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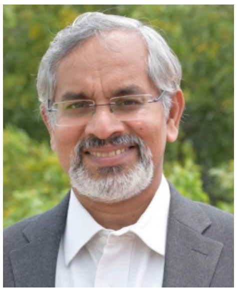
Impact of Indian Ocean Dipole on the surface chlorophyll distribution of the Indian Ocean



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Indian Ocean is a highly productive basin which exhibits large sensitivity to the tropical climatic variability. Biophysical characteristics of the Indian Ocean are unique compared to other tropical oceans owing to the prominent seasonal cycle dictated by the monsoons. This seasonality is often regulated by the Indian Ocean Dipole (IOD), a dominant mode of interannual variability in air-sea coupling over the tropical Indian Ocean (Saji et al., 1999; Webster et al., 1999). IOD is characterised by the basinwide modulations in the physical settings of the Indian Ocean, including anomalous cooling (warming) of the eastern (western) equatorial Indian Ocean, strong equatorial westerlies, changes in circulation pattern, mixed layer processes, and the thermocline structure. In response to these dynamical variabilities, surface chlorophyll distribution of the Indian Ocean exhibit large deviations from the climatological pattern.

Biological response of the Indian Ocean to IOD vary spatially and is dependent on the phase of the dipole mode. During positive IOD (pIOD), the eastern equatorial Indian Ocean and the Bay of Bengal (BoB) exhibit positive chlorophyll anomalies, whereas, the Arabian Sea exhibits negative anomalies. These responses are mainly determined by the direct and indirect influences of the IOD-related wind anomalies on the local mixing and upwelling of nutrient-rich subsurface waters (Wiggert et al., 2009; Currie et al., 2013). In the northeastern BoB, local wind stress curl during pIOD is favourable for enhanced open-ocean upwelling. At the sametime, the upwelling Kelvin and Rossby wave propagation associated with the pIOD remotely drive thermocline shoaling. Weakening of barrier layer due to this remotely controlled thermocline shoaling also enhances the mixed layer entrainment (Girishkumar et al., 2012). Cyclonic eddies with long residence time, in the absence of second downwelling Kelvin waves during pIOD, are crucial in supporting the intensification of regional blooms in the BoB (Chen et al., 2013). In the Arabian Sea, thermocline deepens during the pIOD phase due to weaker upwelling Rossby waves and reduced coastal upwelling due to anomalous northeasterly winds (Wiggert et al., 2009). The deepening of thermocline favours enhanced convective mixing and dilution of phytoplankton biomass leading to a reduction in surface chlorophyll concentration (Wiggert et al., 2002).

Most of the studies focussed on the impact of pIOD on the biological productivity of the Indian Ocean since the surface chlorophyll anomalies are generally stronger during pIOD compared to that during negative IOD (nIOD). The impact of nIOD was not explored in detail due to the weaker chlorophyll anomalies and lesser frequency of strong nIOD events. In 2016, the Indian Ocean witnessed an extreme nIOD (Lim and Hendon, 2017; Lu et al., 2018), whose intensity was comparable to the strong 1998 nIOD and duration even longer. This was a suitable time period to investigate the biophysical interactions of the Indian Ocean associated with the negative phase of IOD. A striking anomaly during this period was the formation of unusually intense surface chlorophyll blooms in the southeastern Arabian Sea (SEAS), with the highest magnitudes ever observed in the region in the past two decades.

Unusual intensification of surface chlorophyll in the SEAS during 2016

The SEAS is a highly dynamic sector in the north Indian Ocean, characterised by strong coastal upwelling off the coast of Kerala during summer. Upwelling triggers the formation of intense surface chlorophyll blooms, which peak during the peak phase of the summer monsoon and decay by the late summer (Fig. 1a-d), contributing significantly to the country's fisheries production. In 2016, this climatological seasonal cycle was disrupted due to the unusual intensification of surface chlorophyll by late summer and fall (Fig. 1e-h), with a two-fold increase in magnitudes (1.0 mg m^{-3}) compared to previous years (Fig. 1i). The region is highly sensitive to IOD with the surface chlorophyll anomaly exhibiting a strong negative correlation (−0.6) with the DMI (Fig. 1j), indicating the impact of teleconnections.

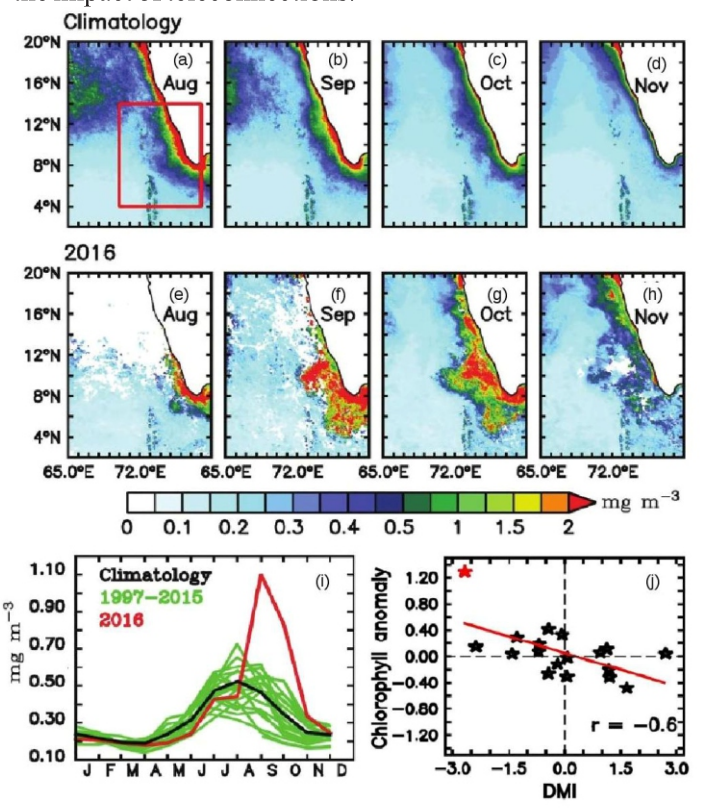

Figure 1. Spatial distribution of chlorophyll in the SEAS for August–November from climatology (a–d) and during 2016 (e–h). i) Annual cycle of mean chlorophyll in the SEAS for 1997–2015 (green), 2016 (red), and climatology (black). j) Relation between chlorophyll anomaly in the SEAS and DMI during September for 1997–2016. Red star indicates year 2016.

