducted using mathematical models by removing the internal tide activity showed that in the absence of strong internal tide induced mixing, deeper waters in the Andaman Sea would have been significantly cooler than the present state (Fig. 2). This is a clear evidence of the elevated mixing induced by internal waves playing an important role in maintaining warm water in the interior ocean.

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Research Highlights

Potential mechanisms responsible for occurrence of core oxygen minimum zone in the north-eastern Arabian Sea

Deoxygenation is one of the most important changes occurring in the marine environment that impacts marine biodiversity, primary production, trace gases emissions, and carbon and nitrogen biogeochemical cycles. Open ocean oxygen minimum zone (OMZ) occurs in many regions of the world ocean such as the Eastern Tropical Pacific (ETP), northern Indian Ocean Arabian Sea (AS) and Bay of Bengal (BoB), Eastern Equatorial Pacific and Tropical Atlantic, but denitrification is noticed only in the former two basins. The denitrification in the Arabian Sea contributes 8-21% of global marine pelagic denitrification. The main denitrification in the upper one-third of the OMZ, where O_2 concentrations fall below 0.06 ml/l (~3μM). This zone is readily identifiable using secondary nitrite maximum due to reduction of No_3 The thickness of oxygen minimum zone (OMZ) in the Arabian Sea has been estimated for the first time using dissolved oxygen (DO) profiles obtained from the Biogeochemical Argo floats collected between 2013 and 2019 in the Arabian Sea. The depth of upper boundary of the OMZ varied narrowly between 70 and 220 m in the entire Arabian Sea whereas the lower boundary of OMZ significantly deepened from southern (500 m) to northern Arabian Sea (1200 m). The thickness of OMZ decreased from north (>1050 m) to south (400 m) with the thickest OMZ in the northeastern Arabian Sea (950- 1050 m). The thick OMZ in the northeastern Arabian Sea is associated with low concentration of depth integrated Chlorophyll-a, primary production in the upper 100 m and sinking carbon fluxes at 100 m depth than other regions. The particle back-scatter, proxy for particulate organic matter, is higher in the northeastern than other regions in the Arabian Sea. The high particle backscatter data is found in the core of OMZ and it is increased from shelf to offshore indicating that cross shelf transport of organic matter may be supporting bacterial carbon demand in the OMZ in the northeastern Arabian Sea. The eastward shift in the OMZ is attributed to weak mixing, high penetration time of intermediate water masses, and organic matter transport from the shelf region. Numerical models estimated negligible changes in DO in the OMZ since past several decades, whereas long-term observational data indicates decline in DO levels in the OMZ. Such contrasting results may be caused by lack of cross-shelf transport of organic matter in the models. Though this study identifies the occurrence of cross-shelf transport, the nature, quality and composition of organic matter transported from shelf is unknown. Nevertheless, inclusion of such processes in the models may improve predictability of possible changes in OMZ in future in the Arabian Sea.

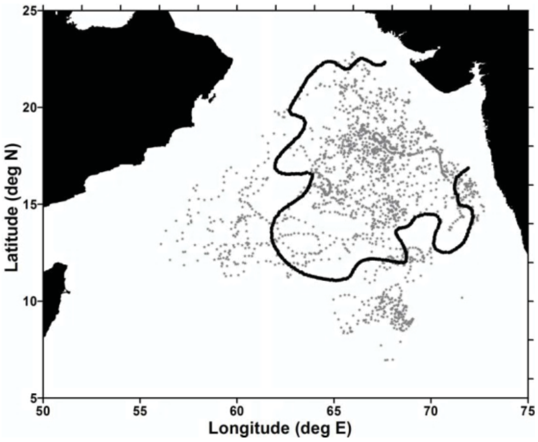

Figure 1. A schematic representation of identified surface current flow during southwest monsoon (blue) and northeast monsoon (red). Currents indicated are WICC-West India Coastal Currents, GW-Great Whirl, RHJRas al Hadd Jet, NEC-North Equatorial Current, and SECSouth Equatorial Current after Schott and McCreary (2001). The region of denitrification is shown as black line after Naqvi (1991). The regions of coastal upwelling are shown and the brown line represents the Findlater Jet where open ocean upwelling associated with Findlater Jet is also known to occur. The positions of the Bio-Argo DO profiles used in this study are given as black dots.

