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Remote Sensing Applications
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Oceans

9.1. Introduction

Oceanography is the systematic scientific study of the Earth's oceans with the goal of understanding its processes and phenomena. Such a study requires an integrated view of the oceans and their relationships with other aspects of the Earth's overall environment. Surface of the earth is 70.8% water-covered. In the zonal direction, there is no land between 85-90 degrees N and between 55-60 degrees S. At meridional direction, 45-70N, there is more land than water and 70-90 S there is only land (Antarctica).

The average earth's radius is approximately 6371 km and the average depth of the ocean is about 3795 m. Thus the ocean is a thin skin on the outside of the earth. The average height of land is 245 m. Compared to the maximum elevation of about 9,000 m (Mt. Everest) over land, the maximum ocean depth is about 11,500 m (Mindanao Trench).

9.1.1. The need for Ocean Studies

Understanding the oceans is required for pure scientific curiosity, global climate change issues, fisheries/ aquaculture conservation, minerals/energy resource (both renewable and non-renewable) exploitation, coastal zone management, transportation/recreation, marine pollution hazards and submarine communication and acoustic propagation for strategic planning. There are several complementary approaches to studying the ocean: (1) observations, (2) process models, including pure theory and simplified numerical models, (3) simulations of the flow using complex numerical models, (4) combined observational/numerical modeling simulations (data assimilation) and (5) statistical approaches/soft computing techniques like multiple regression, genetic algorithm or artificial neural networks. The boundaries between these are not firm - observational analysis often includes modeling, process models are usually based on observations, complex numerical models are often exploited to understand general processes.

9.1.2. Broad disciplines of Ocean Sciences

The study of oceanography can be broadly classified in to three disciplines of physical, biological, and geological oceangraphy, though a clear demarcation is not possible. For example, ocean colour, which is primarily considered to be a biological parameter, has potential applications in physical and geological oceanography.

- Physical Oceanography - The study of waves, currents, tides, physical water properties, air-sea interaction and the physical forces that cause them.
- Biological Oceanography - The study of marine life and its productivity, life cycles, and ecosystems.
- Geological Oceanography - The study of plate tectonics, the geology of the ocean basins, the geologic history of the oceans and coastal processes erosion, sedimentation.

9.2. Physical Oceanography

Physical oceanography is the study of the physical properties of the oceans. Its goal is to understand the processes at all time and space scales, to simulate these processes, and to make predictions if possible. Some investigators consider dynamical oceanography, dealing with purely dynamics of the oceans, as a separate subject from physical oceanography. This deals with surface and internal waves, air-sea exchanges, turbulence and mixing, acoustics, heating and cooling, wave and wind-induced currents, tides, tsunamis, storm surges, large-scale waves affected by earth's rotation, large-scale eddies, general circulation and its changes, coupled ocean-atmosphere dynamics for weather and climate research/predictions.

9.2.1. Forces acting on Oceans

The external forces that act on the oceans are wind stress, wind-waves, swell-waves, turbulence, circulation, short and longwave radiation, evaporation, sensible and latent heat fluxes, precipitation and tidal oscillations. Solar radiation is the main source of heat energy to the oceans, though only 73% reaches 1 cm depth, 45% 1 m depth, 22% 10 m depth and 0.5% 100 m depth. These parameters consist of the heat budget of the oceans. The internal forces acting on the oceans are pressure/density gradients and viscosity or friction. In studying the ocean dynamics, the concept of scale analysis is very important that is summarized below.

9.2.2. Scale Analysis

A very small set of five equations governs all the motions of fluids from nearly-molecular scale to capillary waves to global circulation. This set of equations is nonlinear, which means that many terms are products of two things that vary. Since we can not possibly solve for all ranges of motion at the same time, direct solutions of the complete governing equations are impossible and computational power to cover all possible motions is simply not enough. The nonlinearities make theoretical solutions difficult. As a result we resort to the science of fluid mechanics, which is a science of approximation that differs from the traditional physics and mathematics with precise answers and proofs. Advanced applied mathematics includes the rigorous, justified approximation methods used in fluid mechanics. Approximations must be justified. Much of the debate about validity of a particular numerical model centers on justifying either the physical approximation or the numerical resolution (time and space scales that are resolved). As a first and necessary step, we evaluate the scales (approximate sizes) of the motion that we wish to resolve. We then perform a rigorous analysis of the governing equations, based on this scale analysis.

For oceanic flows, the aspect ratio, which is the ratio of height/length, is small (order 0.1 or 0.01 or smaller). In this case, motion in the vertical direction will be very different (smaller) than motion in the horizontal direction. For example, in case of general circulation, the horizontal scales are of the order of 100 to 1000 km whereas the vertical motions are of the order of 1-5 km, thus making the aspect ration very small.

Another very useful ratio is that of the earth's rotation time scale to the time scale of the actual motion in the oceans. For surface waves, this is a large number, and earth's rotation is not important. For internal waves, tides, this is of the order of 1, where rotation and changing motion are both important. For the ocean circulation, this ratio is very small, and time dependence is much less important than rotation.

9.2.3. Physical Oceanographic Parameters

The major physical oceanographic parameters include waves (both surface, internal and tsunamis), currents/ circulation, sea surface temperature (SST), sea surface height (SSH), and temperature/salinity/current profiles. SST can either be measured from instruments or estimated from the satellite thermal sensors. The profiles of temperature and salinity are generally measured from conductivity, temperature and depth (CTD) or expendable CTD observations. Expendable bathy thermographs (XBTs) provide only temperature profiles. Estimation of these profiles is possible from statistical or soft computing techniques using surface parameters affecting these profiles (Ali *et al.* 2004). Remote sensing of physical oceanographic parameters is discussed in the section on remote sensing observations. Ocean currents can be broadly divided into surface currents, comprising of 10% of waters and thermohaline currents comprising of 90%. Surface currents are mainly wind driven while the thermohaline circulation is due the temperature and salinity, as the name itself indicates. Surface currents are possible from in situ measurements from current meters, ship drifts. Thermohaline circulation is slow compared to the surface circulation. Using temperature and salinity profiles, dynamic topography can be estimated from which geostrophic velocities can be computed at different depths with respect to a depth of no motion. SSH observations from altimeters are also useful in estimating the geostrophic currents. Similarly, waves can be either measured from instruments like thermo-salinograph, wave recorders of bottom pressure recorder or from satellite sensors like synthetic aperture radar and altimeters. All these parameters are also possible to be estimated through ocean models forced by atmospheric parameters.

9.2.3.1. Ocean waves

Waves are periodic deformations of an interface. Surface waves in oceanography are deformations of the sea surface, i.e., the atmosphere-ocean interface. The deformations propagate with the wave speed, while the particles describe orbital or oscillatory motions at particle speed and remain at the same position on average.

In deep water, particle paths are circles. In shallow water, the particle paths flatten to ellipses. The change from deep to shallow water waves is observed when the wavelength λ becomes larger than twice the water depth h. A change in wave properties occurs also at $\lambda = 20h$. It is therefore useful to distinguish between deep water waves, transitional waves and shallow water waves or long waves. The distinction between deep and shallow water waves has little to do with absolute water depth but is determined by the *ratio* of water depth to wave length. The deep ocean can be shallow with respect to waves provided the wave length exceeds twice the ocean depth. This is the case for example with tides and tsunamis. Tsunamis are long waves generated by any disturbance generating vertical motion in the water column, generally, the submarine earthquakes.

9.2.3.2. Ocean currents

Ocean currents are due to the movement of water in the oceans. These currents could be due to the wind forcing, thermohaline gradients or tidal forcing. These currents are influenced by the earth's rotation through Corriolis deflection. Geostrophic currents are due to a balance between the pressure gradient force and the corriolis force. Geostrophic currents obtained through altimeter SSHA observations or through dynamic height computation using temperature and salinity profiles can be considered as actual currents over a spatial scale of 2 degrees and temporal scales of 2 days. Ocean currents play a very prominent role in transporting heat from equatorial to the polar regions.

9.2.3.3. Sea surface temperature

SST is the water temperature close to the surface. In practical terms, the exact meaning of *surface* varies according to the measurement method. A satellite infrared radiometer indirectly measures the temperature of a very thin layer of about 10 micrometres thick (referred to as the *skin*) of the ocean which leads to the phrase *skin temperature* (because infrared radiation is emitted from this layer). A microwave instrument measures subskin temperature at about 1 mm. A thermometer attached to a moored or drifting buoy in the ocean would measure the temperature at a specific depth, (e.g., at 1 m below the sea surface). The measurements routinely made from ships are often from the bucket temperatures and may be at various depths in the upper few meters of the ocean. In fact, this temperature is often called sea surface temperature.

9.2.3.4. Sea surface height

SSH is the height of the sea surface above the reference ellipsoid. The height above the geoid is termed as dynamic topography. SSH above a reference datum can be measured from tide gauges, whereas sea surface height anomalies (SSHAs) from the satellite altimeter observations. Since we do not have accurate estimations of the geoid, we cannot have absolute height measurements from altimeters. SSH variations are causes by the changes in the heat content of the oceans, currents and tidal oscillations. This is one of the very useful parameter of the oceans as it gives the integrated picture right from the bottom to the surface.

9.2.3.5. Radiation

Radiation coming from the sun is the main source of energy to the oceans. Since the atmosphere is transparent to the short wave radiation, energy reaches the ocean surface in the visible shortwave radiation. The radiation budget comprises of insolation, reflected shortwave radiation, out going longwave radiation. Besides radiation budget parameters, sensible and latent heat fluxes are the components of the heat budget of the oceans. Most of the dynamic phenomena taking place in the oceans are due to this net heat. Even the winds that drive the surface ocean currents are caused by the pressure difference due to the differences in the net heat at different places.

9.2.4. Applications of Physical Oceanographic Parameters and Processes

The physical oceanographic parameters like SST and processes like mixed layer dynamics, upwelling and currents have many applications in day to day life. Some of these aspects are discussed below. Identification of potential fishing zone that uses physical parameters like SST/SSHA is described under Biological Oceanography section.

9.2.4.1. Influence of oceans on weather and climate

Physical oceanographic parameters/processes, through air-sea interaction, play a very prominent role in cyclones, monsoons and climate change. The influence of land-sea breeze in moderating the coastal climate and the impact of El Nino or La Nina phenomenon on the global climate, particularly, on the Indian summer monsoon are the two well known examples.

Using a coupled ocean-atmospheric model, *Mao et al.,* [2000] reported that the rate of intensification and final intensity of cyclones are sensitive to the initial spatial distribution of the mixed layer. *Shay et al.,* [2000] described details of the response of the hurricane to a warm core eddy. Thus, a well-mixed upper ocean layer, due either to the mixing processes or to eddies, may be a more effective means of assessing oceanic regimes for tropical cyclone studies.

Water has amazing property of high thermal inertia, which helps to control our climate and make life on Earth possible. Ocean waters continuously move around the globe as if they were on a huge conveyor belt (Figure 9.1), moving from the surface waters to the deep and back again. Wind, salinity and temperature control this movement. This ocean circulation helps to spread the heat from the Sun throughout the Earth. This circulation also helps in transporting the heat received at the tropical regions to the polar regions.

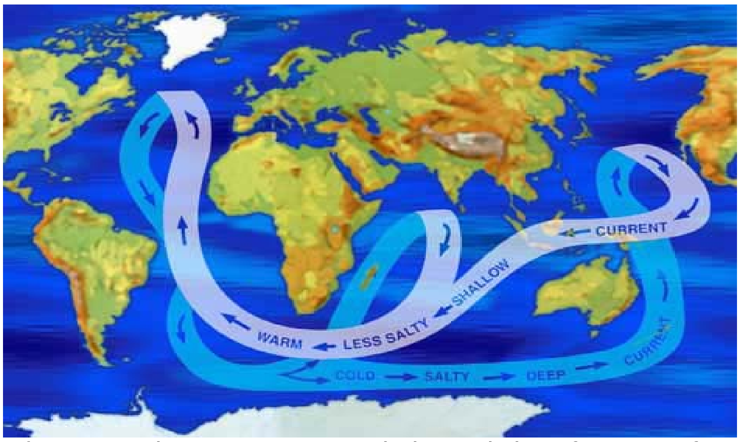


Figure 9.1: The ocean conveyor belt consisting of warm surface and cool deep water circulation (Source: http:// climatechange.wikispace.com)

9.2.4.2. Optimum ship route planning

Information on wind, currents, waves and swell help deciding on the optimum ship route planning through models, by which both time and fuel can be saved. Optimum ship route planning involves providing a vessel with a route recommendation prior to sailing and thereafter closely monitoring the progress of the vessel en route and updating the Master to ensure the vessel achieves either the earliest possible safe arrival or arrives safely at the required time. In case of the latter a clam sea speed setting will be suggested taking into account the weather, sea and current forecast ahead and an allowance for any variation in the expected speed loss. This service can also be of great use on "coastal" routes, by providing the master with advance warning of heavy weather conditions which might be encountered, for example, Tropical Storm conditions. Standard Ship Routing services can also be provided in combination with an onboard voyage planning system. Routing advice will be provided in addition to the regular weather data when sailing any cross ocean passage or in vicinity to severe weather events.

The provision of ship routing services should only be provided by those who have a wealth of experience and can be relied upon 24 hours a day, seven days a week, and are soley dedicated to ship routing. Only through complete dedication, extensive experience and high professional standards can any operator or owner rest easy knowing the best service is being provided. Any company can purport to provide ship routing but the recommendations and results can be entirely different and with disastrous results.

9.2.4.3. Strategic Applications

Acoustic signals that can travel great distances in the ocean are used in a wide range of scientific strategic applications. The important applications of sound propagation are in the detection of underwater targets and acoustic communication. Extremely complicated acoustic feature of the oceanic medium due to its inhomogeneous nature hampers the application of this important property. Speed of sound that is about four times faster than that in air varies with the characteristics of the medium through which it travels. Since the sound speed increases with increasing temperature, pressure and salinity, variations in these parameters control changes in sound speed profiles (SSP).

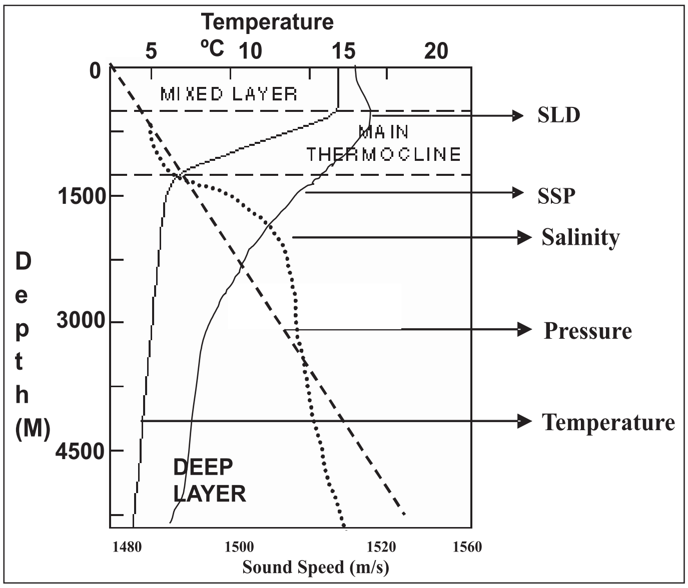


Figure 9.2: Vertical distribution of temperature, salinity, pressure and sound speed

Within the mixed layer, the temperature in the ocean remains almost constant and the pressure increases with depth. Hence, the sound speed also increases with increasing pressure/depth. On the other hand, in the thermocline region, effect of decreasing temperature dominates over the effect of increasing pressure. In this region temperature decreases sharply with increasing depth and hence, sound speed decreases even though the pressure increases (Figure 9.2).

Under favourable conditions, shadow zones that have important bearing on the strategic applications are created below the mixed layer by this property of sound propagation. The vertical gradient of sound speed determines the direction that sound wave propagate that has both regional and temporal variations. Conventionally, SSPs are obtained either by a velocimeter that measures sound speed directly or by using the *in situ* temperature and salinity (T/S) profiles that control the sound speed. Since *in situ* observations of these parameters at all locations in the ocean are difficult to obtain due to the limitations of measurements, it is worthwhile to estimate SSP from surface parameters obtainable from remote sensing platforms. An application of SSPs is the estimation of sonic layer depth (SLD), which is the near surface maximum sound speed in the ocean, knowledge of which is used to reduce errors in sonar surveys.

