# Ocean research in India: Perspective from space

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**India, with a long coastline spanning over 7500 km and positioned in the central part of the Indian ocean, is one of the important regions for many developments. Oceans play an important part in the social and economic life of people in the region and hence there is growing interest to study about them. Much about the oceans still remains to be understood, largely due to lack of detailed and accurate observations. Satellite platforms have recently been demonstrating reliable and long-term observations. Data from such observations can be used together with point-based *in situ* data for sustainable exploration and exploitation of ocean resources and for improving the accuracy of forecast of weather conditions, ocean state and longer-term climatic changes. Significant progress has been achieved in India during the past few years in demonstrating the utility of satellite-based remote sensing data for oceanographic research and applications. As part of these efforts, techniques have been developed to retrieve and measure various ocean parameters and processes such as ocean surface waves, wind, sea surface temperature, chlorophyll pigments, oceanic eddies, heat budget, mixed layer depth and latent heat studies. In order to meet the specific and increasing data demands in ocean research, concerted efforts are being made for developing and launching state-of-the-art satellites for ocean applications. The first in the series of the ocean satellites, IRS-P4 (Oceansat-1), was launched successfully on 26 May 1999 using the indigenous Polar Satellite Launch Vehicle (PSLV) from Sriharikota. A well-knit plan has been initiated for the proper utilization of data from Oceansat-1 mission. This paper highlights ocean research in India as well as ocean observation missions which aim to provide operational ocean information services in the country.**

INDIA, with 7500 km of coastline, supports vast resources (living and non-living) in the seas around and in the oceanic islands. Besides, the Indian Ocean plays a key role in influencing weather and climate systems in the region. People living in the maritime environment are increasingly exploring and exploiting the ocean for marine fisheries, offshore oil and gas, marine transport and as dumping ground for disposal of wastes. The increased dependence on the ocean for these activities has been causing concern and a major threat to sustaining the biological richness of oceans and coastal areas. Therefore, there is a need for a long-term management and sustainable development of ocean resources which should be based on a sound understanding of the ocean dynamics and a proper evaluation of the exploitable potential benefit of marine resources. This calls for a systematic scientific observation and detailed study of the ocean both spatially and temporally. Though the study of the Indian Ocean began long ago, our understanding of the ocean is far from complete largely due to the availability of only limited observations essentially from ships/buoys and coastal stations. The advent of satellites which provide repetitive and wide-area coverage, has radically changed the nature of oceanographic observations in recent years for retrieval of many ocean geophysical parameters and understanding of their interlinkages more scientifically. Utilizing the advantages offered by satellite remote sensing, significant progress has been achieved in retrieval of various oceanographic parameters and processes as well as their applications including coastal zones over the last decade.

## Sensors and their potentials for ocean research

Many instrument concepts and techniques have been tried from outer space for ocean research. The main instruments (sensors) that are being used for satellite oceanographic observations are visible, thermal and microwave (both passive and active) sensors, viz. Ocean Colour Monitor (OCM), Thermal Infrared Radiometer (TIR), Scatterometer (SCAT), Synthetic Aperture Radar (SAR), Altimeter (ALT), Microwave Radiometers, Imaging Spectrometers and High Resolution Imagers. These instruments provide a wealth of information on a diverse range of geophysical and biological parameters and phenomena, such as surface or near-surface colour, sea surface temperature, wave fields, surface roughness, large-scale surface topography, wind fields, etc. Measurements of these features and their variations over space and time can be interpreted to provide information relating to biological productivity, fish location, currents, sea state, surface winds, water composition and quality, sedimentation patterns, pollution and other phenomena. Integration of complementary data from different instruments is often used, to increase the information content of the data collected. Detailed study of open water phenomena are best done with sensors designed for oceanographic observations, while coastal studies can often be done with remote sensing satellites designed for land applications.

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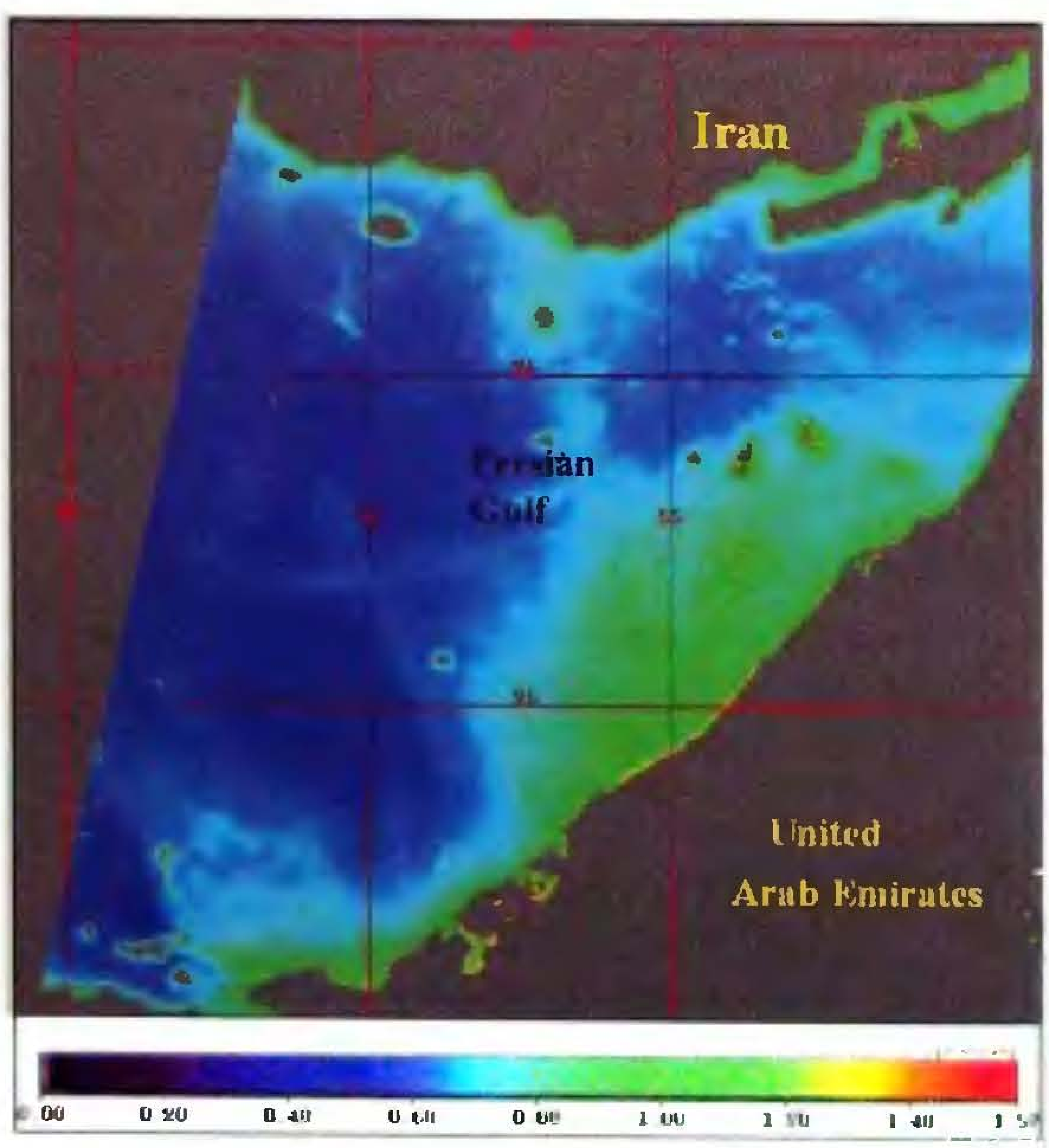
*Remote sensing applications in coastal zone studies*