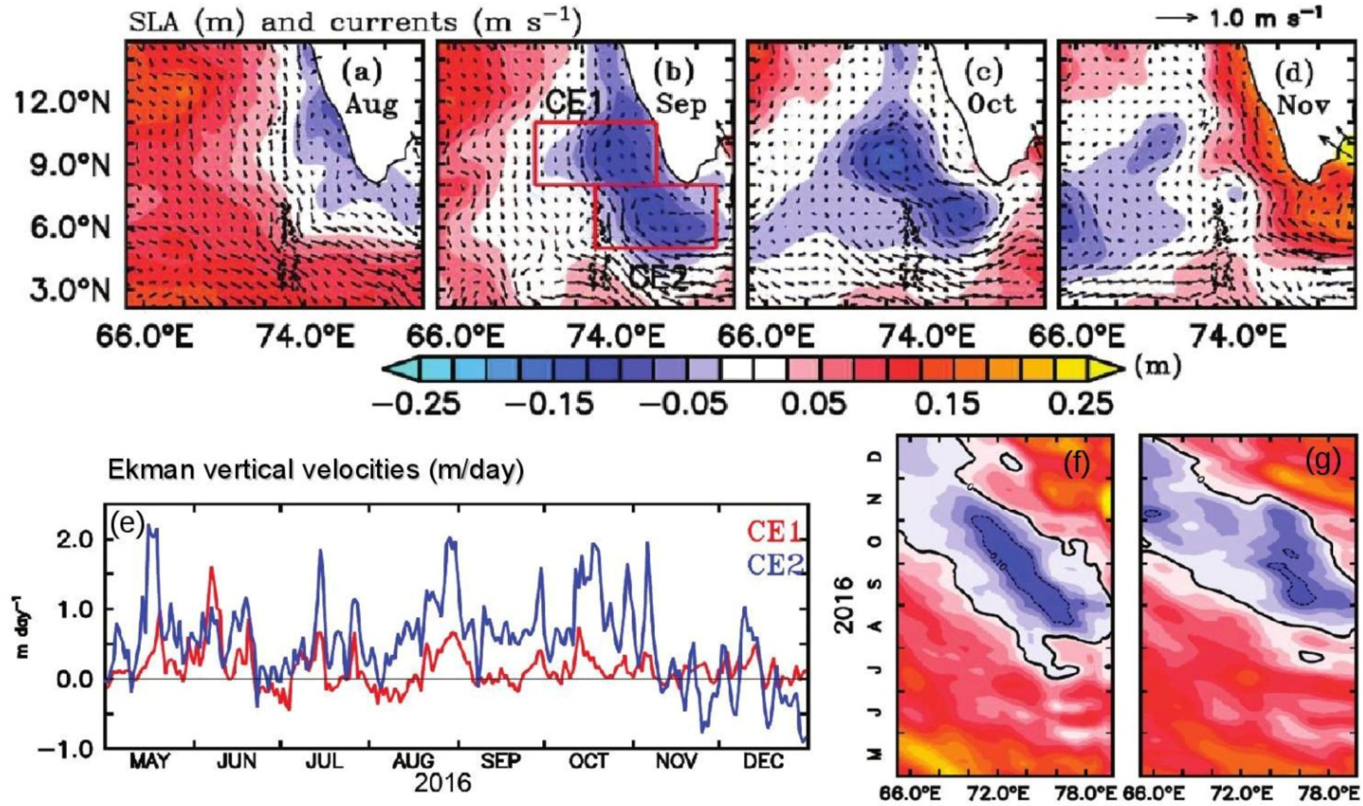

Figure 2. *a-d) Sea level anomalies (SLA; m) and surface currents (m s^{-1}; vectors) in the SEAS for August–November, 2016. Boxes in panel b) represent the regions of cold-core eddies, CE1 and CE2. e) Ekman vertical velocities (m day^{-1}) averaged over the regions of CE1 (red) and CE2 (blue) for May–December. Time-longitude hovmoller diagram of SLA (m) in the latitudinal band of f) CE1 and g) CE2.*

The observed chlorophyll anomaly in the SEAS during 2016 is mainly attributed to the presence of two strong cold-core eddies along the periphery of the coastal upwelling zone (Fig 2a-d). During the formation of eddies, thermocline was already shallow due to coastal upwelling during the peak monsoon phase. With this favourable preconditioning, eddy activity lead to anomalous shoaling of thermocline compared to previous years, indicating enhanced vertical supply on subsurface nutrients and chlorophyll. The formation of eddies is attributed to both local and remote forcings in association with the nIOD. Local Ekman suction favoured upwelling during eddy formation (Fig. 2e), however, thermocline variability was not always consistent with Ekman vertical velocities. At the same time, the westward propagation of negative SLA (Fig. 2f and 2g) indicated the presence of upwelling Rossby waves and the remote influence on eddy formation (Shankar and Shetye, 1997). Observational evidence suggest that strong upwelling around Sri Lanka and the southern tip of India forced by the nIOD-related wind anomalies, and the resultant propagation of upwelling Kelvin waves along the west coast of India forced the upwelling Rossby wave signals in the SEAS.

Largescale climatic oscillations like the IOD can lead to unprecedented modulations in the climatological distribution of primary productivity. The underlying biophysical interactive mechanisms are complex and need to be understood in detail, considering the non-negligible impact of oceanic biological feedbacks on the climate, especially in a basin like the tropical Indian Ocean where the ocean-atmospheric coupled interactions are strong.

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Challenges in Ocean Wave Modeling in context to the North Indian Ocean - the way ahead*

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Ocean surface gravity waves are the manifestation of sea surface that results from wind stress acting over the air-sea interface. It is dynamic region that accounts for the direct transfer of heat, momentum, gas and particle exchange in the global oceans. Surface gravity waves generated by wind stress evolves dynamically in both space and time, and have typical wave periods ranging between 2 s to 30 s. The subject of wave generation, propagation, and dissipation mechanisms have been a subject of immense interest for the past several decades having significant practical applications and socio-economic implications. Also, in the recent past, there has been significant research on the study of wind-waves due to increasing marine and offshore activities, and operational centres are involved in ocean state forecasts. Precise knowledge on ocean state conditions and its prediction are very important for various ocean related activities such as efficient ship routing, strategic naval operations, marine activities, port and harbour operations, coastal zone management etc. The scientific and engineering community has immense interest to understand the associated kinematics and dynamics of surface gravity waves for routine forecast and location-specific studies. Ocean waves play a significant role in influencing coastal processes in the coastal and nearshore environments. Winds blowing over the ocean surface generates wavelets and the spectral components eventually develop over time extracting energy from the wind stress. Through non-linear wave-wave interaction process, the energy within a wave system gets redistributed thereby determining the overall wave energy at a particular location and time, and that can be conveniently expressed in the form of a wave spectrum.

The free surface boundary is quite dynamic in nature, wherein the exchange of momentum, heat and gas occurs. Wind stress acting on this boundary layer generates wind-waves or the surface gravity waves that have wave period ranging between 2s to 30 s. There has been immense interest amongst the scientific community over the past several decades in understanding the characteristics of wind-waves such as their generation mechanism, propagation, and dissipation characteristics having significant practical applications and economic importance. Over the recent decades that has been significant research on the study of wind-waves and its prediction owing to increasing marine and offshore related activities. Precise knowledge on prevailing sea-state and its prediction is very vital for many marine related operations, efficient ship routing, naval operations, port and harbour development activities and many more. Nevertheless, the scientific and engineering community have significant interest to understand the associated kinematics and dynamics of ocean wind-waves for routine forecast and location specific case studies.