Other physical oceanographic applications dealing with the biological and geological oceanographic parameters are discussed in their respective sections.

9.3. Biological Oceanography

Biological Oceanography concerns the biology and ecology of oceanic, marine, coastal and estuarine organisms. These range from viruses and bacteria to microbes and phytoplankton, from zooplankton and benthic invertebrates to shellfish, fish and marine mammals. The organisms live in a dynamic fluid easily described as a chemical soup that covers ~71% of the earth’s surface and is intimately coupled to the atmosphere, the seafloor and the land. Thus, to determine how organisms are influenced by their environment, biological oceanographers must function across many sub-disciplines such as biochemistry, genetics, physiology, behaviour, population dynamics and community ecology.

Besides ocean colour, an important biological oceanographic parameter, the physical parameters also influence the biological processes.

9.3.1. Ocean Colour

Information on ocean colour is critical for some of the following applications:

- To identify the Potential Fishing Zones(PFZ) for improving catch efficiency
- To provide an accurate and detailed understanding of the oceanographic environment for offshore platform design - reducing the risks
- Provide timely information on strong currents, eddies, fronts, sediment plumes and mixing zones, for ocean environmental monitoring
- Synoptic maps of ocean colour (chlorophyll), spatial structure of pelagic ecosystem at synoptic scales

Ocean colour sensors provides valuable information for the understanding of some of the key scientific issues like

- Determine the spatial and temporal distribution of phytoplankton blooms with the magnitude and variability of primary production on global scale
- To compute regional and basin scale marine primary production
- To quantify the oceans role in global carbon cycle and other bio-geochemical cycles
- Identify and quantify the relationship between ocean physics and large scale patterns of productivity
- Elucidate the complex mechanism between upwelling and large scale circulation patterns in ocean basins
- Provides a better understanding of the processes associated with mixing along the edge of coastal currents, eddies, western boundary currents and fronts

9.3.2. Applications of Ocean Colour

Since the upwelling brings nutrient rich bottom cool waters to the surface, information on ocean colour can be used in identifying the upwelling regions (other parameters that help in locating the upwelling zones are SST and SSH). These upwelling areas attract fish and are the potential fishing grounds.

9.3.2.1. Coastal Upwelling

Vertical movement or upwelling of deep, cold, nutrient rich water is an important process in the marine ecosystem. Upwelling areas tend to be highly productive and are often the site of important fisheries. Upwelling is largely caused by wind stress and may occur in the coastal ocean and deep ocean. When winds are favourable this varies on time scales of 3 to 5 days and on length scales from a few tens to several hundred of Km. Arabian sea one of the worlds most productive regions of the ocean during summer monsoon, June-September. The coastal upwelling along Somalia and Arabia (Morrison *et al.*, 1998) and along the southwest coast of India (Shetye *et al.*, 1990) turns the coastal waters into a region of high biological productivity. The Open ocean upwelling (Bauer, *et al.*,1991), wind driven mixing (Lee *et al.*,2000) and lateral advection (Prasanna Kumar *et al.*,2001) makes the open ocean waters of central Arabian Sea more productive. Whereas in the Bay of Bengal upwelling reported is mainly confined very close to the coast along the southwestern boundary seems to be episodic (Murthy and Varadachari, 1968 , Shetye *et al.*, 1991). Extensive work has been carried out by many researchers in identification and monitoring of coastal and open ocean upwelling in the Arabian sea using ocean colour sensors data like CZCS and SeaWiFS. Vinayachandran *et al.*, (2004) studied the increased chlorophyll concentration in the waters around Sri Lanka during July 1999 using IRS-P4 OCM images and attributed the enhanced chlorophyll due to the coastal upwelling driven by monsoon winds causing the nutrient enrichment in the surface layer.

9.3.2.2. Coastal currents using sequential ocean colour images

Having 360 meters spatial resolution (high among ocean colour sensors), IRS-P4 OCM data has been used for computing sea surface velocities along North Orissa coast. The patterns of ocean colour images are used as tracers to measure the displacement of surface waters. Surface velocities can be computed using the sequential OCM images. Computed velocities were compared with simultaneous in-situ measurements along the coast using current meter observations with careful navigation of the OCM images with respect to in-situ measurements using ground location measurements provided by ship GPS locations. The pair of OCM images co-registered within an error limit of one pixel. Prasad *et al.*, (2002) found that the measured and retrieved surface velocities using OCM sequential images are highly comparable (R^2=0.99) for both magnitude and direction using the maximum cross-correlation technique for OCM sequential images. Also retrieved the suspended sediment concentration along North Orissa coast for January 2000 using OCM.

9.3.2.3. Seasonal Phytoplankton Blooms

Many researchers studied the seasonality of chlorophyll and phytoplankton blooms in the Arabian sea. Joint Global Ocean Flux Study (GOFS) identified the Arabian Sea as one of the areas for biogeochemical processes study. Under the Indian JGOFS programme studied are confined to the central and eastern Arabian Sea, whereas other countries extensively studied the western Arabian Sea. Arabian Sea experiences significant temporal and spatial variations with respect to biogeochemical properties. During this period due to strong vertical mixing processes, deep rich nutrient water are well mixed with near-surface waters that are depleted of nutrients. The net effect is fertilization of the upper layers of the ocean and stimulation of rapid phytoplankton growth as the daily sunlight increases during spring. Ocean colour measurement provides information on large scale distribution and timing of spring blooms in the global ocean. In the Arabian Sea, the general occurrence of the sub-surface chlorophyll maximum at around 40-60 meters during May (Bhattathiri et.al., 1996). The addition of nutrients into the surface layer leads to the growth of phytoplankton blooms. Banse and English (2000) reviewed the seasonal distribution of chlorophyll-a and phytoplankton blooms in the Arabian Sea. Sarangi *et al.*, (2001a, 2001b) studied the phytoplankton distribution using IRS-P4 Ocean Colour Monitor (OCM) data and observed very high concentrations of chlorophyll-a in the range of 2-5 mg/m^3 in the bloom. Chauhan *et al.*, (2001) studied the surface chlorophyll distribution in the Arabian Sea using OCM data. Vinayachandran *et al.*, (2003) used the satellite derived chlorophyll images to study the phytoplankton blooms in the Bay of Bengal during northeast monsoon (November- February). OCTS (1996) and SeaWiFS (1997-2000) chlorophyll images shows the presence of a phytoplankton bloom in the southwestern Bay of Bengal during November- January. The chlorophyll concentration in the bloom is as high as 2.0 mg/m^3 compared to near zero values before the bloom. Using IRS-P4, OCM chlorophyll maps Vinayachandran *et al.*, (2004) studied the increased chlorophyll concentration in the waters around Sri Lanka during July 1999 and explained the physical processes which lead to the phytoplankton bloom using upper ocean temperature profiles, satellite derived winds, sea surface temperature (SST) and sea level anomalies (SLA).

9.3.2.4. Study of potential fishing zones

One of major applications of ocean colour is in delineating the potential fishing zones by combining the information obtained from SST. It is established that, most of the very good fishing grounds of the world oceans are located in the areas, where upwelling is found to occur. Nearly 50% of the estimated global potential annual fish production comes from the upwelling areas. Modern fishermen require timely, reliable and accurate information on meteorological and oceanographic parameters, such as ocean colour, sea surface temperature, winds, waves, circulation etc. Several researchers have made use of Advanced Very High Resolution Radiometer (AVHRR) thermal infrared data from the NOAA Satellite series to identify the potential fishing zones. Since more than two decades, advanced countries and some of the developing countries have been using sea surface temperature (SST) information to detect thermal fronts, upwelling zones, currents and large scale oceanic eddies to aid the fishermen at sea on an operational basis (Laurs *et al.*, 1981, Gower 1982, Laurs and Brucks 1985).

India has a very long coast line of about 7500 kilometre, spread in 10 maritime states comprising of 3100 fishing villages with 1588 fish landing centres (CMFRI, bulletin). The Potential Fishing Zone (PFZ) forecast information from NOAA-AVHRR thermal infrared data (SST) has been made available to the fishing industry in India since late 1991 on an experimental basis and was made operational from late 1992 (Deekshatulu *et al.*, 1992, Nath *et al.*, 1992). The validation results show that on an average the Catch Per Unit Effort (CPUE) is more along the thermal boundaries in comparison to the catch obtained from other areas. The feedback on the utilisation of potential fishing zone information inferred from SST manifested surface features, revealed that they are highly useful and aid to the fishermen in saving the fuel and search time. Other than physical processes which inferred from SST, chlorophyll/ phytoplankton biomass is another indicator for locations of fish schools in tropical oceans where SST gradients are weak.

With the availability of real-time data from Ocean Colour Sensors and thermal sensors synergistic analysis of IRS-P4 OCM chlorophyll and AVHRR SST was carried out to understand the patterns of variability of oceanic features along the Indian coast at some selected stretches. Chlorophyll and SST features were found coincided at many locations indicating that the biological and physical processes are strongly and closely coupled. Achieved fish catch locations were plotted on the SST and chlorophyll images to understand the relationship with oceanic features and fish catch. High catches were found in the vicinity of matching oceanic features in both the images. Dwivedi *et al.*, (2002) developed an experimental PFZ forecasts integrating chlorophyll with SST off Gujarat and Kerala coast and forecasts were generated during 1999-2000, 2000-01 and 2001-2002. From the composite image only matching features from chlorophyll and SST were demarcated as PFZs and communicated to Fishery Survey of India (FSI), Veraval (Gujarat) and Gujarat Fishery Department for validating these forecasts along Gujarat coast and also communicated to CIFT for validation along Kerala coast. About two folds increase in catch was reported in the pelagic catch during validation phase of 1999-2000 (Solanki *et al.*, 2001). Validation experiments continued for the fishing seasons 2000-2001 & 2001-2002 along Gujarat and Kerala coasts. Catch Per unit Effort (CPUE) with high catch were found in fishing hauls taken in the vicinity of features and comparatively low catch were reported away from the features.

A joint programme was undertaken for the generation of potential fishing zones (PFZ) along East coast of India using the composite of SST and chlorophyll image during the years 2002, 2003 and 2004. Flow chart (Figure 9.3) explains the processing methodology for the retrieval of SST (AVHRR), Chlorophyll (IRS-P4, OCM), and generation of integrated PFZ(IPFZ) chart.

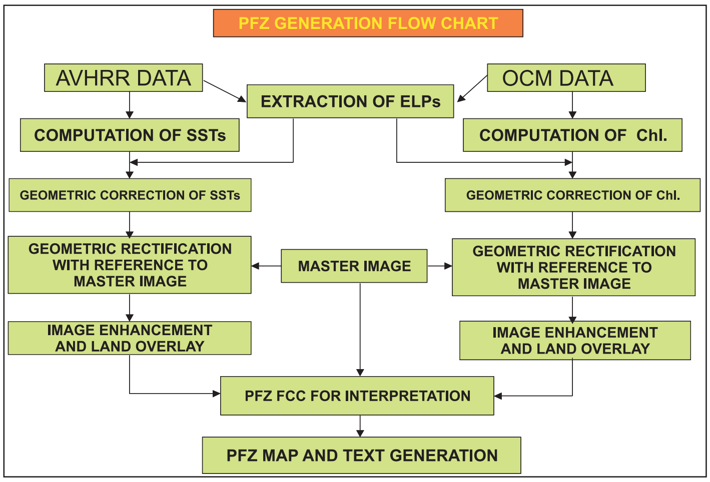


Figure 9.3: Showing the processing steps for generation of PFZ chart using AVHRR and IRS-P4 OCM data

Validation experiments were conducted along North Andhra by National Remote Sensing Agency (NRSA) and Fishery Survey of India (FSI), Viskapatnam base during November 2002, April 2003, December 2003 through - February 2004. Observed that chlorophyll gradients are prominent (moderate to strong) compare to SST (feeble) gradients along the

North Andhra and Orissa coast. All the times it is observed that fish catches are more in the areas where SST and chlorophyll features are strongly coupled. Figure 9.4 shows the SST and Chlorophyll images for the period 14-17th November 2002 and integrated PFZ(IPFZ) chart generated using SST and Chlorophyll image depicting the potential fishing areas valid up to 22nd November 2002 along north Andhra and Orissa coast. In these areas fish catches are about 150- 400 kg for hall and other areas catches are only 10-100 kg.

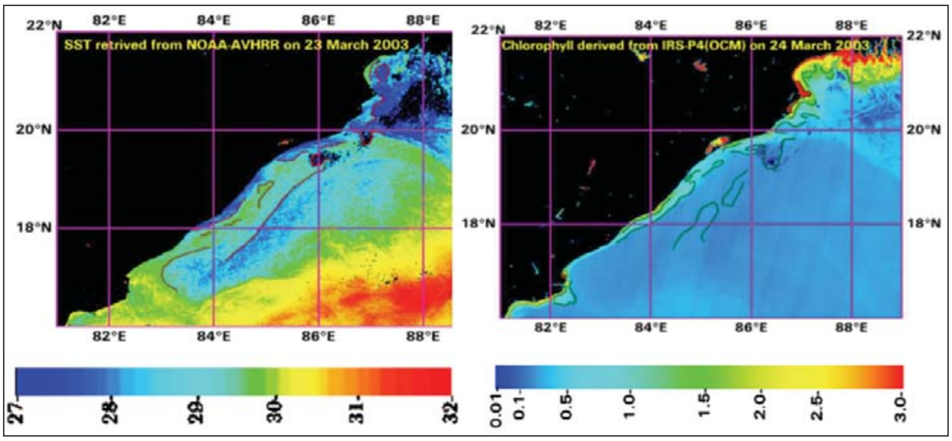


Figure 9.4: Synergy of SST and Chlorophyll derived from NOAA and OCM respectively

A comprehensive validation programme was conducted in collaboration with FSI & INCOIS during the 2004 fishing season along North Andhra and Orissa coast. Figure 9.5 shows IPFZ forecast during 21-24th March 2004 (valid till 28th March 2003) along Orissa and Andhra coast. Plotted fish catches on IPFZ chart observed high catches 100-450 kg in the integrated fishing zones and minimum to nil catches in other areas. Validation is only from the FSI fishing vessels covering a limited areas, depicting the exact fishing locations and actual fish catches.

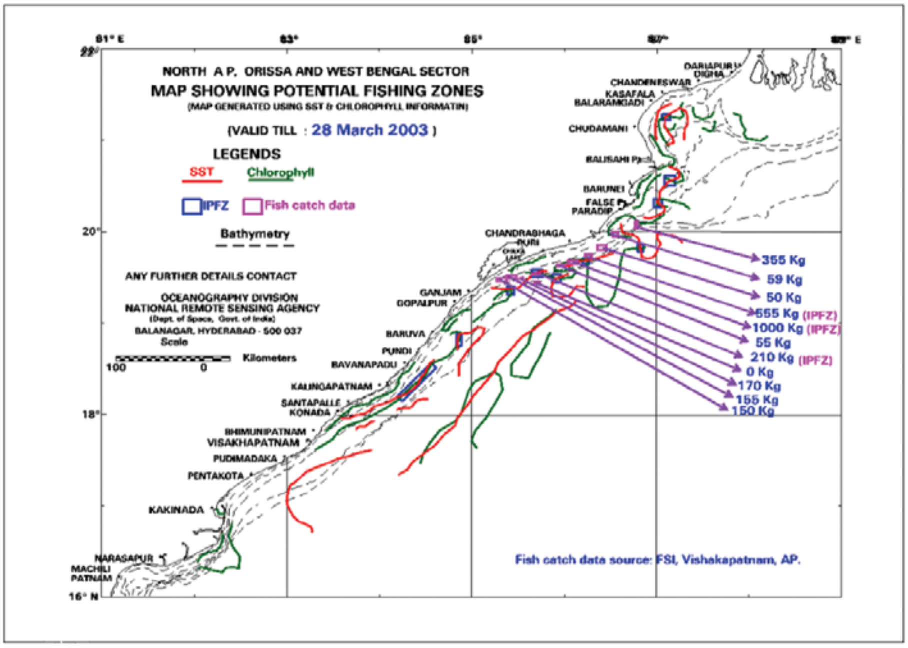


Figure 9.5: IPFZ Validation Experiment (Source: FSI, Visakhapatnam) Map showing Fish Catch data with respect to IPFZ forecast

9.3.2.5. Impact of tropical cyclones on ocean colour

Tropical cyclones are a major hazard in tropical coastal regions, both in terms of loss of life and economic damage. The effect of the tropical cyclone to the cooling of Sea Surface Temperature (SST) is widely known (Gopalakrishna *et al.*, 1993; Murthy *et al.*, 1983, Premkumar *et al.*, 2000), its effect on the distribution of phytoplankton and chlorophyll in the open waters is yet to be documented. In the open sea, tropical cyclones may deepen the mixed layer by 20-30 m (Malone *et al.*, 1993). The nutrients injected to the well-lit euphotic zone in such events trigger the growth of the plankton. Shortly after a cyclone event an increase in phytoplankton biomass and productivity is observed by Delesalle *et al.*,(1993). Satellite ocean-color for chlorophyll concentrations is a new approach for understanding the influence of tropical cyclones on biology, such as phytoplankton blooms, and oceanic physical processes, such as eddies.

