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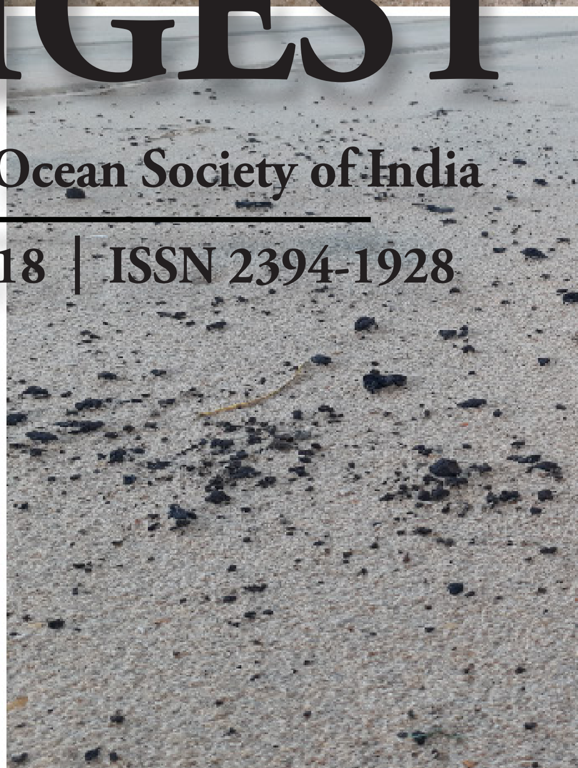

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The need to understand coastal processes: case studies along the coast of India

Invited Article






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Introduction

Coastal environments are transition zones between land and sea, and they represent productive and economically important areas. Coastal areas are assuming greater importance in recent times in view of their strategic location for residential, recreational and industrial activities. In the last few years India has seen a tremendous growth in industries, especially along its coastal zone. Type of industries varies from salt works to power plants. It is very essential to promote industries for economic growth, but a balance need to be maintained between industrial growth and coastal health. A need has arisen to preserve and maintain the coastal zone against the natural and anthropogenic stresses. The ever-increasing human population and industries in the coastal cities discharge sewage and untreated/semi-treated industrial effluents into coastal waters, thereby degrading the water quality. In this scenario, it is essential to understand the levels of pollutants and contaminants in the Indian coastal waters and their impact on biogeochemical processes and subsequently on fishery resources of India. Coastal erosion, pollution, acidification, eutrophication and deoxygenation are some of the major threats that affect the biota in the coastal zone. While, coastal erosion leads to loss of land thereby putting more stress on the coastal population, rest of the pressures lead to loss of safe environment to marine living organisms which in turn affect the food web, threatening the coastal ecology. Scientific understanding of various processes, namely physical, chemical and biological, occurring in the coastal region is essential to monitor and predict the impacts of coastal and offshore activities on the coastal environment; however, in this article, emphasis is given to physical processes, and their implications in some of the coastal issues.

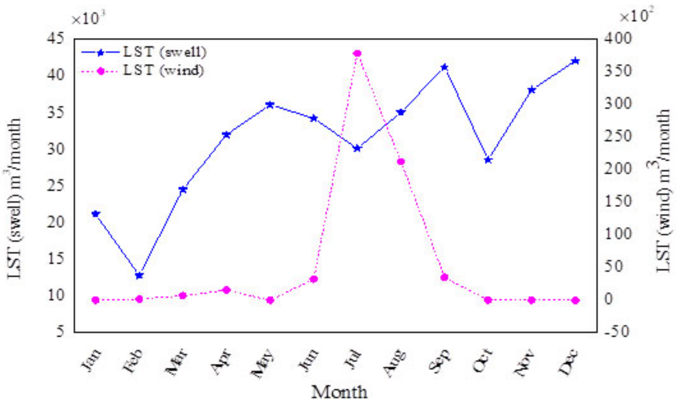

Figure 1: Monthly swell and wind wave induced LST variation.

The study of coastal processes requires a multidisciplinary approach, where scientists and engineers from all the relevant fields need to collaborate for better understanding of the various phenomena associated with coastal processes. The following specific processes are briefly reviewed and presented here with illustrations: wave-current interaction during cyclones and shamal winds, wave energy dissipation due to suspended sediments (e.g. in the region of mudbanks), sediment transport and pollutant transport (oil spills and tar balls). The impact of climate change on the coastal environment is illustrated with sea level changes, SST trend, sediment transport and revisiting the design parameters. It may be noted that due to semi enclosed nature of the North Indian Ocean, regional oceanographic processes are linked to exclusive economic zones of other littoral countries.

Need of the study

The coastal stakeholders such as fishing community, industries, policy-makers and government agencies such as State and Central Pollution Control Boards, Shipping and Ports & Harbours will find the results of these studies useful, especially for mitigation of human induced changes. It is expected that by 2030, there will be a sharp increase in the number of ports, as the existing Indian ports are unable to handle the many-fold increase in cargo transported through the sea, and in order to overcome this limitation, the ambitious Sagarmala project is being planned by the Government of India (GoI). Construction of additional structures will aggravate the shoreline stability further. Add to this, land-use changes, industrialization and urbanization will further lead to significant deterioration of coastal environment and ecology. The need of the study is to ensure that developmental activities do not cause significant and irreversible damage to the coastal habitats. The studies fall under a few of the Sustainable Development Goals (SDGs) chartered by the United Nations as well as the policies and vision of the government.

Quantitative understanding and thorough knowledge of longshore sediment transport (LST) in the littoral zone are essential for the design of coastal protection measures, design and maintenance of navigation channels and maintenance of tidal inlets. Sediment transport models for combined wave-current flows usually are formulated either in terms of flow energetic or bottom shear stress. Suspended load is understood better than bed-load owing to the difficulty of obtaining measurements of the motion of particles in the thin bed-load

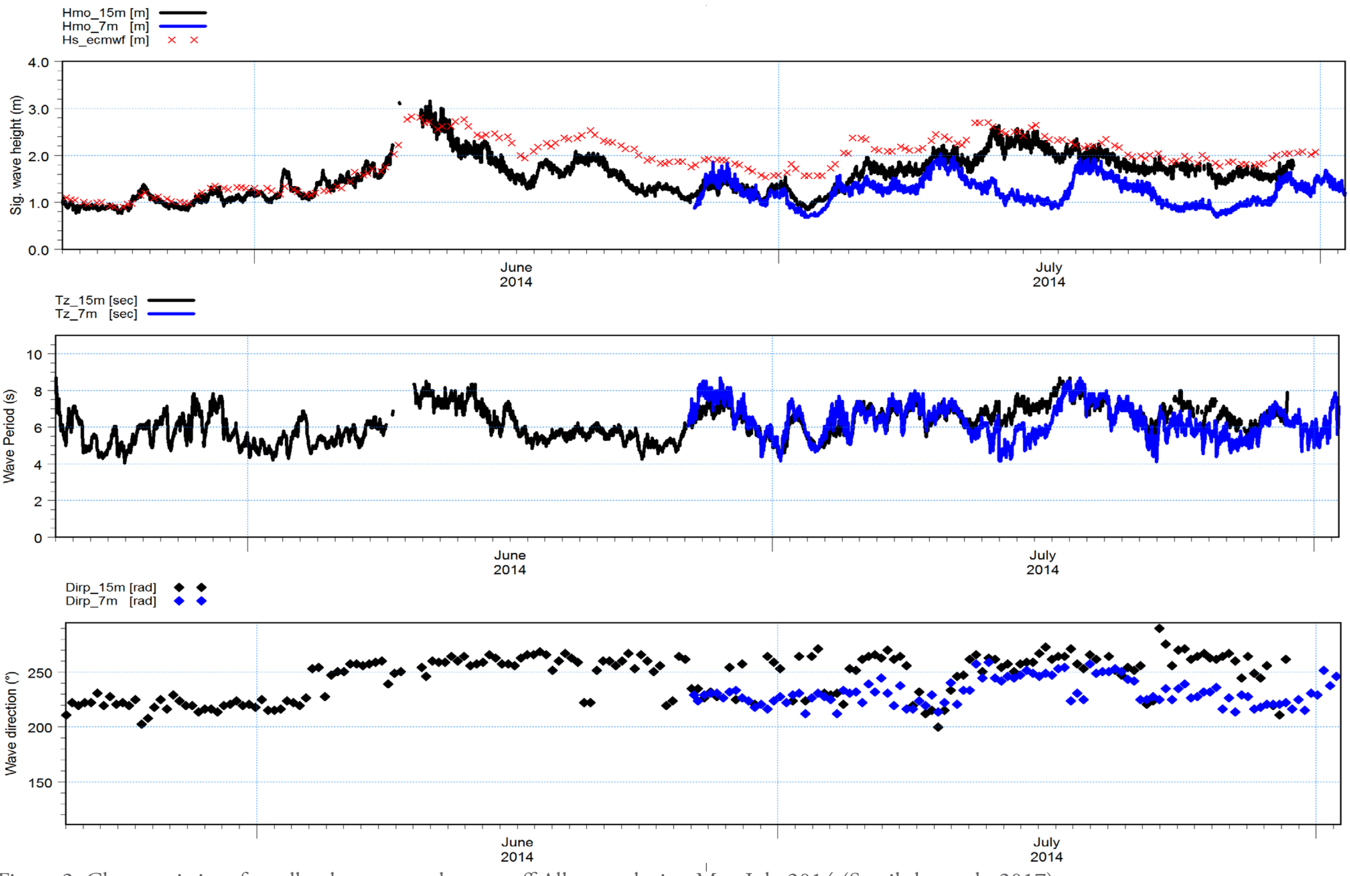

Figure 2: Characteristics of mudbank attenuated waves off Alleppey during May-July 2014 (Samiksha et al., 2017).

layer. Most of the sediment transport studies are laboratory based with semi-empirical formulations with limited inputs such as waves, currents, sediment size and nearshore slope. Dominant wave energy dissipation in the nearshore is due to the bottom friction, percolation and backscattering caused by bottom irregularities. Very few studies used field measured sediment transport values for calibration of the numerical models. Most of the studies did not consider the bed level changes.

The long term "Coastal Ocean Monitoring and Prediction System (COMAPS, 1991-2012) program and "Sea Water Quality Monitoring" (SWQM) program (2012- continuing) of MoES, GoI reveal that environmental quality of relatively pristine site (Goa coastal region) is also declining over the period of time due to increasing anthropogenic stress in these areas. The results of "Shoreline changes program" of MoES also demonstrate coastal erosion at select regions, and that too warrants for mitigation measures.

At present, we do not have full information on coastal currents along the entire coast of India, though a few institutes have initiated this activity. This is very much needed at times for societal purpose (for example, in dealing with drowning cases, to know the pollutant movement, for planning the developmental activities, etc.).

Understanding the coastal processes

In the last few decades due to technological advancements it is possible to obtain observations using remote sensing techniques, deployment of instruments using moorings, buoys, Autonomous Underwater Vehicles (AUV) and Autonomous Vertical Profilers (AVP) and gliders at high spatial and temporal resolutions. Numerical modelling results complement the in situ measurements. To evaluate the morphological changes, assess the erosion and accretion zones, vulnerability of coastal zones to natural hazards and climate change (in the form of inundation), we need to understand the coastal processes. Coastal morphological processes are mainly controlled by wave characteristics, nearshore circulation, sediment characteristics, beach form, etc. Shoreline oscillation along the coast of India due to erosion and deposition has become a major concern in recent times. For any application of the water-front, it is important to understand the coastal processes, which continuously alter the shoreline, namely, erosion, deposition, sediment transport, flooding, sea level changes, etc. of the region. With reference to waste assimilative capacity of a coastal region, if the input of waste materials is higher than the self-purification capacity of the water body, it can cause irreversible deleterious effects, and affect the ecosystem processes. However, the physical processes have an important role in the ultimate fate of pollutants and thereby influencing the assimilative capacity of the water body.

