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1.1 BACKGROUND:

Remote sensing of Ocean Biology encompasses development of techniques for exploration and conservation of marine resources for sustainable yield. Methods for locating potentials fishing zones (PFZ) from satellite data were developed during the period 1988-89 under IRS Utilization Programme. The basic approach was to detect SST (sea surface temperature) gradients revealed by oceanic features like fronts, eddies and up-welling. These features are known to be sites of productive waters and hence, conducive to fish aggregation. NOAA-AVHRR data were used for generating SST images. After successful demonstration of the technique in the waters of Gujarat in March 1989, the same was extended to all the maritime states. At present, this technique is being operationally used at national level with update of fishery forecasts twice a week. However, SST-based approach has constraints in the tropical waters. Thermal gradients are inhibited by strong incident solar radiation, particularly during summer. For this reason, SST images are not all time adequate for PFZ identification. Ocean colour data enables retrieval of chlorophyll and have potential to overcome this limitation. Retrieval of ocean colour makes use of satellite data in visible bands. Visible radiation of electromagnetic spectrum has ability to penetrate water down to one attenuation depth and hence, ocean colour image reveals gradients and fronts even in summer when water masses are stratified. Ocean Colour Monitor (OCM) on-board IRS P4 was launched in May 1999. An integrated approach using chlorophyll from OCM and SST from AVHRR was developed for generating improved fishery forecasts. Subsequently, an experiment
was designed to validate the approach and to assess benefits with inclusion of new indicator, ocean colour. Results obtained from the validation exercises have been summarized.

Besides fishery application, efforts have been made for developing model to estimate mixed layer primary productivity, which makes use of combined data set from satellite and ship. This is an analytical approach as developed by T. Platt using photosynthesis-light relation and it has been implemented in the Arabian Sea. There is a plan to extend knowledge of this parameter for fish stock assessment. Also, methods have been developed to estimate New Primary Production as an indicator of uptake of carbon flux from atmosphere hence, reduction in Greenhouse effect.

1.2 NEED FOR REMOTE SENSING OF OCEAN BIOLOGY

Fish is supplementary source of food and hence, its effective exploration is important. Remote sensing technique has been used for this purpose by various countries for two decades. Knowledge of distribution and abundance of fish requires synoptic view of the ocean area. Satellite provides this capability with frequent receptivity, unlike ship based search methods. Even in situation where fish catches resulting from satellite forecasts are average, the time and fuel saved in searching for fish improves profitability of fishing. Moreover, it is being noticed that coastal resources are over exploited and there is need to reduce fishing load from these waters. One approach for this could be to divert fishing efforts from coastal waters to deep waters. Ocean colour signature indicative of fish availability in deep oceanic waters has been identified with positive feedback. There is a need to practice this approach for profitable fishing.
Modeling of Primary Productivity is a step towards assessment of fish stock. This is important information for management and conservation of fishery resources. Space-time pattern of productivity can also be used developing approach for long-term fishery forecasts. Apart from biological application, estimation of New Primary Production provides estimation of carbon that is removed from the carbon cycle. Production, which uses nitrogen in the form of nitrates and nitrites, plays an effective role in removing carbon dioxide from the atmosphere. Photosynthesis reaction followed by upwelling, which brings the nitrates from below, is so fast that carbon dioxide is driven away from the carbon cycle. This enables one to perceive potential of oceanic waters to absorb carbon dioxide from atmosphere. Increased production of phytoplankton would lead to increase the secondary and territory production. This ensures fixation of atmospheric carbon dioxide into organic matter, which may be removed from the carbon cycle either by man or by death/decay organisms, which ultimately sink to sea bottom. Various ocean provinces respond differently to increase carbon dioxide concentration in the atmosphere, hence it is proposed to study in detail large scale primary production and its seasonal variations in the Arabian Sea.