Detailed study of tropical cyclone-generated phytoplankton bloom in the eastern Arabian Sea during 19 May – 5 June 2001 using the IRS-P4 Ocean color data was well documented by Subrahmanyam *et al.*, 2002. Processed OCM data using an operational scheme available at NRSA developed by Ramana *et al.*,.(2000). Retrieved chlorophyll from OCM using operational OC2.V.4 algorithm developed by O'Reilly *et al.*, (2000) after applying the atmospheric corrections. Cyclone formed and developed in the eastern Arabian Sea during

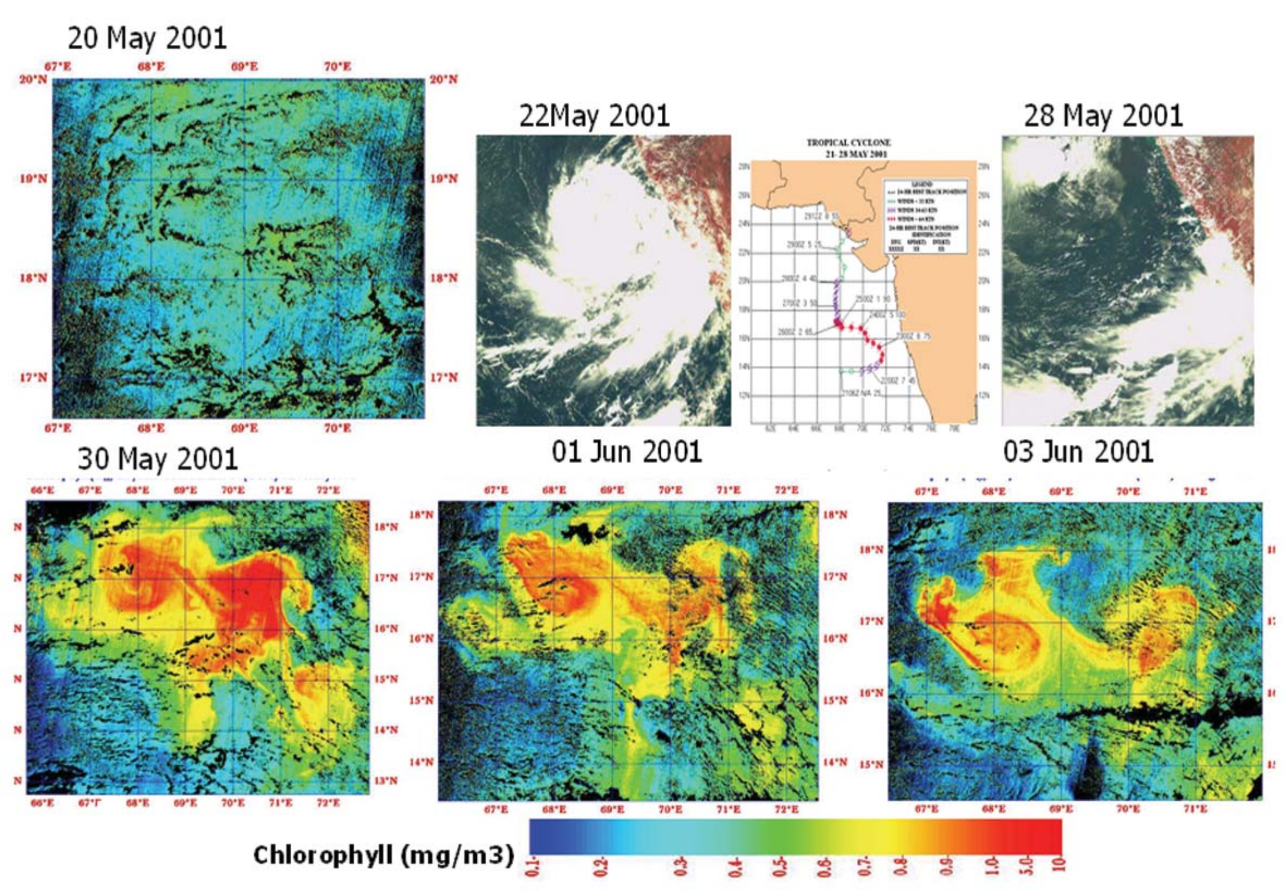


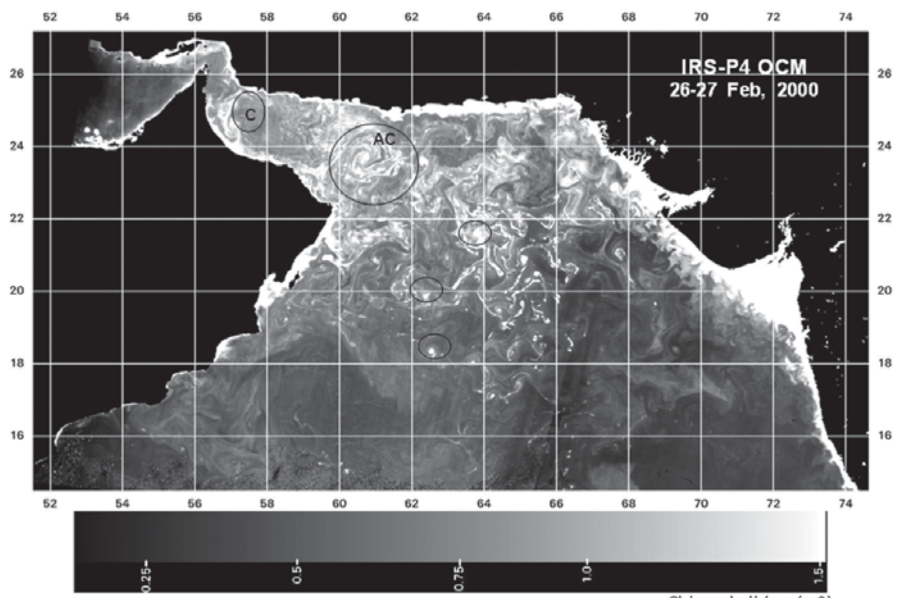
Figure 9.6: Enhanced Chlorophyll for the Tropical Cyclone during 21-28th May, 2001 in the Arabian sea

21-28 May 2001, system intensified and further moved in a north-westerly direction from 14°N, 71.8°E on 22 May to 17°N, 68°E on 26 May, 2001. After 26 May, the cyclone weakened and moved towards north. While processing the OCM images for this area it was noticed intensive phytoplankton blooms with high chlorophyll values (> 5.0 mg m^{-3}) at the centre of the blooms located along 17°N from 67°E to 71°E. Owing to overcast skies a cloud-free OCM data could not be obtained during the period of cyclone (23-28 May 2001) figure 9.6. Prior to the cyclone, the chlorophyll levels were minimum ranging between (0.1 to 0.4 mg m^{-3}) which is in agreement with the reported values in literature, exhibiting the oligotrophic (nutrient depleted) conditions during the period of intense heating (May) in the Arabian Sea (Bhattathiri *et al.*, 1996, Prasannakumar *et al.*, 2000). After the cyclone is fully intensified and moved towards north, higher concentrations of chlorophyll appear as blooms in the region influenced by the cyclone. The blooms look like round-shaped cyclonic eddies of 250-300 km diameter on 30 May between 16° and 18°N. These blooms persist with gradually reduced intensity till 3rd June 2001. It is also noticed that the blooms with decrease of chlorophyll concentration persisted for another one week, after the cyclone vanished from the Arabian Sea.

Another case study was carried out using OCM data in the Bay of Bengal tropical cyclone during December 2000. A depression formed about 800 km southeast of Pondicherry at 11.00deg N, 90.00deg E on 26 November, 2000. It further intensified into a cyclonic storm about 300 km east of Pondichery/ Cuddlore stretch by 29 November, intensified and remained stationary for a day at 12.00N and 82.13E on 30th November and then moved to west and crossed the land on 1st December 2000, further moved to the Arabian sea crossed the west coast with less intensity of 30 knots and gain intensified along 11.0 N and further weekend. During 16-23 November, 2000 the Chlorophyll concentration in the Southwest Bay of Bengal is around 0.25 mg/m^3. After the passage of cyclone there is an increase in the chlorophyll concentration, which reached to 0.55 mg/m^3. Maximum increase in chlorophyll concentration is located around 11.0^{0}N lat. and 81.0^{0}7' E long. where the values increased from 0.35 mg/m^3 to 0.70 mg/m^3 for a few pixels. Study also has been carried for another cyclone in the Bay of Bengal during 5-19th May 2003. Maximum cyclonic winds are on 11th May 2003 around 86.5^0 E.Lon.,12.0^0 N. Lat. Processed OCM data for 5th May (before) and 19th May (after) 2003 and retrieved chlorophyll. These are the only images (partially cloudy) available during this period. Observed enhanced chlorophyll concentration after the cyclone. Chlorophyll increased from 0.35 to 0.85mg/m^3 due to the cyclonic wind mixing.

9.3.2.6. Studies of small scale eddies/gyres

Variability of ocean health can be assessed through the small scale features like oceanic eddies and small scale gyres. Oceanic eddies scoops nutrient rich water from sub surface depths to surface layer in different spatio-temporal dimensions. Indian ocean eddies are transitional in nature, reverse its direction and changes its intensity with the reversal of monsoon. The cyclonic eddies are generally considered as biologically rich with high nutrients and cold temperatures. The dimensions of these small-scale features are clearly visible in satellite imagery. OCM images dated 26-27th February 2000 showing the small scale gyres and spiral eddies in the western Arabian Sea. A strong anticyclonic (AC) spiral eddy with a size of 100 km with high chlorophyll concentration is clearly seen on the image centered around 61.0^0 E.Lon, $24.^0$ N.Lat. Derived chlorophyll values from OCM clearly indicates the location of high chlorophyll eddy, appears to be entraining upwelled water from the Oman coast. West of the Anticyclonic eddy a small cyclonic eddy is seen on the image centred at 57.0^0E.Lon, $25.^0$N.Lat. The presence of two gyre system is confirmed in the chlorophyll image (Figure 9.7). The position of these gyres are similar to that reported by Reynolds during 1992 NE monsoon. Several small spiral eddies are also seen on OCM image in Northern Arabian Sea with high concentration of chlorophyll during last week of February 2000. Contrary to this image OCM derived chlorophyll during January 2003 has shown a large cyclonic eddy centred at 24.0^0 N. Lat, 61.0^0 E. Long. OCM chlorophyll images clearly shown the presence of cyclonic & anticyclonic eddies in this region. OCM data clearly demonstrated the spatial extent (size, area) and the seasonal occurrence of these small scale features and its importance for the study of increased chlorophyll distribution in the northern Arabian Sea.



Cyclonic (C), anticyclonic (AC) and spiral eddies with high chlorophyll concentration in the North western Arabian Sea

Figure 9.7: OCM chlorophyll images showing the Cyclonic & Anticyclonic eddies in Arabian Sea during 26-27 th February 2000

9.3.2.7. River Plumes

Riverine and estuarine plumes contain relatively high concentration of suspended organic and inorganic material which are highly reflective in the visible spectrum. This high reflectance is easily observed by satellite borne ocean -colour sensors. To understand the fate of fluvial nutrients and their possible effects on carbon budget requires an understanding of the sedimentation and circulation processes that control the exchange of material across the continental shelf. The river plumes spread 100 of km across the shelf. The sediment flow towards the equator confirming the earlier flow patterns along this coast during this season. Ocean colour data provides plume information and its dissipation on continental shelves and insight into other processes that effect the rate at which river and ocean water intermix.

9.4. Geological Oceanography

Marine Geology is concerned with the earth beneath the sea including the near shore zones (beaches, marshes, lagoons, and reefs), the shelf seas and -margins. Adjacent to these shallow water areas continental and island slopes connect the shallow water regions with the deep-sea basins that occupy around 80% of the sub sea-surface. Other aspects of marine geology addressed here include ocean circulation, plate tectonics, and critical events in present past global oceanography like sea-level changes. Geological processes at work in the sea are responsible for various marine environments ranging from the near shore estuarine and coastal environments to those of the deep ocean basins.

The shoreline is in a dynamic state, constantly adjusting to the combined effects of natural processes. Winds, waves, tides, and currents are the major agents active in the depositional and erosional processes. Coastal zone has been fastest emerging region in the globe for developing port, harbour cities and became gateway to the global population. Many thickly populated cities such as Mumbai, Shanghai, Seoul, Karachi, Istanbul, Jakarta, and New York are located on the coast. Considering the total global population about twenty percent of the population lives within 30 Km and twice within 100 Km (Cohen *et al.*, 1997). More than 75% of the human population lives within 60 km of a coast by 2000 (Michener *et al.*, 1997). Human pursuit for food, habitation, commerce, recreations, and defense expanded beyond coast into sea for centuries. Growing population demands for more land, this ultimately leads to fast depletion of coastal land cover and loss of coastal habitats. Many coastal wetlands and sandy beaches are reclaimed for settlements and infrastructure developments. Global warming, increased land and seas surface temperature and decreased global ice cover resulting rise in sea level. Frequent storm and wave energy increase flood, erosion, and sedimentation in some areas of the coast (Ericson, 2006). More land habitations are under inundation by sea and hydrochemistry of ground and seawater, ecosystems characteristic, biodiversity, and human health are also been affected. The responses of the coastal system to climatic changes and anthropogenic impact are well recognized. Hence, oceans become more energetic and complex than expected. Understanding of changing physical, biological and biogeochemistry characteristics of the coastal system and their dynamics are insufficient due to time lag between process and system response.

The marine ecosystem is the largest aquatic system on the earth which receives light and heat energy from sun, mixed by the wind, mechanical energy from the tides (Nixon, 1988) and hence more dynamic. It is intrinsically linked global climate changes in many ways as it covers 70% of the earth's surface and act as a huge reservoir for both heat and carbon dioxide. Ocean plays very active role in climate conditions by releasing heat and carbon dioxide from ocean surface or takes it to atmosphere (Bryan and Manabe, 1985).

The coast is a transitional zone between land and sea and integration of marine and terrestrial ecosystems. Human needs mounting force on the coastal ecosystem to a new changing environment. Both industrialization and urbanization have claimed more coastal land areas. Industrial and urban waste contaminations over a long period jeopardize the coastal ecosystem integrity including stability, sustainability, biodiversity, community composition, etc. (Burke *et al.*, 2001[a]). The changing and dynamic nature of the coast and coastal zone mean that it rarely fits within the static human boundaries often used for administrative and planning purposes (King, 1998).

Integrated Coastal Management (ICM) is a dynamic process by which decisions are taken for the use, development, and protection of coastal/marine areas and resources. Most often-coastal zone management approaches are integrated, adaptive, and experimental (Burbridge, 1999; Walter, 1997) evolved within traditional sectoral, political, socioeconomic boundaries. It recognizes the distinctive character of the coastal zone itself a valuable resource for current and future generations (World Bank, 1996). An effective coastal management plans for sustainable coastal development need thorough knowledge on short and long-term processes, its response to natural disaster and anthropogenic hazards. ICM analyzes conflicting coastal and ocean usages, interrelationships and implications between physical processes and multisectoral human developments. A successful coastal management ensures sustainable development of coastal area, protect marine resources, reduce vulnerability of coastal habitats from natural hazards and conserve biodiversity by maintaining ecological balance sufficiently among all support systems. The adaptive management is a conceptual approach and an implementation strategy to cope the uncertainties. Adaptive management provides effective approach to tackle uncertain complexities in natural resource system and its processes. It has capacity to adapt by learning from their surroundings and incorporate timely information from system itself (Lee and Lawrence, 1986). This procedure can be carried out at all levels from planning, designing to implementation and extend beyond at regular intervals for midcourse corrections. The following sections provide a comprehensive detail to the readers on various coastal issues related to coastal ecosystem functions, vulnerability and ecosystem health and coastal processes including the highlights on application potential of remote sensing data and Geographical Information System tool (Sridhar, 2008).