Sediment transport

The primary driving forces for the transport and dispersal of sediments in the coastal regions are winds, waves, currents and tides. Sediment transport and dispersion could be studied through field measurements, satellite data and numerical modelling. In general, along the coast of India, sediment transport direction and quantity is seasonal (varies with southwest and northeast monsoons) and site specific. For example, the unique sediment plume detected off Kakinada in the Krishna-Godavari Basin from the 1999-2006 Ocean Color Monitor (OCM) data showed that the extent, orientation and intensity of this plume have both seasonal and interannual variations, and its existence is due to the jet of water flowing away from the Kakinada coast. The characteristics of the jet control the presence, extent, intensity and the direction of the plume. Though high sediment concentration is present all along the east coast of India, the offshoot of the plume is present only at Kakinada Coast. It is difficult and expensive to conduct field experiments all along the coast for all seasons to study the sediment dispersal and transport. However, it is possible to conduct numerical experiments with limited field data; but the performance of the model depends on how accurately physical processes are accounted in the model, as still models use empirical formulation.

The Gulf of Kachchh (GoK) is a macro-tidal water body located in the northeastern part of the Arabian Sea, and about 150 km south of the Indus River mouth. In spite of semi-arid climate and lack of major rivers flowing into it, the Gulf is highly turbid with suspended sediment concentrations during October–November 2002 ranging between 0.5 and 674 mg/l. Highly turbid waters are observed towards the northern portion of the mouth of the Gulf, at the head of the Gulf and adjacent to the numerous shoals present within the Gulf due to resuspension of sediments by strong tidal currents, shallow bathymetry, presence of fine-grained sediments on the sea floor and resuspended sediments from the numerous meso and macro-tidal creeks of the Indus delta. Numerical model studies show that there is a dynamic barrier in the central Gulf, which prevents the exchange of water and suspended sediments between the outer and inner Gulf. This dynamic barrier associated with strong east–west tidal currents restricts the turbid waters mainly to the northern Gulf, resulting in relatively clear waters (SSC < 10 mg l^{-1}) in the southern and central portions of the Gulf.

Optimal dredging, deepening of navigational channels, etc. can be decided using model studies. For example, sediment plume studies carried out for the Palk Bay-Gulf of Mannar region showed that only the fair-weather period (February and March) is favourable for dredging; with the onset of westerly winds in April, the current pattern changes, and therefore, in the next three months (April-June), the sediment plume moves towards coast. The study also indicated that the possibility of dredged material from the dumping location reaching the eco-sensitive region during any season is very remote. Through modelling studies, we can predict hydrodynamics of the coastal region, assess the erosion and deposition patterns along the coastline, estimate the sediment movement, dispersion and settlement of dredged material, and finally we can estimate the geomorphological changes along the coast. Also, a holistic approach may be followed to investigate the morphodynamic response of coastal environment of India in relation to natural and anthropogenic perturbations, which could also help to understand their implications on climate change – both in long-term and short-term.

Long-term changes in wave climate have potential impacts on the evolution of regional coastlines. An investigation was carried out along the central west coast of India to study the impact of variable wave climate on the temporal dynamics of longshore sediment transport (LST), which plays a major role in defining the overall coastal geomorphology of regional coastlines (Chowdhury et al, 2017). This region experiences oblique waves from the W-SW direction with an annual average significant wave height and wave period of 1.32m and 8.10s respectively, and that induces a gross southward transport of approximately 450,000 m^3/year. The monsoon and post-monsoon cyclogenesis was found to be responsible for the high rates of swell induced sediment transport. The total LST was observed to have a decreasing trend of about 5% over the period of analysis. The decay in LST is found to be linked with decrease in wave activity in this region. The temporal decay in the LST rate was found to be associated with a decrease in swell generation in the lower latitudes (between 0 and 20°). The swell wave induced sediment transport is an order of magnitude higher than the wind wave induced LST (Fig. 1). It is observed that the swell generation in the lower latitudes has decreased, resulting in reduced swell wave induced LST in the study area. Both swell and wind wave induced LST show seasonal variation. In addition, the latitudinal position of the inter-tropical convergence zone (ITCZ) was observed to have a direct link with the strength of seasonal wind wave induced LST. This study presents a sound basis for understanding the wave induced sediment transport regime along the west coast of India.

Coastal erosion / accretion

Central Water Commission, GoI, reports that almost a quarter of the coastal area along the Indian coast is under erosion (Kumar et al., 2006). Erosion of coastline is expected to be intensified by sea level rise along with potential changes in the wave climate. So far only hard coastal protection measures have been considered, with little comprehensive scientific understanding on the causative factors and their interaction with local and remote physical processes. Though the general principles of erosion and accretion are well known, the quantum of erosion/accretion along most of the coastal stretch of India is poorly studied and seldom understood comprehensively. The natural stresses for coastal geomorphological changes are due to physical and geological processes such as winds, waves, currents, tides, river discharge,

Figure 3:Schematic diagram of processes involved in coastal megacities contributing to climate change (Renjith et al, 2014)

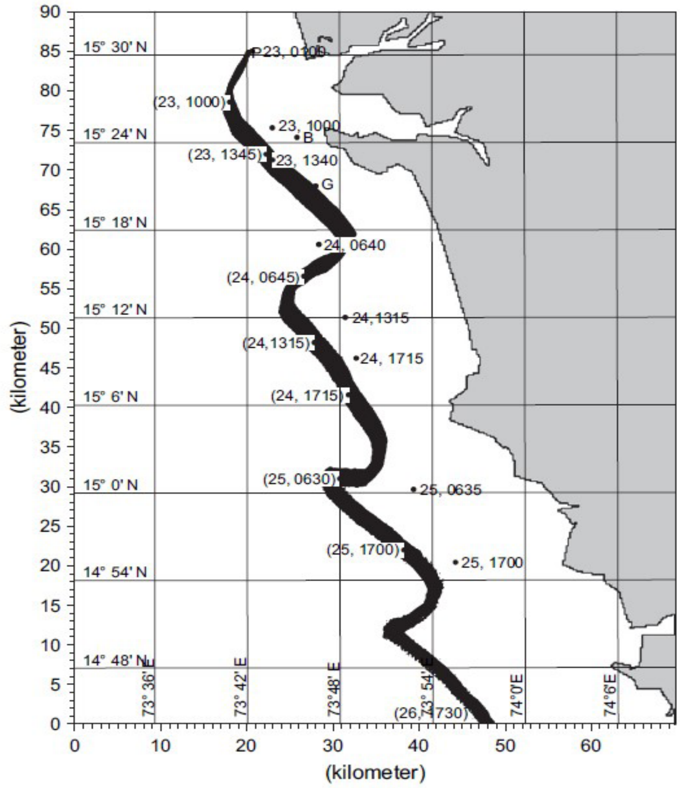

Figure 4: Simulated trajectory of oil spill off Goa validated with the observations (Vethamony et al., 2007).

cyclones and tsunamis. Thorough knowledge of the local and remote physical processes arising out of the forces such as winds, waves, currents and tides in the nearshore region that impact the bed sediment removal, sediment re-suspension, sediment movement and sediment deposition, collectively termed as sediment transport, is essential to comprehensively understand the erosion/accretion processes that mainly regulate the coastline stability, navigation channels, coastal inlets and coastal developments. Some of the major human-induced stresses that cause coastal erosion are construction of shore abutting structures, dredging of navigation channels, sediment removal from estuarine and beach regions.

GoI is keen in developing ports and associated activities through Sagarmala Project. For design and maintenance of navigational channels of Ports and other coastal protection measures, quantification of sediment transport rate is essential. The state of the art of understanding sediments in suspension (suspended load transport) is better than the sediment transport along the bed (bed load transport) owing to the difficulties in obtaining measurements of the motion of particles in the bed-load layer (Van Rijn et al., 2013). Most of the sediment transport studies are laboratory based with semi-empirical formulations and limited input parameters such as waves, currents, suspended sediment and nearshore seabed gradients. Numerical models are continuously improved based on different approaches, using both statistical techniques and utilising the physical processes.

Wave-current interaction

- During cyclones

Wave-current interaction is strong during extreme weather events, and it effects both waves and currents. With the advancement of numerical models, it is possible to model the cyclone generated waves and the prevailing currents, and through coupling of wave and circulation models and parameterization of input and boundary conditions, the processes involved in wave-current interaction can be simulated. SWAN wave model coupled with ADCIRC circulation model is used to simulate cyclone waves, storm surges and prevailing currents, and further to study the interaction between them. For this, the extreme weather event considered is the Hudhud cyclone, which developed near the north Andaman Sea in October 2014. In general, along the east cost of India (ECI), East India Coastal Current (EICC) flows northward before and during summer monsoon, and reverses its direction and flows southward with maximum current speed varying from 0.2 to 0.5m/s in NE monsoon. The present simulations predicted current speeds upto 0.5m/s, and this range matches very well with the other studies as well. The two way coupling (ADCIRC+SWAN) increased the current magnitude by 0.25m/s (due to waves) along the cyclone track and near the landfall point. When the cyclone made a landfall near Visakhapatnam, the current speed increased from 0.5m/s to 1.8m/s for a short duration (6h) with direction of flow towards south (Samiksha et al, 2017). After 6h of landfall, current speed again reduced to 0.1m/s, with reversal in current direction (towards north). The current pattern showed semi-diurnal variation associated with the tidal currents.

The effect of currents on the wave field is examined by comparing the wave parameters collected off Visakhapatnam and the model results obtained from SWAN alone and SWAN+ADCIRC just before the landfall. An increase in current speed (of the order of 1.8m/s) was observed just before the landfall; an increase of ≈0.2m was noted in Hs also. It was found that when waves were travelling normal to the coast after crossing the shelf area, and currents were flowing in the southwest direction, wave heights reduced due to wave-current interaction. Subsequently, increase in wave height was observed on the left side of the track, when waves and currents opposed each other (waves were propagating from southwest and currents were flowing towards southwest).

- During shamal winds

It may be noted that the general wave conditions in the Arabian Sea during pre-monsoon period also depend on the swells coming from the far northwest Arabian Sea due to northwesterly blowing shamal winds. Shamal winds normally occur in the Arabian Peninsula during winter (November - March) and summer (June - August). The associated wind speeds can reach upto 20.0m/s, and these winds can generate surface waves as high as 3.0 to 4.0m in the Arabian Gulf. Data of ERA Interim winds and measured winds, waves and currents were analysed to study the impact of waves generated in the Arabian Gulf due to shamal winds on the existing current system, propagating towards the west coast of India. Waves measured during shamal events showed a shift in wave height and wave direction, compared to those of non-shamal events. The shamal swells propagating from the Arabian Gulf to west coast of India influence the wave characteristics with increase in wave height and change in wave direction from NW. Further analysis shows that wave parameters exhibit distinct characteristics, namely, increase in wave heights associated with decrease in swell period and a common propagation direction (NW) for wind sea, swell and resultant waves. It has been observed that the northward flowing current, changed its direction to southeast when shamal winds (from NW) approached the coast. The analysis showed that, in general, the residual currents remained very