1.3 HISTORY OF REMOTE SENSING APPLICATION OF FISHERY IN INDIA:

Remote sensing technique for fishery application started way back in 1980 in this country. With commencement of joint experiment Programme a systematic work plan for application of remote sensing technique was made in collaborative efforts of Indian Space Research Organization (ISRO), Fishery Survey of India (FSI) and Indian Council
of Agricultural Research (ICAR). The objective of this Programme was to develop methodology for exploration of marine living resources using remote sensing Programme. The efforts for execution of this task involved sea truth data collection for bio-optical algorithm development to retrieve phytoplankton from satellite data. Also, digital image processing techniques were developed to retrieve chlorophyll and diffuse attenuation coefficient (K) from Nimbus-7 Coastal Zone Colour Scanner (CZCS) data. The activity was carried forward under the Remote Sensing Satellite Utilization Programme (IRS-UP). Sea surface temperature gradients are seen in the form of thermal boundaries in SST image and they represent sites of productive waters. It is believed that fish may aggregate here for feeding. If this logic works then it may be possible to develop an approach for fish finding from the satellite data. As a step in this direction, SST gradients detected from NOAA-AVHRR data were studied to investigate their correspondence with fish aggregation pattern. A definite pattern of accumulation of fish for feeding in the waters that revealed SST gradients was observed. Besides normal SST gradients, other oceanic features responsible for causing accumulation of fish eddies, upwelling and meanders. With this basic study, the first experimental fishery forecasts was generated from SST image of March 29, 1989 at Space Applications Center (SAC) having identified fishing site southeast of Diu in Saurashtra Coast. The then Commissioner of Fisheries of Gujarat State agreed to join validation exercises of the forecasts and motivated a few fisherman to perform fishing operation in the suggested fishing zone. The first feedback received was encouraging and the generation of forecast using SST gradients as indicator of fish availability continued for Gujarat coast. After some consistent results, the technique of fish location was transferred to National Remote
Sensing Agency in 1991 and extended to other maritime states. Subsequently, officers of Gujarat State Fishery Department were trained for processing of satellite data and interpretation of SST images to locate fish. This department started generating SST based forecasts for the state then after.

Potential fishing zones (PFZ) identified in the coastal waters using SST gradients consistently yielded good catches overall. However, this approach of fish location had limitation that it used SST, a physical parameter, to get a signal of fish aggregation through indirect link. Also, this parameter represents surface layer of top 10 microns only. It inhibits frontal structures in tropical waters during summer months even though fronts and high productivity below surface might prevail. Because of this limitation, there was feeling that there could be possibility of existence of high productivity areas and good fishing grounds which SST images failed to reveal. For this reason, use of ocean color in our waters as an aid to knowledge of fishery distribution and abundance was inevitable. Retrieval of ocean color makes use of satellite data in visible bands. Visible radiation of electromagnetic spectrum has the ability to penetrate water down to one to one attenuation depth and hence, ocean color image reveals gradients and fronts even in summer when waters masses are stratified. This parameter has an additional advantage that it is possible to retrieve chlorophyll from it. Chlorophyll being base in the food chain of marine eco system, it is a direct indicator for productivity of waters. IRS P3 MOS bridged the time gap when CZCS was not active and operational ocean color sensors like SeaWiFS and OCM were yet to come. Experience of retrieval of ocean color study of variability in chlorophyll distribution proved to be enormous value. Latter, Marine Fisheries project was identified as one of the core projects under IRS P4 OCM Utilization.
Programmed by Space Application Center with collaboration of fishery survey of India, Central Marine Fisheries Research Institute, Central Institute of fishery Technology, Central Institute of Fishery Nautical & Engineering Training, and Gujarat State Fishery Department etc. focus of this project was on utilization of ocean color information to improve the SST based operational fishery forecasts. Numbers of time series chlorophyll images were generated from SeaWiFS data to study signature of ocean color in context to Fisheries. Subsequently, an integrated approach was developed for PFZ identification using chlorophyll and SST. Experimental plans to validate fishery forecasts generated using this modified approach were prepared and executed during the three fishing seasons during October-March 1999-2002. After consistent positive feedback for pelagic and demersal fish, the integrated approach has been considered operational and transferred to INCOIS/DOD for operational use.

1.4 GLOBAL STATUS

USA: Under U.S. West Coast Commercial Fishing Experiment executed by National Ocean Service of NOAA, SST boundaries (contours) are merged with chlorophyll image to generate commercial fishery charts. Strong colour fronts associated with favorable temperature range are selected as the best fishing areas. Probability is assigned to fishing grounds inform of high and medium depending on strength of the colour front.

NASA/JPL Programme to US coast fisheries conducted by National Oceanic and Atmospheric Administration (NOAA) generated SST charts three times a week for distribution to fishermen via radio facsimile.