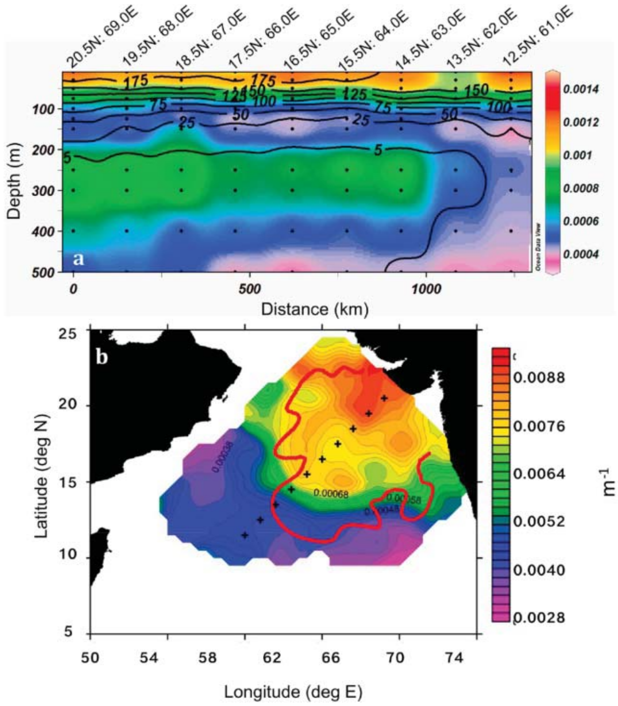

Figure-2: Spatial variations in back-scatter -1 (m) (a) along northeast-southwest transect (color shade) shown in (b). The dissolved oxygen concentrations are shown as contours. The positions of the profiles are shown in the upper x-axis. (b) distribution of back-scatter at the core of OMZ (300 m depth) in the Arabian Sea. Red line shows the denitrification area.

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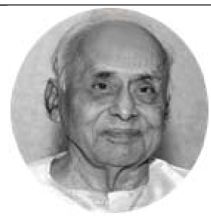
Dr. D. Srinivasan Endowment Award OSI 2021



The Ocean Society of India (OSI) is pleased to announce 'Dr. D. Srinivasan Endowment Award 2021' in the fond remembrance of Dr. D. Srinivasan, former Director-NPOL, DRDO, a veteran Oceanographer and father of Indian underwater acoustics. This award is to honor eminent Scientists/Engineers who made outstanding contributions in the field of Ocean Science & Technology for national development and their applications of these by the researchers in India. The scientific contributions should cover any aspect of ocean sciences including development of innovative technology; new designs and concepts for standardization; development of information systems and applications; education, training, policy development and related aspects.
Nominations for this award are invited from the Heads of Research Organizations/Centers; Vice-Chancellors of Universities; Secretaries of Government Scientific Departments, former Dr. D. Srinivasan Awardees, President of National Academies; Presidents of recognized scientific or technological societies of India, Past Directors/Secretaries of the above Institutes/ Ministries and Scientists of eminence such as Bhatnagar, Padmashri Awardees or two life members of OSI with more than 10 year as life member jointly.

The format for nomination is given in OSI website. Nominations should be sent to: The General Secretary, Ocean Society of India, MoES-National Institute of Ocean Technology, Pallikaranai, Chennai- 600 100 with an advance email copy to osi.secretary@gmail.com. The last date for receiving nominations is ***June 8, 2021.*** *Self-nominations will not be accepted.*

Call for contributions
Articles/research highlights of general interest to the oceanographic community are invited for the next issue of the Ocean Digest. Contributions may be emailed to **osioceandigest@gmail.com**

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OSI PG Dissertation Awards 2019-2020