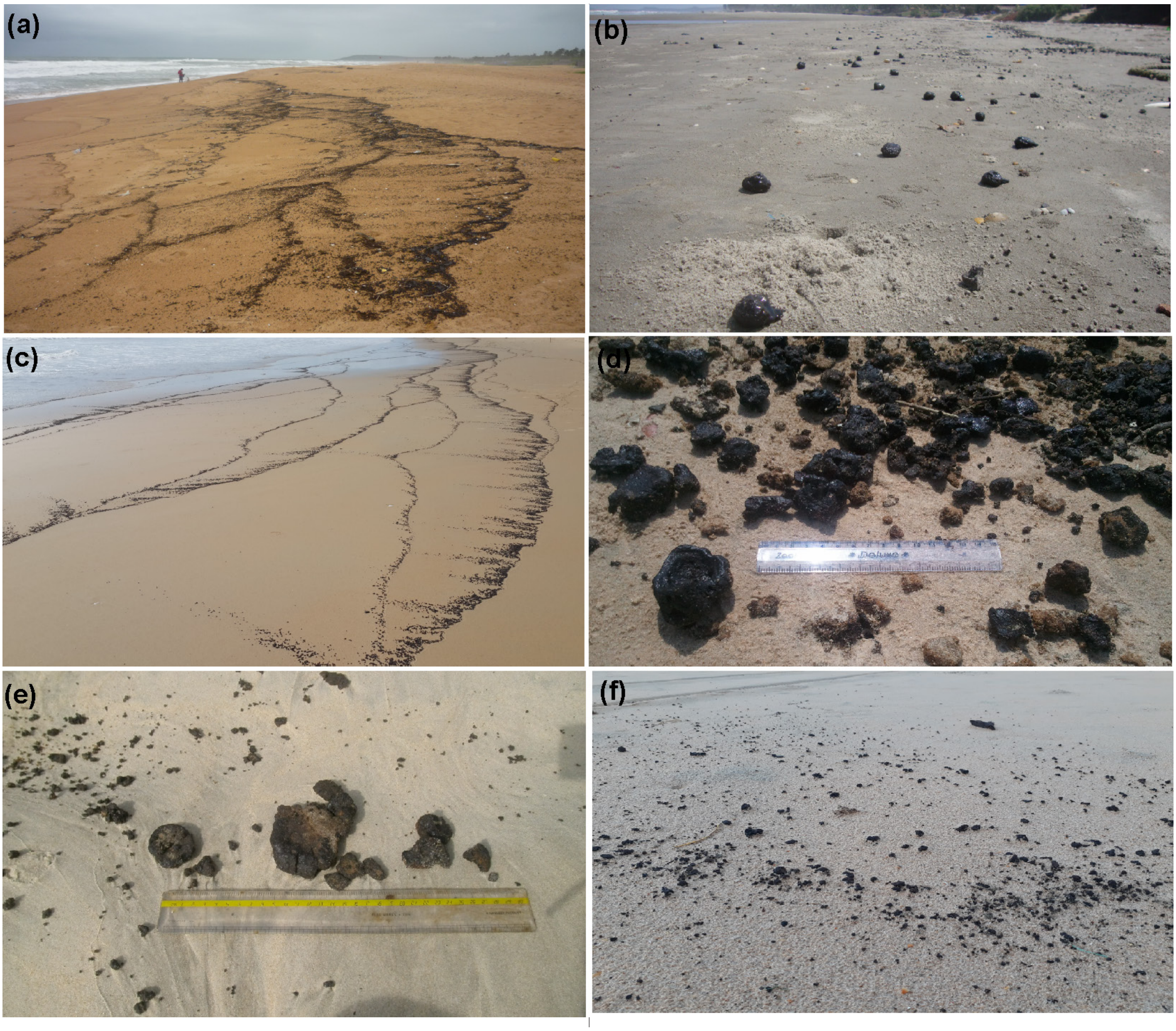

Figure 5: Deposition of tar balls on the Goa beaches: (a) on 02/09/2010 at Candolim, (b) on 25/05/2011 at Mandrem, (c) on 26/05/2013 at Mobor, (d) on 08/06/2014 at Candolim, (e) on 05/06/2015 at Benaulim and (f) on 31/05/2017 at Varca.

weak in the region dominated by tides. But, during the shamal events, the maximum residual current speed reached upto 0.15m/s, and there was an increase (0.07m/s) in the current speed during the shamal event compared to non-shamal period (Samiksha et. al., 2017). This change is further evident in the residual velocity components, especially in the alongshore component during the shamal events. From the above analysis, it was concluded that during shamal events, when the waves propagate from N/NW and currents off Ratnagiri flow towards north, the waves and currents oppose each other, and intensify the currents.

Wave energy dissipation due to suspended sediments

The different processes involved in this dissipation are percolation, bottom friction, motion of soft muddy bottom and bottom scattering. In shallow water, waves exert pressure on the seabed, causing liquefaction of mud layer into a viscous "fluid mud", resulting in dampening of incoming waves by the fluid mud layer. One of the finest phenomena for studying the wave-mud interaction or wave attenuation due to suspended sediments is mudbanks (MB) off Alleppey, Kerala coast. For making wave measurements in the MB region, two wave rider buoys were deployed at 2 water depths (15m and 7m) during May-July 2014. In addition to field observations, the interaction of waves with suspended sediments in the MB region was also studied using the new modules introduced in the Wave Watch 3 (WW3) model.

It has been speculated that MB may shift its position depending on oceanographic and meteorological conditions, but this was not determined from the data. This study proved that MB shifts its position, and the dissipative property of the MB is non-stationary. A maximum reduction of 65% was observed at 7m water depth in 2014 (Fig.2), implying that MB activity has reduced relative to earlier years. A few typical wave energy spectra at both the locations, has been chosen in order to analyse the evolution of wave energy dissipation as well as wave spectral behaviour before, during and after the mudbank formation between the two buoy locations. All the wave spectra show that there is considerable dissipation in the wind sea part of the spectrum when waves travelled from

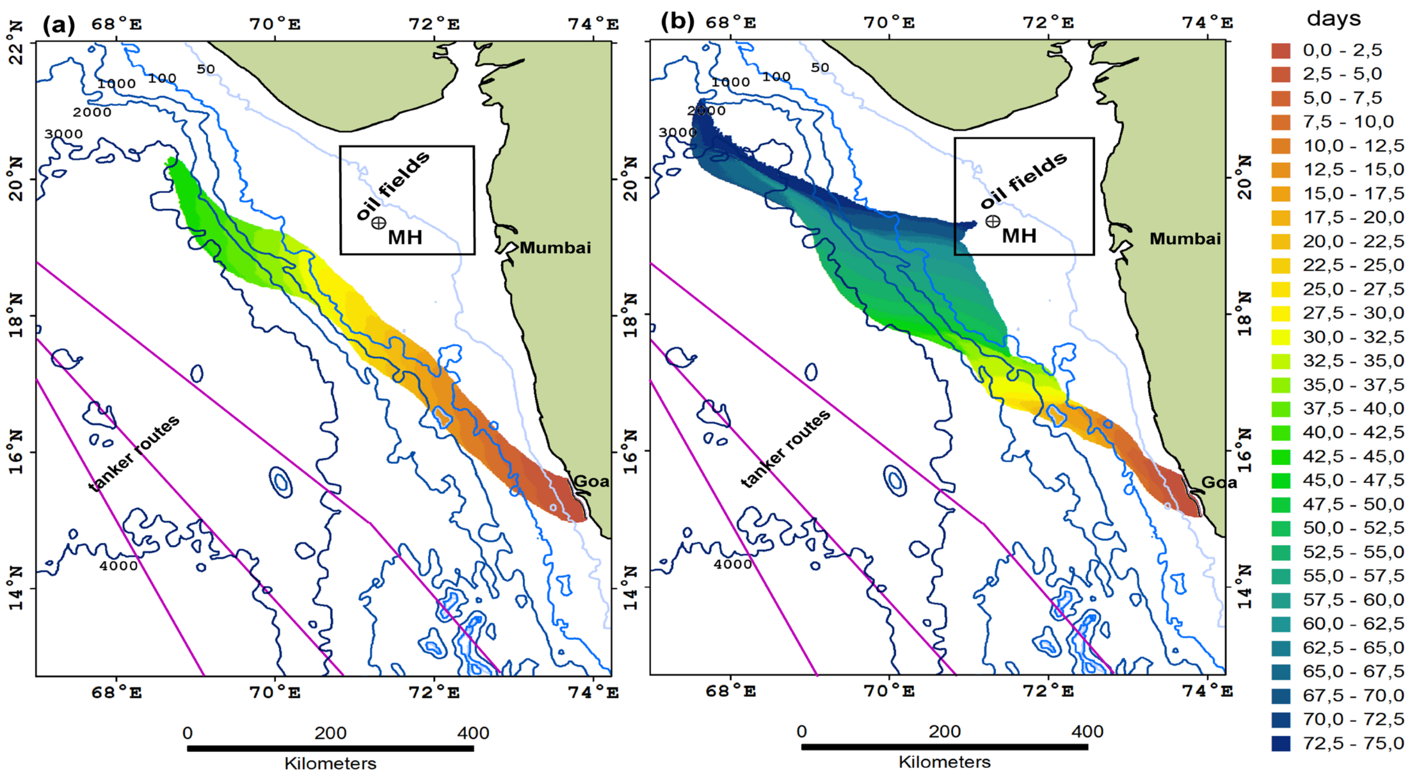

Figure 6: Simulation of tar ball trajectories off Goa coast using backtrack model (Suneel et al., 2016)

15m depth to 7m. These analyses show that as waves travel towards the coast, mudbank heavily attenuates wind seas compared to swells. As waves propagate into shallow water, the nonlinear interactions approach resonance, allowing large and rapid transfers of energy from higher to lower-frequency motions, where dissipation rates will be much greater. The combination of high frequency dissipation and nonlinear energy transfer from higher-frequency waves to low frequency waves can result in reduction of energy across a wide frequency range, including waves that are too short to feel the bottom.

Climate change and coastal processes

Climate change and its impact on the world population had been topic of interest in the last several years, and many researchers are involved in this program. Climate change has societal impact as 40% of the world population is living in coastal areas, and these areas are prone to sea-level-rise and other coastal vulnerabilities. The Fourth Assessment Report (AR4) of IPCC projected that global sea level rises upto ~60 cm by 2100 in response to ocean warming and glaciers melting. Over the past 40 years, nearly 84% of the increase in the earth's heat budget has been absorbed by the surface of the oceans that increased the average temperature of the upper 700 m of water column by 0.1°C. The Indian XBT observations collected over 27 years (1990-2013) in the central Indian Ocean show that SST has increased by 0.2 C during this period.

One of the impacts of ocean warming is decrease in dissolved oxygen content of waters as solubility of oxygen is less in warm waters compared to cold waters. Oxygen decline rates are more severe in a 30 km band near the coast than in the open ocean. A recent study reveals significant warming of 71% in the world's coastal waters by quantitative estimates of changes in coastal Sea Surface Temperature (SST). When the effluents are discharged into the warming coastal areas, these effluents further aid in depleting the Dissolved Oxygen (DO). The low oxygen values first lead to hypoxic condition and then to anoxic condition, and ultimately decreases the waste assimilative capacity (WAC) of coastal waters. An example is the coastal waters of Mumbai megacity (Fig. 3), which receives substantial amount of sewage load per day which is around 2300 MLD (million litres per day); Mumbai population generates about 731,250 kg/day Biological Oxygen Diamond (BOD) (Renjith et al., 2014). The waste water generated by the city is discharged into the coastal water, and this has given rise to hypoxic condition in the subsurface coastal waters of Mumbai. The results show hypoxia (DO concentration is below 1 mg/L) in the subsurface layers. The temporal variation in DO off Mahim also indicates hypoxic layers.