Coastal zones are one of the most dynamic areas of our planet, being the meeting place of the land, sea and air. Owing to the existence of diverse and productive habitats important for human settlement, development and local subsistence, there has always been hectic human activity coupled with many developments. Of late, developments are taking place in such a manner that coastal areas are facing problems such as erosion, siltation, over-population, salt water intrusion, flooding, pollution, devastation of natural habitats, etc. Rational development of coastal areas, which form the habitat of over 25% of India's population, living within 60 km of the shoreline, can only be achieved by understanding the various interactive processes that are operative in our coastal environment. The major issues which require immediate attention to prevent degradation of coastal areas include (i) monitoring long-term trends of dynamic changes, (ii) planning and implementing coastal protection, (iii) formulating proper criteria for the location of industries, aquaculture and recreational activities, (iv) monitoring and conserving critical environmental features, (v) assessing the impact of reclamation of land from the sea, sand mining, dredging and recreational activities on coastal ecology, (vi) managing renewable and non-renewable resources optimally, (vii) controlling pollution of coastal and estuarine waters, and (viii) improving navigation systems, etc.

The major requisites for coastal zone monitoring and management are the availability of information on existing conditions and changes that may have occurred over the years. For example, the mangrove forests (mangals) in India now occupy an area less than 2600 sq km, having suffered a loss of 85% since pre-agricultural times. World over the loss of mangrove forests is about 60% during this period. In India, unplanned expansion of aquaculture along the coastline has resulted in the destruction of mangroves, besides causing floods during the monsoon. Continuous monitoring of these consequences along with other coastal changes calls for integrated studies. The United Nation's Conference on Environment and Development held at Rio de Janeiro in June 1992 has emphasized the need for an integrated management and sustainable development of coastal areas.

Several national, regional, sub-regional, and global initiatives launched in this regard have revealed that the limitations posed by conventional means of information gathering with respect to space and time have been among the major constrains in achieving these goals. On the other hand, several scientific studies carried out using satellite data for addressing various issues related to the coastal zone have proved to be extremely useful in mapping, detecting, quantifying and monitoring these features. This is mainly because satellite remote sensing has the advantage of providing multi-spectral, synoptic information over large areas including inaccessible regions on a repetitive basis, which are essential requirements for studying the coastal zone on an integrated basis. Taking cognisance of this, several scientific studies have been carried out using satellite data, mainly obtained from Indian Remote Sensing Satellites (IRS-1A/1B). These have proved to be of immense use in identifying and monitoring various coastal zone features such as tidal wetlands, mangrove forests, salt marshes, tidal flats, coastal land




IRS-P4 OCM aerosol optical depth image over the Persian Gulf (25 July 1999).

**Table 1.** Status of remote sensing-based coastal zone studies

| Project | Achievements |
|---|---|
| Wetland/Landform | Maps showing mudflats, beach, mangroves and coastal zone on 1 : 250,000 and 1 : 50,000 scale for the entire country's coastline. |
| Shoreline changes | Maps showing erosional/depositional areas on 1 : 250,000 and 1 : 50,000 scales for the entire country's coastline. |
| Coral reef | Maps showing type of reef and associated features on 1 : 50,000 scale of the major four coral gulf reef areas, viz. Gulf of Kachchh, Lakshadweep, Bay and Gulf of Mannar, Andaman and Nicobar. |
| Suspended sediment | Qualitative sediment mapping of pre- and post-monsoon period for Kerala and Tamil Nadu coast. |
| Coastal regulation zone | Maps showing wetland areas between high and low water lines and landuse features within 500 m strip from high water lines on 1 : 25,000 scale. |
| Coastal zone information system | Pilot scale study mainly based on remote sensing inputs is under development for providing decision support for coastal zone planners. |

forms, assessment of potential aquaculture sites, shoreline changes, dynamics of erosion/accretion, coastal landuse/cover and inshore aspects like suspended sediment dynamics, coastal currents, near-shore bathymetry, etc[1]. The important coastal zone studies carried out so far in India using satellite data are given in Table 1.

The advantages of using Geographic Information System (GIS) for integration of various thematic information derived from satellite data with other collateral data such as socio-economic and cultural data are significant in arriving at an integrated coastal zone management practices. Such an approach helps in initiating an integrated system for controlling development and other human activities that affect the economic resources and the quality of environment in coastal zones. Efforts are in progress to assess the areas suitable for brackishwater aquaculture and develop an integrated coastal zone model through GIS coupled with remote sensing for selected regions of the coast in the country towards better planning and management practices of coastal zones.

The availability of high resolution data from second generation Indian Remote Sensing Satellites, IRS-1C and 1D, which have improved spatial resolution, extended spectral bands, stereo-viewing and faster re-visit capability are assisting coastal zone studies through improved mapping and analysis capability. Identification of no-impact zones for developmental activities in the critical coastal habitats, development of islands eco-system, understanding the dynamics of estuarine/tidal flats, the prediction of shoreline changes in the most vulnerable area through modelling efforts and study of suspended sediments are some of the major projects which are being carried out using these high resolution data.