Engineering community working in related disciplines of ocean engineering, naval architecture, civil and hydraulic engineers require precise wave information to design, operate and manage structures in the marine environment. Wave information is also required by coastal engineers in understanding natural processes in the coastal and nearshore environments. Ocean waves play a very significant role in controlling the coastal processes in the coastal and nearshore environments. Based on existing knowledge, the wind blowing over ocean surface generate wavelets and the spectral components eventually develop over time extracting energy from wind stress. The nonlinear interaction between waves redistributes the overall energy within the frequency-direction space of the wave spectrum. This is the present state of knowledge acquired despite several years of research in the field of ocean wave modeling. Random nature of waves and its complex interaction in terms of kinematics and dynamics of wave evolution was a major challenge since the past. One can find the fundamental and classical studies on water waves and development of mathematical formulations that dates back to the 19th century. An overview on the major advances and developments made on wind-waves during the past few decades are illustrated in Table 1.

In the Indian context, focused studies on wave research started during the 1980s and using the SMB (Sverdrup-Munk-Bretschneider) method hindcasts were made for wind-seas and swells off Mangalore coast during the southwest monsoon of 1968 and 1969 (Prasada Rao and Durga Prasad, 1982). Their study postulated that significant ocean wave characteristics in terms of both wave height and period predicted using this method compared well with the recorded data. In addition, their study (Prasada Rao and Durga Prasad, 1982) proposed a bottom friction factor of 0.05 suitable for the study region in evaluating the shallow water wave characteristics off Mangalore coast. In another study, Prasada Rao (1988) reported on the spectral width parameter for wind-generated waves based on wave data analysis using a ship borne wave recorder.Data analysis covered various locations of deep and shallow waters along the east and west coast of India.

S.No.	Advances	1940s	1950s	1960s	1970s	1980s	1990s	2000s
1	Statistical theory	Theory of random noise	Wave Statistics & Spectral developments	Mathematical developments in Wave Spectra - nonlinear effects	Similarity form and work on directional spectra	High Frequency wave Spectrum	Wave number - Frequency Spectra	Wave number - Frequency Spectra
2	Nonlinear theory	Nonlinear theory of regular waves	Nonlinear theory of random waves	Wave instability and wave interaction studies	Computation of dispersion relation	Wave breaking computational works	Wave breaking and Energy Dissipation	Wave breaking and Energy Dissipation
3	Experiments (Lab. and Field Measurements)	Basic studies and visual based observations	Observations from Instrument	Advances in Field based campaigns and planned experiments	Studies on Equilibrium - planned ocean experiments	Wave Dynamics - use of Satellite observations	Microwave Remote Sensing	Ocean observing systems and satellite-based platforms
4	Air-Sea Interaction Studies and Wave Projects		Sun Glitter Project		JONSWAP field experiment	HEXOS	SWADE, RASEX	Coupled atmosphere-ocean models
5	Wave Forecasting Techniques	Sverdrup and Munk	SMB and PNJ wave forecasting methods	First Generation Wave Models	Second Generation Wave Models	3G Wave Models (WAM)	3G Wave Models with Data assimilation (WAM, WW3)	Third generation wave models – ensemble modeling

Table 1: Research advances in the field of ocean surface waves during the past few decades (source: Mitsuyasu, 2002 from Bhaskaran, 2019)

The study (Prasada Rao, 1988) indicated on the bias in the estimation of spectral width parameter using higher order moments. A parametric wave prediction model based on time delay concept was reported by Prasada Rao and Swain (1989). The study used datawell wave rider buoy data recorded from an oceanographic research vessel. Analysis of the data revealed growth and decay phase of sea-states for varying wind speeds. The parametric model used a time delay concept in place of wind duration limit (Prasada Rao and Swain, 1989). Studies on wave characteristics and its refraction patterns relating to beach erosion for Kerala coast was reported by Baba et al. (1983). A significant and pioneering study on ocean wave research for India was reported by Baba (1985) that initiated the modern ocean wave research in India. It brought out a concise picture on the latest developments made in the interpretation of ship-based observations, wave hindcasting, measurements of ocean waves. New approaches on the study of short-term distributions, seasonal and annual climatology, and long-term distributions are discussed (Baba, 1985). Importance of nonlinear effects in short-term distributions of wave heights and periods are also highlighted.

Developments on ocean wave research in India, wave spectra, numerical methods for wave hindcasting, transformation, tapping of wave energy, remote sensing techniques are discussed along with recommendations for future research (Baba, 1985). In another study, Baba et al. (1989) investigated the wave spectra off Kochi, and the study highlights that spectral shape was multi-peaked and wide-banded with high-frequency sides exhibiting similar slopes. The study revealed that the slope was milder than that proposed by Philip's formulation for fully developed conditions. Kurian et al. (1985) reported on the prediction of nearshore wave heights using a refraction program. In their study, the Dobson wave refraction program was modified to incorporate the attenuation characteristics due to bottom friction that was verified for prediction of nearshore wave heights. The study focused on the shelf waters off Alleppey coast in Kerala. Swain et al. (1989) used a numerical wave prediction model and performed many case studies for the Arabian Sea and Bay of Bengal. In another study, Ravindran and Koola (1991) investigated the potential for harnessing wave energy emphasizing on the Indian Wave Energy Program. Using ship-based observations, Chandramohan et al. (1991) developed wave statistics for the Indian coast. In another significant study, Sanil Kumar et al. (1998) estimated the wave direction spread in shallow water utilizing measured wave data for a period of two months at 15m water depth along the east coast of India. Their study (Sanil Kumar et al., 1998) advocated that shallow water wave directional spread was narrowest at peak frequency and widened towards the lower and higher frequency bands. The observed uni-directional spectra were in close resemblance with the Scott wave spectra. Further, Sanil Kumar and Deo (2004) postulated the design wave estimates considering the directional distribution of ocean waves.

Based on one year measured data at three locations along Indian coast and 18 years of ship reported data, the design wave heights were estimated considering the directional distribution of significant wave heights. Another important contribution by Sanil Kumar et al. (2010) investigated the waves in shallow waters off the west coast of India during the onset of summer monsoon period. The study signifies that about 67% of measured waves are attributed due to swells that propagate from south and south-west regions and wind-seas from south-west to north-west directions. Also using measured data, the variations in nearshore wave power for different

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shallow water locations in the east and west coast of India was reported by Sanil Kumar et al. (2013). Shahul Hameed et al. (2007) using measured data reported on the seasonal and annual variations in wave characteristics off Chavara coast in Kerala. For the Goa coast using measured wave spectral data, Vethamony et al. (2009, 2011) reported on the super-position of wind-seas one existing swells during the pre-monsoon season. The above discussed review covers some of the seminal studies that are being carried out on ocean wave research for the Indian coast. At present the Earth System Science Organization (ESSO) - Indian National Centre for Ocean Information Services (ESSO-INCOIS) located at Hyderabad provides information on Ocean State Forecast (http://www.incois.gov.in/portal/osf/osf.jsp).