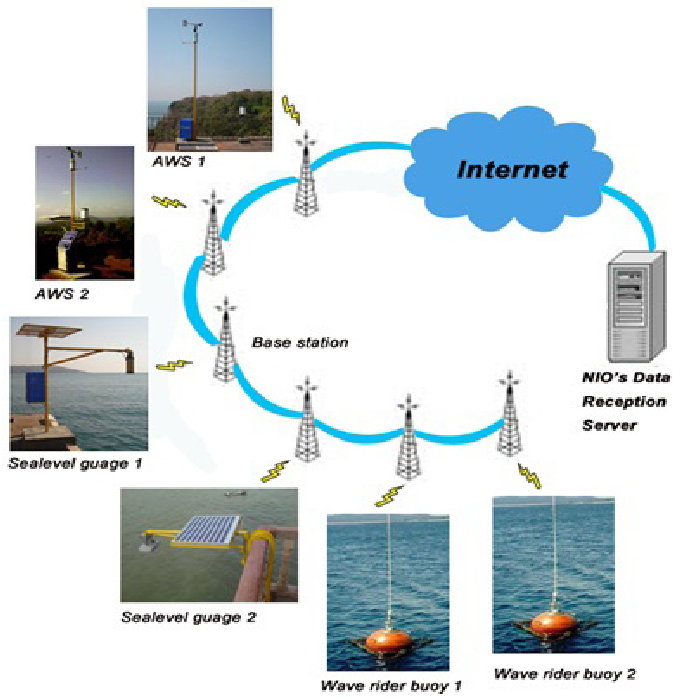

Figure 7: Integrated Coastal Observation Network (ICON)

The changes in wind conditions bound to affect the magnitude and behavior of wind-generated waves. As we know, coastal and offshore structures are typically designed for significant wave heights and average spectral wave periods, corresponding to a return period of 100 years. Because of climate change, it is necessary to assess possible changes that may arise when calculating design waves based on past and projected wind conditions. As a typical case, for the western coastline, historical waves were simulated using a numerical wave model forced by wind data extracted from the archives of the National Center for Environmental Prediction and the National Center for Atmospheric Research, while future wave data are generated by a state of the art Canadian general circulation model. A statistical extreme value analysis of past and projected wave data carried out with the help of the Generalized Pareto Distribution showed an increase in 100-year Hs and Tz along the Indian coastline pointing out the necessity to reconsider the safety of offshore structures in the light of global warming.

Processes that affect the sea level observations (use of GNSS)

Tide-gauges are used to estimate mean sea-level by averaging observations of the vertical variations of sea-level with respect to physical markers located at solid ground. The time-series observations should be long enough (though may contain a few data gaps) to remove variations associated with tides and other periodical effects. The observed time-series also permit us to estimate possible variations in the mean sea-level by fitting polynomials through the observations. However, there is an ambiguity associated with any observed variation of the mean sea-level with respect to the ground reference. For example, when a positive vertical variation is observed, the question is whether it is due to rise in sea-level or ground subsidence (vice-versa, in the case of a negative vertical variation). Such ambiguity can be efficiently removed by installing Global Navigation Satellite System (GNSS) stations as close to the tide-gauges as possible. Since the vertical positions directly derived from the GNSS observations are completely independent of the sea-level variations (they are referred to the ellipsoid), they allow us to remove the above-mentioned ambiguity, and consequently, to estimate the absolute variations of sea-level.

Pollutant transport - Oil spill transport

For the last three and a half decades the average number of incidents involving large oil spills (>700 tonnes) from tankers has reduced progressively and since 2010 stands at an average of 1.8 large oil spills per year. Six medium spills (i.e. between 7 and 700 tonnes) of various oils were also recorded for 2015. If oil spill trajectories are developed for various crude oil properties, meteorological and oceanographic conditions for sensitive areas, then it is possible to plan for the containment when the actual spill occurs. A typical case study that we conducted for the Goa coast is presented here. An oil spill occurred off Goa, west coast of India on 23 March 2005 due to contact damage by the barge MV Prapti. The quantity of spilled Heavy Fuel Oil (HFO) was reported to be 85 tonnes. There was a fear that the present spill might reach the Grandi Island, which is sensitive for ecologically (presence of coral reefs), archeologically (ship-wrecks), economically (tourism) and strategically. Therefore, the Indian Coast Guard (CG) and other authorities immediately took initiatives to track the spill and contain it. Field data on spill position at different

Figure 8: Integrated Coastal Observation Network (ICON) Map

times were obtained by the CG, and these were used to validate the simulated trajectories (Vethamony et al., 2007).

It was noticed that the maximum flow was due to winds rather than currents. Usually, fair weather prevails along the west coast of India in March. This particular year when the incident occurred (March), the winds and waves were relatively stronger. Therefore, the winds forced the spill to move away from the coast, and subsequently, the spill trajectories mostly followed the winds. Moreover, as the currents inside the estuaries are stronger (reaches up to 1.0 m/s) than the coastal currents, the spill could not enter into it (Fig. 4).

- Tar ball transport

The spilled oil undergoes different physical, chemical and biological processes known as weathering. The lighter components of the oil evaporate within a few hours, leaving behind heavy oil, which mixes with seawater to form emulsion. Due to winds, waves and turbulence at sea surface, this emulsion breaks into smaller pieces. These pieces adsorb onto the surface of any suspended matter or organism to form tar balls. Deposition of tar balls (TB) along the west coast of India is a common phenomenon; it occurs only during pre-monsoon to southwest monsoon season every year, and it is a major concern to the stake-holders. Typical TB deposition on the Goa beaches during six different years is presented in Fig. 5. Tar balls are oil fragments that have a solid or semi-solid consistency whose formation mechanisms are less known.

A large number of oil spill models are in use in the world today. But, no suitable model is exclusively developed for tar ball trajectory prediction. However, an attempt has been made by Suneel et al (2016) to predict the trajectories of tar ball transport from sea to coast using a hydrodynamic model coupled with the particle tracking model, and coast to sea using backtracking model. The results show that winds, currents and tides are the major forces that transport the tar balls to the coast in which wind is the major driver.

This is the reason for the transport of tar balls to the coast only during pre- monsoon and southwest monsoon seasons, when the winds and wind-induced currents are conducive. The backtrack simulation trajectories are shown in Fig. 6. We have been sampling tar balls along the Goa and Gujarat coasts since 2010 for fingerprinting to identify the source oil. The tar balls deposited along the Gujarat coast during July 2012 were identified as that derived from the Bombay High oil fields existing in the offshore region off Gujarat coast. Whenever a tar ball deposition occurs, the stakeholders including media often blame the ships. But, it needs not be true; other sources are also responsible.

Establishment of observation systems for measurement and real time reporting of coastal sea level, surface meteorological and related parameters

There is a need for closely sampled time-series of sea-level and surface meteorological data for a variety of oceanographic and related studies. Long term data is useful for understanding the climate variability on seasonal, interannual and decadal scales. Real time information is useful for harbor operations, navigation, monitoring and issuing storm surge and tsunami warning. The systems designed and developed at NIO, Goa provide data at fine temporal resolution. Sea level gauges incorporating sub-surface pressure as well as downward-looking microwave radar sensors have been developed and deployed at various locations. The sub-surface pressure based real-time reporting and Internet-accessible sea level gauge stations established at Kavaratti Island and Verem Naval jetty in Goa allowed real-time monitoring of the arrival of the September 2007 tsunami at these locations. The autonomous weather stations (AWS) developed at NIO also features both self-recording and real-time reporting capability. The latest development in the system design has incorporated low-power embedded Linux platform which allows maintaining accurate system clock using Internet network time protocol (NTP). Real time data is being reported by these systems installed at several coastal locations of India (Figs. 7 and 8).

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Surface and subsurface Temperature trends in the North Indian Ocean during the recent decade and role of oceanic processes

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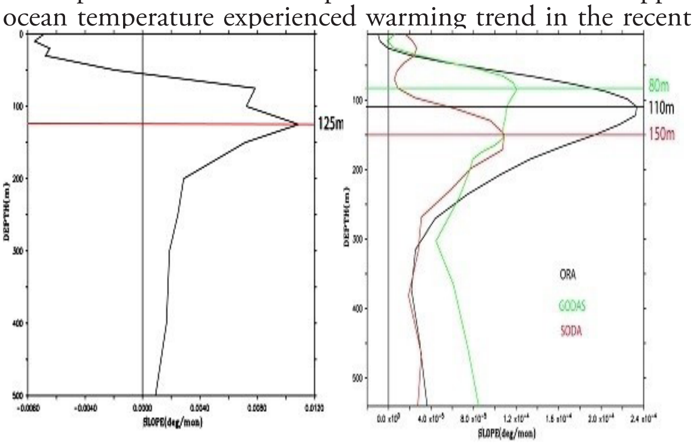
Introduction

Oceans absorb the excess heat trapped by Greenhouse gases (GHGs) and are major source for change in global heat content over the past 50 years (Levitus et al., 2005). Recently, many studies have reported the continuous basin wide Indian Ocean warming (Alory et al., 2007; Thompson et al., 2008; Rao et al., 2012; Roxy et al., 2014). The Sea Surface Temperature (SST) increase in the Indian Ocean basin was strongest and most robust among the global oceans, mainly due to the stronger wind stress curl and subtropical gyre (Alory et al., 2007; Cai et al., 2007). This warming trend is supported by the surface latent heat flux changes and surface long wave radiation changes (Dong and Zhou, 2014). The observed globally averaged SST time series shows little stagnation or even a slightly negative trend during the period of 2002-2009 which is called as hiatus period (Meehl et al. 2011; Chen and Tung, 2014). Previously, many studies have reported that the warming is not confined to the surface, but also the deeper ocean (Cai et al., 2007; Thompson et al., 2008; Cheng et al., 2017).

Temperature at different depths in recent decade show increasing trend, however trend in sub-surface temperature is found to be strong over the NIO from ARGO observations. The highest (0.06 °C/year) warming trend is found at the depth of 100 m. Earlier studies have reported increasing trend in SST and decreasing trend in deep ocean temmperature. Thus in the recent decade trend of temperature has reversed the pattern with depth. This increasing trend is also reported at even the depth of 500m, thus whole upper ocean temperature experienced warming trend in the recent



Figur 1: Vertical profiles of temperature trends from (a) Argo and (b) ocean reanalysis in North Indian Ocean

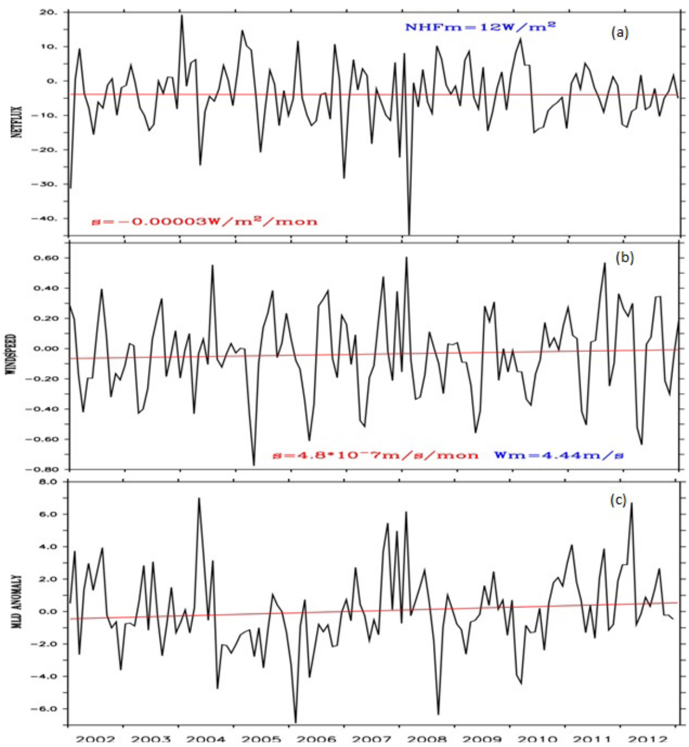


Figure 2: Time series of (a) surface net heat flux anomaly (b) surface wind speed (m/s) anomaly and (c) of MLD anomaly in North Indian Ocean.

decade but interestingly maximum trend is reported in the subsurface (100 to 150m) and minimum trend is reported in the surface (Fig. 1a). Corresponding surface heat content shows (0-50m) weak negative trend, while subsurface heat content has strong increasing trend. The highest positive slope of heat content is found at the depth in between 100-150m. Thus though trend of temperature and heat content are maximum at 100 to 150m but it is positive throughout the depth of 500m. This indicates that in the recent decade more heat is getting trapped in the subsurface of NIO. This leads to weak decreasing trend in density, subsurface density displays strong decreasing trend. The strong negative slope of density is found at the depth of 100m. This clearly indicates that density decrease is mainly due to the increasing trend in temperature supporting thermal expansion and resulted in decreasing trend in density. This trend in the density supports stratification enhancement in the thermocline region.