### *Remote sensing applications in marine fisheries*

Experience gained by fishermen the world over shows that information on ocean features such as water colour, turbidity, sea state, flotsam and jetsam, wave size and direction, wind patterns and temperature distribution over the sea surface has a direct influence on fishing strategies. Thus, efforts have been made to use a satellite-based remote sensing approach for the identification and exploitation of potential fishing grounds to maximize fish catch. Techniques have been developed to retrieve environmental parameters available through data from various space-borne sensors. Remote sensing satellites, with their capability to cover large spatial areas over oceans on a repetitive basis, have proven to be of substantial economic benefit, particularly for nations like India having a long coastline and extensive exclusive economic zones. This technology provides information for a judicious harvesting and mapping of valuable fishery resources.

Identification of potential fishing zones involves an understanding of oceanic processes and interaction of hydrobiological parameters. Fluctuation in any of the environmental conditions over the ocean affects the distribution, abundance and availability of fish. While it is not possible to measure the entire spectrum of information needed to assess such changes in the marine environment, basic information on important environmental factors and processes can be retrieved using ocean surface measurements from satellite sensors for locating marine fish. Towards this, techniques have been developed and operationalized for Sea Surface Temperature (SST) retrieval and ocean colour sensing (measurement of chlorophyll pigments) using data from various sensors, for identification of Potential Fishery Zones (PFZ).

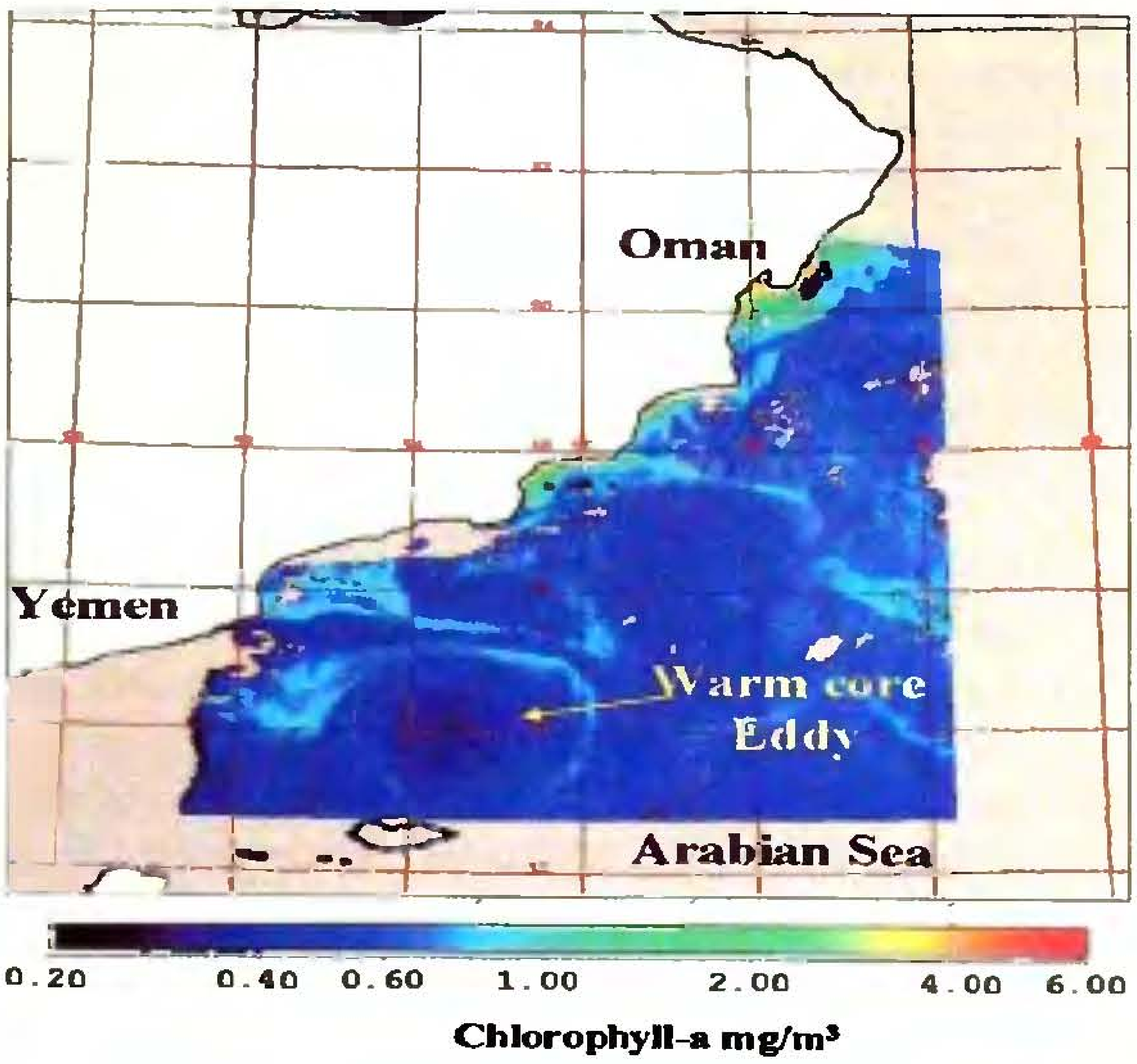
Presently, in the absence of operational colour data, efforts are being made to provide operational satellite-derived fishery forecast based only on sea surface temperature gradients derived from NOAA/AVHRR data[2]. The important thermal gradients selected for providing information on the likely availability of fish include thermal fronts, eddies, meandering patterns, up-welling zones, current boundaries, etc. The validation results have indicated substantial increase in the catch per unit effort in the PFZ areas compared to non-PFZ areas.

Considering the limitations in the present fishery forecast which is based only on SST gradients, efforts are being made to provide integrated fishery forecasting with the scenario of availability of new sensors optimized for deriving various other ocean features in the coming years. Currently, validation of the IRS-P3 MOS (Modular Opto-electronic Scanner) sensor (launched in March 1996) performance and development of a technique for ocean colour retrieval based on the Linear Inverse Principal Component Analysis Model technique is being persued jointly with DLR, Germany[3]. Other methods are also being explored.