The concept of energy balance equation was formulated by Gelci et al. (1957) to understand the phenomena of wave evolution. The second and third generation wave models used energy balance equation as the governing equation. At present, the third-generation wave models are used for routine wave forecasting of surface gravity waves for the North Indian Ocean region. Third-generation wave models use sophisticated parameterization of physical processes as compared to the second-generation wave models. Quality of wave forecasts have also drastically improved in the recent years attributed due to tremendous boost in computational power, data acquisition systems, availability of satellite data, and increasing number of in situ observational platforms.

Broadly speaking, the wave models can be classified into phase-averaging or phase-resolving, wherein the phase averaged models are expressed in terms of energy balance with appropriate sources and sinks used to represent the relevant physical processes. Phase resolving models are based on the governing equations of fluid mechanics formulated to obtain the free surface condition. However, the phase averaging models have no priori restriction on the area to be modelled, whereas the phase resolving models have an inherent limitation on the spatial dimension of the computational area. The various physical processes that are accounted in phase averaged models includes (i) wave generation by wind accounted due to momentum transfer from atmosphere to ocean, (ii) refraction due to water depth, (iii) shoaling due to shallow water depths, (iv) diffraction due to obstacles, (v) reflection due to impact with solid obstacles, (vi) bottom friction due to heterogeneity of bottom materials, (vii) wave breaking effects when steepness exceeds a critical level, (viii) non-linear wave-wave interaction due to quadruplets and triads resulting in wave energy redistribution, and (ix) wave-current interaction effects. In deep water environment the physical processes can result from the combined effects of wave generation by wind, quadruplet wave-wave interaction and dissipation due to white-capping mechanisms. Deep water waves transform on reaching shallow waters attributed by dominant physical processes like refraction, bottom friction, depth induced breaking, triad wave-wave interaction, wave-current interaction, diffraction and reflection (Holthuijsen, 2007). Hence, choosing an appropriate wave model for the desired task is very important considering the dominant physical processes relevant to the study area.

Wind field and bathymetry are the primarily input that governs the dynamic evolution of wind-waves. The spatio-temporal evolution of wave energy is dependent on both wind field and local bathymetry. In addition, the ocean wave spectrum forms an integral part in wave models, as they provide the necessary initial conditions, wherein the energy has a dependence on the wind speed. Formulation of wave spectra has been an active area of research since the 1950s. The Phillips spectra developed for the first time provided an insight on the high-frequency tail, wherein the energy is proportional to f^{-5} However, this spectrum forms the basic foundation for other ocean wave spectra developed over time. The practical application of Phillips spectra is limited as it represents only the shape of the high-frequency tail. Thereafter, the Pierson-Moskowitz (*PM*) spectra developed in 1964 represented the fully developed seas.

A better form of wave spectra *JONSWAP (1973)* considered the shape factor, finding better application in representing ocean waves in both deep and shallow waters. State-of-art wave models used *JONSWAP* spectra for routine wave forecasts in the global oceans. The ocean wave climate in the North Indian Ocean is primarily governed by remote forcing effects. Specifically, the Southern Ocean is a potential region for swell generation that can propagate 1000s of kilometre influencing the local wind-wave climate of distant regions. Wave field in the North Indian Ocean is strongly modulated and modified by distant swells and that is reflected in the directional wave energy spectrum measurements. Most of the time, the wave energy spectral distribution is either bi-modal or multi-model. Therefore, an indigenous development of ocean wave spectra specifically for the North Indian Ocean is a need and necessity. In other words, the *JONSWAP* wave spectra developed for the Atlantic Ocean and acclaimed universally valid needs introspection.

Studies investigated the high-frequency tail characteristics at three different locations in the east coast of India. Firstly, a nearshore modeling study was carried out at Gopalpur location to understand the high-frequency tail in coastal waters (Umesh et al., 2018). Over the years, there is an uncertainty in the -4 and -5 frequency exponent representation observed in the slope of high-frequency tail of wave spectrum. For the Gopalpur location, an assessment was made to understand the slope of the high-frequency tail using measured data recorded for 3 years. The study demonstrated that the high-frequency spectral slope varied seasonally in the range between -2.13 to -3.48. Swell and wind-seas calculated by separation frequency method, showed that 64.6% of waves were dominant by swell and the rest 34.9% by wind-seas annually. Single, double and multi-peaked spectra occur

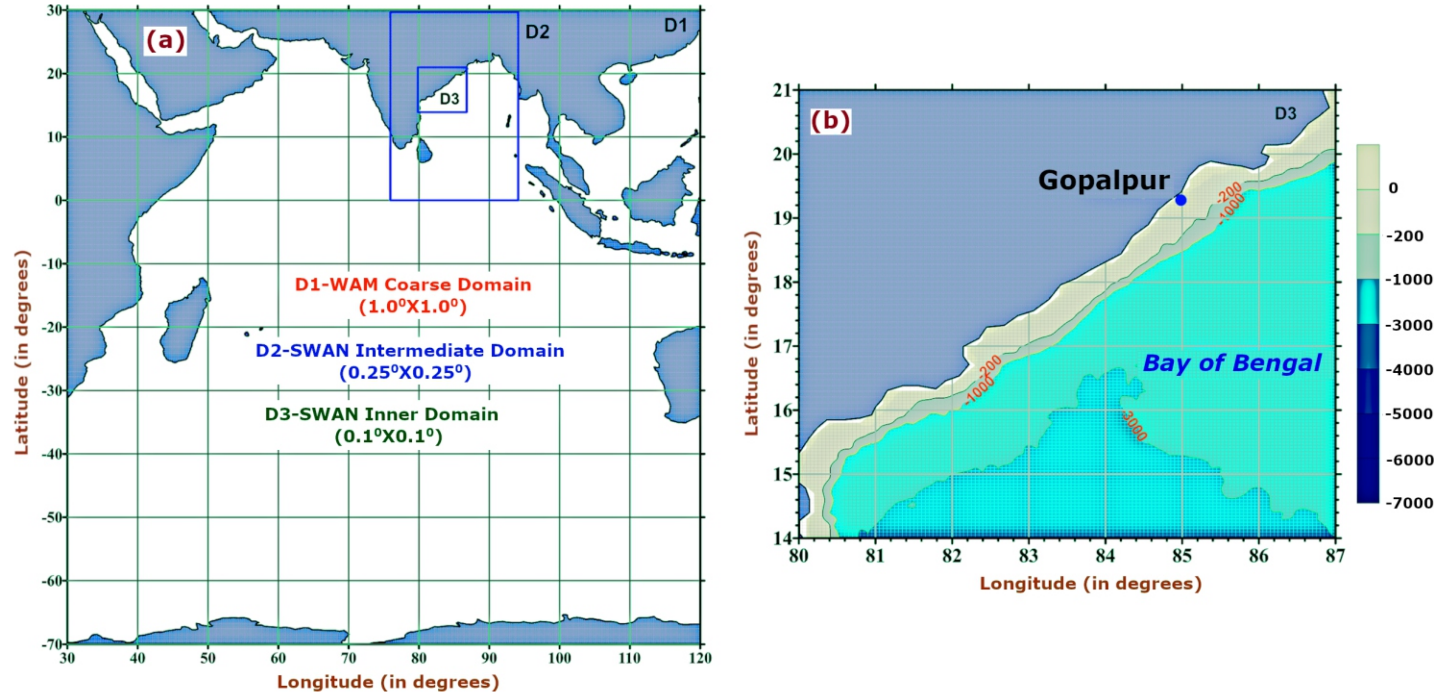

Figure 1: (a) Modeling architecture using nested grids, (b) coastal location off Gopalpur