9.4.1. Geological Processes

Coastal changes have different order of magnitude and dimensions and also varies from site to site. Climatic changes, sea surface warming, polar ice melting and sea level oscillations are long-term processes that have impact on the global coastal zone. Relative sea-level rise, due to whatever cause, has a number of biogeophysical impacts such as increased erosion and flood potential. These processes could modify the coastal physiography at a steady and slow pace. Short-term processes such as tsunami run up, storm surges, cyclone and floods devastate coast through beach erosion, inundation, and saline water intrusion and sedimentation. The fluctuating biogeochemistry can stress coast and marine systems (Michener *et al.*, 1997[b]); thus, resilient systems can survive and rest succumbs. This has direct or indirect effect on coastal environment and socio-economics of the coastal people (Nicholls, 2003). Both long and short-term coastal processes have unique and common causes and effects with regional and global scale implications. At large, an effective coastal management looks into long and short-term processes and their responses to natural and man made changes.

9.4.1.1. Long-term changes

The current prediction of global sea level estimates a rise between 0.1 and 0.9 meters by 2100 (IPCC, 1998). The potential impact of sea level rise on the coastal zone has drawn much attention in the recent years. Impacts of global warming and sea level rise are inundation of low lying and loss of coastal wetlands, shoreline erosion, flooding due to frequent cyclonic storms, salt water intrusion into freshwater aquifers, change in sedimentation pattern and salt water mixing into estuaries, rivers, bays due to altered tidal range, change in water quality and marine productivity (Tsyban *et al.*, 1990). Climate changes have significant impact on river basin sedimentation and sediment flux. Raising sea level floods the river mouths, this can reduce the sediment transport to the sea. Nicholls *et al.* (1999) estimated that as much as 22% of the coastal wetlands could be lost throughout the world by the 2080 due to sea-level rise. Corals and mangrove ecosystems may suffer due to sedimentation or hypersalination. Sea level rise is likely to accelerate coastal erosion at the seaward margins and wetlands or add new areas that are now retreating and initiate erosion on new beaches that are presently stable or accreting (Bird, 1987). Sea level rise tends to move waves further closer to the shore and increases the capacity of alongshore transport. Higher sea level, can allow waves to attack untouched coastal and enhance alongshore transport (Sorensen, 1978). Enhanced long shore transports render new areas to erosion or accelerate erosion at one area and propagate to nearshore waters. Nutrient rich sediment flux enhances productivity and blooming. Blooming in coastal waters could leads to fall in dissolved oxygen (eutrophication) and marine mortality. Nevertheless, high turbidity can also control light penetration and decrease primary production.

The estimation of coastal evolutionary tendency, however, is a difficult science due to the variety of spatial and temporal scales over which coastal changes occur, and the inter-dependence between different components of the coastal system (Nicholas and Jay, 2001). Both long and short-term processes contribute to morphodynamics and evolution of the shoreline. However, knowledge on the response of coastal system to both long and short term processes at various stages of project implementation enhance understanding of coastal engineering and resource management problems for successful coastal resource management.

9.4.1.2. Short-term changes

Both natural and human-induced factors are responsible for shoreline variability and evolution. Tides, wind, waves, currents, and storm surges are the major forces responsible for shoreline dynamics. The study of coastal morphodynamics reveals the dynamic evolution of shoreline owing to forced mechanism over a wide range of spatial and temporal scales. Tides have predicted cycles and generate current to move sediments in and out of the coast. The combined action of low tides and strong shoreward winds can transport huge sediments from beach into dune in a short period.

Waves and currents can act locally to move suspended as well as bed load within and to near shore as well as arrange beach sediments to shape the coast. A single storm event can remove the entire stretch of large coast within few hours and alter the coastal morphology considerably. The magnitude of such changes depends on intensity and duration of the storm. Waves and wave-derived currents are responsible for seashore sediment transport. The wave propagated from deep ocean to shallow water break obliquely to generate alongshore currents. The convergence of wave rays due to refraction on small-scale changes in bathymetry concentrates wave energy along the coast and is a probable cause of erosion. The alongshore currents move sediments through length of the coast. Construction of coastal protection structures such as jetties or breakwaters in one location can disturb the entire coastal system altering the existing sediment budget. This upset the mechanism of coastal morphology and hydrodynamics. Sediment budget finds net sediment loss and gain by accounting the rate of sediment supply from all sources and the rate of sediment loss to all sinks from an area of coastline. Sediment exchange between the beach and the shelf is regulated by fluvial, tidal, coastal and ocean currents and is an integral part of the seashore sediment budget. Sediment budget quantifies the effects of changing sediment supply on the coastal system necessary for large-scale morphological responses of the coastal system and shoreline behavior.

Human intervention in natural processes is accelerating erosion rates, perhaps by a factor of about two on a global scale (Vitousek *et al.*, 1997). Much of the problem of managing beaches and dunes in developed areas relates to the conflict between the human desire for a system that is stabilized to make it safe, maintain property rights or simplify management and the tendency for a healthy natural coastal system to be dynamic (Nordstrom, 2003[a] & 2003[b]).

9.4.1.3. Coastal changes due to shoreline development

Coastal zone is highly sought by human for residential, commercial, recreational and defence usage. Overexploitation of living and non-living resources has caused irreparable damage to the coast and its habitat. Frequent natural disasters and man made hazards like indiscriminate conversion of beaches and dunes to built-up areas, mangroves and wetlands to aquaculture sites, foreshore to ports and harbours, estuaries and tidal inlet to navigation channels have aggravated the coastal processes, specifically coastal erosion and accretion. Hence, construction of shoreline protection measures along the eroding coasts has become unavoidable. Aggravating calamities like global warming, sea-level rise, deep-sea earthquake, tsunami, hurricane, tropical storm and flood have caused concern to costal zone management world over. The problems related to coastal processes other than human induced erosion and accretion are frequent storms, heavy rainfall, flooding, river breaching, and inundation of deltaic flood plains above the intertidal regions. Nicholls (1998) has indicated that the accelerated sea level rise in coming decades to makes general erosion of sandy shore and more likely to change the local coastal conditions particularly in sediment supply. The reduction of sediment delivery, lack of beach nourishment into bays end up in increased overwash and creation of new inlets, inundation of marsh habitat and increase in open water habitat. The changing environmental scenario has forced dedicated restoration of coastal marine habitats such as estuaries, wetlands, mangroves, beaches, dunes, barrier islands and corals and conservation of their biodiversity to preserve socio-economic and environmental quality of mankind.

9.4.1.4. Physical forcing and sedimentation process

Movement of sediment in the coastal region is a natural phenomenon. Current forces mass transfer and conservation of sediment along shoreline. Currents are result of forcing mechanism driven by wind, wave or thermohaline. The currents move loose sediments from source to sink within the transporting cycle as the result, tidal inlet channels generally suffer heavy sedimentation from long shore input of sediments induced by waves. The natural sedimentation areas are known as shoals, flats, banks, sheets, bars, etc. These areas reduce the navigability of the channel due to shoaling. In a wave dominated coast, the sediment transporting capacity of the hydraulic system is reduced due to the decrease of the steady flow (currents) and oscillatory (waves) flow velocities and related turbulent motions that result in sedimentation problems. Areas, where wave energy is relatively low, tidal conditions dominate due to restricted fetch or offshore conditions trap or deflect incident wave energy, as the results the inlets at low energy regime are greatly affected by erosion related problems. A shoreline said to be in equilibrium, when the sediment input volume is balanced by outgoing volume. The estimation of sediment transport in given a cell (defined space) over a period is called sediment budget. A sediment budget balances sources and sinks of sediment. Such budgets are often formulated at a regional scale together with the resultant morphology change for a particular area and time period. But in a classical sediment budget approach, the dynamics of the processes underlying the transport gradients responsible for the sources and sinks is not resolved. However, Oceansat- I, Ocean Colour Monitor (OCM) is a high resolution ocean colour

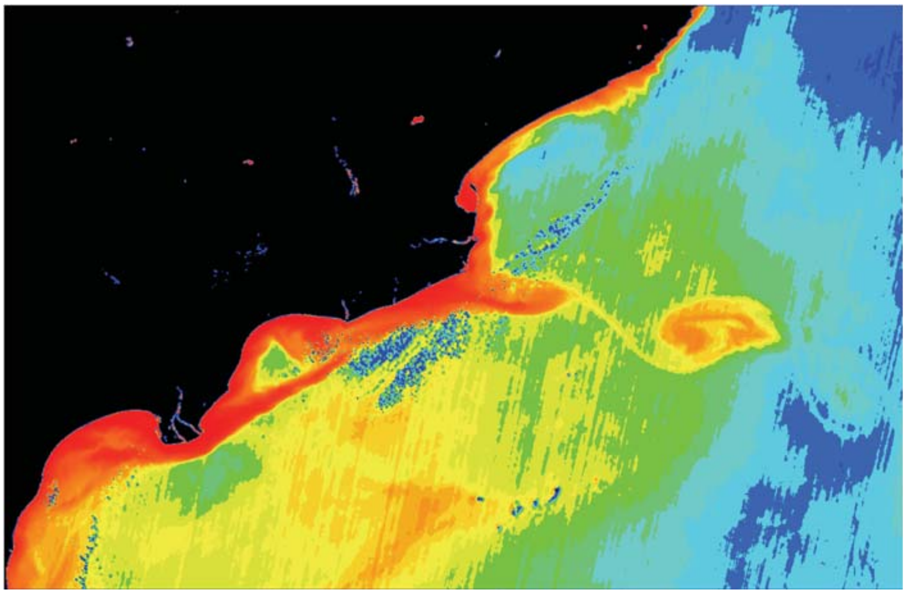


Figure 9.8: Oceansat –I, OCM SCC data showing sediment plume off KGB

data useful mapping surface sediment concentration and sediment dynamics like littoral transport, river flux and sediment plumes (Figure 9.8).

9.4.2. Coastal Ecosystem functionality and vulnerability

The functional significance of coastal ecosystems is environmental, esthetical, and economical. Coastal wetlands and tidal flats regulate nutrients, filter sediments, toxins, and pollutants to safe marine lives (Burke *et al.*, 2001[b]). Estuaries, lagoons, and salt marshes provide feeding, spawning, nursing ground, and shelter for many marine animals and their juveniles (Lean and Hinrichsen, 1992). Costal ecosystems are also a vital source for food and recreation. Coast zone provides gamut of services as ports of commerce, primary producers of fish, shellfish, and weeds, source of industrial, household products, and construction materials. The beaches, dunes, and mangroves buffer hinterland and protect from storm, high waves including tsunamis. Coastal areas are highly vulnerable to environmental impact from anthropogenic pressures and climatic changes. Over the past 30 years, destructive nature of cyclone is increasing to cause damage and loss of lives (Emanuel, 2005). Increasing land and sea surface temperatures and high sediment and nutrient loads brought by rivers into coastal waters severely alters the coastal water quality and health of aquatic systems. Changing wind and wave pattern manipulates coastal productivity and fisheries by varying temperature, coastal upwelling, and nutrient cycle. The coastal margins are prone to erosion, intrusion seawater into freshwater and flooding and inundation of low-lying areas. Slight sea-level rise substantially inundate coastal wetlands, where tidal excursions are at large (Harvey and Caton, 2003). Periodic fluctuations in sea surface temperature resulting coral bleaching and mortality (Montgomery and Strong, 1994). Frequent temperature and rainfall fluctuations have disturbed mangrove species biological diversity. Depending on local topography adaptable mangrove species have moved landward during past sea level rise (Alongi, 2002). Overall, the status of coastal ecosystem health is under extreme stress and requires monitoring mechanisms and management solutions for ecosystems protection and conservation.

9.4.3. Role of Spatial data in coastal ocean studies

Ecosystem-based management requires integration of multiple system components for identifying and striving sustainable outcomes, precaution in avoiding deleterious actions, and adaptation based on experience to achieve effective solutions (Boesch, 2006). Over the past few decades, remote sensing and GIS techniques have been increasingly used to support the environmental monitoring and assessment of estuarine ecosystems because of their cost-effectiveness and technological soundness. The remote sensing and GIS forms a powerful tool for multi-scale spatial data acquisition and analysis in continuum of a complex ecosystem.

Satellite remote sensing had undergone a tremendous development since 1972 especially in mapping, monitoring coastal zone by overcoming limitations in accessibility. Several land and ocean sensors onboard satellites with 1 m to 1 km spatial resolution provide an excellent scope for mapping and monitoring coastal habitats at desired scales. Remote estimates of coastal water quality indicators, such as dissolved organic and inorganic substances, suspended particulates matter, temperature, salinity, turbidity, oil and thermal pollutants have been under development for almost two decades (Xiaojun Yang, 2005). Ocean colour sensors are having high radiometry to measure water quality with reasonable accuracy and precision. Thermal infrared sensors provide sea surface temperatures (SST) and features with varying sea surface temperatures. Large-scale regional pollution (oil) and land discharge are monitored with ocean colour and thermal data. Transient nature of the dynamic coastal system exposes inadequacy of passive sensors to monitor short-term processes or events during night and cloudy days. Microwave sensors have overcome these limitations but normally available in course spatial resolutions. However, microwave sensors have large footprint of several kilometers with short-term acquisition capability. Some of the important microwave sensors are microwave radiometers (0.3 cm to 100 cm), scatterometers, altimeter, Profiling Radar and Synthetic Aperture Radar (SAR). The scatterometer infers sea surface wind by measuring backscatter from ocean surface. The altimeter helps ranging and sea surface height measurements where as SAR measures the surface ice, wind, sea state, marine pollution including oil slicks.

Geographic Information System (GIS) is a powerful tool for spatial data base management and modeling. The combine power of 1) Remote Sensing, 2) GIS, and 3) Global Positioning System (GPS) provide precision mapping, timely monitoring, and evolution of ecosystems vulnerability. Coming sections provides a brief account of different coastal ecosystems, their status and vulnerability studied using satellite data under GIS environment.

9.4.3.1. Ecosystem Assessment

India has been identified as one amongst 27 countries, which are most vulnerable to the impacts of global warming related accelerated sea level rise (UNEP, 1989). The ecosystem distresses are widely prevalent in both aquatic and terrestrial ecosystems. Ecosystem health assessments require analysis of linkages between human pressures on ecosystems and landscapes, altered ecosystem structure and function, alteration in ecosystem services, and societal response. The assessment of ecosystem integrity is concerning biodiversity, ecosystem functions, and stressors. Effective diagnosis requires exploring and identifying the most critical of these links (Costanza, 1992). A healthy ecosystem is being stable and sustainable, maintaining its organization and autonomy over time and its resilience to stress. Linking ecosystem health to the provision of ecosystem services and determining how ecosystem dysfunction relates to these, services are major challenges (Rapport, 1998). Ecosystem health is as much about implementing strategies in environmental management.

The existence of diverse faunal and floral communities over centuries suggests that ecosystems are adapted to cyclic natural phenomena such as seasonal storms and climatic fluctuations. In contrast, status of ecosystem health and extinction of many florae and fauna show human disturbances are generally continuous, non-cyclic events for which organisms are not adapted as the frequency of these activities and their impact increases with increasing human populations and human use of the ecosystem. The following sections describe the processes of environmental transformation leading to degradation in three coastal ecosystems of India viz. Kadmat coral reef, Pichavaram mangrove forest, and Pulicat lagoon.

9.4.3.2. Coral Reefs Ecosystem

Corals are sedentary marine animals in the tropics. The corals play an active role in the global climatic changes by acting as carbon dioxide sink and marine productivity. Coral are colonial animals, thrive on firm substratum with a temperature range of 25 to 29^{o} C, salinity of > 28 psu and sufficient light for symbiotic algal production. Elevated water temperature, fall in salinity, increase in sedimentation and nutrients can cause coral bleaching (Bell, 1992; Brown, 1997). Under physical stress, corals expel brown-green algae from within their body and become pale called *'coral bleaching'*. Bleaching exposes coral to more solar radiation and mortality and this is an indicator of environmental change.