The linear inverse technique to develop the algorithm mainly consists of radiative transfer modelling used to generate Top of the Atmosphere (TOA) radiance data sets for MOS-B spectral channels corresponding to variations of water constituents and atmospheric parameters. Then Principal Component Analysis (PCA) of the simulated data is used to determine the spectral information content of the data and weighting of the contribution of each spectral channel to the retrieval of the geophysical parameters. The geophysical parameters to be derived from the satellite detected radiance can be represented in the form of a linear combination of top of the atmosphere detected radiance by the following equation:

$$P_i = \sum_j K_{ij} L_j + C_i,$$

where $P_i$ is estimate of the geophysical parameters, e.g. chlorophyll-*a*, suspended matter, yellow substance and aerosol-optical thickness, $K_{ij}$ is weighting coefficient of channel $j$ for parameter $i$, $L_j$ is measured top of the atmosphere radiance in channel, $j$, $C_i$ is offset value for parameter $i$, $j$ is measurement channel number from 1 to $N$,




Chlorophyll-*a* concentration image derived from IRS-P4 OCM data around the Oman coast (3 July 1999).

where *N* is the number of spectral channels on the satellite payload. Besides this, several other models are also being tested for retrieval of chlorophyll from MOS to ascertain the level of accuracy.

Since IRS-P3 MOS is an experimental sensor and also the repetitivity is once in 24 days, and smaller swath width, data are not being used for operational applications in our efforts to improve PFZ advisories. However, development of different algorithms and models for retrieval of chlorophyll from MOS will form the base to optimize techniques for operational utilization of Ocean Colour Monitor (OCM) sensor, which was launched on 26 May 1999 on-board IRS-P4 (Oceansat-1). It is also useful to develop a model to integrate chlorophyll information along with SST as a first step towards providing integrated fishery forecast to predict likely availability of fish more accurately[4].

### *Applications of remote sensing for study of ocean dynamic parameters and ocean processes*

The ocean and the atmosphere form two important components of the climate system. The time scales of oceanic phenomena range from a few hours and are influenced mainly by the ocean's upper layers. Satellite systems operating at polar and geo-stationary orbits are the most suitable for recording surface and upper layer features of global oceans on time scales of several times a day, to once in two weeks. Complementary conventional systems, e.g. ships and buoys, will provide detailed temporal and in-depth coverage at a selected few points, whereas satellite observations provide a synoptic view of an area. These combined data sets can be utilized effectively in understanding how the ocean shapes global conditions and also proper evaluation of the potential benefits of ocean resources. Considering this, several ocean remote sensing projects were carried out for retrieval of various ocean dynamic parameters using meteorological and microwave satellites data (NOAA, ERS-1 and 2, Topex-Poseidon, Geosat, etc.).

*Ocean surface wind stress*: The ocean surface wind is the main driving force for ocean circulation and for generation of waves. Knowledge on the temporal and spatial variability of wind stress is essential in order to construct accurate predictive models of ocean behaviour and sea state. Scatterometers are used to measure near-surface winds over the ocean in the range 4–24 m/s with an accuracy of 2 m/s and 20°. Although radar altimeters and microwave radiometers have also been used to measure wind speed, scatterometers are unique in that they allow measurements of vector winds (both direction and speed). The radar scatterometer on-board Seasat obtained the first global measurements of winds over the ocean. In three days, the scatterometer obtained about 35,000 wind measurements providing global coverage. This amounts to more than 100 times the number of wind observations available from ships and buoys during the same period.

The basic working principle of the scatterometer as an anemometer is straightforward. A microwave radar transmits energy at wavelengths which are resonantly back-scattered (Bragg scattered) from centimeter length ocean waves. The strength of the return signal is related to the amplitude and density of the capillary waves, which are in turn related to ocean surface stress and near surface wind. The capillary wave spectrum is proportional to wind speed and its shape depends on wind direction, so that two radar 'looks' from different azimuth angles give information about wind speed and direction[5].

The average characteristics of radar backscatter from surfaces are described by the differential scattering coefficient $\sigma^0$. The radar backscatter power $W_r$ from a point target is:

$$W_r = W_t G_t A_r \sigma / (4\pi R^2)^2,$$

where $W_t$ is the transmitter power, $G_t$ is the gain of the transmitting antenna, $A_r$ is the effective aperture of the receiving antenna, $\sigma$ is the scattering cross-section of the target, and $R$ is the range from the radar to the target.

An area target such as the surface of the sea is normally considered to be collection of point targets contributing returns whose phases are random. The ensemble average of the returns from this scattering complex is described by:

$$W_r = W_t G_t A_r \sigma^0 \mathrm{d}A / (4\pi R^2)^2,$$

where $\sigma^0$ is the differential scattering cross-section. The integration is carried out over the area contributing to the return at any instant. From measurements of $W_r$ and other quantities, the radar backscatter coefficient $\sigma^0$ used for geophysical parameter retrieval from radar measurements is estimated. Based on this principle, different algorithms have been developed to retrieve wind speed and directions. In India, maps of fortnightly and monthly mean wind vector fields over 10 × 10 grids over Indian Oceanic regions for August 1992 to July 1993 have been generated and published in the form of an atlas[6]. These maps are useful for air–sea interaction, ocean circulation studies, besides other oceanographic applications such as, upwelling, fisheries, shipping and bio-geo-chemical and transport studies. The operational retrieval of ocean surface winds will form an essential input parameter for numerical models of ocean circulation and wave forecast which are used for oceanographic applications and climatic studies. It is also an indispensable parameter, along with a few others, for the prediction of storm surges caused by storms formed in the ocean which hit coastal regions. The scatterometer wind is also a precursor to the onset of monsoon[7].

Methodologies have also been developed to retrieve information on mixed layer depth, heat budget, latent heat flux and oceanic eddies utilizing satellite-derived wind vector information along with other conventional data. These oceanic processes will help to understand the tropical atmospheric circulation, monsoonal forcing on oceanographic phenomena, air–sea interaction, biological activity, etc.[8,9].

*Ocean circulation/currents*: Ocean circulation is controlled by winds, density structure, bottom topography and coastal boundaries. The ocean currents affect climate, bio-geochemical cycles and the marine food-web. Ocean currents can be detected from their influence on ocean topography. If the ocean were still, its large-scale surface topography would be that of the geoid. This undisturbed shape is influenced solely by gravity and the earth's rotation. However, large-scale ocean movements, the geostrophic currents, cause bulges or depressions in the sea surface. The difference between actual surface topography and the geoid gives a measurement of the speed and direction of large-scale ocean currents.