12.23, 71.80 and 15.37% annually (Umesh et al., 2018). Comparisons of measured and theoretical spectra indicate that *JONSWAP* model could not describe the high-frequency tail of measured spectrum. It is evidenced by very high Scatter Index ranging from 0.24 to 1.44. Whether there exists a correct slope for the high-frequency tail is still a question. The study used nested WAM-SWAN runs using a multi-scale approach (Fig. 1a) to simulate the waves off Gopalpur (Fig. 1b). The coarse grid domain (D1) covers the geographical area 30E120E; 70S30N shown in Fig. 1a used for WAM cycle 4.5.3 run with a spatial grid resolution of 11. Model spectral domain was prescribed with 25 logarithmic frequency bins ranging between 0.041 to 0.411 Hz and 12 directional bins to represent the 2D wave spectral distribution. Wave spectral information at each grid point was considered at every 6-hourly interval for the model simulation. Bathymetry of the study region was prepared using blended ETOPO2 dataset.

Boundary information from coarse domain D1 was provided as input to the intermediate domain D2 that had a grid resolution of 0.250.25 (77.5E94.5E; 0.5N29.5N). Further, the boundary information from domain D2 was provided as input to the inner domain D3 that had a spatial resolution of 0.10.1 (80E87E; 14N21N).

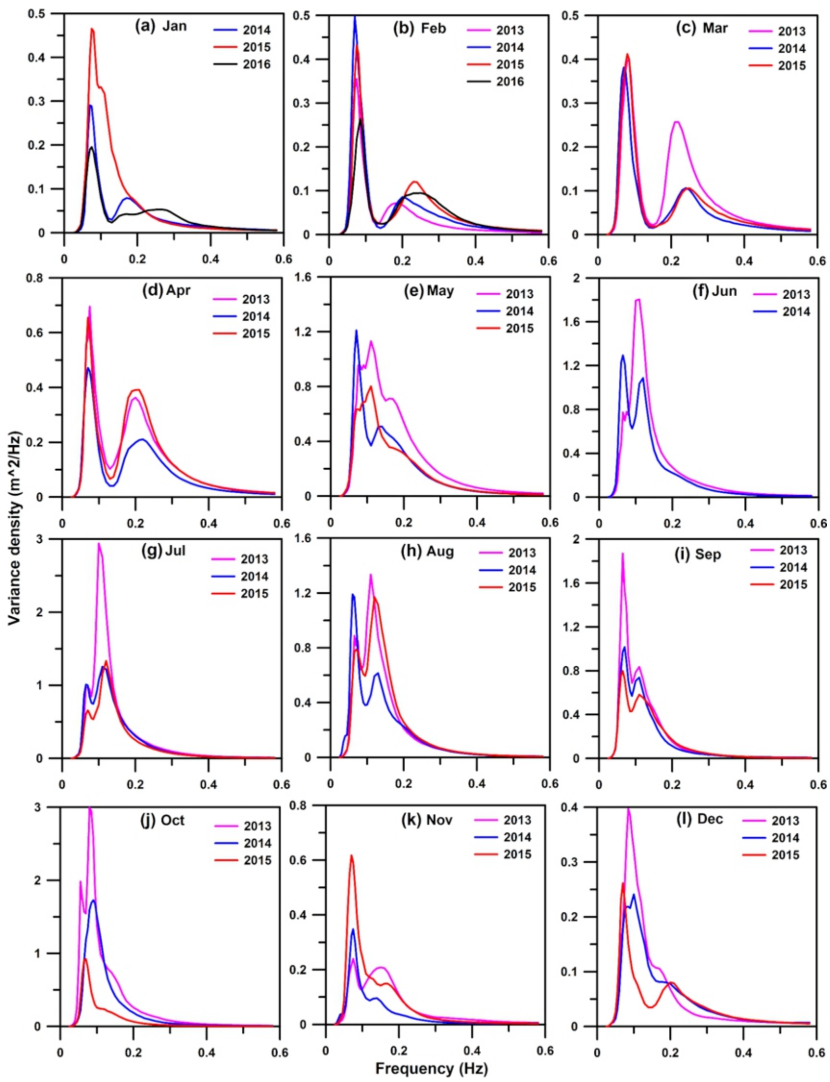

Figure 2. Monthly averaged wave spectra off Gopalpur during 2013-2016

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SWAN model used the boundary condition from D1 to simulate waves in D2 and D3 domains. Considering the southern boundary at 70S accommodates the swells reaching the North Indian Ocean region from the Southern Ocean. Fig 2 shows the monthly averaged wave spectrum analysed for the period (2013-2016). The spectral distribution shows the presence of double peaked wave spectra dominated by wind-seas during June to September. This occurs due to the locally generated wind waves that dominate the swell regime during the southwest monsoon period as compared to the other months. Normal wave spectra are either double or multi-peaked in the Bay of Bengal region due to existence of wind-seas together with the swell component.

The time series variation of spectral slope in the high-frequency tail of the spectrum for the period 2013-2015 is shown in Fig 3. Slope variations are minimal during January, with highest variations in April, July, and August. The slope increases in the month of July and decreases in September-December over the years. Also, the slope of high-frequency tail slowly increases during the southwest monsoon season, and decreased during post-monsoon, followed by a sharp decrease in slope during northeast monsoon over the years. It indicates there is a seasonal variation in slope and the slope of high-frequency tail becomes smoother when the non-linearity increases. The spectral tail is also influenced by bathymetry and local wind conditions.

The second study focused on understanding the spectral modeling of high-frequency tail characteristics in shallow waters off Puducherry (Umesh et al., 2019a). About eight years of measured wave spectra (June 2007–December 2014) for this region was analyzed to understand the slope of high frequency tail of the wave spectrum and to determine occurrence of single peaked, double-peaked and multi-peaked spectra in varying sea-states. Results indicate that wave spectra were multi-peaked from June to October and predominantly double peaked during the rest of the year (Umesh et al., 2019a).

Measured wave spectra were compared with numerical wave model outputs. Analysis on the slope of high frequency tail of the wave energy spectra shows that slope varied seasonally in the range of -1.96 to -3.27 at the coastal location. The third study considered numerical simulation and analysis of spectral slope of high-frequency tail characteristics using a nested WAM-SWAN model in shallow waters off Visakhapatnam considering the measured data for the period November 2011 to December 2015 (Umesh et al., 2019b). Results signify that high frequency slope of the spectra varied seasonally in the range between −1.80 and −3.77. Annually 75.11% of wave conditions were dominated by swells and the rest 24.89% by wind-seas (Umesh et al., 2019b). Using spectral fitting method, the *JONSWAP* spectra was compared with measured spectra; and that demonstrated significant deviations from the measured spectra revealing high Scatter Index ranging between 0.24 to 1.73. The set of these three experiments clearly reveal the complexity involved in determination of a universal high-frequency tail spectral shape for coastal waters off Indian seas.