To confirm whether observed trends of warming are captured by the ocean reanalysis products, similar trend analysis for temperature at different depth is carried out for Ocean Reanalysis (ORA), Simple Ocean Data Assimilation (SODA) and Global Ocean Data Assimilation System (GODAS). The SST shows weak decreasing trend at surface, however observed SST shows weak warming trend (Fig. 1b). The strong positive slope of temperature is found at the depth of 125m in observations while reanalysis have about 110m. Subsurface warming trend is better reported in ORA data followed by SODA and GODAS. Thus models and observations show subsurface warming trend however trend amplitude in different reanalysis is one order less than observed. Consistent warming is reported throughout the upper ocean except surface, trend is decreasing with depth below the 100m.

Processes associated with the Temperature trends:

The surface net heat flux shows (Fig. 2a) no trend in the present decade. That is the surface net heat flux is not affecting the subsurface temperature. The surface (10m above the ocean surface) wind speed over the study region shows weak increasing trend in the present decade (Fig. 2b). The slope of the wind speed is 4.8×10^{-7}m/s/mon. The mixed layer depth trend shows weak increasing trend in the present decade (Fig. 2c). Further analysis of meridonal advection trend at the southern bounday of the study region in the present decade shows increasing trend at the surface and decreasing trend in the subsurface. Increasing trend at the surface support more warm surface water transport to south and subsurface trend is out of phase with the observed temperature trend. It reveals that up to 100m it has positive trend however below it has negative trend. This positive trend in horizontal heat flux trend might have supported the subsurface warming trend in the NIO.

In summary, subsurface temperature shows strong increasing trend during recent decade in NIO. These results are consistent with ocean reanalysis data. Detailed analysis conclude that net heat flux trend does not support warming however increasing trend in vertical velocity and positive trend in the zonal advection flux are in phase with the subsurface warming trend in NIO.

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Indian Bio-Argo program: A review

Review Article

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1. Introduction

The year 1998 saw emergence of a bold idea to build a global array of 3000 floats up to 2000 m depth named Argo program which eventually became the pioneer of 21st century climate observing systems. The Argo program initiated in 2000, has become a critical part of the global climate observing system. Argo provides continuous observations of temperature, salinity and velocity in the upper ocean. As planned, floats with a spacing of 3˚x3˚ were deployed by various countries in the global ocean. The main goal of Argo is to detect climate variability, calibrate and validate satellite measurements and initialize climate models.

Indian Ocean (IO) is a data void region since long and before the commencement of Argo program, the only source of temperature and salinity (T/S) were the one obtained along the tracks of scientific cruises. These data were measured for fulfilling specific scientific objectives and were restricted to the planned cruise. These limitations ensured sparseness and inhomogeneity in spatial and temporal data distribution. India's participation in the Argo program in 2002 has improved this scenario and enabled more continuous, consistent and accurate sampling of T/S data in the IO. Indian National Centre for Ocean Information Services (INCOIS) was entrusted with the job of deployment, maintenance, data processing, quality control and dissemination to Global Data Assembly Center. Accordingly, INCOIS is acting as national Data Assembly Centre (DAC) and Argo Regional Centre (ARC) for India and Indian Ocean respectively. In total India had contributed 425 floats to the International Argo program as of today. IO is no more under sampled w.r.t to T/S largely due to Argo program. However, the case of biogeochemical data in the Indian Ocean is still worse compared to T/S data. With the success of core Argo program many countries started to deploy Argo floats with biogeochemical sensors. Keeping in view the scenario of biogeochemical data pertaining to Indian Ocean, India has started deploying the first set of floats with biogeochemical sensors in 2006.

2. Evolution of Indian Bio-Argo program

India deployed Argo floats with oxygen sensors along with regular CTD sensors starting from 2006. A total of 16 Argo floats with dissolved oxygen sensors were deployed. Of these 3 floats are fitted with Aanderra 3830 Optodes and 13 with SBE integrated dissolved oxygen sensors. The Aanderra Optode 3830 sensor provided absolute oxygen content in micro molar (μM) directly. The seabird integrated dissolved oxygen float returned the oxygen data in the form of internal frequency values with a resolution of 1 Hz. These frequency values are then converted to oxygen using T/S from CTD and a set of calibration coefficients. These floats with oxygen sensors are followed by deployment of biogeochemical Argo floats starting from the year 2012. These floats have oxygen, chlorophyll, backscattering sensors in addition to the core CTD. The oxygen sensors are mainly from Aanderra Optode 4330 and chlorophyll and backscattering are from Wetlabs FLBB sensors. This Aanderra Optode 4330 does not report the actual oxygen concentration, instead, it reports various quantities that require additional processing. The values reported in TPhase are used along with the calibration coefficients to obtain the dissolved oxygen. The WETLabs FLBB reports three channel values that represent the output of an analogue-to-digital measurement. The quantities FSig, BbSig, and TSig represent the fluorometer, back-scatter, and temperature channels, respectively. A calibration equation is then applied to these channels in order to obtain chlorophyll concentration, back-scatter, and temperature in engineering units. Table 1 shows the floats with various types of biogeochemical sensors along with the manufacturers, deployed by India. Figure 1 shows the spatial distribution of 59 biogeochemical floats deployed by India.

Float Type	Manufacturer	Additional Sensors	No.
APEX-8C	Web Research Corp, USA/ Aanderra/ Wetlabs	SBE - Dissolved Oxygen (DO) + CTD	13
APEX-		Anderra DO + CTD	03
Iridium (9I)		Chl, Backscattering, Aanderra DO + CTD	25
PROVOR-Iridium	NKE, France/ Aanderra/ Wetlabs	Chl, Backscattering, Aanderra DO + CTD	18

Table 1: Types of Argo floats with oxygen and other biogeochemical sensors from various manufacturers.

Management of data from these biogeochemical floats is the responsibility of INCOIS. The T/S data from these floats are passed through a set of 19 predefined standardized quality control checks (Wong et al., 2015). In addition oxygen and chlorophyll data are also subjected to real time quality control following Virgine et al (2016) and Catherine et al (2014) respectively. The quality controlled T/S and biogeochemical profiles are then forwarded to the Global Telecommunications System (GTS) for distribution and also to two Argo Global Data Assembly Centres (GDACs), one in France and one in the US. These two GDACs synchronize their data holding and serve the complete Argo datasets to users via the Internet

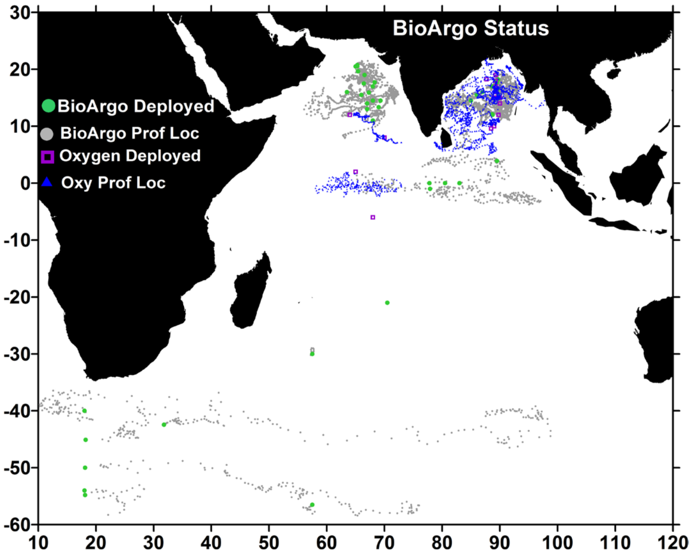

Figure 1: Distribution of biogeochemical Indian Argo floats.

without any restrictions. INCOIS has formed a Bio Argo working group to assess the quality of the data from these biogeochemical floats. This group is also entrusted with the responsibility to prescribe the best practices for deployment of biogeochemical floats, collection of ship borne data for inter comparison and adjustment of drifts. Also it is envisaged that ship borne profiles are to be collected near to all possible active biogeochemical floats while undertaking any scientific expedition.

3. Applications of Bio-Argo data

Uses of Argo data can be categorized for: core/basic research, operational activities, and education/outreach. Lack of adequate data in the Indian Ocean and over dependence on

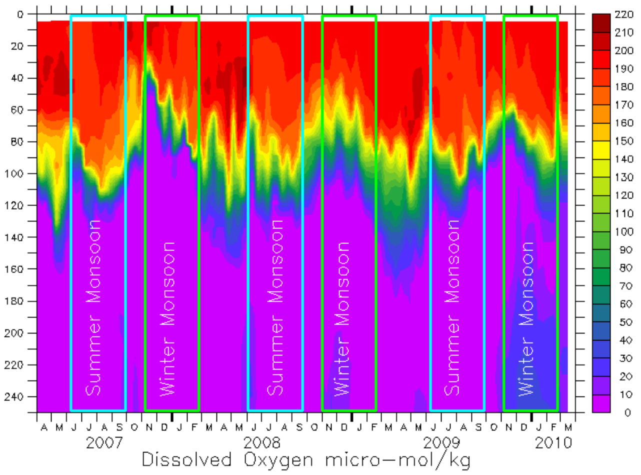

Figure 2a: Time series plot of dissolved oxygen in the upper 250m obtained from oxygen sensor equipped Argo float, WMOID 2900776. (Image courtesy: Prakash et al., 2012, Journal of Sea Research)

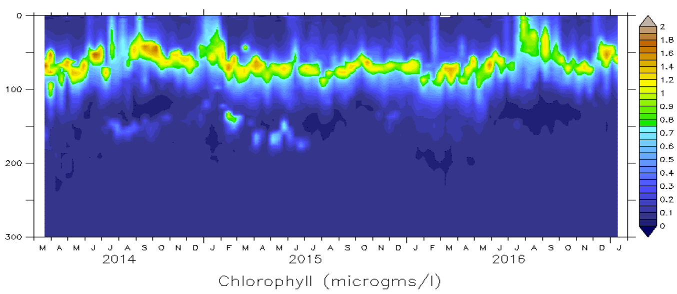

Figure 2b: Time series plot of chlorophyll in the upper 300m obtained from Argo float, WMOID 2902124.

specific scientific cruises had limited the research of IO only to the regions of these cruises. Though the vast amount of in situ T/S data from Argo floats which are homogeneous both in space and time had enabled researchers to unravel many interesting scientific insights about the IO, the data from biogeochemical sensors is yet to reach such a stage.

Though the data from Bio-Argo floats are limited and in early stages in the Indian Ocean, some insightful studies have been done and results were published by some of the researchers. Prakash et al (2012) utilized data from a float to carry out studies on Oxycline depth in the Arabian Sea OMZ (Fig 2a), Dufois et al. (2017) used the chlorophyll data to study its distributions in eddies. Ravichandran et al (2012) studied the variability of chlorophyll in the south eastern Arabian Sea. Udaya Bhaskar et al., (2016) and Chacko (2017) studied the sub-surface structure of the chlorophyll during cyclones (Fig 2b), which was otherwise not possible. Prakash et al. (2013) used the oxygen data from the floats to validate the oxycline depth estimated from satellite altimetry. As the data stream matures and the quality of data is improved with time, there will be many more studies under taken by various researchers both from India and abroad using this biogeochemical data. More detailed list of publications using both T/S and biogeochemical data are available at http://www.argo.ucsd.edu/Bibliography.html.

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Coastal oceans- understanding the complexity of carbon cycling

Review Article

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Coastal oceans are dynamic, biologically very productive and strongly influenced by anthropogenic factors than any other part of the ocean. From the socio-economic viewpoint, coastal oceans are vital to humans for the purpose of habitation, livelihood and natural resources. Around 50% of the world's population lives within the vicinity of coasts and almost half of the ocean ecosystem good and services come from coastal oceans (Costanza et al 1997).