Surface topography is determined by a radar altimeter which measures the time for a transmitted pulse to travel to the surface and back again to the satellite. The distance between the satellite and the sea surface, combined with the knowledge of the satellite orbit, is then used to construct a map of the shape of the surface. If the satellite carrying the altimeter repeats its track exactly, then any changes in the sea surface can be related to changes in the ocean currents. Thus, variability in ocean currents can be deduced solely from altimeter measurements provided that tidal effects are properly extracted. Other requirements for measurement of the variability of ocean currents are the precise determination of the orbit and a better knowledge of the geoid.

Measurement of sea level and the ocean topography has been demonstrated by a series of altimeters of increasing accuracy and precision flown on Skylab, Geos-3, Seasat and Geosat. Data from Seasat have allowed oceanographers to map the surface topography of the ocean and the oceanic geoid in unprecedented detail. The launch of Topex/Poseidon mission in 1992 is providing substantial contribution to our understanding of global ocean dynamics by making precise and accurate observations of the oceanic topography using radar altimeters on a well-tracked satellite. The European Remote Sensing Satellites (ERS 1 and 2) launched in 1991 and 1995, have altimeters and scatterometers to measure the wind speed and direction, sea level and ocean topography. Using these data, demonstration of 2-D sea surface topography and sea level variability has been carried out in India over the Arabian Sea and the Bay of Bengal. An atlas of the eddies derived from sea surface heights has been prepared over the north Indian ocean at 10-day intervals for five individual years from 1993 to 1997 and for the five-year average period from the Topex altimeter[10]. Basu *et al.*[11] have also developed another advanced method for detection of ocean eddies with altimeter data using a match filter technique.

*Ocean waves*: Surface waves are generated by surface winds and are responsible for the downward mixing of heat thereby increasing the thickness of the heat storage layer. Wave data obtained from *in situ* measurements and from buoys are insufficient for any climatic study. Satellite-derived information on wave periods (direction, speed and periods) through wave scatterometry, altimeter and SAR are found to be feasible. Techniques have been developed to convert SAR image spectrum into 2D wave height spectrum by appropriately modelling the so-called modulation transfer function[12] and also by using an empirical technique[13]. Altimeters in particular are capable of giving significant wave heights (average of the highest one-third of the wave height) of the order of 20 cm and provide useful information about the sea state. The vast number of altimeter measurements over a period of time can be averaged and represented in the form of maps[14]. A numerical model for the forecast of off-shore surface waves over the Indian Ocean, up to 4 days in advance has been developed and is ready for semi-operational use. This information is important both from economic as well as safety point of view for off-shore industries, shipping companies and fishery community in planning their activities well in advance.

*Bathymetry*: Monitoring of coastal bathymetry is vital for exploration and exploitation of living and non-living resources, operations on engineering structures and ocean circulation studies. Accurate bathymetric measurements by ships and buoys over the vast stretches of coastal waters are found to be expensive and inadequate. These *in situ* measurements can be synergistically complemented with those by remote sensing techniques.

Bathymetry is inferred through (i) direct reflection from sea bottom in shallow and clear water conditions in coastal region, (ii) wavelength of waves refracted from sea bottom, and (iii) shape of the geoid measured by an altimeter. Sea surface waves propagating towards a shore undergo a decrease in wavelength and change in the direction due to refraction, if the angle of incidence of the incoming wave is oblique[15]. This phenomenon can be utilized to determine coastal ocean depths whenever waves are clearly seen in a SAR image[16]. The shallow water dispersion relation of a surface gravity wave is:

$$W = \frac{2\pi g}{\lambda} \tanh\left(\frac{2\pi h}{\lambda}\right),$$

where $W$ is the frequency, $\lambda$ is the wavelength, $g$ is the normal value of gravity and $h$ is the depth of water. A wave travelling from deep ocean towards the shore maintains the same frequency but undergoes wavelength change as,

$$\frac{2\pi}{\lambda_0} = \frac{2\pi g}{\lambda_1} \tanh\left(\frac{2\pi h_1}{\lambda_1}\right),$$

where $\lambda_0$ is the wavelength in the deep ocean and $\lambda_1$ is the wavelength at depth $h_1$. By measuring the wavelength of a shoreward propagating wave at different points, the corresponding ocean depth can be obtained from above equation as:

$$h_1 \frac{\lambda_1}{2\pi} \tanh^{-1}\left(\frac{\lambda_0}{\lambda_1}\right).$$

The 2D fast Fourier transformation (FFT) is an efficient method for accurate retrieval of wavelength and propagation direction of a wave in a SAR image[16]. Since SAR images often contain waves of many wavelengths, this may lead to confusion in keeping track of each wave from deep ocean to the coast. To avoid this, a spatially continuous chain of smaller subimages is defined in the original SAR image with sufficient overlap and each subimage is analysed using a 2D FFT to measure the gradual wavelength and direction change of waves.

*Sea surface temperature*: Sea surface temperature (SST) forms an important parameter of the oceans. Knowledge of SST changes has been recognized as an important component of climate prediction models. Solar inputs, ocean mixed layer processes and wind speeds on the ocean surface have direct bearing on SST variation. SST observations in different spatial and temporal scales are essential for the understanding of a variety of processes relating to the interaction between the ocean and the atmosphere. For example, small changes in ocean surface temperature in the tropical region are found to influence the weather at the mid-latitudes. Oceans exert considerable influence on the Indian monsoon and its dynamics which has been very well correlated with thermal regimes in ocean waters. The impact of monsoonal flow on Indian Oceanic waters causing extensive upwelling regions especially in the south-west coasts has been well documented. Climatic studies have shown that the potential areas of cyclogenesis and formation of weather systems is closely linked to temperature patterns of the upper oceanic layers. Information on SST is also crucial for understanding the ocean dynamics related to mixed layer depth and circulation. SST charts showing prevailing and changing ocean environment are useful towards identifying potential fishery zones. Currently, SST is being retrieved operationally using NOAA-AVHRR data using an empirical multichannel equation[2]:

$$\text{SST} = 1.02455\, T_4 + 2.45(T_4 - T_5) + 0.64(T_4 - T_5) \times \sec(\theta - 1) - 280.67,$$

where SST is the sea surface temperature, $T$ is the brightness temperature for the respective infrared channels and $\theta$ is satellite zenith angle. The *in situ* validation of satellite-derived SST shows an accuracy of ± 0.81°C (NRSA). Efforts are on to retrieve SST with an accuracy of ± 0.3°C through improvement in atmospheric corrections and availability of data from improved thermal sensors, particularly by the dual-angle approach.

