Understanding our seas: National Institute of Oceanography, Goa

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The present article summarizes the research done at the CSIR–National Institute of Oceanography in 2014 in ocean science, resources and technology. Significant research has been conducted on air–sea interactions and coastal circulation, biogeochemistry, biology, marine geophysics, palaeoceanography, marine fishery, gas hydrates and wave energy. Technological advances covered topics like oceanographic tools. Major strides have been made in marine resources research and evaluation.

Keywords: Air–sea interactions, coastal circulation, marine resources, ocean science.

THE CSIR–National Institute of Oceanography (CSIR–NIO), with its headquarters in Goa and three Regional Centres in Kochi, Mumbai and Visakhapatnam, conducts research 'to continuously improve our understanding of the seas around us and to translate this knowledge to benefit all'. The Institute studies all aspects of oceanography from basic to applied research, the latter particularly in service to society, including industry.

Scientific research

Physical

Air–sea interactions and heating of the surface ocean lead to changes in climate and vice versa. Study on the variability of Indian Ocean Warm Pool (IOWP) revealed its annual cycle with minimum and maximum intensities in August and April respectively. The Pool has large inhomogeneity in zonal mode; eastern Indian Ocean is warmer than the west. It is also deeper in the eastern equatorial Indian Ocean[1]. The frequency of tropical cyclones varies with the dynamics of air–sea interactions. The results suggest that El-Niño events mostly suppress the formation of cyclones over various basins than those of El Niño-Madoki. More number of cyclones over the Arabian Sea and the Bay of Bengal form during El Niño Madoki and El Niño years respectively[2]. An evaluation of the role of warm and cold core eddies associated with the East Indian Coastal Current revealed that the severe cyclone of 16–19 October 1999 has been intensified by 260% due to its interaction with a warm core eddy.

A 'river in the sea' found as a freshwater flow of 100 km wide originates in the northern Bay of Bengal, travels along the coast and reaches India's southern tip in about two and a half months. This phenomenon is unique to the Bay since elsewhere in the global oceans, a low-salinity signal easily gets blurred by local phenomena since the coastal currents are weak[3].

Unpublished data revealed the formation of strong salinity fronts, driven by coastal currents and eddies, in the Bay of Bengal after monsoon. Current studies based on seven moorings in the Equatorial Indian Ocean revealed the occurrence of 40–50-day period intra-seasonal oscillations at 2000 m, while biweekly period oscillations prevailed at 4000 m. Observations of Continental Tropical Convergence Zone (CTCZ) cruise in 2012 indicated a strong and deep summer monsoon current with a geostrophic flow extending to 1000 m. This current in 2012 was quite different from other years as the intra-seasonal meanders were weaker.

Biogeochemical

Deposition of dust over oceans is influenced by climatic factors and supports biological productivity. Anti-clockwise winds associated with tropical cyclones in the Arabian Sea are found to entrain dust and transport it mostly towards the west or in southwesterly direction (Figure 1). Cyclones over the northern Bay of Bengal aid advection of dust plumes from southwest Asia and Thar Desert over highly populated regions of the Indian Subcontinent[4].

Banerjee and Prasanna Kumar[5] have shown a mechanistic relationship between episodic phytoplankton blooms and dust deposition in the Arabian Sea during winter, away from the active winter convection zone. The inter-annual variability of aeolian dust-mediated chlorophyll biomass has implications to oceanic CO_2 budget in a changing climate scenario.

Denitrification is the major pathway for the loss of fixed nitrogen in the Arabian Sea, which in turn is

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controlled by the supply and quality of the organic matter[6]. Carbon and nitrogen isotopic composition of suspended particulate organic matter (SPOM) in the Zuari Estuary, exhibited marked seasonality (Figure 2), with autochthonous and terrestrial components being the major SPOM sources during periods of low and high river discharges respectively[7].