Coastal ocean is usually shallow (< 200 m) and covers approximately 7% (26 x 10 6 km^2) of the global ocean surface (Gattuso et al. 1998). Most importantly, coastal oceans represent repertoire of biologically rich and productive biomes including mangroves, lagoons, intertidal zones, estuaries and continental shelves. However, coastal oceans are also subjected to intense natural and anthropogenic forcings including from sediment transport, wind stress, ocean circulation and climate variability.

Elemental cycling such as carbon cycling in coastal ocean is considered to be a key component of the global carbon cycle and budget estimates as it represents the connection between land-ocean boundaries. Given the dynamicity of coastal oceans, carbon fluxes can be influenced by natural and anthropogenic factors. Moreover, many of the biomes that are integral part of coastal oceans can add to the complexity of understanding coastal carbon cycling. In the last decade or so, there has been a significant effort to collect inorganic and organic carbon data (e.g. PCO_2) across waters along with unlocking critical steps from the biogeochemical viewpoint making this an exciting time to investigate coastal carbon cycling. In addition, the gradual shift of the coastal ocean from source of CO_2 to sink of CO_2 over the last century has critical consequences for its role in the ocean and global carbon cycles.

There is a lot of focus to understand the sources, fates and inter-conversion of organic and inorganic carbon in the coastal oceans globally. In particular, understanding the role of biological communities in influencing key steps of carbon cycling in coastal oceans is extremely important. Riverine inputs of inorganic and organic forms of carbon constitute a key source in coastal oceans globally. The input of riverine carbon in both particulate and dissolved forms is an important segment of the global carbon cycle. It has been estimated that the global riverine carbon flux is approximately 0.77-1.33 $PgCy^{-1}$ (Meybeck, 1993; Gattuso et al. 1998). It is now well known that weather factors such as extreme rainfall arising from tropical storms are responsible for most particulate organic carbon (POC) export from watershed areas to the coastal ocean. A single tropical storm can be responsible for more than 40% of average annual riverine DOC export. The terrestrially washed down organic carbon, also referred to as 'terrestrially derived organic carbon (TerrOC) can also come from vascular plant detritus, soil associated organic carbon (SOC), and from soil organic charcoals and anthropogenic soots (black carbon). Estuaries which are integral part of coastal oceans tend to become temporarily autotrophic during seasonal or episodic blooms caused by an increase in phytoplankton abundance where photosynthesis exceeds total system respiration and thus contribute to the coastal carbon cycle. The DOC and POC pools in estuaries are thus derived from terrestrial, marine and estuarine primary production. At the same time significant losses of organic carbon in estuaries occur mainly due to microbial degradation and photochemical oxidation . It is increasingly becoming evident that microbial communities such as bacterioplankton play critical roles in mediating some of the essential stages linked to degradation of organic carbon in estuaries (Ghosh and Bhadury 2017). The emission of CO_2 from estuaries represents a significant component of the regional CO_2 budget. The CO_2 emissions from estuaries generate a large flux compared to CO_2 exchanges between the open ocean and atmosphere. But, uncertainty in global estuarine CO_2 emission flux is high

Figure 1: Sundarbans Biological Observatory Time Series

due to limited availability of field data along temporal and spatial scales. Such lack of data can be supplemented through time-series coastal ocean monitoring program which can prove to be ultimately useful to also understand physical and biogeochemical variability associated with estuarine CO_2 emission flux. Incidentally dissolved inorganic carbon (DIC) is usually higher in estuarine water which can be exported to continental shelf waters.

Several other factors including exchanges with tidally influenced wetlands, sources and sinks of carbon in continental shelves, reactivity of organic carbon in shelves and carbon-dioxide exchanges in shelves can affect cycling of carbon in coastal oceans and many of these factors can vary temporally and/or spatially. But lesser known forms of carbon such as the role of carbon monoxide from the view point of carbon cycling is not very well understood. Activities such as burning of grasslands and fossil-fuel combustion form the dominant sources of atmospheric carbon monoxide while ocean surface waters are reported to be ubiquitously supersaturated with carbon monoxide generated internally. Diurnal fluctuations of carbon monoxide in sea-surface are driven by photolysis of coloured dissolved organic matter (CDOM) in presence of sunlight which is then rapidly removed by microbial oxidation. Microbial carbon monoxide oxidation rate coefficients for coastal water range from 0.01 to 0.11 h^{-1} (Tolli and Taylor, 2005). However, the distribution and function of active carbon monoxide oxidizing microbial communities in coastal oceans are yet to be thoroughly investigated. The importance of microbial communities, in particular heterotrophic bacterial communities in utilization of dissolved organic carbon (DOC) pool in coastal oceans is starting to be clearer. Modern tools such as genomic approaches have shown that heterotrophic bacteria have developed unique strategies to utilize substrates that make up the DOC pool in coastal oceans. However, the scale of such strategies at the temporal or spatial level is not very well understood.

To address some of these questions which are implicitly linked to coastal carbon cycling, time series observational program can be very helpful. Globally there are numerous time series programs linked to coastal oceans including the Western Channel Observatory and Helgoland Roads Time Series. In India, time series for coastal oceans can be critical towards better estimation of regional carbon budget and to understand land-ocean-atmosphere interactions. One of such time series has been started in the Indian Sundarbans of the Northern Bay of Bengal- Sundarbans Biological Observatory Time Series (SBOTS). This time series intends to address and understand the role of biological communities in influencing coastal carbon cycling. The time series can ultimately help towards understanding the exact implications of the coastal oceans as a net sink of CO_2 during post-industrial times.

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A glimpse of the Equatorial Indian Ocean current system

Review Article

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Surface Current

The surface and subsurface current system in the equatorial Indian Ocean is unique in the global ocean. Over the tropical Pacific and Atlantic Oceans, trade winds from both hemispheres converge at the equator, and the mean winds over the equator are observed to be easterly throughout the year. In contrast, the annual cycle of surface wind field over the Indian Ocean is dominated by boreal (northern) summer and boreal winter monsoons and the resultant cross equatorial winds force a semiannual reversal of winds with weak easterlies during the summer and winter monsoons and westerlies during the monsoon transition period (spring and fall). This prominent semiannual cycle is a prime feature unique to the equatorial Indian Ocean resulting weak annual mean westerly winds. The resultant mean sea surface temperature along the equator in the eastern basin is warmer than the west, which is in marked contrast to the situation in the other tropical oceans. The equatorial Indian Ocean current system is dominated by the semiannual eastward flowing Wyrtki jets, which occur during the monsoon transition periods (Figure 1). The equatorial jets or Wyrtki jets were discovered from monthly maps of surface currents in 1973 (Wyrtki, 1973). He found that these jets deepen the thermocline in the eastern equatorial Indian Ocean and raise it in the west, thereby providing an east-west thermocline (and temperature) gradient. The jets are strongest between 60°E to 90°E and 2°S to 2°N with speeds reaching up to 1 m/s and they develop rapidly as a response to westerly winds (Figure 1). Since the discovery of the jets, there have been several observational and modeling studies which have explored Wyrtki jets dynamics. In his innovative paper,

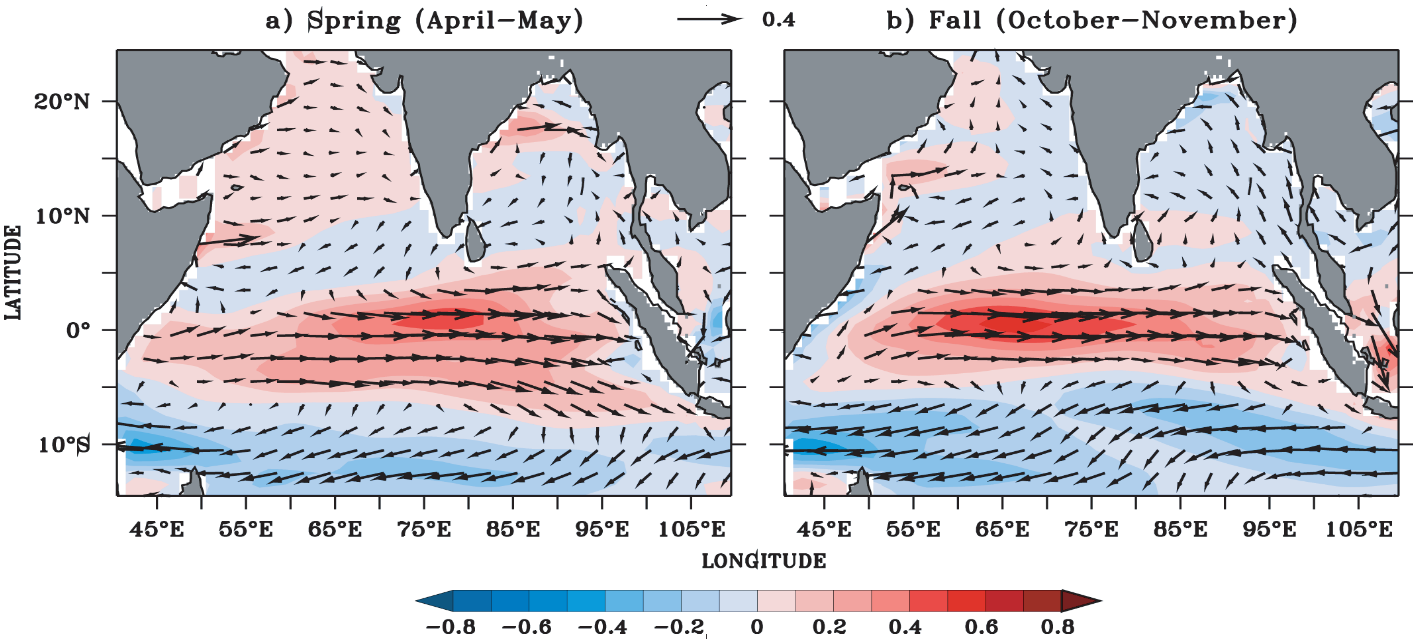

Figure 1: Zonal current (m/s) climatology superimposed with current climatology vectors from OSCAR current data for (a) Spring and (b) Fall.

Wyrtki proposed that the jets are observed as a direct response to westerly winds during the inter-monsoon period. The jet influences the water mass structure as it transports surface waters eastward over a period of two months, decreasing the mixed layer thickness and sea level in the west but increasing them in the east (Wyrtki, 1973). These observations were confirmed by a series of modeling studies. A 2-layer model first showed that the jet developed in the equatorial Indian Ocean as a response to switched on westerly winds. The importance of wind forcing on these jets is later confirmed from a 2.5-year current observation data obtained near Gan Island (0°41'S, 73°10'E). Later, a 2 & ½-layer model was used to find that the currents were strengthened when they were concentrated in a shallow mixed layer (Schott and McCreary, 2001 and references therein). Han et al. (1999) used a hierarchy of models to isolate and quantify the processes responsible for the jets. They found that the jets develop as a response to the direct forcing by the zonal winds, and that the effect of Rossby waves, resonance and mixed layer shear are all necessary to produce jets with realistic strength. The presence of equatorial wave propagation associated with the Wyrtki jets is evident in the observations and models. These waves in fact act as messengers carrying ocean properties from the equatorial Indian Ocean to different parts. Upon arriving at the eastern end of the basin, part of the Wyrtki jet signal reflects as Rossby waves and part propagates poleward as coastal Kelvin waves. Along the way, the eastern-boundary waves generate slowly-propagating mid-latitude Rossby waves that radiate into the Bay of Bengal and eastern Arabian Sea. On the other hand, the northward-travelling boundary waves carry equatorial variability around the coasts of Bay of Bengal and around Sri Lanka into the Arabian Sea (Schott and McCreary, 2001; Rao et al., 2010).