*Sea mounts detection*: Indian seas are infrequently surveyed for deep ocean bathymetry and topography due to large lead time required through conventional methods, besides being laborious and expensive. However, charting of sea mounts is important as they disturb the flow of ocean currents and large amplitude internal waves around them. Also, identification of sea mounts is crucial for sea mining, submarine navigation and deep ocean circulation studies. Sea mounts in the deep ocean are ideal fishing grounds. Satellite altimeters are very useful in charting sea mounts. An advanced signal processing known as matched filtering technique using satellite altimeter has been developed for detecting charted sea mounts in the Indian Ocean. It uses the generic undulation signature due to sea mount and the statistical characteristics of background noise present in the data. The variations in gravitational acceleration over the earth's surface result in an uneven distribution of water mass in the ocean. The gravitational acceleration is slightly stronger over the bumps on the ocean bottom and slightly weaker over depressions in the bathymetry. In the absence of other forcing (e.g. pressure gradients, wind forcing or tides), the sea surface would be a surface of constant gravitational potential (the marine geoid). Mathematically, the marine geoid with potential $\phi_g$ is related to the vector gravitational acceleration $g$ as $g = \nabla\phi_g$. The geoid undulation signatures of large sea mounts can be easily observed. A procedure that is effective in detecting signals of known form, in a background of noise having known statistical characteristics is matched filtering which can be implemented as an automated technique to search radar altimeter data on track by track basis. Based on this technique, an atlas of newly discovered and verified sea mounts has been prepared for the Indian seas[17]. Further verification and deduction of sea mounts is being planned using ERS and Topex/Poseidon satellite data.

*Marine pollution*: Pollution of the marine environment is now recognized as a serious global problem, with oceans becoming a dumping ground for waste products containing hydrocarbons, heavy metals, pesticides, heated waste water and several other pollutants from various industries. Remote sensing data from satellites have been successfully used in monitoring oil spills. Since oil normally exhibits a lower temperature than water, thermal infrared scanners are useful in the surveillance of oil spills. Passive microwave radiometers are useful for oil surveillance since oil films modify the surface roughness of water and alter the microwave signature. Studies have also shown that ocean waste and water quality can be assessed using remotely sensed data. While positive identification of a pollutant is difficult, remote sensing has become an indispensable tool in detecting areas in the ocean affected by polluted discharge and the general characteristics of dispersion pattern of pollutants.

*Assimilation in numerical ocean models*: Efforts have also been made towards assimilation of satellite data in the ocean model describing the circulation in the north-western Indian Ocean. Impact of ERS-1 scatterometer winds and assimilation of sea level variability data from Topex altimeter on this model have been studied using adjacent approach. Also, impact has been studied using analysed wind stress as well as ERS-1 scatterometer-derived wind stress fields. Misfit between the model and the observation has been minimized with model equations acting as constraints. It has been observed that assimilated sea level with scatterometer wind forcing gives much better results in comparison with unassimilated sea level[18,19].

*Future plans*: The future thrust is to improve the retrieval accuracy of ocean parameters, assimilation of oceanographic parameters into ocean weather services and meteorological applications, besides the development of techniques for many newer applications. The status in retrieval accuracy of various geophysical parameters and future targetted accuracies is given in Table 2.

Study of ocean processes and model forcing functions, data assimilation in numerical models and forecast methods, bathymetry mapping, marine atmosphere and boundary layer studies, antarctic snow/ice sheet studies and development of atmospheric correction, retrieval of oceanic parameters and their validation are the other important ocean research perspectives initiated from space. Such an effort is ultimately aimed at providing services to downstream users. One of the major services being contemplated in the country with the availability of Oceansat-1 and 2 is the ocean weather forecast, the structure of which is outlined in Table 3.

Measurement of many ocean parameters such as winds, currents, surface temperature and ocean colour from space is also useful to support various on-going international programmes on global environmental applications such as World Ocean Circulation Experiment (WOCE), Tropical Ocean and Global Atmosphere (TOGA), Global Ocean Flux Study (GOFS), Global Ocean Observation System (GOOS), Committee on Earth Observation Satellites (CEOS) and Indian Ocean Experiment.

**Table 2.** Status in retrieval of geophysical parameters and future directions

| Parameter | Range | Desired accuracy | Accuracy achieved |
|---|---|---|---|
| Sea surface temperature | 0–35°C | ± 0.3°C | ± 0.85°C |
| Surface wind speed | 4–24 m/s | ± 0.5 m/s | ± 2 m/s |
| Surface wind direction | 0–360° | ± 10° | ± 30° |
| Wave height | 1–20 m | ± 0.3 m | ± 0.5 m |
| Wave direction | 0–360° | ± 10° | ± 10° |
| Wave-length | 50–1000 m | ± 10% | – |
| Chlorophyll | 0.1–1.9 mg/cm$^2$ | ± 10% | ± 30% |
| Sea surface topography | 1–2 m | ± 1–2 cm | ± 3–5 cm |
| Surface currents | 0–200 cm/s | – | ± 1 cm/s |
| Coastal bathymetry | 0–50 m | ± 0.3 m | ± 1 m |

## Development of indigenous satellites for ocean applications

With encouraging ocean research results from space and realizing the importance of availability of satellite data on continuous basis for practical applications, efforts are on

**Table 3.** Ocean weather services

| *Daily* (Sea state bulletins) | *3–5 days* (Short-term forecasts) | *Monthly* (Medium-range forecasts) | *Decadal* (Long-term changes) |
|---|---|---|---|
| SST | SST | Ocean circulation | Circulation patterns |
| S.S. winds | S.S. winds | Pseudo-stress | Upwelling patterns |
| Tides | Tides | Tides | Sea level variability |
| Currents | Currents | Coastal circulation | Primary productivity |
| Waves | Waves | Eddies/gyres | Monsoon variability |
| Precipitation | Storm surges | Monsoon prediction | Bathymetry |
| Atmospheric water vapour | Cyclones | MLD | Sea mounts |
| S.S. pressure | Tsunamies | Heat budget | Shore-line changes |
| | Monsoon advance<br>Upwelling<br>Internal waves | Sea level | |

to develop a series of indigenous satellites for ocean application. A brief description of these satellites which are specifically tuned to meet the operational requirements of various oceanographic applications is given below:

### *Oceansat-1*

The first in a series of ocean satellites developed by India towards meeting the urgent requirements of the user community is the IRS-P4 mission, known as Oceansat-1. It was launched successfully on 26 May 1999, using PSLV from Sriharikota, India. The 1050 kg satellite has been placed in a polar sun-synchronous circular orbit of 720 km at an inclination of 98.28° with the local time of equator crossing in the descending node at 1200 h. Oceansat-1 carries two on-board payloads, viz. an Ocean Colour Monitor (OCM) and a Multifrequency Scanning Microwave Radiometer (MSMR) both providing data once in two days. Oceansat-1 is expected to meet some of the critical data requirements of oceanography and ocean meteorology and will then be a forerunner to a fully operational satellite programme.