Based on fundamental physical concepts and knowledge gained for more than four decades of research, the nonlinear wave–wave interaction mechanism is important for waves propagating in deep and shallow water environments. Better parameterizations need to be addressed in context to computational time to evaluate the exact nonlinear wave–wave interaction which is a quite difficult task.Another important physical process is the white-capping dissipation mechanism that governs the net energy balance of wind-wave evolution. Wave evolution process in this context is not well understood and combines basic intuition with a pragmatic approach, and the usual practice followed is its specification as a tuning parameter in wind-wave models. Another important sink mechanism is the bottom dissipation term for wind-waves that interacts with the heterogeneous nature of the sea bed in Indian seas. Wave attenuation effects due to bottom interaction are very important for waves approaching coastal and nearshore waters from deep water location. Cavaleri et al. (2007) provided a concise description on these aspects.

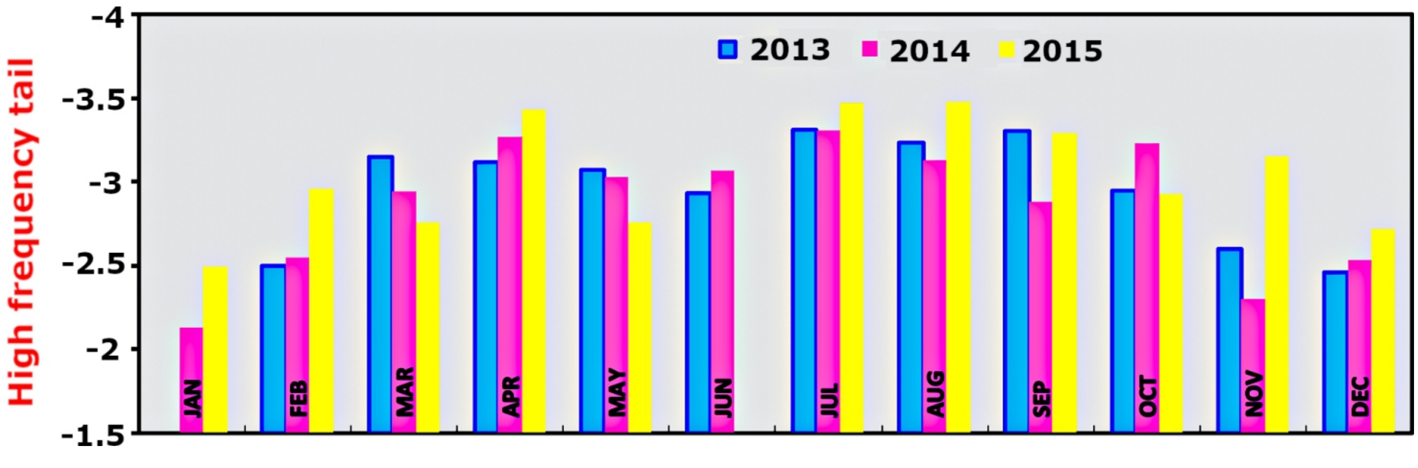

Figure 3. Spectral slope of high-frequency tail during 2013-2015 (years with continuous data are only included in the figure)

There are many other issues that are also important and require attention of the scientific community for regional scale wave modeling. Especially for tropical regions like India that experiences torrential rainfall over the oceans, the interaction of rain with water waves leading to the modification of resultant energy balance is an important parameter that also requires attention for operational purpose. For the Indian coast, regions in the near vicinity of river drainage systems also receive fine sediments such as silt and clay. The head Bay of Bengal has numerous river drainage systems that supply exceptional high loads of sediments to the nearshore areas. Fine heterogeneous sediment deposits over the seabed such as mud and clay can considerably attenuate wave energy as compared to wave propagation over sandy bottoms. Hence, there is a need to develop appropriate parameterization in numerical wave models that accounts for wave dissipation in seabed comprising of clay and mud deposits. Coastal and nearshore wave hydrodynamics on wave scattering effects due to vegetation such as mangroves that thrive in selected pockets along the Indian coast is another area that requires attention by the wave modeling community. Bhaskaran (2019) provides a comprehensive review on the challenges and future directions in ocean wave modeling with special emphasis on the Indian coast. Another important research area that requires wide attention is forecast of 'freak waves' or 'rogue waves' that is extremely dangerous for mariners and navigation. These are sporadic giant waves that can be potentially dangerous. However, there are different thoughts related to generation mechanism and propagation characteristics of rogue waves in the global oceans. It is a fascinating area of research that requires a separate and detailed study.

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THE SCIENCE WE NEED FOR THE OCEAN WE WANT

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1.0 Background

The United Nations has proclaimed a **Decade of Ocean Science for Sustainable Development (2021-2030)** (https://oceandecade.org/)to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework that will ensure ocean science can fully support countries in creating improved conditions for sustainable development of the Oceans. The term 'Sustainable Development of Oceans' refers to the sustainable development of the ocean, seas, and coasts. The main principle is that the Decade should utilize a multi-disciplinary understanding of ocean processes and solution-oriented research to generate new knowledge to support societal actors in reducing pressures on the ocean, preserving and restoring ocean ecosystems, and safeguarding ocean-related prosperity for generations to come. The identified six societal outcomes are:

- **A clean ocean** whereby sources of pollution are identified, quantified, and reduced andpollutants removed from the ocean.
- **A healthy and resilient ocean** whereby marine ecosystems are mapped and protected, multiple impacts, including climate change, are measured and reduced, and the provision of ocean ecosystem services are maintained.
- **A predicted ocean** whereby society has the capacity to understand current and future ocean conditions forecast their change, and impact on human well being and livelihoods.
- **A safe ocean** whereby human communities are protected from ocean hazards and where the safety of operations at sea and on the coast is ensured.
- **A sustainably harvested and productive ocean** ensuring the provision of food supply and alternative livelihoods.
- **A transparent and accessible ocean** whereby all nations, stakeholders, and citizens have access to ocean data and information, technologies and has the capacities to inform their decisions.

The Intergovernmental Oceanographic Commission of UNESCO (IOC/UNESCO) was tasked to coordinate the Decade's preparatory process (2018-2020). This involved inviting the global ocean community to jointly prepare an implementation plan for the Decade in ocean science and technology to deliver, together, the ocean we need for the future we want. This Implementation Plan will be submitted for approval to the 75th session of the UNGA in autumn 2020.