Suspended particulate matter (SPM) increases seaward in the Mandovi and Zuari estuaries, associated with estuarine turbidity maximum, and shows an inverse relationship with particulate organic carbon (POC). The $\delta^{13}C_{org}$ of SPM indicates largely terrestrial OC during wet season, but estuary-derived at river end and marine plankton-derived at sea end during the dry season. $\delta^{15}N$ values are altered by biogeochemical processes in both estuaries and cannot be used to trace source, except during the wet season in Mandovi[8]. The Mandovi estuary sediments are ore material-dominated in the upper/middle estuary and silicate-dominated in the lower estuary. Positive Ce anomaly is due to ore material, whereas negative Ce anomaly is due to source rocks[9] (Figure 3). Eu anomaly is inherited from ore material and also controlled by sediment constituents. Low LREE/HREE ratios indicate loss of fine-grained weathered material from the estuary under high-energy conditions. An intact sediment-core-incubation experiment revealed significant nutrient effluxes that can sustain phytoplankton community in a seasonally N-limited shelf system off Goa[10].

Speciation of metals determines their bioavailability and toxic nature. Studies have been made to understand

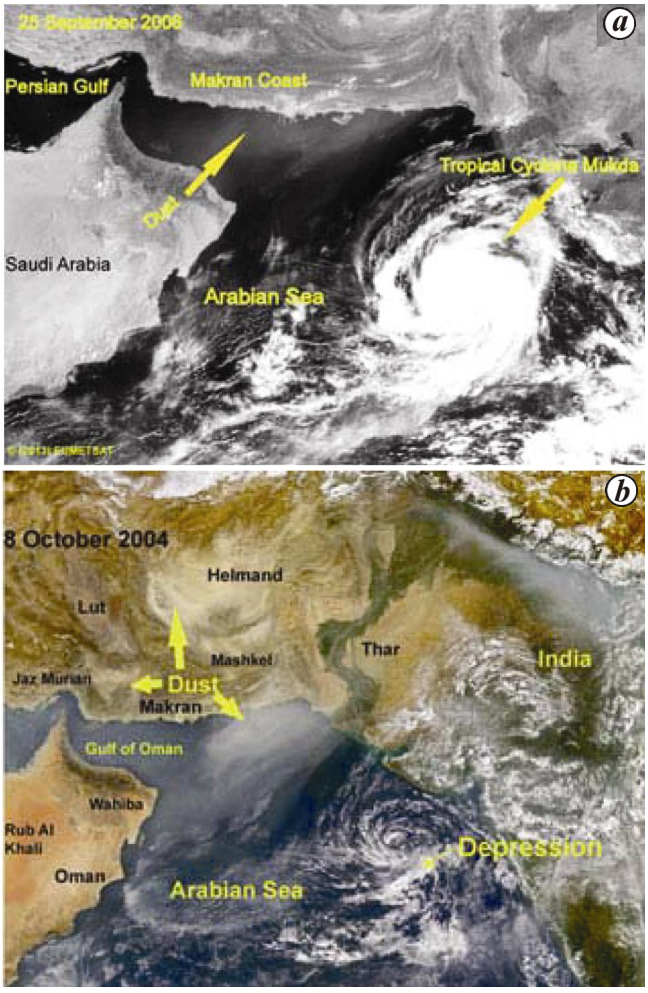

Figure 1. Dust entrainment and transport by tropical atmospheric disturbances: ***a***, tropical cyclone 'Mukda' and a major dust storm over SW Asia in September 2006; ***b***, a minor depression in the NE Arabian Sea in October 2004 (from ref. 4).

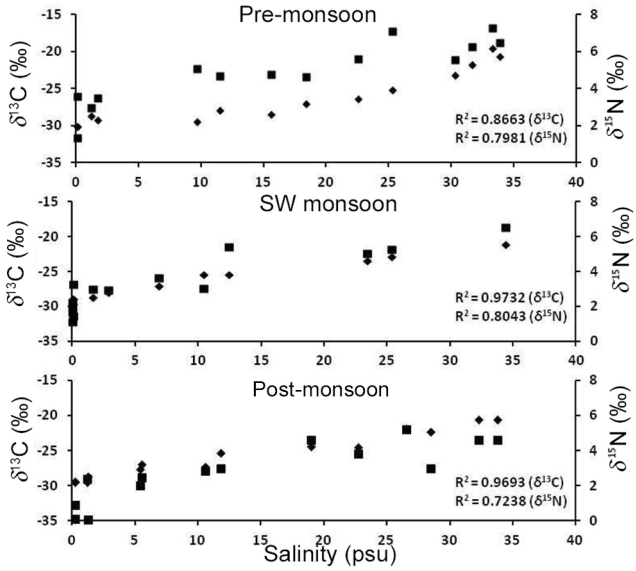

Figure 2. Seasonal variations in the mean $\delta^{13}C$ (squares) and $\delta^{15}N$ (circles) of suspended particulate material with salinity in the Zuari Estuary (from ref. 7).