*Ocean colour monitor*: OCM is a solid state camera operating in push-broom scanning mode, using linear array Charge Coupled Devices (CCDs) as detectors. This camera has 8 narrow spectral bands operating in visible and near infrared (NIR) bands (402–885 nm) with a spatial resolution of 360 m, 12 bit radiometric quantization and swath of 1420 km. OCM has separate wide angle, tele-centric optics and CCD detector for each spectral band, thus, helping to optimize the performance of individual channels. Since the ocean observation is planned at the local time of equator crossing close to 1200 h noon, the camera will be tilted ± 20° in the along-track direction at the nadir view, through a tilting mechanism to avoid sunglint. Details on the specifications of OCM and performance parameters of other similar ocean sensors are given in Table 4.

Since OCM is designed to provide the highest spatial resolution among the contemporary ocean colour sensors with unique regional and global coverage, it is expected to provide ample opportunities/application potentials, for both scientific and commercial uses in the following areas:

- Measurement of phytoplankton and assessment of their distribution, both spatially and temporally; detection of algal blooms and their dynamism
- Identification of potential fishery zones, as well as upwelling and other high productivity regions optimal for fish production
- Delineation of coastal currents and eddies
- Estimation of optical properties and phytoplankton abundance for marine resource and habitat assessment
- Observation of pollution and sediment inputs to the coastal zone and their impact on marine food
  Sediment dynamics, dynamics of estuarine/tidal inlets, prediction of shoreline changes, coastal circulation and dispersion pattern, etc.

*Multifrequency scanning microwave radiometer*: MSMR with its all-weather capability is providing measurements in four frequencies and two polarizations (6.6 GHz V and H, 10.65 GHz V and H, 18 GHz V and H and 21 GHz V

**Table 4.** Performance parameters of some ocean sensors

| Sensor parameters | Sea WiFS | MODIS | OCTS | GLI | OCM |
|---|---|---|---|---|---|
| GIFOV (km) | 1.1 LAC<br>4.5 GAC | 1.0 | 0.70 | 1.0 | 0.36 |
| Swath (km) | 2801 LAC<br>1502 GAC | 1780 | 1400 | 1600 | 1420 |
| Repetivity (days) | 2 | 2 | 2 | 2 | 2 |
| Local time (hours) | 12 noon | 13.30 | – | – | 12 noon |
| Scan plane tilt (deg) | ± 20 | ± 50 | ± 20 | – | ± 20 |
| Spectral bands | 402–422<br>433–453<br>480–500<br>500–520<br>545–565<br>660–680<br>745–785<br>845–885 | 430–440<br>485–495<br>515–525<br>560–570<br>615–625<br>660–670<br>680–690<br>760–770<br>+ 28 NIR & TIR bands | 402–422<br>433–453<br>480–500<br>510–530<br>555–575<br>655–675<br>745–785<br>845–885<br>3550–3880<br>8250–8800<br>10300–11400<br>11400–12500 | 16 Spectral bands each of width in the spectral range of 375–870 | 402–422<br>433–453<br>480–500<br>500–520<br>545–565<br>660–680<br>745–785<br>845–885 |
| Quantization (bits) | 10 | 12 | 10 | 12 | 12 |
| Absolute radiometric Ac | 5% | < 2% | < 10 | – | < 10 |
| Polarization sensitivity | < 2% | < 2% | < 2–5% | – | < 2% |

LAC, Local Area Coverage; GAC, Global Area Coverage; Sea WiFS, Sea viewing Wide-Field of-View Sensor; MODIS, Moderate Resolution Imaging Spectrometer; OCTS, Ocean Colour and Temperature Scanner; GLI, Global Imager; OCM, Ocean Colour Monitor.

and H) with a conical scan system having a constant look angle of 43.13° at each scan position. This can be achieved with a conical scanning of the offset parabolic reflector along the yaw axis of the spacecraft. The circular scan rate of the antenna is around 11 rpm. Two dual frequency sky horns viewing cold space are provided for calibration. MSMR specifications are given in Table 5. The frequency bands have been selected considering the spectral emission properties/characteristics due to various geophysical parameters. The data will be useful for deriving both physical oceanographic and atmospheric parameters. The various geophysical parameters retrievable from MSMR and their estimated accuracy as well as the application potentials are given in Table 6. The specific advantage of MSMR is that it has the frequency channel at 6.6 GHz (V and H) which is not available in any other contemporary satellite during this time frame.

### *Oceansat-2*

Oceansat-2 planned for launch during 2003, will carry a complete set of oceanographic payloads, viz. scatterometer, altimeter, thermal infrared radiometer (TIR) and passive microwave radiometer (PMR). This mission is expected to provide a full range of oceanographic observations such as wind field, wave height, sea surface topography, ocean surface currents, internal waves, SST, etc., which are useful for providing operational oceanographic-related services to users. Details of the proposed Oceansat-2 payloads are given below:

*Thermal infrared radiometer*: The thermal infrared scanner will have an observation capability in five spectral channels namely one in visible, two in short/middle infrared and two in split thermal infrared wavelengths for measurement of SST. The visible channel is to help in identification of cloud contamination of thermal channel outputs. The instrument would be designed to provide two views of any given point on the ground through two different atmospheric path lengths of the same region. Such a configuration is expected to provide more accurate SST values.