Global and regional consultative workshops are essential mechanisms in the Decade design process to achieve the objectives and to engage various communities through a multi-stakeholder process and structured dialogues. The first Global Planning Meeting held in Copenhagen, 13-15 May 2019, brought all key stakeholders interested in the Decade to the same level of information. Following this first global planning meeting, a series of regional workshops were planned to identify regional specific priorities and requirements as well as contributions to global objectives. It is in this connection the Regional Planning Workshop for the Northern/Central Indian Ocean countries as well as ROPME Sea was held at NIOT during January 8-10, 2020.

2.0 Regional Planning Workshop for the Northern/ Central Indian Ocean countries as well as ROPME sea area

The Regional Planning Workshop for the Northern/Central Indian Ocean countries as well as ROPME sea area was conducted by the Ministry of Earth Sciences, Govt. of India in the National Institute of Ocean Technology, Chennai, located in the southern part of India between the 8th-10th January 2020 to identify the region-specific priorities, requirement and contribution to the objectives of the UN decade of Ocean Sciences for sustainable development. The agenda for the three-day workshop had an inaugural session followed by well-structured panel discussions comprising of experts identified across six working group followed by group discussions and a final wrap up with the summary and recommendation of each working group. As a prelude, an Intergovernmental Oceanographic Commission regional committee for The Central Indian Ocean (IOCINDIO) leadership workshop on developing the regional framework for coastal Vulnerability was held from January 6-7, 2020.

3.0 Inaugural Session

Dr. M.A. Atmanand welcomed the delegates and gave a summary of the Global Planning meeting held at Copenhagen and on the activities of the National Institute of Technology. Dr. Justin Ahanhanzo, IOC, spoke on the genesis and overview of the UN Decade. Dr. Vladimir Ryabinin, Executive Secretary, IOC, talked about the importance of the UN Decade and gave an overview of the various plans to be taken forward (through video conference). Dr. Ariel Troisi, Chairperson, IOC, highlighted the importance of the Ocean decade and gave an overall action plan (through video conference). Dr. M. Rajeevan, Secretary, MoES, reiterated the commitment of India to the various SDG goals and the UN decade action plan (through video conference). Dr. Karen Evans, EPG, IOC, highlighted the draft science plan for UN Decade. She highlighted the cross-cutting and inter-connections between the various science themes. Dr.Sateesh C. Shenoi, Vice-Chair, IOC, gave the Keynote address. In his address, he highlighted six major issues viz. Climate Change–Sea Level Rise, de-oxygenated ocean (BoB, Arabian Sea), Ocean acidification, exploitation of living and non-living resources, marine biodiversity, marine pollution, particularly plastics and risks. Dr. M.V. RamanaMurthy, Director, National Centre for Coastal Research (NCCR), gave the Vote of Thanks.

About 100 delegated from the various **IOCINDIO** Member States including Australia, Bangladesh, France, India, Kuwait, Maldives, Saudi Arabia, UK, participated; SACEP countries was represented by the Director General, SACEP; IOC-EPG members from Australia and Russia, NOAA-USA, IOC-Africa also participated in the three-day workshop. The participants were well-represented form all concerned sectors, including Government organisations, academia, research institutes, etc. and about 23% were women delegates.

Inaugural Session

Delegates and Invitees to the Workshop

4.0 Working Groups

To steer the deliberations in the right direction, six working groups and panel members were identified, and detailed deliberations were held. The six working groups were:

- WG-I: Clean Oceans
- WG-II: Healthy and Resilient Ocean
- WG-III: Predicted Oceans
- WG-IV: Safe oceans
- WG-V: A sustainably harvested and productive ocean
- WG-VI: A Transparent and Accessible Ocean

Working Group deliberations in progress

4.0 Some of the major recommendations of each working group are as follows:

WG-I on Clean Oceans recommended for collection of litter before it enters the marine system, and recycling of plastic waste, awareness on the usefulness of change in the public perceptions towards plastic use, developing and implementing a proper plan for disposal of the marine litter collected during the beach clean-up operations.

WG-II on Healthy and Resilient Ocean has stressed the need to identify the boundary between healthy and unhealthy ecosystems and the drivers affecting the ecosystems' health and environment, including invasive species, bio-fouling, and the restoration steps needed to improve the health and resilience of oceans. The involvement of local communities in resource conservation, the use of local knowledge for protection and conservation of resources, and promoting ecosystem value services have all been identified as priority areas for a healthy and resilient ocean.

WG-III on Predicted Oceans have recommended the establishment of a data hub for the mid-eastern region under the IOCINDIO platform. In addition, an ocean prediction science team to be formed and a regional forum established to address all the issues related to the predictive ocean.

WG-IV on Safe Oceans, major points that emerged during the discussion includes mitigation or elimination of risk by developing proper models for risk assessment for operations at sea and a comprehensive coastal vulnerability assessment and efforts to minimize or eliminate false alarms about a possible extreme event.

WG-V on the Sustainably harvested and productive ocean has identified the need to develop a working concept that brings together the modes and means to enhance economic benefits and coastal livelihoods by sustainably harnessing the marine resources through capture fisheries and through responsible mariculture.

WG-VI on Transparent and Accessible Ocean, the major recommendations were that data and information goals should be user-driven, and the ocean science community needs an accessible data system/portal to deliver data and info and should be coupled with an internationally developed and recognized data policy.

As part of IOCINDIO–IOCAFRICA collaboration initiation, interactions were held with participants from Cameroon and Ghana. A coastal vulnerability capacity building program is being initiated with IOCAFRICA through Kuwait, Bangladesh, Saudi Arabia, and India. Participants from Bangladesh and India are expected to participate at the regional UN Decade planning workshop to be held at Nairobi during the month-end. A session was organized by Dr. Jay Pearlman (over Skype) and Drs. Sidney Thurston and R Venkatesan on ocean best practices, which is to be taken care of during all observations planned during the Decade. A session by Early Career Ocean Professionals (ECOPS) involved an exclusive interaction with the students' community, and about 80 students participated actively and interacted with Scientists/mentors from various countries.

5.0 Major Outcome and recommendations

The major recommendations from this region for the UN Decade for Ocean Science for Sustainability are:

- To develop a Regional Framework for Coastal Vulnerability towards the Safety, Security, and Sustainable Development of Member States in the Indian Ocean.
- Monitoring and Management of Marine litter and research on microplastics
- Tsunami Early Warning in the Indian Ocean.
- Inventory with knowledge gaps in existing programmes, studies, and researches maximizing their wide and equitable usage towards the UN Decade success.
- Establishment of the Indian Ocean Youth Leadership Network of Ocean, Climate and Atmospheric Scientists and Professionals.
- Establishment of Indian Ocean Leadership Mentoring Network.
- Progress Review Follow up of the Recommendations at the IIOE-2-2020 Meeting in Goa, India, March 2020.

The Regional Planning Workshop for the Northern/Central Indian Ocean countries as well as ROPME sea area provided an excellent platform for bringing together experts and stakeholders related to various aspects of the coastal and ocean science and technology to deliberate and identify the region-specific priorities, requirement, and contribution to the global ocean science needed to support the sustainable development of our shared ocean.