It took close to three decades to piece together the story of equatorial Indian Ocean dynamics, and the recent observational and modeling studies are now focused on understanding the variability in the jets and how it affects the north Indian Ocean circulation. Reppin et al. (1999) observed from their ship drift data that the inter-annual variability of the eastward surface jets was related to El Niño signals. It has been argued in the recent literature that the effect of El Niño Southern Oscillation (ENSO) dominates the basin south of 10°S, and the Indian Ocean Dipole (IOD) forcing dominates the equatorial region. However, Gnanaseelan et al. [2012] demonstrated that positive IOD and ENSO forcing have significant impact on fall Wyrtki jets. In the recent years, Nagura and McPhaden (2010) studied the impact of the reflected waves due to IOD forcing on the source region of Wyrtki jets. Equatorial Indian Ocean has a strong variability at intra-seasonal timescales as well. From observations, Reppin et al. (1999) also reported small-scale variability in the currents near Sri Lanka. Sengupta et al. (2007) used model simulations to show that both spring and fall Wyrtki jets are modulated on intra-seasonal timescale. They further concluded that while the spring Wyrtki jet is modulated by a single intra-seasonal event, the fall Wyrtki jet is modulated by two to three events. By far, the least studied feature of equatorial Indian Ocean has been the spring Wyrtki jet and the subsurface currents in the equatorial Indian Ocean. While the spring Wyrtki jet has never been addressed as a separate entity, recent studies have found that its variability cannot be explained by IOD and ENSO forcing which dominate the fall jet variability, instead it is explained by the intra-seasonal oscillations (Deshpande et al., 2017).

Equatorial Undercurrent

Recent observations and modeling studies have shown that the features of the Equatorial Undercurrent (EUC) in the Indian Ocean are as unique as that of the surface circulation (Figure 2). Over the equatorial Atlantic and Pacific Oceans, the prevailing trade winds drive a quasi-permanent eastward zonal pressure gradient force along the equator, which leads to a semi-permanent eastward EUC in both these oceans. The seasonal flip-flop of surface winds over equatorial Indian Ocean drives a transient EUC associated with equatorial waves (Schott and McCreary, 2001; Chen et al., 2015). An eastward EUC occurs in the Indian Ocean only during boreal spring and has been documented in several observational studies (Reppin et al., 1999). Modeling studies forced with idealized winds demonstrate that an EUC structure can develop in the time it takes equatorially trapped Kelvin and Rossby waves to propagate across the zonal extent of the basin, or of the wind itself for a wind patch confined within the interior of the basin, thereby establishing the necessary pressure gradient to drive the flow (Schott & McCreary, 2001 and references therein). Most numerical models are able to simulate the spring time appearance of the eastward EUC in the Indian Ocean. It can appear in other seasons as well, when anomalous easterly winds occur. Thus EUC in the Indian Ocean is defined more generally, as being any current cores at the upper thermocline level that lie beneath opposite-flowing surface currents, or more generally, even below weaker surface currents of the same direction (Schott and McCreary, 2001).

With the definition given above, an eastward EUC is known to occur in the Indian Ocean through February to June and is known to merge with spring Wyrtki Jet. Concurrent to the surface flow, the subsurface currents in the equatorial Indian Ocean also exhibit significant inter-annual variability. Positive phase of IOD is associated with strong easterly wind anomalies, which often weakens or reverses the surface currents (and therefore the Wyrtki Jets are expected to be weaker than normal during fall of these years). The easterly winds further favour upwelling in the Sumatra coast and these in turn force an eastward undercurrent. During positive IOD years, the EUC has been observed during the months of August-September as well, due to the occurrence of strong easterly wind anomalies (Reppin et al, 1999; Chen et al. 2015, Gnanaseelan and Deshpande, 2017). An anomalously strong eastward undercurrent is evident in the equatorial Indian Ocean during the evolution of strong positive IOD years (Deshpande et al., 2014), which supplies the cold subsurface waters to the east equatorial Indian Ocean region (supplied by an anomalously strong eastward undercurrent). In contrast, during weak IOD years the EUC is well defined only during the peak phase of positive IOD. In this manner, the equatorial undercurrent affects the evolution of SST anomalies in eastern Indian Ocean through the supply of cold subsurface water to the upwelling region of east Equatorial Indian Ocean. A well-defined dynamic coupling is seen only during strong positive IOD years, and hence thermocline variations should be accounted for, while determining the magnitude and impact of these events. This coupling is supported by subsurface current response in the equatorial Indian Ocean, where the anomalous eastward undercurrent evolves coherently since June and continues to remain strongly eastward till the peak phase of strong IOD years. In contrast, the lack of subsurface current evolution may be one of the reasons for the inconsistent SST, thermocline response during weak IOD years.

With the availability of the satellite and mooring observations (Figures 1 and 2), many of the proposed mechanisms governing equatorial Indian Ocean dynamics are being

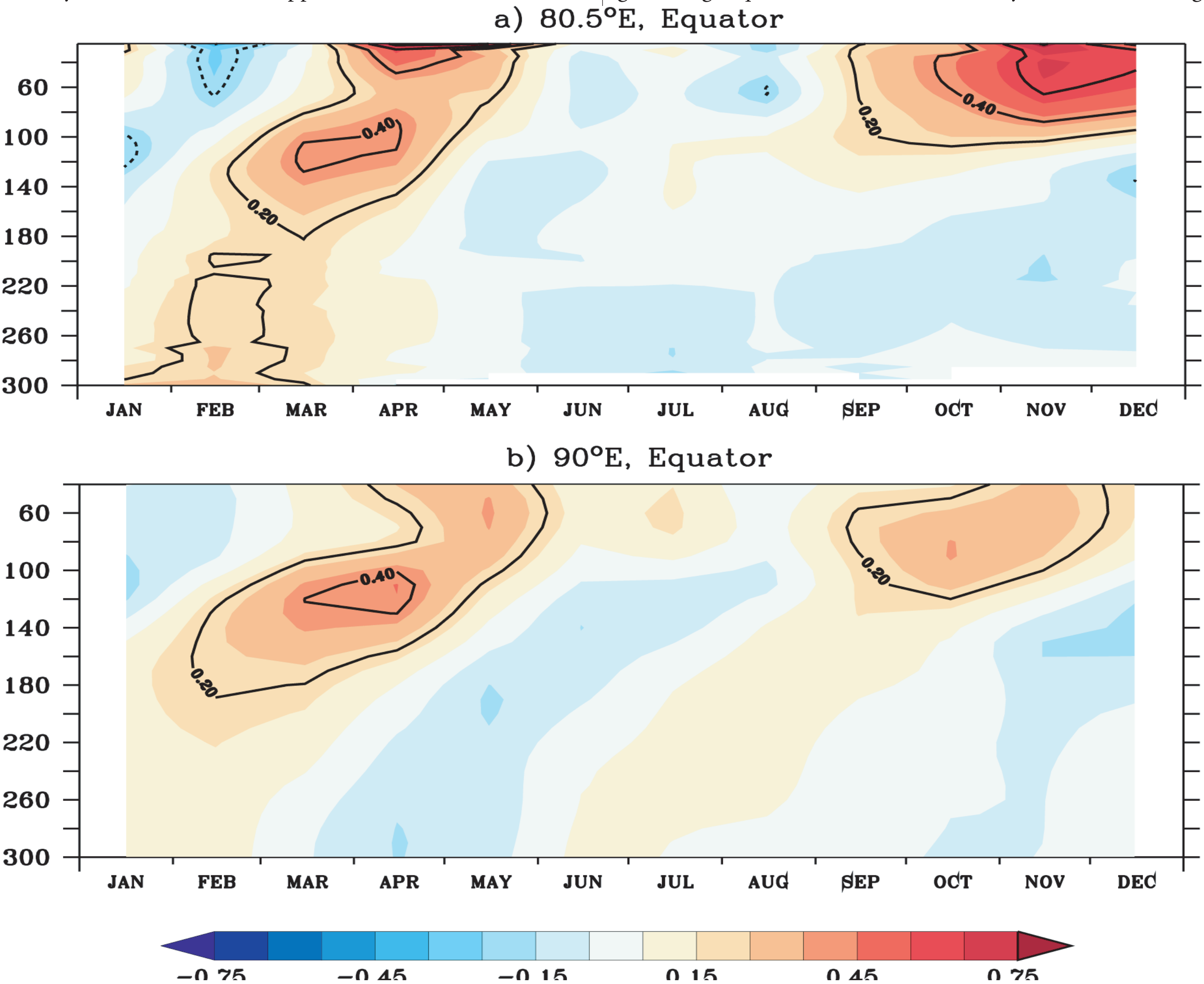

Figure 2: Zonal current (m/s) climatology superimposed with its contours from ADCP mooring data at equator at (a) 80.5°E and (b) 90°E.

tested and new ideas are emerging regarding the behaviour of equatorial currents (Gnanaseelan et al., 2012). An accurate understanding of the role played by equatorial Indian Ocean in modulating north Indian Ocean climate is still not complete.

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Nano Computers : Age of Nano Computing

Contributed Article

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Computer technology has been advancing steadily ever since its advent around World War II. After the fabrication of first computer, lot of revolutions came in computer industry. After supercomputers, demand for smaller and faster computers has been increasing tremendously over the past few years. Numerous advances came in computer fabrication technology that resulted into the evolution of powerful and extremely small computer system architectures. With the ease of technology where materials tuning was done towards atomic scale, properties at atomic scale differ significantly from those at a large scale. Technology of small scale, in the range of Nano meter – one billionth part of a meter, is known as 'Nano Technology' – a term proposed by American theoretical physicist Richard Feynman (1918 –1988). Nano computing is the use of Nano technology on extremely small applications towards 'Internet of Things'. Nano technology based 'Quantum Computers' would revolutionize computing and increase their computing power tremendously. Quantum computers are faster in performing calculations than any silicon based computer. Nano computing will enable technologists to meet the quest to pack power of computing into smallest possible devices without compromising on speed and accuracy. Technology is like a river which always keeps on moving forward and never stops. Technology has benefitted all domains including computers, finance, marketing, forensics, education and so on. Nano technology based computers have reduced physical size, high computing power and high performance and are more responsive than silicon based computers we had before the advent of Nano technology. Nano computing is an evolving paradigm that provides speed and performance of supercomputers at much reduced physical size. Nano computing is a totally new emerging technology enhancement.

Nano computing is fast becoming an essential part of our real lives. Nano computing reduces the size of computing devices which may work in areas beyond the reach of conventional computing devices. Nano computing is an interdisciplinary field of research in Nano technology and is the new quest of faster computing used in many new applications. Nano computers have the potential to revolutionize the twenty first century and revolutionize the way computers are used. Nano computing is an optimistic approach to provide fast computing speed and power of supercomputers at extremely small physical size. In today's innovation fueled world, 'Nano' concept has hovered over almost every sphere ranging from the size of SIM-cards to the size of gadgets. Everyday different approaches are being researched and developed to reduce the sizes of our computing gadgets and make them nimbler and efficient towards environment. Demand of Nano computing devices grew rapidly due to its focus on performance, portability, reliability and efficiency. Nano computing is a totally non clichéd concept. Nano computing challenges the abilities of supercomputers in a perfectly fabricated and smaller version of it. Computer with Nano technology based microscopic physical dimensions is called 'Nano Computer'. Nano computing has shown its impact in many applications in the fields of Life Sciences, Robotics, Power Systems and Medical Sciences. With emerging trends in Nano computing, it is becoming the crucial concept of consideration in many other fields. Nano computing is a growing fascinating field of technology which covers almost every domain of our lives. To enhance the computing speed at tiny sizes, four perceptible trends are identified and encompassed in 'Nano Computing' viz. Quantum Computing, Molecular Computing, Optical Computing and Biological Computing. Quantum computing describes some rules which are different from those of classical computing. Boolean logic and algorithms are used in traditional classical computing environment and are associated with bits which are digitally represented by 0 and 1. In quantum computing digital bit of classical computing is replaced by 'Qubit' – Quantum Bit. Qubit is represented as a normalized vector in Hilbert space. Qubit of quantum computing is different from bit of classical computing. Classical computing digital bit is like a tossed coin after it has fallen on the ground whereas quantum bit is like a tossed coin while it is still spinning in the air. Nano technology based quantum computers would revolutionize computing and increase their computing power tremendously. Comparative study of 'Quantum Computing versus Classical Computing' has shown that (1) Quantum computing is exponentially faster than classical computing, (2) Quantum computing would break the most sophisticated code and (3) Quantum computers are fast enough to do computer simulations for nuclear explosions and weather forecasts. In molecular computing, individual molecules are used as microscopic switches. It has been observed by Nano technologists that molecular devices are easy to handle and potentially cheap to make. Molecular computing is also called as 'DNA Computing', as the basic unit of all cells is gene and a gene is made up of DNA which behaves as information storage system. There are many genetic algorithms proposed in DNA computing. Following table gives brief comparison between current and future Nano technology architectures.