Recent years, Lakshadeweep corals in the Arabian Sea experience frequent bleaching and mortality (Figure 9.9) and this is attributed to worldwide sea surface warming due to El Nino (Arthur, 2000[a]). During 1997-98, the under water survey by remotely operated vehicle mounted with underwater camera showed less than 1% of live corals in the reef slope Kadamat coral reef. The SST anomalies derived from TRMM/TMI (Tropical Rainfall Measuring Mission/Microwave Imager) and NOAA AVHRR data of period 1997 - 2003 have showed two different trends e.g., 1) December 1997 to June 1998. (2) July 1998 to December 2003. During first part, the average mean SST was ranged from 28.51 to 31.89°C. From December 97 to March 98, the SST was estimated around 29°C. Later it suddenly rose to 31.89 °C by May 98, which is 3.38°C above previous months. Succeeding months, SST fell from 31.89 to 27.9°C by July 1998 and gradually rose to 30°C till March 2002 and the highest temperature was 31.5°C during May 2002. Both maximum SSTs are corresponding to EL Nino in the central Pacific Ocean (Arthur, 2000[b]; Mc Phaden, 2003). However, bleaching was severe during the first phase. During winter months (December -February) the south west coast of India experience warm *pool*, an event of elevated SST (>2°C at 30°C) without significant coral bleaching suggest that coral can withstand fluctuation of 2-3°C up to 32°C. This suggests Lampshade coral have been experienced a temperature fluctuation of 2 -3°C with a maximum of ~ 32°C. However, in the May 1998, the SST reached a maximum of 31.89°C with a deviation of 3.38°C during that period several bleaching of corals have recorded/reported. These observations confirm that corals are susceptible to climatic changes can withstand high SST up to 32°C, but sudden increase in temperature will stress the corals.

9.4.3.3. Estuarine Mangroves Ecosystem

Mangroves are morphologically adaptive coastal vegetation found in tropical and subtropical climatic conditions. Generally, significant changes in environmental conditions alter the vigor or zonations of vegetation (Jimenez *et al.*, 1985). Worldwide mangroves are under going degradation due to change in sedimentation rates, soil subsidence, insufficient freshwater mixing, lack of tidal forces, and sea level rise.

Pichavaram mangrove forest in the east coast of India is located in between Vellar, Chennavaikal, and Collidam

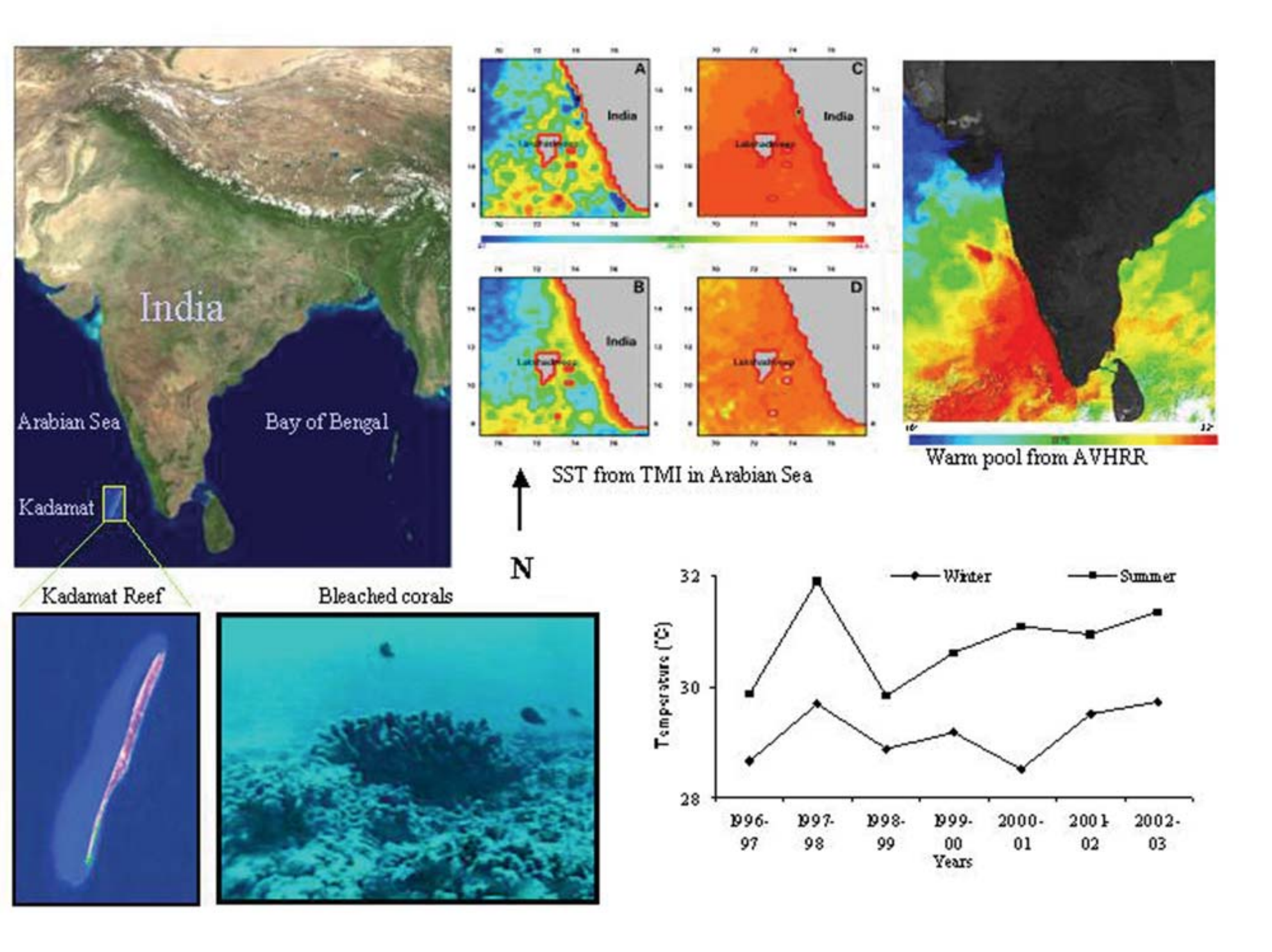


Figure 9.9: TMI and AVHRR data showing peak SSTs during 1998, 2001 and 2003 summer Seasons with a maximum of 31.89° C, rise of 3.38°C during severe bleaching event.

estuaries (Figure 9.10). Three distinct zones are found in this forest namely 1). Core mangrove dominated by *Avicennia* in high intertidal region, 2). Fringe mangroves are predominantly with *Rhizophora* and *Suaeda* found on the banks of creeks and narrow channels, and 3). Peripheral mangroves found in high tide wetlands with mixed mangrove species including *Avicennia marina, Arthrocnemum indicum, Salicornia brachiata, Suaeda maritima* and *Suaeda monoica*. *Avicennia marina*. Over three decades Pichavaram mangroves are undergoing degradation in all the three zones. Several conservation and restoration measure are being taken to keep this estuarine mangroves intact. However, ecosystem based management solution unique to each zones is appropriate for conservation and restoration of this ecosystem health. GIS based decision support was attempted primarily based on the analysis of TM (1987) and Indian Remote Sensing (IRS) satellite LISS (Linear Image Scanning Spectrometer sensors) III & IV of 1998. This study results show that the Pichavaram mangroves are affected by both natural (direct and indirect) and human impacts. Direct and indirect natural impacts are on changes hydrological regime and plant disease. The sedimentation in inlets and poor tidal circulation condition within the estuary combined with and poor rainfall are direct impacts. Pichavaram estuaries are exposed to hydrological venialities due to damming of upstream water (Purvaja and Ramesh, 2000) that can deprive essential sediment and freshwater supply to mangroves is an indirect impact. Cutting and felling of mangroves for timber, fodder, and fuel, conversion mangrove wetlands to aquaculture and agriculture developments are impacts due to human activities.

The GIS analysis results show that the fringe and core mangrove areas are prone to both direct and indirect natural impacts. The fringe mangroves are inaccessible to human and animal and hence the degradation of fringe mangroves is largely due to hydrological changes. Apart from the reduced flow of freshwater and sediment supply, large mangrove seedlings are immobilized and prevented from regeneration in lieu of old degraded mangroves. The core groups of mangroves occur in high tidal flats have become hyper-saline due to evaporation, poor runoff, and tidal mixing. In course time, even saline tolerant species like *Avicennia* have succumbed to hyper salinity. The peripheral mangroves have been used as a source of fodder, fuel, timber, and accessibility to human and cattle and fall into third category. Therefore, conservation and restoration measure for each zone should be unique and species specific.

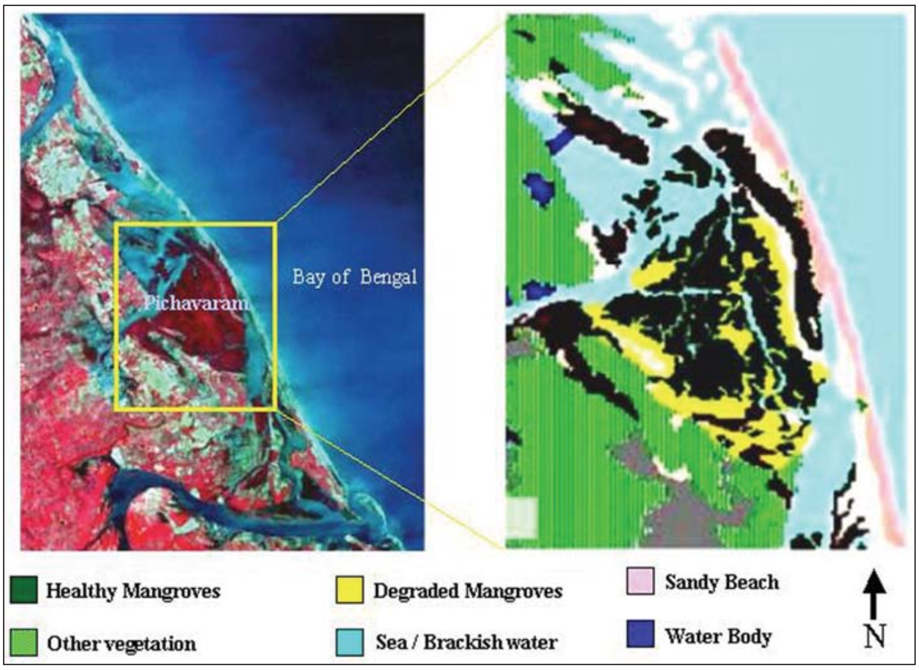


Figure 9.10: Pichavaram estuary with healthy and degraded mangrove forest in IRS LISS III data under GIS environment

9.4.3.4. Coastal Wetlands Ecosystem

The coastal ecosystem functions, health, and services are linked to adjacent marine, freshwater, and terrestrial systems. Uncontrolled developments in any one system have greatest threat to habitats and services. Over exploitation of anyone, undermine subsistence of rest. Wetlands are the most threatened coastal ecosystem. One the most severe impact to this ecosystem in futurity is interference with hydrology and freshwater flow to the coast (Pringles, 2000). Recent days, Pulicat lagoon in the east coast of India, which is the second largest brackish water lagoon and designated Ramsar site having water spread area of 600 Sq Km has declined in biodiversity and productivity. This has lead to the fall in fishery potential and livelihood of local fishing communities. Laterally, Nanda Kumar *et al.*, (2001) have reported poor water quality due to land-based effluents. Water quality of semi-enclosed coastal lagoon depends on hydrological variability like freshwater flow and seawater mixing by tidal circulation. The inlet tidal prism, bathymetry, and nearshore wave energy are the three major factors of inlet circulation. Poor flushing and land-derived pollutants can also affect the water quality of enclosed coastal water bodies (Vieira, 2000).

The study of Pulicat inlet morphodynamics using IRS-LISS III and PAN shows that the two inlets, (one in north and the other in south of Sriharikotta Island) were prone to inlet sedimentation during 1997- 2004. In general, seasonal rainfall and flooding free the sand bars at the inlet. However, the construction of two breakwaters at the southern part of Pulicat i.e., at Ennore Port had accelerated long shore sediment drift towards north that is to Pulicat inlet mouth. As a result, development of well defined sand spit at the southern headland trending towards north is

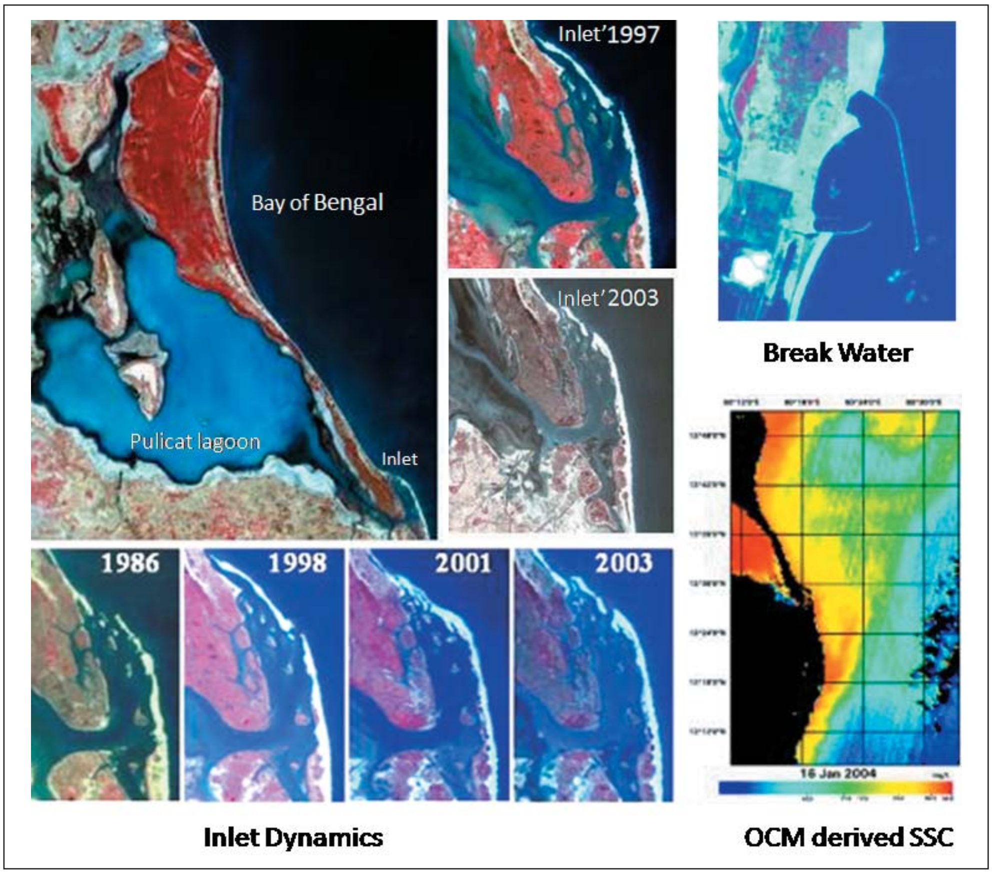


Figure 9.11: Pulicat Lagoon and its inlet dynamics at different development stages as observed from IRS LISS III and OCM data

observed in the satellite data. OCEANSAT-Ocean Colour Monitor (COM) data have showed high sediment transport from Ennore coast in the south as shown in Figure 9.11. The net alongshore drift towards north has been estimated around 0.6 million m^3 (Pranesh, 2000). Increased sediment flux from south, development of channel bars under micro tidal regime, poor surface water flow into the lagoon have resulted complete closure of the inlets during the year 2001. In-situ observations on the water salinity in Pulicat lagoon show hyper saline condition (> 45 PSU) during this period. High salinity in brackish water ecosystem is detrimental to the productivity and biodiversity and biodiversity *per se* can influence human health in many ways (Dobson and Carper, 1993). Whether impact on the coastal ecosystem may be natural or human induced, direct or indirect the resultant effect is irrevocable.