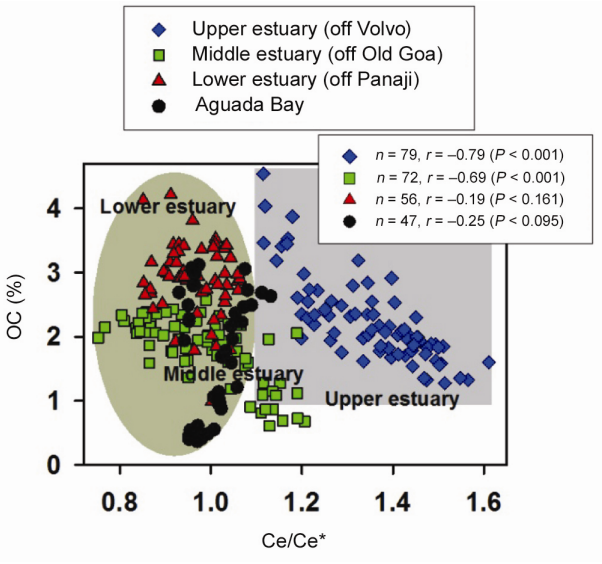

Figure 3. Relationship between organic carbon (OC) and Ce/Ce* in sediments of Mandovi Estuary (from ref. 9).

the interaction of metals with dissolved and particulate organic carbon in different depositional environments of coastal waters[11–16]. Quality and quantity of organic matter, metal loading and chemistry of sediments (e.g. Fe/Mn-oxyhydroxide) are found to play key roles in controlling metal speciation. Terrestrial and marine organic materials are found to have different complexing capacities for different metals. The coastal sediments from the central east coast of India are found to act as a sink for mercury (Hg). The east coast of India has been found to be less contaminated by metals than the west coast. Sediments in estuaries adjacent to major cities are found to be more contaminated.

Biological

Characterization of phytoplankton pigments and functional community structure in the Gulf of Mannar and the Palk Bay indicated that the latter is mostly dominated by cyanobacteria, whereas the former by nanoplankton community[17]. Benthic population in and around Visakhapatnam port has shown an increasing trend over the last 20 years. Higher species diversity is found in the outer harbour, which is semi-polluted[18]. The ecological status of the intertidal region of Colaba (Mumbai) was affected in August 2010 immediately following the MSC *Chitra* and MV *Khalijia* collision and oil spill leakage, but recovered in later months[19].

Antibiotic-mediated changes in the fouling diatom community are found consistent across the seasons; however, the rate at which the fouling communities changed depended on the initial species composition[20]. Biofouling diatoms *Amphora* and *Navicula* were able to remain viable and photosynthetically healthy under dark conditions without undergoing asexual reproduction. On re-exposure to light, these diatoms further improved their photosynthetic efficiency and growth, which indicates that biofoulers survive during long-distance ballast water transport and can invade foreign waters.

The Kerala coast experiences natural mud banks (Chakara) with high biological resources at different locations along the coastline during the southwest monsoon. Although a target of many research programmes, the current understanding of these ecosystems and associated biological resources is rudimentary. During 2014 CSIR–NIO, in collaboration with Central Marine Fisheries Research Institute (CMFRI), Kochi initiated a multidisciplinary experiment to understand the process of formation of mud banks together with impacts on biogeochemical processes and biological resources. Weekly (water and sediment) and mooring studies were made from April to October (end of the mudbank season). Simultaneous studies on fishery productivity were carried out by CMFRI. The results point to the emerging new insights about the Allapuzha mudbanks.

Geological and geophysical

The Afanasy Nikitin Seamount is found unrelated to the 85°E Ridge and has evolved by multiple volcanism[21]. The proximity of the southern end of the 85°E Ridge to the Afanasy Nikitin seamount seems coincidental. Jacob *et al.*[22] deciphered plate tectonic evolution of the Wharton Basin and modelled the structure and age of the subducted lithosphere under Indonesia. Boron (δ^{11}B) and chlorine isotope (δ^{37}Cl) proxies helped trace hydrothermal activity in the Central Indian Ridge (CIR)[23]. The δ^{11}B and δ^{37}Cl in a 2000 m seawater column at Vema and Vityaz transform fault areas in the CIR, showed significant variations below 300 m associated with hydrothermal activity and low temperature alterations in Vityaz transform fault. Increased lability of Cu in the Central Indian Ocean Basin hydrothermal sediments with increasing depth suggests enhanced release of bioavailable Cu during deep-sea mining operations[24].