At present for tuna forecasts, specific range of temperature and thermal fronts, eddies etc.
detected from SST image are being used. SST online service of USA generates fishery charts from SST images generated from NOAA data. Information on lat/long, Grid, inshore structures and 30/50/1 00/500/ and 1000 fathom curves showing canyon areas. These charts are available to users on payment basis.

ORBIMAGE's SeaStar Pro Service includes plankton s, weather information to daily SST images as well as currents estimated from sea surface height. Roffer's Ocean Fishing Forecasting Service, Inc. (ROFFSTM) is a scientific consulting company based in Miami, Florida (U.S.A.), founded in 1987 by Mitchell A. Roffer. They combine fisheries oceanographic data with satellite and other oceanographic data to produce tactical and strategic fisheries forecasts. Oceanographic Fishing Analysis incorporates numerous factors including: water temperature, water color, orientation of local currents, bottom topography, biological quality of the water, forage preference of the target species, availability of forage, and habitat preference of the forage and target species.

Daily Fishing Oceanographic Analyses are transmitted to their clients who are involved in recreational (sport fishing) and commercial fishing. Each analysis is composed of a map and a written forecast. The maps are derived from nautical charts, which are enhanced with high-resolution bathymetry and navigational aids. Each map depicts oceanic frontal zones primarily derived from satellite derived sea surface temperature, as well as, from other sources of ocean environmental data. Specific locations are marked where the catch ability of fish is greater than the surrounding areas. Additional information on current direction, water color and flotsam (weed concentrations, etc.) is often included. Different chart formats are provided for inshore, offshore and high-seas fishermen. Oceanographic Fishing Analyses are distributed
through telephone facsimile. Often the analyses are faxed directly to the fishing vessels over satellite communication systems and cellular phones. The analyses are also available in color via electronic mail. The company also provides consulting services on fishing gear and fishing techniques, as well as, weather satellite (Geo-stationary and polar orbiting) image acquisition and processing systems for personal computers. ROFIS™ plans to introduce a cost-effective product based on the water color (plankton) data derived from the MODIS sensors on the U.S. Terra satellite. There is plan to augment our services with one or more altimetry products, as well as, weather products.

**Japan:** Fish location scheme makes use of oceanic features like fronts, eddies, meanders etc. observed through ocean colour difference, SST, depth inputs and ground information of fishing data. Also a prominently defined Kuroshio and Oyashio current systems serve as a guide for fishermen. Tuna fishing efforts follow specific water mass at absolute temperature e.g. 18° C. Ocean colour is found more reliable factor for guiding tuna fishing efforts as compared to perature. It is reported that though 18° C is a good temperature for tunas, they change course when meet bad colour. Blue colour of water is considered better for tuna fishing than creamy colour. While Japanese Fisheries Information Service Centre (JAFIC) provides satellite-based information on fishing grounds at national level, some fishermen also use portable NOAA receiver and processor to acquire knowledge on fishing sites. This minimizes delay that normally occurs in communication of the forecast information. There is also mention about an approach for making favorite temperature and ocean colour spectrum. This is essentially generating histogram for satellite derived SST and colour.
**Australia:** Major activities are resource surveys and monitoring of population dynamics. The project on resource surveys provides baseline and repeat surveys for a range of subtidal habitats with an emphasis on coral and fish. Remote sensing techniques are being developed for deeper habitats. New protocols are being developed for monitoring health of coral reefs. Recruitment of corals and fish is monitored to estimate population resilience. With exploited stock, basic life history information and knowledge of species interaction is acquired to ensure that harvest rates are ecologically sustainable. Also remote video surveillance techniques are used to assess fish abundance. There is also plan to increase knowledge of fish stock assessment. In summary, while exploiting fish stock, there is emphasis on sustainable fishery and ecosystem management. As regards use of remote sensing data for tuna fishery exploration Australia has developed automated system based on SST. It is observed in Australian waters that at regional scales ocean colour adds little additional value to information obtainable from SST for fisheries operations. There is further mention that better atmospheric correction and cloud detection algorithms for tropical oceans will add more value to existing open ocean SST data sets.