6.0 Way Forward

Presently, the draft Implementation Plan (Version 2.0) of the United Nations Decade of Ocean Science for Sustainable Development, together with a summary version of the Plan has been finalised, taking into account the many valuable comments and feedback gathered from the member countries through the regional workshops held in different parts of the world. In keeping with UNGA Resolution 74/19, Version 2.0 of the Plan has been submitted to the UN Division for Ocean Affairs and the Law of the Sea (DOALOS) in advance of the seventy-fifth session of the General Assembly of the United Nations.

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The authors gratefully acknowledge the support extended by Dr. Vladimir Ryabinin, Executive Secretary, IOC, and Dr. Justin Ahanhanzo, IOC, Dr.M. Rajeevan, Secretary, MoES, and the financial support extended by the Ministry of Earth Sciences, Govt. of India for the conduct of the Regional Planning Workshop for the Northern/Central Indian Ocean countries as well as ROPME sea area. This workshop has paved the way for initiating a number of programs that would contribute to the UN decade of **Ocean Science for Sustainable Development (2021-2030).**

Research Highlights

Bay of Bengal Sea surface salinity variability using a decade of improved SMOS re-processing

Temperature and salinity are the most important physical parameters of the ocean. Ocean temperature is considered as the flywheel of weather and climate, and due to its importance scientists started monitoring ocean surface temperature from space way back from1960's. But the ocean salinity an equally important physical parameter, which can control ocean temperature, ocean dynamics and productivity was really a challenge to monitor from space. This issue was overcome by the launch of SMOS (Soil Moisture and Ocean Salinity) satellite by European Space Agency (ESA) on 2 November 2009 and AQUARIUS (SAC-D) and SMAP satellites by NASA (National Aeronautics and Space Administration) on 10 June 2011 and 31 January 2015 respectively. These satellites are capable to provide global maps of ocean surface salinity every 8-10 days at 25km spatial resolution. But these satellites have difficulty in monitoring salinity near the coast due to potential contamination from land and radio frequency interferences linked to artificial sources. Hence, the first attempts to estimate surface salinity over land locked areas and relatively low salinity regions were unsuccessful because of a sub-optimal processing of systematic errors and too stringent quality control in the dataset. But recently a large improvement has been made on the data retrieval algorithms.

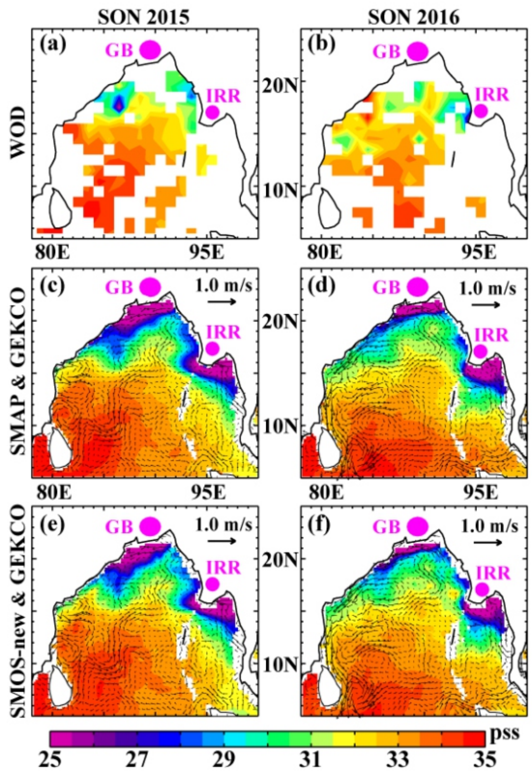

Fig. 1 Sep to Nov (SON) average map of (a, b) World Ocean Data (WOD) sea surface salinity (SSS), (c, d) SMAP SSS (colour) and GEKCO currents (vector), (e, f) SMOS-new SSS (colour) and GEKCO currents (vector) for (1st column) 2015 and (2nd column) 2016. Locations of Ganges-Brahmaputra (GB) and Irrawaddy (IRR) estuaries, the two main rivers in to the Bay of Bengal, are marked on the panels

Bay of Bengal (BoB) is a basin that is land locked over most of the area and has very low surface salinity due to the strong monsoon precipitation and large river inflow in to it. The intense freshening in BoB is believed to influence tropical cyclones intensity and biological productivity, and a proper monitoring of the BoB surface salinity is hence a necessity for the countries along the rim of BoB. Hence, in this study we analysed the updated version of the satellite derived surface salinity to investigate whether the most recent processing can provide accurate surface salinity retrievals in BoB. To validate the satellite data we used all the available *in-situ* observations collected by national and international agencies in BoB. Our results show that the newly available satellite retrievals are able to capture the surface salinity variability in BoB reasonably well at different time scales (monthly, seasonal and year to year), and so can be confidently used to monitor the BoB surface salinity and to study its mechanisms. This study further confirms the teleconnections of Indian Ocean Dipole on East Indian coastal current and the equator ward transport of fresh water along the east coast of India. These results strengthen the previous findings of National Institute of Oceanography on surface salinity variability in BoB, based on Field samples and Ocean general circulation models.

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[**Report Courtesy:** Dr. Akhil Valiya Parambil, NIO, Goa, India. Email : akhil@nio.org]

OSI Webinar series

In view of the Global Pandemic COVID-19, and social distancing is the new norm, OSI could not take up new outreach activities like our flagship training programme OSIMOD, world ocean day celebration and associated awareness programmes during 2020. Therefore in the OSI GC meeting held on 20 June 2020, it was decided to organise webinar lecture series of one hour. A three member committee under the chairmanship of Dr. C.V.K. Prasada Rao was formed to conduct the OSI Webinar through Google Meet. The first webinar was given by Dr. Pasad K. Bhaskaran, Professor, Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur, West Bengal. It was well appreciated by the ocean community across the country. The second paper in this issue of Ocean Digest is based on the webinar held on 10 August 2020.

Upcoming Event

Annual Monsoon E-Workshop (AMW 2019 & 2020) and National E-Symposium on "Cloud and Precipitation Processes" during 21-23 Dec 2020 (Monday - Wednesday). Jointly Organized by: Indian Meteorological Society, Pune Chapter (IMSP) and Savitribai Phule Pune University (SPPU), Pune (In association with IITM Pune & IMD Pune)

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Important dates:
Registration & Abstract Submission: 26 Oct to 15 Nov 2020
Communication of Acceptance of Abstracts: 10 Dec 2020

Call for papers in the upcoming special issue titled "Impact of Covid-19 lockdowns on the global oceans and coasts" in the journal "Frontiers in Marine Science"

Deadlines
Abstract submission: 15 Nov 2020
Manuscript submission: 31st Dec 2020 (eligible for full waiver of Article Processing Charges)
Manuscript submission: 28 Feb 2021 (with APC)
Link for further details and scope:
https://www.frontiersin.org/research-topics/15556/impact-

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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**

Comments and responses invited

In order to improve the content of the Ocean Digest, valuable suggestions from the readers are invited. Comments on the papers/articles are also welcome. Your response can be accompanied by your name and affiliation.

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