Refractory metal nuggets of three (l, S and G) types in different cosmic spherules from the deep-sea sediments in the CIB were recovered with G-type for the first time in the world[25]. A fremdling-like object in a cosmic spherule was also discovered, which has a nugget encased in Fe–Ni and sulphide phases, similar to those typically observed in Ca–Al-rich inclusions of CV or CO chondrites.

The depth differentiation of benthic foraminifera can be used to reconstruct the extent and intensity of oxygen minimum zone and palaeobathymetry[26]. The B/Ca ratio of surface planktic foraminifera in the northern Indian Ocean core is not related to seawater salinity, pH or dissolved organic carbon[27]. Increase in productivity and denitrification in the Arabian Sea during the last 7000 years has been found to be coeval with the low dissolved oxygen in bottom waters[28]. During glacial periods, abrupt climate changes in the North Atlantic region affected primary productivity and the population of marine calcareous organisms in the eastern Arabian Sea[29]. Intensified inter-monsoon equatorial westerly jets increased productivity and terrestrial organic matter input during the Last Glacial Maximum (LGM)[30]. Even the influx of low-salinity water from the Bay of Bengal to the eastern Arabian Sea was reduced probably due to decreased freshening of the Bay during the LGM[31]. The amount of warm and saline water transported from the southwestern Indian Ocean to the Atlantic Ocean has been found to have reduced during the LGM[32]. Concomitant changes in sea level and rainforest vegetation have been found in the southeastern Arabian Sea during the last ~140 ka (ref. 33). An inverse relationship between summer and winter monsoons during late Holocene is found in a well-laminated sediment core from the Pakistan continental margin and is attributed to a shift in the Inter Tropical Convergence Zone[34].

Resources research

Biological

To develop a forecasting system for potential zones for fishing, our approach has moved from 'expedition mode', in which most ecosystem research has been done so far in India, to an 'experimental mode' that includes mesocosm and laboratory experiments besides field observations. This shift helps in better understanding the ecosystem functioning in the Indian Exclusive Economic Zone (EEZ), in which all biogeochemical processes have to be addressed holistically. Two mesocosm designs have been tested in the open ocean and experiments were successfully conduced off the east and west coasts of India.

Unpublished data acquired in two cruises in which waters in frontal regimes were sampled, indicate that the sea-surface temperature (SST) frontal regions, in spite of the weak SST gradient found in our waters, tend to be more productive (Figure 4). The data suggest, however, that the biological response depends on the age of the front, making it necessary to track their evolution while issuing fishery advisories. These results are also important because data gaps are more in commonly used satellite chlorophyll data than in satellite SST data, implying that potential fishery zone (PFZ) advisories cannot be issued for cloud-covered regions due to absence of chlorophyll data. Nutrient concentrations are higher and a unique phytoplankton assemblage is found within the filament and frontal waters compared to those in surrounding region[35]. Laboratory and field experiments suggested that temperature is an important abiotic factor of ecological significance in maintaining the sponge population in nature[36]. In the exploration of bioactive substances, new antifouling and antifungal agents were identified by constructing and screening a library of 2-aryl benzimidazole core inspired from marine natural products[37–39].