The OSI has instituted PG Dissertation Awards to motivate young talents who are doing research in ocean-related areas at post-graduatelevel. One award each under the seven themes of Ocean Sciences and Technology viz. Physical Oceanography, Ocean and Atmospheric Sciences, Chemical Oceanography, Geological Oceanography, Biological Oceanography, Ocean Engineering & Technology, and Marine Microbiology & Biotechnology were introduced. A PG Dissertation Awards Committee consisting of eminent scientists/ academicians representing the different themes was constituted to oversee the implementation of the programme. The Announcement inviting nominations for the PG Dissertation Awards Programme for the academic year 2019-20 was released in Aug 2020. In response to the announcement, a total of 38 nominations were received from Universities spread across the length and breadth of the country. The dissertations received have been evaluated following the Methodology finalised by the Awards Committee. Panel of Experts evaluated the dissertations based on the Guidelines and Proforma worked out by the Awards Committee in the first round of evaluation. The top three dissertations under each theme subject to a minimum score of 60% marks were shortlisted for the second and final round of evaluation, encompassing presentation-cum-discussion sessions held online during 26- 27 Mar 2021. Details of the Awardees under the different streams based on the decision of the Awards Committee and approval of the OSI GC are given below. The citations and cash prizes for the Awardees are to be presented during the OSICON-21 Conference scheduled to be held at NCPOR, Goa, in August 2021.

Stream/Theme	Student	Title of Dissertation	University-Institute
Physical Oceanography	Ardra D	Spatial and temporal variability of OH minimum over Indian Ocean	Cochin Univ. of Science & Tech - IIT Kharagpur
Oceans and Atmosphere	Gopikrishnan G S	Assessment of formaldehyde over the Indian Ocean and its impact on the marine environment	Kerala Univ. of Fisheries & Ocean Sciences - IIT Kharagpur – IITM
Chemical Oceanography	Sreevidhya R	Role of organic nutrients on the sustainability of primary production in the Bay of Bengal	Kerala Univ. of Fisheries & Ocean Sciences - NIO RC Visakhapatnam
Geological Oceanography	Anjana Gireesh	Boron isotope study of foramineral carbonate from Arabian Sea	Cochin Univ. of Science & Tech-NCPOR
Biological Oceanography	Akalesh Patel	Monitoring of farmed shrimp from Nagapatnam for Salmonella contamination	Tamil Nadu Dr. J. Jayalalithaa Fisheries University
Ocean Engineering & Technology	Teppala Vikranth	Real time estuary observation system for monitoring of Bhavanapadu estuary by utilizing Internet of underwater things	Andhra Univ. – NIOT
Marine Microbiology & Biotechnolgy	Nizam Ashraf	Studies on diversity of bacteria associated with selected corals of Lakshadweep and their bioactive potentials	Kerala Univ. of Fisheries & Ocean Sciences - NIO, Kochi
Special citation for exceptionally brilliant students	Saranya JS	Marine heat waves in Indian Ocean and their impacts on atmospheric convection	Kerala Agricultural University - IITM

Conference Venue: NCPOR, Goa
(Hybrid meeting: Online + in-person)
Online Registration open since April 01, 2021
Last date of Abstract Submission: May 25, 2021
Notification of acceptance of Abstract: June 30, 2021
Date of Closure of Online Registration: July 31, 2021
Further details: http:/www.osicon21.ncpor.res.in
Email: osicon21@ncpor.res.in

ANNOUNCEMENT FOR AWARDING OSI FELLOWSHIPS

Ocean Society of India (OSI) has introduced a Fellowship program for its Life Members who have made an outstanding contribution to ocean and allied fields of Science and Technology. Fellowship for Life Members of OSI with a minimum residency period of 10 years will be conferred on the most outstanding/distinguished Indian researchers and other professionals in the areas related to oceans, working anywhere in India or abroad, in recognition of their contributions to the field of Ocean sciences and related fields with exceptional merit.

The selection of OSI Fellows are from among nominated by Vice-Chancellors of Universities / Directors or Heads of leading Academic Institutions / Directors of R & D Institutions in Scientific, Technological and Ocean related research in India / Fellows of Reputed Indian Academies OR Members of the prevailing Governing Council of OSI.

The nominations for the Fellowship should be submitted only in the prescribed Proforma, available in the OSI website on or before **30 June 2021** to the General Secretary, Ocean Society of India, MoES-National Institute of Ocean Technology, Pallikaranai, Chennai- 600 100 with an advance email copy to osi.secretary@gmail.com