9.4.3.5. Coastal Zone Management and Solutions

Wave-induced alongshore currents provide vital energy for the flow of sand for beach development and shoreline equilibrium profile. The revetment, bulkhead, seawall, breakwater and groins are the most common structures at the approach of harbour entrance to protect it from waves and coastal currents. Some protective structures trap sand and allow beaches to expand up in the up drift direction, but interrupt the flow of sand to other beaches. Coastal structures have both positive and negative affects on sand movements along shoreline. Some structures could accumulate sediment around one segment at the expense of destabilizing other as happening at Kadamat Island coast (Figure 9.12). Structures located too close to the ocean are vulnerable to severe damage during cyclonic storm. Other practical difficulties of the coastal structures are cost effective maintenance and operations. Beaches are natural shore protection structures; when maintained at proper dimensions it can effectively dissipate wave energy. When beaches have narrowed because of long-term erosion trends or severe storms, beach restoration is often proposed (Anonymous, 1989). Beach nourishment technique directly increases the beach width by depositing sand and cost effective. Some of the advantages of beach nourishment are it provides 1) a wider recreational beach, 2) its protection to shoreline structures, 3) dredged material can be nearby sources and 4) reclaimed to other beach management methods in the future. Beach nourishment can also protect threatened or endangered plants in the dune area, and restore habitat for sea turtles, shore birds, and other transient or permanent beach organisms (Greene, 2002). Still, the technique could be detrimental to marine lives both in source and drop

Figure 9.12: Concrete revetments to control the wave run up disturb the natural beach profile at Kadamat Island reef area located in the Arabian Sea

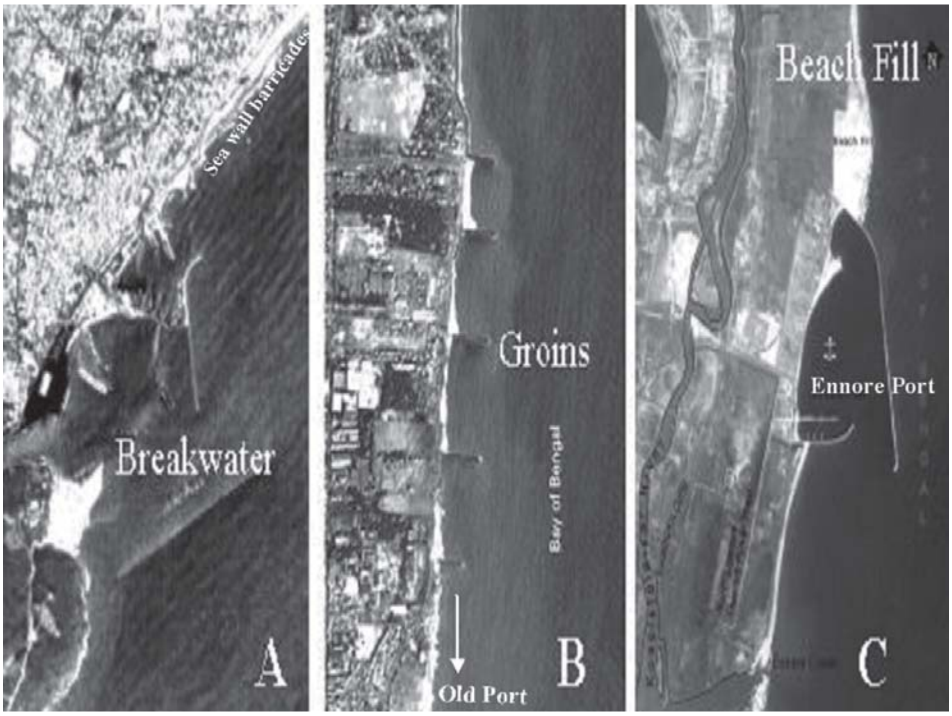


Figure 9.13: Coastal structures irrespectively cause adverse effects on the coast, classic examples are A- Vishakapatnam, Sea wall constructed to control erosion in the beach north of port break waters, b-Progressive groin at Chennai cost north of Chennai Port, C- Beach filling north of Ennore Port, Chennai, all these areas erosion is on the down drift direction of predominant long shore movement

areas due to sand extraction method. Setting buffer zone to natural processes remain active with in the buffer zone and regulate coastal activities beyond the buffer zone is the most effective coastal zone management practice is to allow the natural process remains unrestricted. Satellite data of panchromatic (PAN) mode with high spatial resolution are found to be an important tool especially to monitor the developmental activities as well as the changes in coastline configuration (Figures 9.13 and 14). The technique that it preserves aesthetic values of natural environment and decreases the need for backshore protections. Relocating threatened structures to safer ground potential erosion could another solution but there is a possible conflict between stakeholder (shareholder of coastal enterprise) and government since investor expects financial commitment by government or from insurance.

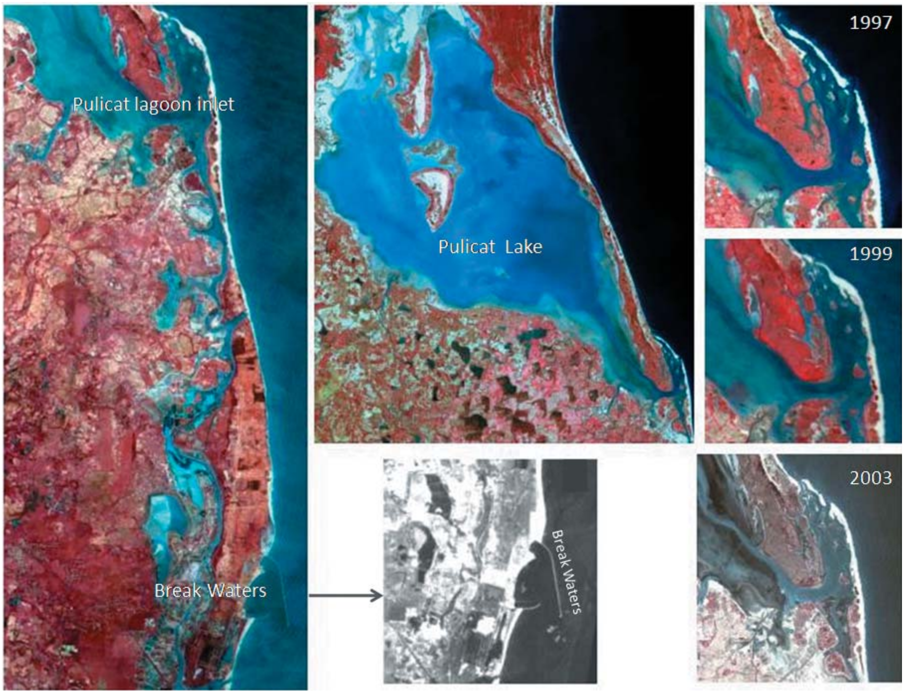


Figure 9.14: Indian Remote Sensing Satellite (IRS-LISS III) data showing Pulicat inlet dynamics before (1997) during (1999) and after to 2003 the construction of Ennore break water in the south

9.5. Remote Sensing Observations

The satellite sensors useful to observe physical oceanographic parameters are a) altimeters b) scatterometers c) synthetic aperture radar and d) radiometers.

9.5.1. Altimeter

The satellite altimeters provide information on significant wave height, wind magnitude and the sea surface height above the geoid or reference ellipsoid. The altimeters in orbit as of today are Jason-1&2, ERS-2, Geosat Follow On (GFO) and Envisat. Indian Space Research Organisation, in collaboration with CNES is going to launch for the first time a ka-band altimeter with a smaller foot print that can provide information closer to the coast.

Satellite altimeter is a remote sensing sensor providing an integrated picture of the atmosphere and the oceans over large spatial and temporal extents. A satellite altimeter is a nadir pointing active microwave sensor designed to measure characteristics of the surface of the Earth. The return signals from oceanic regions provide information on significant wave height, surface wind speed and a range measurement from the satellite to the sea surface immediately below. A radar altimeter operates by timing the delay between emission of a short microwave pulse and the subsequent detection of the returned echo, recording the time and distortion of the returned signal.

The first requirement for any remote sensing instrument designed to observe the Earth's surface is that atmospheric attenuation of the electromagnetic signal be sufficiently small that detection of the return pulse is possible. Through most of the infra-red region, signal attenuation is large due to atmospheric water vapour and gases such as carbon dioxide and oxygen. In the microwave region between 100 MHz and 10000 MHz, however, signal attenuation is small; but certainly of considerable magnitude.

Emission of electromagnetic radiation by an aperture results in diffraction, the width of which is determined by the wavelength of the radiation and the size of the aperture. A uniformly and coherently illuminated circular aperture will produce a diffraction limited beam width defined by Fraunhoffer diffraction theory. At 13 GHz (wavelength ~2.3cm), Ku-band microwave signals emitted by a 1 m antenna will have a beam width of 28 mrad or 1.6 degrees, which from an altitude of 800 km covers a disk of diameter 22 km. For higher frequencies or large antennas, this figure is correspondingly reduced (the latter being the basis for the resolution of Synthetic Aperture Radar techniques).

There is a second problem associated with the frequency of microwave radiation used: when a surface such as the ocean is illuminated by a coherent single frequency source, differences in optical path length cause constructive and destructive interference which can radically distort the signal received by the instrument. For a perfect single frequency transmitter, this produces an infinitely coherent source. In reality, all transmitters have a spectral width, and it is partly to avoid the problems of interference (known as fading) that radar signals are 'chirped', giving them a limited coherence length which is small enough to avoid fading for all but the flattest of reflectors. Bandwidth is defined as frequency spread of the emitted radiation. For ERS-1, the altimeter bandwidth is 330 MHz, resulting in a coherence length of around 90 cm.

A spot size of 20 km is too great for many applications of the data (for example high resolution geoid determination). There is therefore a need for a large antenna, a higher frequency or some other refinement to the emitted radiation. A large antenna on board the satellite is impractical while at higher frequencies, there is greater atmospheric attenuation of the returned signal; therefore the only alternative is the use of pulse limited altimetry. In this way, the leading edge of the return pulse provides sufficient information for an accurate estimate of the ocean height over a significantly smaller area. This is the second reason for chirping the emitted signal as this can simulate a short but sharply modulated pulse, the distortion of which is analysed on its return.

Besides these technical problems, the measurements from the altimeter have to be corrected for the instrumental, atmospheric and media errors which are discussed in the following sections.

9.5.1.1 Errors involved in Altimeter Measurements

The principle of obtaining the height of the altimeter above the sea surface is simple – it is computed as

$$D=Ct/2$$

where, D is the distance between the satellite and the sea surface, C is velocity of light and t is the round-trip travel time taken by the microwave radar pulse to travel from the satellite to ocean surface and back. But obtaining the sea surface height (SSH) or the dynamic topography is complicated. In order to realize the full potential of satellite radar altimeter data, it is necessary to take into account a number of error sources and apply their associated corrections with an accuracy that is compatible with the proposed measurement precision. The two classes of altimeter errors playing significant roles in signal processing are:

(a) Errors that influence the measurement of the height of the ocean surface, (b) Errors that influence the interpretation of the measurements

The origin of these discrepancies and their corresponding rectifications can be separated into the following five categories:

- Instrument Errors
- Propagation Medium Corrections
- Geoid Modelling Errors
- Effects of Temporal Variations in Ocean Surface (Tides, Barometric Pressure)
- Space Craft Orbit Determination Errors

A] Instrument Error

The instrument errors consist of a random part and a systematic long wave part. The random component refers to the precision of the instrument. This precision for the first altimeter flown on Skylab in 1973 was 60 cm which could hardly deduce the sea surface slope across the Gulf stream. This was gradually improved and the present precision for the Topex/Poisodon and Jason-1 is 2-3 cm which is sufficient to detect even small amplitude eddies. The different instrument errors that have to be accounted for are the following:

Tracker Bias: This correction arises from the calibration bias in the discrete samples of the return waveform used in the onboard tracking algorithm which is designed to accommodate linear changes in the height (constant velocity) of the altimeter. When there is a rapid acceleration in height, for example when the altimeter passes over a narrow ocean trench, there is a corresponding induced height error which must be compensated for.

Waveform Sampler Gain Calibration Bias: This correction occurs due to the fact that the amplitude of the received signal varies with the cross section of the monitored surface. An automatic gain controller is used for this signal attenuation adjustment, but rapid changes in echo strength mislead the circuit that tracks the position of the leading edge of the pulse, thereby producing a calibration error.

Pointing Errors: Actually a combined effect of the satellite antenna gain pattern in relation to the antenna off-nadir pointing error on the shape of the return waveform correction occurs when the sub-satellite point is near the edge of the area illuminated by the altimeter. The resulting radar echo distortion produces an unwanted error bias.

Average Pulse Shape Uncertainty and Time Tag Bias: The error in return pulse shape stems from the uncertainty due to random variability of the pulses used to calculate the mean echo. The residuals associated with averaging, say, 1,000 pulses, therefore contribute noise to the measurement. Also, the aging of microwave parts and long term clock drifts can induce height errors. Clock drifts can be accounted for by comparing the altimeter clock with some reference. Drifts in the height measurement induced by aging can be partially compensated for with the altimeter's internal calibration mode.

Propagation Medium Corrections: Two types of errors are included in this category: (a) Total sea state bias of the onboard tracker estimate of mean sea level, and (b) resultant decrease in the local speed of light due to index of refraction changes as the altimeter's signal travels through earth's atmosphere.

Sea state Bias: Two effects contribute to the discrepancy between the electromagnetic (EM) sea level estimated by the onboard tracking algorithm from averaged return waveforms and that of true mean sea level:

Electromagnetic Bias: This correction arises because of the height difference between mean sea level and the mean scattering surface. The way this occurs is through the differential backscattering of power per unit surface area between wave troughs and that of wave crests. This deviation results from the fact that the power backscattered from a small wave facet is proportional to the local radius of curvature of the long-wavelength portion of the wave spectrum. In general, ocean troughs have a large radius of curvature than wave crests; thereby creating a bias in backscattered power towards wave troughs. A greater prominence of small scale "wavelets" super-imposed on wave crests creates an increased roughness which further scatters the altimeter pulse in directions away from the incident radiation; effectively enhancing the bias. The backscattered power measured by the altimeter is therefore greater from wave troughs than from wave crests, thus inducing an EM sea level bias towards wave troughs. A direct correlation between significant wave height (SWH) growth and EM bias increase allows researchers to estimate the required correction.

Skewness Bias: This error occurs because of the height difference between the mean height of specular scatterers and the median scattering surface that is actually measured by the onboard tracker. This is a direct result of the non-gaussian distribution of the sea surface height which shifts the median from the mean sea level toward wave troughs; which in turn also contributes to the EM bias towards wave troughs.

B] The atmospheric effects

The atmospheric errors are introduced into the altimeter measurements because the speed of electromagnetic propagation in the real atmosphere differs from that in vacuum basing on which the altimeter range is estimated. The two major sources of errors are from ionosphere and the troposphere.

(a) Ionospheric Correction: This correction takes into account the variation in the number of free electrons present in the sub-satellite ionosphere location. Typically, the electron content varies from day to night (very few free electrons at night), from summer to winter (fewer during the summer), and as a function of the solar cycle (fewer during the solar minimum). The signal delay encountered is inversely proportional to the altimeter monitoring frequency squared. Topex/Poseidon is the first satellite which carried a dual frequency altimeter to obtain an accurate estimate of the ionospheric effect basing on this property.

(b) Tropospheric Correction: This correction is related to water vapor content and other gases present in the path of the signal. There is both a wet & dry tropospheric delay which must be accounted for. The dry correction can be modeled via surface pressure measurements. The wet portion is typically adjusted from measurements made by an onboard radiometer. It is significant to note that the dry term includes the weight of the water molecules while the wet term accounts for their additional influence on the index of refraction.

C] Geoid Modeling Errors

To obtain ocean dynamics information from sea surface height measurements a detailed knowledge of the geoid is required. This necessity arises from having to refer the acquired surface height and slope data to the ellipsoid/ geoid reference frame (due to the non availability of exact geoid information) in order to yield sea surface topography. The deviations of the geoid from the reference ellipsoid range from -100 m (South of India) to +64 m (near New Guinea). The spatial variability can be large. For example, the geoid can vary by several meters over a few kilometers in areas where there are ocean trenches or ridges. This is in contrast to the variability of sea surface topography which is typically +/- 1.5 m. In order to determine the ocean surface topography accurately it is necessary to know the geoid shape to an accuracy that is required by a feature over length scales of the order of the ocean phenomenon being monitored. There are essentially three ways in which to measure the earth's geoid: 1)Satellite orbit tracking, 2) Direct measurements of gravity, and 3) Satellite altimetry. Gravity fields deduced from satellite orbit tracking data include spherical harmonic expansion terms of rather low degree and order (typically less than 50). Discrepancies in the spherical harmonic coefficients and truncation of the spherical harmonic expansion produce errors in these models, the majority of which are due to inadequate global observation information at the short spatial scales referred previously.