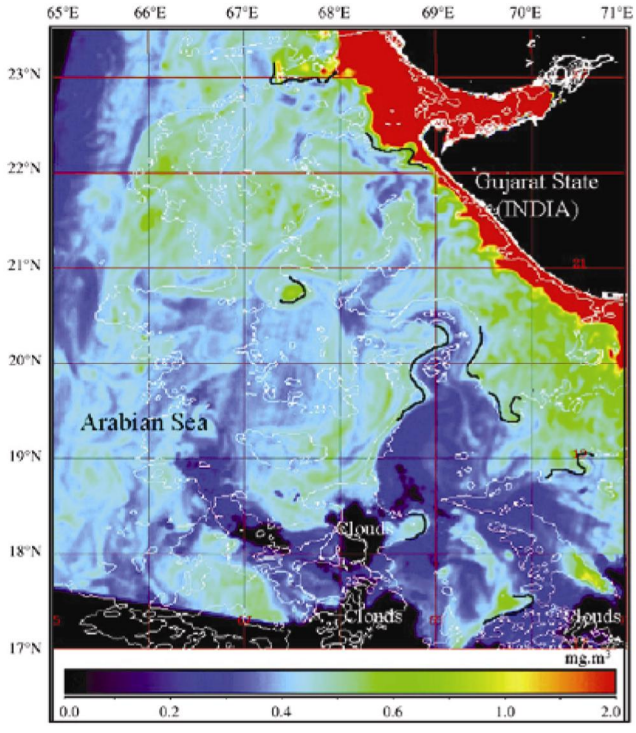

Figure 4. Typical composite image generated from satellite-derived chlorophyll concentration image (background image) and sea surface temperature (SST, °C) contours. Synchronous near-real-time satellite data of 8 March 2000 were used. The image shows matching features of chlorophyll (a biological variable) and SST (a physical variable). Black lines in the image indicate the suggested potential fishery zones (PFZs).

Non-renewable energy

Discovery of gas hydrates in the Bay of Bengal, in the Krishna–Godavari, Mahanadi and Andaman Basins, has placed India prominently on the global gas hydrate map. Extensive coring and logging operations were carried out[40,41] on-board JOIDES resolution in 2007. The results revealed many geological signatures, e.g. link between methane seepage events and palaeoclimate, benthic life in sulphidic sediment–water interface, deep biosphere and microbial ecology linked to methanogenesis and methanotrophy, hydrate destabilization/seabed instability and effect of shale tectonics-induced structures on hydrate localization[42–51] of far-reaching consequences. The geothermal gradient (GTG), influenced by depositional environments, in the KG basin increased in the vicinity of the fault system (Figure 5) due to fluid advection but decreased over the mass-transport deposits and inner toe-thrust regions because of rapid sedimentation/upliftment[52].

Renewable energy

Assessment of wave power, made through studies of its temporal variations at 19 locations along the Indian shelf seas[53], revealed significant inter-annual variations (10–20%) at a few locations. The mean annual wave power (MAWP) along the east Indian shelf (2.6–9.9 kW m^{-1}) is lower than that in the west (7.9–11.3 kW m^{-1}). It is maximum (11.3 kW m^{-1}) at a southern location, which coincides with low seasonal variation.

The ratio of the maximum wave height (13.5 m) to significant wave height (7.3 m) is higher than the theoretical value when the ratio of the crest height to wave height during the PHAILIN cyclone[54] is 0.6–0.7. Statistically declining trends are found in the mean and extreme wind speeds (90th percentile), but increasing trend in extreme significant wave height between 1979 and 2012 in the central Bay of Bengal[55]. Opposing trends in the wind speed and wave height are mainly due to the swell dominance.

Technological advances

The Soil Moisture and Ocean Salinity and Aquarius SAC-D satellite sensor-derived salinities were used to track