Architecture Feature	Current Vs Future Architectures of Nano Technology	
	Current	Future
Logic	Boolean	Neural Networks
Data Representation	Binary	Associative and Memory Based
Connectivity	Global	Nearest Neighbor
Architecture Kind	Von Neumann	Integrated Memory Logic

In optical computing, conducting polymer is used to make components which are much faster than those of silicon based computers. With the rapid growth of Internet and communication technologies and demand of terabit speed, Optical computers came into development. In 1980s optical computing was a heated and widely discussed research area but due to the non availability of materials to make optical chip, progress and interest in optical computing went down drastically. With the limitations imposed by electronic components, electro-optical devices are available these days. Biological computers are a kind of biosensors and are normally used in medical applications. Biological computing has emerged as an interdisciplinary field which uses Molecular Biology, Computer Science, Chemistry and Mathematics for studying human body activities. Biological computer is a device which is implantable and is designed for performing tasks like monitoring the body's activities, imaging of internal organs, electrical simulation and inducing therapeutic. The whole process is done at molecular level or cellular level. DNA is the fundamental building block of molecular and biological Nano computers. There is a bright future for biological and molecular computing where CPU will be completely replaced by biological molecules and silicon chips based computers will become computing devices of past. Computer fabrication technology has evolved, advanced and undergone many revolutionary changes since its earliest days of 'Abacus Computers' to the emerging 'Nano Computers'. Abacus was the earliest finite state information storage device. In abacus, numerical data is represented by the position of beads on a string. Following table shows kinds of generations of classical silicon based computers during different periods of growth of computer technology.

Generation	Period	Computer Technology
First	1940 – 1956	Vacuum Tube Based
Second	1956 – 1963	Transistor Based
Third	1963 – 1971	Integrated Circuit Based
Fourth	1971 – 2010	Microprocessor Based
Fifth	2010 – Beyond	Artificial Intelligence Based

Nano computer is the logical name for a computer smaller than microcomputer which is smaller than minicomputer. Eventually computers will be developed with fundamental parts that are no bigger than a few nanometers. There are several ways Nano computers might be built using Mechanical, Electronic, Biological or Quantum technology thereby giving us 'Mechanical Nano Computer', 'Electronic Nano Computer', 'Biological Nano Computer' or 'Quantum

Nano Computer'. Nano computing is a new paradigm used to enhance the computing speed at small sizes. Use of Nano technology in the fabrication of computers will ensure manufacturing of smaller, faster and more reliable computers. With Nano computing device technology advances, computer architectures have improved. Nano computing devices outperform the limits of any conventional silicon based computing device. Nano computing gives real time solutions to many problems. Computing at the Nano scale is poised to revolutionize the landscape of traditional computing. Nano computing is a constituent of the fast emerging Nano technology. Nano computing is an important feature in the rise of computer technology. A computer scientist has described Nano computer as an invisible super computer. The future of Nano technology is completely unchartered territory. It is almost impossible to predict everything that Nano science will bring to the world considering that this is a young science. There is a possibility that future of Nano technology is very bright and Nano science will be the science of the future and no other science can live without Nano science. There is also a chance that Nano science will make the world highly uncomfortable with its potential power to transform the world. Nano computing shall take some more time to reach common user and will definitely provide growth in every area of technology. Nano computing is the new quest of computing.

News and Views

Recent Updates

New Eocene fossil data suggest climate models may underestimate future polar warming

A new analysis by Dr.Evans on marine fossils show that warming of the polar oceans during the Eocene, a greenhouse period that provides a glimpse of Earth's potential future climate, was greater than previously thought. By studying the chemical composition of fossilized foraminifera, tiny single-celled animals that lived in shallow tropical waters, Dr.Evans team generated precise estimates of tropical sea surface temperatures and seawater chemistry during the Eocene Epoch, 56-34 million years ago. Using these data, they fine-tuned estimates from previous foram studies that captured polar conditions to show tropical oceans warmed substantially in the Eocene, but not as much as polar oceans. Instead, the models consistently underestimated polar ocean warming in the Eocene.

Reference: D. Evans et al., Eocene greenhouse climate revealed by coupled clumped isotope-Mg/Ca thermometry. *Proceedings of the National Academy of Sciences*, 2018; 201714744 doi: 10.1073/pnas.1714744115.

Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation

Substantial response of Amundsen Sea ice shelves to global and regional climate variability was observed with rates of change in height and mass on interannual timescales that can be comparable to the longer-term trend, and with mass changes from surface accumulation offsetting a significant fraction of the changes in basal melting. This implies that ice-shelf height and mass variability will increase as interannual atmospheric variability increases in a warming climate.

Reference: F. S. Paolo et al., Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. *Nature Geoscience*, 2018. doi:10.1038/s41561-017-0033-0.

Rising CO2 is causing trouble in freshwaters too, study suggests

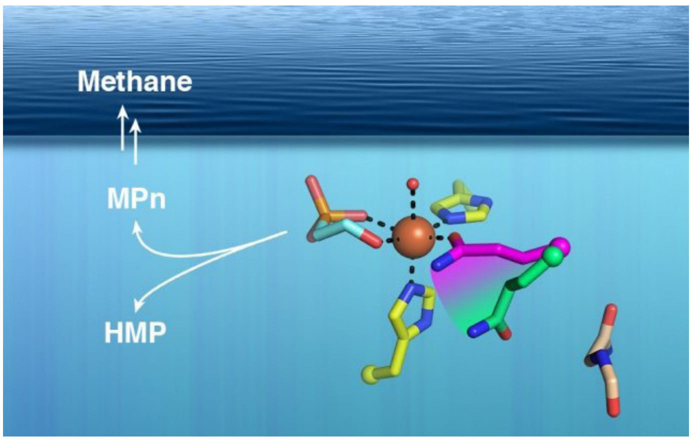
As carbon dioxide (CO_2) levels in the atmosphere rise, more CO_2 gets absorbed into seawater. As a result, the world's oceans have grown more acidic over time, causing a wide range of well-documented problems for marine animals and ecosystems. A research report in Current Biology on January 11, 2018 present some of the first evidence that similar things are happening in freshwaters too. This study found that some freshwater ecosystems have become more acidic with rising pCO_2 (partial pressure of CO_2). There findings suggest that increasing CO_2 levels may be having widespread effects on freshwater ecosystems.

Reference: L. C. Weiss et al., Rising pCO2 in Freshwater Ecosystems Has the Potential to Negatively Affect Predator-Induced Defenses in Daphnia. *Current Biology*, 2018; DOI: 10.1016/j.cub.2017.12.022.

Researchers finally establish long-sought source of ocean methane

A significant amount of the methane naturally released into the atmosphere comes from the ocean. This has long puzzled scientists because there are no known methane-producing organisms near the ocean's surface. A team of MIT researchers made a discovery that could help to answer this 'ocean methane paradox.' They have determined the structure of an enzyme that is found in ocean microbes and can produce a precursor to methane.

Reference: D. A. Born et al., Structural basis for methylphosphonate biosynthesis. *Science*, 2017; 358 (6368): 1336 DOI: 10.1126/science.aao3435.



Structure of an enzyme found in ocean microbes and can produce a precursor to methane. Credit: David Born

Conferences

Upcoming Events

- University of Leicester and IIT Kanpur jointly hold a workshop at IIT Kanpur on "An Introduction to Earth Observation Techniques: Applications to Land and Atmosphere" from March 26th to March 29th 2018. Last date for the application: 31st January, 2018.
- 10th International Aerosol Conference (IAC 2018) to be held from September 2-7, 2018 at the America's Center in St. Louis, Missouri, USA [link].
- International Conferences on Subseasonal to Decadal Prediction. Second International Conference on Subseasonal to Seasonal Prediction (S2S) and Second International Conference on Seasonal to Decadal Prediction (S2D) to be held from 17-21 September 2018 - NCAR, Boulder (CO) - USA [link].
- 2018 International AMOC Science Meeting to be held from July 24–27, 2018 at Coconut Grove, Florida to discuss about the changes in the strength of AMOC in a changing climate [link].
- ICTP Summer School on Theory, Mechanisms and Hierarchical Modelling of Climate Dynamics: Multiple Equilibria in the Climate System to be held from June 25 - July, 5 2018 at ICTP, Trieste, Italy [link].

Opportunities

Jobs/Fellowships

- Aryabhatta Post-Doctoral Fellowship (APDF) and regular Post-Doctoral Fellowship (PDF) positions are announced by ARIES. For more information: https://www.aries.res.in/academics/apdf.html
- Fully funded PhD Scholarship Opportunities, School of Earth, Atmosphere and Environment at Monash University, Australia. For more information: https://www.monash.edu/science/schools/earth-atmosphere-environment/postgrad/phd-eoi
- Postdoctoral Positions in Ocean,Atmosphere and Climate Dynamics at Yale University. For more information: https://earth.yale.edu/postdoctoral-positions-ocean-atmosphere-and-climate-dynamics

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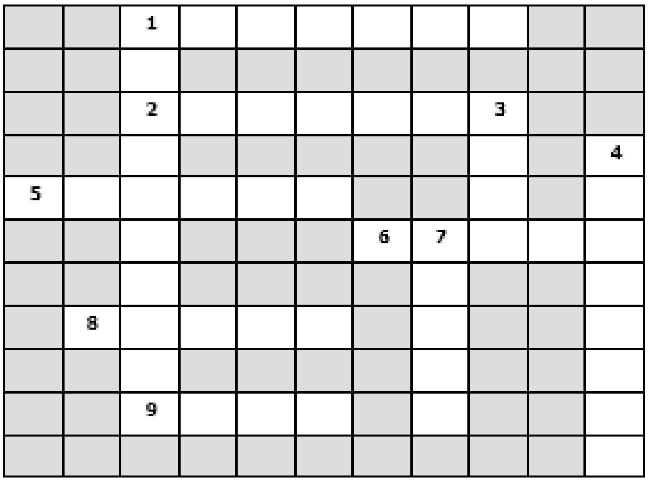
Crossword

The clues for the Earth Science Crossword can be traced to the present and previous issues of Ocean Digest. Enjoy.



ACROSS

1. The well-known ocean conveyer belt is the global scale thermohaline ocean circulation, mainly driven by gradients of (7)
2. This ocean has the most number of trenches (7)
5. It is the SI derived unit of pressure (6)
6. An object-detection system that uses radio waves to determine the range, angle, or velocity of objects (5)
8. Rain that often appears in streaks or shafts extending from the bottoms of clouds, which evaporates before hitting the ground (5)
9. This tide results after seven days of spring tide, when the sun and moon are at right angles to each other (4)

DOWN

1. Process under which water vapor can change directly to ice without becoming a liquid first, is termed as (10)
3. The North Atlantic Subpolar Gyre (SPG) is relatively _____ in temperature (4)
4. The circle of constant longitude passing through a given place on the earth's surface and the terrestrial poles is termed as (8)
7. It is the highest waterfall of the world (5)

Compiled by Bhupendra B. Singh