D] Effects of Temporal Variations in the Ocean Surface

These include solid earth and ocean tides and the inverse barometric effects. The gravitational perturbations induced by the moon and sun are the primary factors controlling influence of earth's solid & ocean tides. Although third body effects from the other planets contribute, their magnitudes are negligible in comparison. Since the relative interaction/orientation of the earth-moon- sun system is known very accurately, its effect on the tide-generating potential at any point on earth can be determined rather precisely. This potential can be closely approximated by only the six constituents with the largest amplitude, all of which are diurnal (one cycle per day) or semi-diurnal (two cycles per day). The problem arises from the presence of continental boundaries and complex ocean floor topography and the effects of earth's rotation which introduce large errors in equilibrium predictions of these semi-diurnal and diurnal tides (not to mention the parameterization of friction in these models). Sophisticated models must take into account the time-varying motion of the solid earth, the time invariant latitudinally dependent portion of the deformation, and that portion due to ocean loading forces on the solid earth. However, since the tidal estimations are not very accurate closer to the coast, the altimeter SSH values are not generally considered wherever the ocean depth is less than about 100 m.

The inverse barometer correction is based on a direct proportionality of about 1 cm change in the sea surface height to a change of 1 hpa in the sea surface atmospheric pressure. That is, the ocean surface is depressed in response to the increased atmospheric pressure. Problems can arise in this relationship near storms or near shore where other effects such as wind setup are correlated with pressure. For example, the decrease in SSH due to the anticlockwise rotation of water under the influence of cyclonic winds dominates over the rise due to the pressure drop. Also, while the assumptions hold for weekly and longer periods, there is doubt as to short period ocean response to pressure changes having the same type of characterization.

E] Spacecraft Orbit Determination Errors

The forces, in order of their significance, that contribute to perturbations in the satellite orbit error are parameterized as: a) Gravity, b) Radiation Pressure, c) Atmospheric Pressure, d) Geoid Modeling, e) Solid Earth & Ocean Tides, f) Troposphere, and g) Station Location.

Gravity: The fact that the earth is not perfectly spherical in nature but rather shaped as an oblate spheroid creates an asymmetric potential in earth's gravitational field. The cyclical characterization of this perturbation requires rather a high level of degree and order in the spherical harmonic expansion representation in order to predict precise effects on the satellite orbit.

Radiation Pressure/Spacecraft Radiation: Solar radiation, albedo and infrared emissions are the three external radiative fluxes acting on a spacecraft. The two separate types of flux influencing a spacecraft's temperature are internal and external. Internally the equipment dissipates heat. Externally, the solar radiation, albedo, and infrared fluxes cause surface heating. These types of forces vary with spacecraft shape, orientation and reflectivity during the different phase events of orbit such as, 1) occultation effects, 2) oblique illumination, and 3) the spacecraft's thermal inertia changes.

Atmospheric Drag: The effect of earth's atmosphere at orbit altitude creates a resistance. This is calculated using empirical relationships for air density, together with the known shape and orientation of the satellite which may be different from reality.

Geoid Model: As indicated previously, current geoid models have relatively low orders of degree and order upon which their spherical harmonic expansions are based. These discrepancies combine to perturb the satellite's estimated orbit away from the true orbit.

Solid Earth & Ocean Tides: As noted above, both oceanic and solid earth tides perturb the gravitational potential. Their influence on satellite orbits is calculated from a spherical harmonic expansion involving terms to a relatively low degree and order calculated from hydrodynamic models. It is meaningful to note that the largest amplitude M2 tide constituent is not the dominant contributor to satellite orbit anomalies. However, this same factor plays a significant role in tide frequency vs. altimeter signal aliasing and thus requires highly accurate tracking data in order to best define an adequate representation. Thus, the two most important tide modeling strategies are, 1) to improve the long wavelength tide terms which are in resonance with near-earth satellites and have distinctly large long period orbital effects, and 2) to produce as many as feasibly practical tidal coefficients which encompass many tide lines for inclusion in models thereby creating a whole category of short period perturbations.

F] Troposphere:

As discussed in propagation medium corrections above, the signal delay caused by water vapor content and other gases present in the troposphere must be accounted for in satellite tracking theory and perturbation analysis. Typically, satellite laser ranging (SLR) techniques are involved which use frequencies in the visible portion of the electromagnetic spectrum and thus are not as susceptible as the radio frequency ranging methods to the delays listed.

Station Location: Station position error, i.e. the inability to know the precise location of the tracking stations relative to the center of the earth, used to be the dominant problem in this category. However, with SLR, extremely accurate measurements are now possible. Station distribution is also a significant hindrance, with most SLRs concentrated in the northern hemisphere and on continents rather than being evenly dispersed around the globe. The advent of the DORIS tracking system considerably reduced this problem. Another, smaller in magnitude yet still present, discrepancy is that the coordinate system used to determine the station position is not precisely known because of polar motion and the variations in the length of the day.

9.5.1.2. Applications

Sea level change :

Since a large segment of the population lives in a coastal zone, sea level change is of considerable importance in terms of the socio economic consequences. In addition, the rate of sea level rise is expected to increase in response to the green house warming. Thus, the sea level changes obtained from altimeters can be used to validate the predictions from the climate models (Houghton *et al.*, 1996). Two fundamental problems are encountered in using tide gauge measurement for long term sea level changes. First, the crustal reference point over which the tide gauge measurements are referred, itself may move vertically at rates comparable to the sea level signals (Douglas 1995). Second, because of the limited availability of the tide gauges, they provide poor spatial sampling of the oceans.

Though the current satellite altimeter record is too short to arrive at any definite conclusion, altimeter data was used to study the long term sea level changes. Tapley *et al.*(1992) obtained a sea level change of 5 mm/year using 2 years of Geosat altimeter data. Sea level is the barometer for environmental change. Anthropogenic induced climate change, while likely to increase the global sea level, will actually cause sea level to decline at some locations and rise in others (Nerem & Mitchum, 2001). The true power of satellite altimetry lies in its ability to map the geographic variation of sea level change. Leuliette and Wahr (1999) used the coupled pattern analysis technique and found that most of the long term sea level change signal observed by Topex is caused by changes in sea surface temperature related to ENSO phenomena.

Ocean Circulation:

Because of the ocean's vastness and inaccessibility and the limitations of the insitu measurements, understanding ocean circulation has been a slow process. With the limited data the results were interpreted in the climatological fashion with the assumption that the ocean did not change much with time and space. The capability of satellite altimetry to measure SSH above geoid, known as the dynamic height, gave an opportunity to study the variability of the oceanic processes not only at the surface but at depths as well. Water movements having spatial scales greater than about 30 km and time scales longer than about a day are in geostrophic balance to a first degree of approximation (Stewart *et al.*, 1986). Hence, over large temporal and spatial scales ocean circulation can be conveniently estimated from:

$$U = -g/f \ \partial\eta/\partial y$$

$$V = g/f \ \partial\eta/\partial x$$

Where, U and V are the zonal and meridional components of the current vector, g is the gravitational attraction of the earth, f is the Coriolis parameter and ∂y and ∂x are the distances in the zonal and meridional directions over which SSH, h, is estimated. However, ocean differs from geostrophic balance in a number of ways. For example, in the high core of the Gulf Stream, the downstream balance tends to be measurably non-geostrophic. Evaluation of the velocity fields with time, implying missing time dependent terms in momentum equations is another situation where actual flow deviates from geostrophy. Since absolute SSH cannot be estimated due to the lack of precise geoid information, only the current variability can be estimated. Even from the dynamic height estimations from the in situ measurements current variability alone can be estimated. However, satellite altimetry has an added advantage in the sense that if the SSH observations are referred with respect to a long time period average, the circulation estimated from the altimeter measurements can be regarded as the absolute ones with the assumption that the current vectors average out over longer time scale. This assumption is not, however, valid in regions like Somalia where the currents are towards northeast for about four months and in the opposite direction for the rest of the seasons. Obtaining the SSH to the required accuracy is a big challenge. Wunch and Stammer (1997) showed that for an ocean of 4000 m deep at 24 degree latitude, a one centimeter tilt in the ocean topography is associated with a mass transport of 7 Sv (1 Sv = 1 million tons per second, roughly the transport of all rivers combined), if the entire water column moves with the same velocity. The actual transport varies with latitude and the vertical distribution of the velocity. Measuring SSH from space with an accuracy of 1 cm is a tremendous effort. The present accuracy of 4 cm (rms value at 1/sec data rate) is achieved after two decades of untiring efforts. After spatial and temporal smoothing the accuracy is close to 2 cm on monthly time scales (Cheney *et al.*, 1994).

Ocean Tides:

Ocean tides, the most fascinating natural events, is caused by the gravitational attraction of the sun and the moon. Tides have many impacts in geophysics and oceanography. Knowledge of total dissipation in tides is required in earth rotation studies. In geodesy, tidal loading of the lithosphere has to be considered. For all these studies a good tidal model, which is lacking till the advent of satellite altimetry, is required. Any in situ measurement approach to map ocean tides at global scales is not possible because of the complexity of the tides and the difficulties involved in the installation and maintainance of the instruments. In these two contexts the advent of satellite altimetry, offering to estimate tides all over the globe, has been totally revolutionary. Obtaining SSH observations from altimeter range measurements and correcting these SSH values for the tides obtained from the same range is complicated. Repeat passes or cross-over points are used to solve for the higher frequencies assuming oceanography as noise. Due to this estimated/predicted tides over high energetic regions or coastal regions are relatively inaccurate. Since tidal variations represent more than 80% of the SSH variations, tides must be removed from the altimeter observations to study the ocean circulation. Careful and accurate removal of the tidal information from the altimeter observations is very critical as different altimeter tracks observe different phases of the tides and if not properly removed the results from SSH variations can be interpreted as propagating signals.

Ocean Surface Wind Wave Studies:

Surface waves are the most important oceanic parameters as they provide the spectacular manifestation of the sea state. The slope of the altimeter return pulse is stretched in time because of the delay between reflections from the wave crests and troughs. This information is used to estimate the significant wave height which in turn is useful in correcting SSH observations for electromagnetic bias. The strength of the return pulse gives an estimate of the wind magnitude. Even though it is often difficult to have altimeter observations at the location of the hurricane at a time close to the passage, altimeter is the only instrument that can provide this information over the oceans.

Thus altimeter allows the assessment of the meteorological forecast, based on independent data, enabling the corrections for the improvement of the models. The possibility of having real time sea state information from several altimeters in future will further enhance our ability to monitor and forecast waves generated by hurricanes and cyclones. Altimeter data is also useful for wave climate studies (Vethamany *et al.*, 1999) which otherwise would be difficult from the conventional data collection platforms.

Wind speeds obtained from altimeters over oceans provide an useful information for many applications. Although it is difficult to estimate wind speed greater than 25 m/s with reliable accuracy, this data can provide information on the structure of the cyclones, the degree of symmetry and the spatial extent along the track.

El Nino Studies:

El Nino-related climate variations often have widespread and devastating impacts. Prior to El Nino surface water piles up at the eastern end of the equatorial Pacific Ocean. Satellite altimetry helps to monitor this phenomenon in all weather conditions. Besides, SSH observations offer a part of the solution to the problem of coupled ocean-atmosphere models which have attained significant forecast skill during the past decade, but they continue to be limited by an ocean observing system. In particular, an operational flow of altimeter data has long been desired by the modeling community as a means of estimating changes in upper ocean heat content to first order approximation. But even though altimeters have flown nearly continuously since 1985, two challenges have stood in the way of progress: (1) The altimeter data must be made available fast enough (within 1-2 days) and with sufficient accuracy (a few cm) to track changes in the ocean within a tolerance that is useful for the ocean model; (2) The assimilation method must be capable of using a single parameter, sea level, to correct the model temperature as a function of depth. Using Topex/Poseidon altimeter data, both of these problems have been solved. A phenomena similar to the Pacific Ocean was also observed in the Indian Ocean by Ali and Sharma (1996) using Geosat SSH observations and SST patterns.

Cyclone/Hurricane Studies:

The intensification of cyclones or hurricanes involves a combination of different favorable atmospheric conditions such as atmospheric trough interactions and vertical shear, which lead to good outflow conditions aloft. As a result of this, inflow conditions in the near-surface layer are enhanced. Clearly, as this process continues over the scale of the storm, the upper ocean provides the heat to the atmospheric boundary layer and to the deepening process. In this scenario, the upper ocean thermal structure has been thought to be a parameter that only played a marginal role in hurricane intensification. However, after a series of events where the sudden intensification of hurricanes occurred when their path passed over oceanic warm features, it is now being realised that it could be otherwise. While the investigation of the role of these rings and eddies is a topic of research in a very early stage, preliminary results have shown their importance in the intensification of hurricane Opal (Shay *et al.*, 2000). Therefore, the monitoring of the upper ocean thermal structure has become a key element in the study of hurricane-ocean interaction with respect to the prediction of sudden hurricane intensification. These warm features, mainly anticyclonic rings and eddies shed by the Loop Current or developed due to the wind stress curl, are characterized by high SST at the elevated center, a deepening of several tens of meters of the isotherms towards their centers and with different temperature and salinity structure compared to the surrounding waters. Similarly, cyclonic features have low SST, depressed centre and shallow mixed layer. They can be easily located and identified from satellite altimeters. Ali *et al.*, (1998) prepared an atlas of the North Indian Ocean eddies giving information of the eddies during 1993 to 1997 for every 10 day interval.

Oceanic features such as warm core rings (WCR), and the currents represent a source of enhanced air-sea fluxes to the atmospheric boundary layer that may cause strengthening of atmospheric disturbances. Warm layers exceeding 26°C extend to at least 100 m beneath the surface in these oceanic features, and represent high hurricane heat potential water. Satellite altimeter data from TOPEX is a useful tool to study oceanic mesoscale dynamic processes from of the sea surface height anomaly, and provides information on the vertical ocean structure when complemented by hydrographic data. Gopalan *et al.*, (2001) have shown that cyclonic/anticyclonic eddies can give an integrated picture of the subsurface thermal features in a broader sense.

Based on historical hydrographic measurements placed within the context of a two layer model, TOPEX derived upper layer thickness fields indicated the presence of two WCRs in the Gulf of Mexico during September and October 1995. Hurricane Opal passed directly over one of these WCRs where the wind field increased from 35 m/s to 65 m/s, and the radius of maximum wind decreased from 40 km to 25 km. Pre-Opal sea surface height anomaly in the WCR exceeded 30 cm where the estimated depth of the 20° C isotherm was located between 175 to 200 m. Thus on 4 Oct 1995, Hurricane Opal deepened from 965 hPa to 916 hPa in the Gulf of Mexico over a 14 hour period upon encountering a warm ocean ring during an upper level atmospheric trough interaction. Subsequent to Opal's passage, this depth decreased approximately to 50 m, which suggests upwelling underneath the storm track due to Ekman divergence. The maximum heat loss of approximately 24 Kcal/cm^2 relative to depth of the 26° C isotherm was a factor of six times the threshold to sustain a hurricane (Shay *et al.*, 2000). Composite AVHRR derived SSTs indicated a 2 to 3° C cooling associated with vertical mixing in the along-track direction of Opal except over the WCR where AVHRR derived and buoy derived SSTs decreased only by about 1°C. Thus, the WCR's effect was to provide a regime of positive feedback to the atmosphere rather than negative feedback induced by cooler waters due to upwelling and vertical mixing as observed over the Bay of Campeche and north of the WCR.

Similarly, during August 1999, Hurricane Bret intensified twice in the western Gulf of Mexico over two regions associated with very high (values larger than 90 KJ/cm^2) hurricane heat potential. Thus, it can be concluded that warm core eddies are the sources for the intensification of the cylones. On the other hand, when the cyclone/ hurricane passes over a cold core eddy where the temperatures are less and the mixed layer is shallow, it is likely to dissipate or suffer a reduced intensity.

The close relationship that exists between the dynamic height and the ocean mass field allows these two parameters to be used within a two-layer reduced gravity ocean model to monitor the upper layer thickness (Goni *et al.*, 1996), defined in this study to go from the sea surface to the depth of the 20^o C isotherm. This isotherm was chosen because it lies within the center of the main thermocline and is often used as an indicator of the upper layer flow in the western tropical Atlantic and Gulf of Mexico waters. Although there are other factors controlling the SSH anomaly, it is assumed here that most of its variability is due to changes in the depth of the main thermocline and is of barotropic origin. The hurricane heat potential, Q, is defined here as a measure of the integrated vertical temperature from the sea surface to the depth of the 26^o C isotherm. This parameter is computed from the altimeter derived vertical temperature profiles estimated in the upper ocean. The temperature profiles are estimated using: (a) the sea surface temperature obtained from the Reynolds near real time weekly fields, (b) the altimeter estimates of the 20^o C isotherm within a two layer reduced gravity scheme (Goni *et al.*, 1996), (c) the depth of the 26 ^{o} C isotherm from a climatological relationship between the depths of the 20^o C and 26^o C isotherm, (d) climatological estimates of the mixed layer depth. The hurricane heat potential, is a measure of the integrated vertical temperature between the sea surface and the estimate of the 26^o C isotherm (Shay *et al.*, 2000).