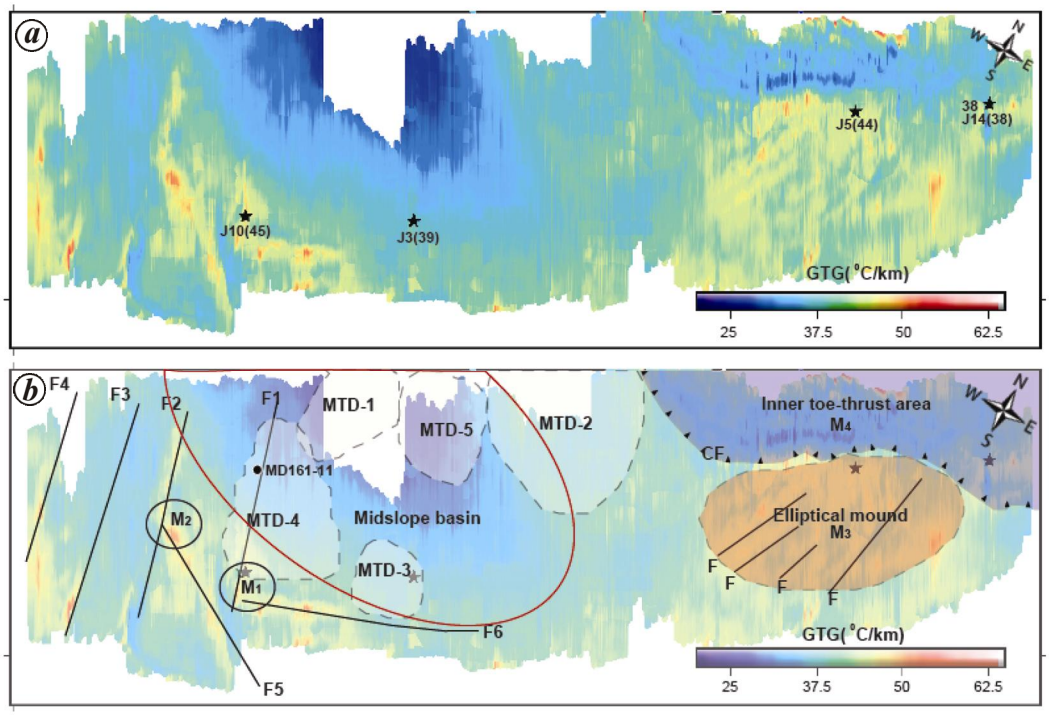

Figure 5. ***a***, Variations in geothermal gradient (GTG) in the Krishna–Godavari offshore basin. GTG values of site NGHP-01-03/05/10/14 are plotted on their respective locations; ***b***, Interpretation of GTG map to illustrate the effect of different processes on the estimated GTG (from ref. 52).

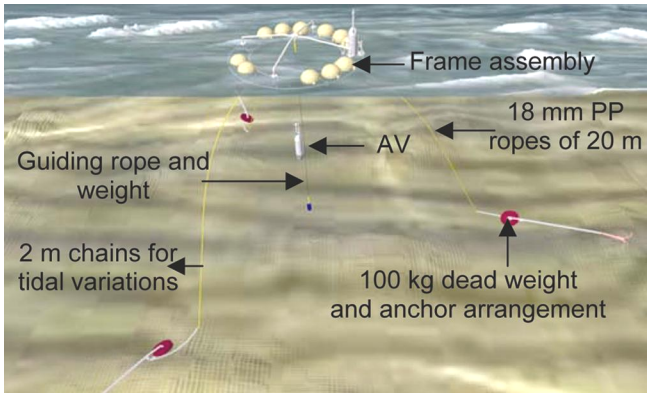

Figure 6. A new suspended configuration of an autonomous vertical profiler mooring system used in mud bank studies.

and estimate barrier layer thickness in the Indian Ocean[56]. However, large multilinear regression model errors due to land contamination limit its use in coastal and island regions.

A software assembled for detecting SST fronts in satellite data using open-source tools enables automated processing of a large number of SST maps. This software has played a crucial role and helped in the tracking of fronts during cruises.

Altimeter and coastal tide-gauge data comparison showed that the former can be a potential complement to study storm surges. Thus the possibility of multiple satellite tracks facilitates efficient capturing of extreme event signals[57]. Development of models with open boundary following the altimetry tracks is proposed to help merge regional solutions into global tidal solutions[58].

A multi-marker methodology has been developed (using *n*-alkanes, pentacyclic terpanes, regular steranes, compound-specific isotope analysis and principal component analysis) to identify the source of oil in tar balls and spills[59].

A nucleic acid-based PCR method was developed that overcomes taxonomic ambiguity and facilitates accurate identification and enumeration of *B. amphitrite* larvae among plankton[60].

Four well-known formulae and the sensitivity of wave parameters were tested to estimate longshore sediment transport[61], which revealed that the Kamphuis formula can be used for annual mean significant wave height ~1 m.

Seismic attenuation estimation has been proposed from multi-channel seismic reflection data and its usefulness demonstrated with a case study from the KG Basin[46].

The autonomous vertical profiler (AVP) developed at the Institute was used to obtain high-resolution profiles of conductivity, temperature, dissolved oxygen, PAR, chlorophyll and turbidity at three locations in the mud bank experiments near Kochi, with a new suspended configuration shown in Figure 6. Through this the AVP can reach

very close to the seabed. The AVP withstood hostile weather, performed four dives per day and transmitted data through a cellular network.

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