*Wind scatterometer*: A pencil beam wind scatterometer has been proposed at Ku band (13.73 GHz) for monitoring surface wind speed and directions over the ocean. A

**Table 5.** Specifications of MSMR

| Frequency (GHz) | 6.6 | 10.65 | 18 | 21 |
|---|---|---|---|---|
| Polarization | | V and H | | |
| Orbit inclination | | 98.25° | | |
| Altitude | | 720 km | | |
| Antenna diameter | | 862 × 800 mm | | |
| Look angle | | 43.13° | | |
| Spatial resolution (km) | 105 × 68 | 66 × 43 | 40 × 26 | 34 × 2 |
| Swath (km) | | 1360 | | |
| Temperature resolution | | 1.0°K | | |
| Dynamic temperature range | | 10–330°K | | |

**Table 6.** Parameters retrievable from MSMR and their applications

| Frequency | Retrievable parameter | Range | Expected accuracy | Application potential |
|---|---|---|---|---|
| 21 with 18 and 10.6 GHz (H and V) | Atmospheric water vapour | 0.2–7.5 g/cm$^2$ | 0.25 g/cm$^2$ | Input to medium-range forecast system<br>Humidity corrections to other measurements |
| 21 with 18 and 10.6 GHz (V and H) | Cloud liquid water | 0–80 mg/cm$^2$ | 10.0 mg/cm$^2$ | Input to medium-range forecasting<br>Validation of numerical models |
| 10.6 with 6.6, 18 and 21 GHz (H and V) | Sea surface wind | 2–24 m/s | 1.5 m/s | Inputs to sea state nowcast<br>Assimilation to medium and extended-range weather forecasting<br>Cyclogenesis studies<br>Mixed layer depth<br>Air–sea exchanges<br>Input to ocean circulation models |
| 6.6 with 10.6, 18 and 21 GHz (V and H) | Sea surface temperature | 273–303 K | 1.5 K | Monsoon convective systems<br>Tropical cyclone genesis<br>Extent/strength of El-Niño<br>Latent heat input to ocean models<br>Mixed layer depth<br>Antarctic ice sheet dynamics |

pencil beam scatterometer will have advantages of measuring even low wind speed and decreased ambiguities in estimation of directional accuracy with viewing from four azimuth angles. Wider swath with no nadir gaps has been planned through use of conical scan mechanism and the resultant constant incidence angle.

*Radar altimeter*: A radar altimeter in Ku band (13.6 GHz) with nadir pointing has been planned to make precise measurements of echoes from the ocean surface. Important parameters measured from echoes include ocean geoid, significant wave height and wind speed. It will have a sophisticated on-board signal processor to estimate the shape and timing of a received echo. The altitude precision will be in the order of 10 cm. The sea topography would indirectly yield ocean circulation.

*Passive microwave radiometer*: The main objective of this sensor is to measure the atmospheric integrated water content (both vapour and liquid) in order to compute the most problematic part of trospospheric path delay in radar signals from the altimeter. PMR will be a fixed, nadir-looking microwave-passive sensor, operating at three frequencies, viz. 18, 21 and 37 GHz.

### *Ocean satellites: Beyond 2005*

Studies are in progress for a mission with all-weather monitoring capability with multi-frequency and multi-polarization microwave payloads – both synthetic aperture radar and other passive microwave instruments such as advanced millimeter wave sounders for many oceanographic and meteorological applications.

## Satellites for coastal applications

Concerted efforts are on to launch two more advanced satellites Cartosat-1 and Resourcesat-1, for land applications, which are useful for mapping and monitoring various coastal zone features with several newer applications.

### *Cartosat-1*

This satellite will have cutting-edge technology in terms of sensor system as well as application potentials. It will carry only one payload-PAN with 2.5 m spatial resolution and 30 km swath and have a fore-aft stereo capability. The order of 2.5 m spatial resolution data will cater to specific needs of cartographers and terrain modelling. It would be possible to map elevation differences of better than 5 m. Data from Cartosat-1 will facilitate coastal application studies with mapping capability of cadastral applications. Cartosat-1 is slated for launch in 2001.

### *Resourcesat-1*

This satellite with improved state-of-the-art payloads optimized mainly for agricultural applications is planned to be launched by 2002. It will carry a 3-band multispectral LISS-IV camera as well as improved version of LISS-III and WiFS cameras to provide enhanced applications for agriculture such as multiple crop and species level discrimination and vegetation dynamics studies. The LISS-IV camera will have a spatial resolution of better than 6 m and a swath of about 25 km with across-track steerability for selected area monitoring. Data from Resourcesat-1 will provide improved capability for coastal zone applications, particularly in assessing the conditions of fragile mangrove ecosystems.

## Availability of international satellites

A look at the international scenario reveals that a number of experimental/operational satellites have been launched with sensors designed for ocean applications during the last two decades. The first operational oceanographic satellite was the Seasat in 1978 and it functioned for only three months. During this brief period of operation, it provided a volume of data hitherto not available and demonstrated the feasibility of measuring global surface winds, wave heights, sea surface topography and ocean currents. Later several specific ocean satellites, viz. NIMBUS-7, Geosat, DMSP, ERS-1 and 2, Topex/Poseidon, JERS, IRS-P3, ADEOS, Seastar and TRMM have been launched by many nations (the ADEOS launched by Japan in August 1996 which had many important oceanographic payloads has ceased to function).

Many countries are preparing to launch more ambitious ocean observation satellites to monitor the ocean on a global scale during the next 15–20 years. These include NOAA series, NPOESS series, ENVISAT, EOS colour, ADEOS-II and III, EOS AM and PM series, METOP-1 and 2, EOS Alt 1, 2 and 3, etc. which not only offer the scientific community better opportunities to understand the oceanic processes, but also provide an opportunity to explore those areas which have not yet been studied. Besides, several high resolution commercial satellites are planned. These satellites with capability to provide a spatial resolution of around 1 m at Panchromatic band and 4–10 m at multispectral bands, are expected to further the coastal zone studies. Indian scientists have some access to most of these satellite data.

## Conclusion

To understand how each of its components contribute to the overall functioning of the ocean is important in providing ideas for long-term management and sustainable development of ocean resources. This calls for detailed studies of the ocean dynamics and a proper evaluation of the exploitable potential benefits of marine resources, including the coastal zones. Also the role of ocean in weather/climate to be understood. Towards this, satellite observations undertaken over the last one decade in the country have provided successful results, which are now being used on an operational mode. The availability of number of satellites in coming years along with our indigenous ocean satellites will radically change ocean research.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