Rainfall Studies:

As mentioned earlier when the altimeter signal passes through a rain cell it is considered as noise to the SSH measurements and such points are discarded for oceanographic studies. On the other hand it is a signal for the estimation of rainfall. Besides, dual frequency radar altimeter observations are useful in estimating the rain rate. Topex and Jason have altimeters operating at C-band along with the nominal Ku-band. The primary objective of the C-band altimeter is to provide collocated ranging measurements to correct for atmospheric path delay in the Ku range estimates. This dual frequency altimeters have two more capabilities: to study the oceanic rainfall and to correct the surface wind speeds. Ku and C band signals are differentially attenuated by the atmospheric precipitaion. Bhandari and Varma (1996) used this property to identify rain events associated with the southwest monsoon. Quartly *et al.*, (1999) studied the seasonal changes of rain rate using Topex dual frequency altimeter data.

9.5.2. Scatterometer

A scatterometer works on the principle that electromagnetic radiation transmitted toward the sea surface is scattered back towards the emitting antenna. The intensity of the backscatter is largely dependent on the centimeter-scale roughness at the sea surface, where the scale of the roughness elements is commensurate with the emitted radar wavelength. These small-scale waves are generated by the local wind stress on the sea. For a given wind speed, the backscattered power varies as a function of cos 2M, where M is the azimuth angle between the look direction and the wind direction, often with some ambiguity in the solution. Thus, by measuring the backscattered power from the ocean surface at several azimuth angles, the wind speed and direction may be retrieved.

9.5.2.1 Principles of Scatterometers

Spaceborne scatterometers transmit microwave pulses to the ocean surface and measure the backscattered power received at the instrument. Since the atmospheric motions themselves do not substantially affect the radiation emitted and received by the radar, scatterometers use an indirect technique to measure wind velocity over the ocean. Wind stress over the ocean generates ripples and small waves, which roughen the sea surface. These waves modify the radar cross section (sigma-0) of the ocean surface and hence the magnitude of backscattered power. In order to extract wind velocity from these measurements, one must understand the relationship between sigma-0 and near-surface winds. This relationship is known as the geophysical model function and model function are used to obtain the ocean wind vectors.

The geophysical product retrieved from QuikSCAT observations is the equivalent of neutral winds at 10-m height (Liu and Tang, 1996), from which the surface wind stress (or momentum flux) can be derived independent of the atmospheric density stratification.

The principle underlying scatterometry remote sensing is expressed as the "radar equation":

$$P_r=(P_tG_t / 4\pi R^2)\sigma_{rt}(A_r/4\pi R^2)$$

where:

- P_r = received power,
- P_t = transmitted power,
- G_t = gain of the transmitting antenna in the direction of the target,
- R = distance between the target and the antenna,
- σ_{rt} = radar cross-section: the area of the target intercepting the transmitted pulse that produces a return pulse equal to the received power,
- A_r = effective receiving area of the receiving antenna aperture.

Of these parameters, P_t, G, and A are all known quantities associated with the radar system, while R is related to the location of the target and can be determined from the duration it takes for the transmitted pulse to return to the antenna. Of greatest interest to scatterometry, then, is the quantity, σ_{rt}, which is a function of the way the transmitted electromagnetic energy interacts with the surface. When this quantity is integrated over a number of pulses, it is referred to as the "scattering coefficient," or "backscattering coefficient," and is commonly denoted as σ°. The quantity σ°, then, which is expressed in decibels (dB), is used to derive geophysical parameters and is the primary variable that scientists work with when using scatterometry data.

There are two physical properties of surfaces and surface volumes that determine the value of σ°: its roughness and its dielectric properties. A perfectly smooth surface will reflect an incident radar pulse like a mirror—90° in the opposite direction from which it arrived - thus, no energy is scattered back into the direction that the pulse came from. A surface must therefore be rough enough that some amount of energy is backscattered to the radar antenna. As a result, rougher surfaces have higher values of σ°. A surface is "rough" from the perspective of a radar pulse depending on the height of the roughness features on the surface relative to the radar's wavelength. This is expressed in the Rayleigh roughness criterion, which considers a surface to be rough if:

$$h>(\lambda/(8 \sin\gamma))$$

where:

- h = vertical relief of the surface roughness features,
- λ = radar wavelength,
- γ = depression angle of the radar pulse.

Based on this criterion, a radar of 2-cm wavelength (or 15 GHz frequency) at a 50° depression angle would only be backscattered if the surface had features with a minimum vertical relief of about 3 mm.

Another result of surface roughness is the impact it has on σ° over a range of illumination angles, or "incident angles." Because smooth surfaces have a mirror-like, or "specular," reflection, a radar satellite will only measure a return signal at nadir, when it is directly above the target (an incident angle of 0°). At the other extreme, an extremely rough surface scatters the signal so much that the antenna receives a relatively equal amount of power regardless of incident angle. This kind of surface is referred to as "isotropic," and the return signal is considered "noncoherent" as opposed to specular, or coherent. Intermediate rough surfaces vary in their angular response of σ° between the specular and isotropic examples. This change in angular backscatter response is important in identifying snow vs. ice surfaces and old, rough sea ice surfaces vs. new, smooth sea ice surfaces. Radar pulses penetrate snow surfaces and scatter multiple times within a volume of snow so that the return response is strongly noncoherent. In contrast, smooth ice is strongly specular while rough ice is less specular.

9.5.2.2. Applications of Scatterometry

Data derived from ocean scatterometers is vital for the studies of air-sea interaction and ocean circulation, and their effects on weather patterns and global climate. These data are also useful in the study of unusual weather phenomena such as El Niño, the long-term effects of deforestation on our rain forests, and changes in the sea-ice masses around the polar regions. These all play a central role in regulating global climate. Computer modeling of global atmospheric dynamics for the purpose of weather forecasting has become an increasingly important tool to meteorologists. Scatterometer data, with wide swath coverage, have been shown to significantly improve the forecast accuracy of these models. By combining scatterometer data of ocean-surface wind speed and direction with measurements from other scientific instruments, scientists gather information to help us better understand the mechanisms of global climate change and weather patterns.

Wind velocity requirements:

Knowledge of wind velocity is very critical for understanding and predicting ocean phenomenon, meteorology and climate. Wind stress is the single largest source of momentum to the upper ocean and drives oceanic motion on scales ranging from surface waves to basin wide currents. Wind velocity is being assimilated in to regional and global numerical weather prediction models. Present available wind vectors data coverage is not sufficient and accurate. Data from moored buoys are highly accurate but a few in numbers. Satellite borne radars are the only systems currently capable of providing accurate, frequent high resolution measurements of near surface winds speed and direction in clear and cloudy conditions. Scatterometer measurements are indirect, requires highlevel processing and suitable model functions to retrieve wind vectors from backscattered power.

Weather Forecasting: Data from ocean scatterometers greatly enhances overall weather-forecasting capabilities. Most of the weather over the west coast of the United States, and some over the east coast, is generated over the oceans. The measurements derived from ocean scatterometers are assimilated into numerical models (computer programs that represent natural processes in terms of equations), which can be used to predict global and regional weather patterns. The data are delivered to the National Oceanic and Atmospheric Administration (NOAA) within two hours, where they are used for timely, accurate weather forecasting.

Storm Detection: The ocean scatterometer data can determine the location, direction, structure and strength of storms at sea. Severe marine storms hurricanes near the Americas, typhoons in Asian waters, and mid-latitude cyclones worldwide are among the most destructive of all natural phenomena. In recent years, our ability to detect and track severe storms has been dramatically enhanced by the advent of weather satellites. Cloud images from space are now routine on weather reports. Data from ocean scatterometers augment these familiar images by providing direct measurements of surface winds to compare with the observed cloud patterns. These wind data help meteorologists to more accurately identify the extent of gale force winds associated with a storm, and provide inputs to numerical models that provide advanced warning of high waves and flooding.

Ship Routing: Wind-observation data from ocean scatterometers is of particular significance in ship routing. Prior knowledge of wind behavior will enable ship masters to choose routes that avoid heavy seas, or high headwinds that may slow ships' progress, increase fuel consumption, or possibly cause damage to vessels and loss of life. In the past, ship captains relied on widely spaced measurements from buoys and sporadic, sometimes unreliable reports from other ships. Data from satellite-based scatterometers are much more regular, extensive and dependable.

Oil Production: Oil and gas production is already on-going at numerous offshore sites around the world the Gulf of Mexico, the North Sea, the Persian Gulf, and other areas. Thorough knowledge of the historical wind and wave conditions at any specific location is crucial to the design of drilling platforms. Safe, efficient drilling operations depend on an accurate understanding of the current sea state and warning of impending storms. In the event of an oil spill, surface-wind information is key to determining how the oil will spread. Ocean scatterometer data could help clean-up and containment crews to minimize the environmental effects of such a disaster.

Food Production: Perhaps the oldest use of the ocean is in the harvesting of food. Today, ocean fishing is a highly systematic activity that makes extensive use of advanced technology to reduce the cost and to increase the value of every "catch". Detailed wind data from the scatterometers can aid in the management of commercial seafood crops. The annual US shrimp harvest in the Gulf of Mexico, for example, depends on favorable on-shore winds that transport offshore, plankton larvae to estuaries where the larvae can develop into adult shrimp. NSCAT and SeaWinds data would be invaluable in the prediction of winds on which such endeavors depend.

9.5.3. Radiometers

Radiometers are the instruments to measure radiation emitted from a source. These instruments can be broadly classified as optical radiometers and microwave radiometers, besides polarimetric radiometers. The thermal microwave radiation of our natural and man-made environment contains many objects with fully polarimetric information. Based on this assumption a quasi-optical imaging radiometer system was designed and realized for the determination of the complete Stokes vector. To demonstrate the system performance, the beam quality was verified by measurements and a polarimetric calibration procedure was developed. Measurements on selected objects have been carried out to demonstrate the polarimetric effects primarily of the third and fourth component of the Stokes vector. The measured results indicate new possible applications for remote sensing and material testing.

The present invention teaches a unique laser radiometer capable of accurately measuring the radiation temperature of a radiant surface and independently measuring the surface's emissivity. A narrow-band radiometer is combined with a laser reflectometer to measure concurrently radiance and emissivity of a remote, hot surface. Together, radiance and emissivity yield the true surface temperature of the remote target. A narrow receiver bandwidth is attained by one of two methods; (a) heterodyne detection or (b) optical filtering. A direct measurement of emissivity is used to adjust the value obtained for the thermal radiation signal to substantially enhance the accuracy of the temperature measurement for a given subject surface. The technique provides substantially high detection sensitivity over a very narrow spectral bandwidth.

A radiometer is a device for measuring the radiant flux (power) of electromagnetic radiation. Radiometers are used to measure SST, wind speed, salinity, soil moisture, sea ice, precipitation, integrated water vapour and liquid water content of the atmosphere. The radiometers can be broadly classified as visible, infrared and microwave radiometers. The radiometer in the visible range measures visible light energy emitted in the visible range. With a spectral sensitivity from 395-465 nm (visible portion of the spectrum), a specially designed photo sensor assembly protects the photo sensor from the high temperatures sometimes associated with today's high-intensity spot lamps.

The very high resolution scanning radiometer is an imaging remote sensing instrument by means of opto-mechanical scan. The mirror conducts line scan which enables the field of view cross over the flight trace and the movement of the satellite around the earth pushes scan line forward, forming two dimensional image of the earth. The primary optical system consists of co-axial and co-focal paraboloids with a diameter of the primary mirror of 200 mm the beam splitters of the visible/IR channels divide the incident beam into infrared, near IR and visible beams.

A Microwave Radiometer (MWR) is a radiometer that measures energy emitted at sub-millimetre-to-centimetre wavelengths (at frequencies of 1-1000 GHz) known as microwaves. Their primary application has been onboard spacecraft measuring atmospheric and terrestrial radiation and are almost solely used for meteorological or oceanographic remote-sensing. Examples of microwave radiometers on meteorological satellites include the Special Sensor Microwave/Imager, Scanning Multichannel Microwave Radiometer and Microwave Sounding Unit. Yet to be launched the Microwave Imaging Radiometer with Aperture Synthesis is an interferometer/imaging radiometer with the capability of resolving soil moisture and salinity over small regions of surface.

Those sensors, which use lenses in the visible and infrared region, are called optical sensors. Cameras and Scanners comes under this category of sensors. OCM (Ocean Color Monitor) on board IRS-P4-OCEANSAT-1, CZCS(Coastal Zone Color Scanner) on board NIMBUS-7 satellite, Landsat-Thematic Mapper, SPOT-PLA/MLA, LISS-I & LISS-II on board IRS-1A/1B and PAN & LISS-III on board IRS-1C/1D are some of the examples of optical sensors. ESA and NASA have made special efforts to develop sensor systems for ocean applications to achieve better accuracies in the retrieval of ocean color information (Example; MERIS on board of ENVISAT-1. SeaWiFS on board OrbView-2 satellites).

9.5.3.1. Thermal Infrared Remote Sensing through Thermal Radiometers

The intensity of emission of electromagnetic radiation at each wavelength and the general shape of the emission curve, particularly the location of the maximum intensity depends on the temperature of the body. The sun emits almost as a black body with a surface equivalent temperature of about 6000^{o} K while the earth emits as a black body with temperature of about 300^{o} K. It may be seen from the sun and earth emission curves that the higher the temperature, the greater the emissive power. The curves have their maxima at short wave lengths. The earth emission is at maximum in the infra-red part around 10 µm.

AVHRR (Advanced Very High Resolution Radiometer) on board NOAA satellite and ATSR (Along Track Scanning Radiometer) ATSR on board ERS-1, ATSR-2 on board ERS-2 sate, AATSR on board ENVSAT, MODIS on board Terra/Aqua satellites are some of the thermal sensors operationally available today. Currently the measurements of sea surface temperatures are available from these sensors.

9.5.3.2. Microwave Remote Sensing Radiometers

Radiometers measure the intensity of radiation emitted or reflected by targets. They operate in the visible, infra-red and microwave ranges. In the microwave range they are passive sensors in that they measure electro-magnetic thermal radiation emitted by the objects. The microwave sensors can 'see through' clouds unlike visible or infrared sensors.

Electrically Scanned Microwave Radiometer (ESMR) on board METEOSAT, SMMR Scanning Multi-Channel Microwave Radiometers (SMMR) flown on Nimbus – 7, Special Sensor Microwave/Imager (SSM/I) on the DMSP series of Dept. of Defense, USA, TMI on board TRMM satellite, MSMR on board IRS-P4 are the examples of passive microwave sensors. These sensors play important role in Meteorology, Hydrology, and Oceanography.

9.5.3.3. MSMR – Multi-frequency Scanning Microwave Radiometer

MSMR on board IRS-P4 – OCEANSAT-1 satellite was launched in May 1999. MSMR, operating in four frequencies in both vertical and horizontal polarizations in the microwave domain, has the advantage of penetrating clouds and hence has all-weather capability. The radiation emitted by the ocean surface passes through the earth's atmosphere, gets modified before getting detected by MSMR. Using a combination of these frequency and polarization, geo-physical parameters like atmospheric water vapour, sea surface temperature, and precipitation over oceans, ocean surface winds and cloud liquid water, among others, could be derived. MSMR is a unique sensor in the international context as no other passive microwave radiometer is operating in the civilian domain today.

Finally it is concluded that the radiometers available starting from optical sensors to Microwave radiometers onboard the satellites are highly useful in the field of Oceanography to study the varied applications in coastal, ocean and atmospheric sciences.

9.5.4. Synthetic Aperture Radar

Synthetic Aperture Radars were developed as a means of overcoming the limitations of real aperture radars. These systems achieve good azimuth resolution that is independent of the slant range to the target, yet use small antennae and relatively long wavelengths to achieve the results. A synthetic aperture is produced by using the forward motion of the radar. As it passes a given scatterer, many pulses are reflected in sequence. By recording and then combining these individual signals, a "synthetic aperture" is created in the computer providing a much improved azimuth resolution.

It is important to note that some details of the structure of the echoes produced by a given target change during the time the radar passes by. This change is explained also by the Doppler effect which among others is used to focus the signals in the azimuth processor.

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