**China:** China has just begun a project entitled "Satellite remote sensing forecasting system on fisheries of the South China Sea" with limited funding. The approach makes use of understanding that the life habitat is strongly influenced by environmental factors such as SST, chlorophyll, current system and ocean upwelling. Information on these elements are derived from satellites like FY, NOAA etc. are used to analyze location of possible fishing grounds. It is also proposed to develop GIS based forecasting system to
predict fish distribution and migration. It is proposed to deliver information to users via "weather service" programme on CCTV. As regards primary productivity, various methods have been proposed to convert pigment fields derived from ocean colour images into primary production images. Several empirical, analytical and semi-analytical model have been developed to estimate primary production from space. Mention of various empirical and semi empirical models including vertically generalized productivity model (VGPM) used for regional scale applications can be found. Also, global scale models of analytical nature, which consider vertical structure of bio mass and spectral dependence of inputs like P-I parameters have been developed.

1.5 Atmospheric correction for ocean colour remote sensing

In the case of space borne ocean colour remote sensing, the sensor detected radiance is heavily contaminated by solar radiation backscattered by the atmospheric air molecules (Rayleigh scattering) and the aerosols (mainly Mie scattering). This part of the radiation, called the atmospheric path radiance, constitutes more than 85% of the radiance at the Top Of the Atmosphere (TOA). In the detection of the oceanic constituents first step is therefore the removal of the atmospheric contribution from the sensor radiances. The procedure for removing atmospheric path radiance from the TOA radiances in different channels of the sensor is called atmospheric correction. The above study is dealt in detail in chapter 2.
1.6 Bio-optical algorithms for the estimation of ocean water constituents using IRS P4 OCM satellite data:

The need for information on spatial and temporal distribution as well as quantitative estimation of ocean water constituents such as phytoplankton and total suspended matter (inorganic and organic origin) has long been recognized in various oceanographic applications. In continental shelf waters, upwelling regions and the oligotrophic oceans, an understanding of photosynthetic processes (primary production) is required to assess the marine biological resources of the globe, including pelagic and demersal fisheries, shellfish and even organic sedimentary deposits. Quantitative assessment of oceanic primary production and its role in the global carbon cycle is an important environmental issue (Scientific Committee on Oceanic Research (SCOR), 1987; Falkowski, 1994). One of the key parameters for accurate assessment for primary production in open and coastal ocean is accurate quantification of phytoplankton amount for photosynthesis (Morel, 1991). Ocean colour information on a global scale is also of importance in studying the bio-geo-chemical cycles of carbon, nitrogen and sulphur. The dispersion and transport of inorganic suspended sediments are useful in the study of coastal processes. In the deep ocean and in shallow sea, the ocean colour features can be used as natural tracers to reveal the transport processes. The patterns of colour distribution, revealing streakiness and patchiness, contain spatial information about dispersion and mixing processes. The above study is dealt in detail in chapter 3.
1.7 Improved algorithm for total suspended matter (TSM) estimation:

Process such as tides and waves, river discharge, wind stress and turbidity currents modulate the transport and distribution of suspended sediments in coastal environment. It has been demonstrated by a large number of studies that satellite based remote sensing can be effectively used in detection and quantification of total satellite based remote sensing can be effectively used in detection and quantification of total suspended matter in coastal seas (e.g. Klemas et al. 1974, Tassan and Sturm 1986, Ritchie et al. 1990, Chauhan et al., 1996). The study of suspended matter has an ecological importance because it is the main carrier of various inorganic and organic substances (including pollutants) and becomes the main substrata for biogeochemical processes (Doerfler et al., 1989). Suspended sediments also affect the penetration of light and the transport of nutrients, shoreline morphology, among other processes. The above study is dealt in detail in chapter 4.

1.8 Remote sensing of the diffuse attenuation coefficient for the Arabian sea and Bay of Bengal using IRS-P4 OCM satellite data

The diffuse attenuation coefficient of oceanic water is a property that is inferred from the ocean color satellite data. It has been used by Jarlov (1951), Smith and Baker (1978) to classify ocean waters. The diffuse attenuation coefficient K is of significance to a variety of problems associated with the penetration of natural light into the ocean and is also an important variable in evaluating propagation of artificial light in sea water for various optical and communication and surveillance systems. Satellite based remote sensing of the diffuse attenuation coefficient K has been demonstrated by Austin and Petzold (1981) for CZCS data. An operational K(490) algorithms was developed for Nimbus-7 CZCS
data relating $K(490)$, in per unit meters, to the ratio of water leaving radiances $L_w(443)/L_w(550)$, at wavelengths of 443 and 550 nm, as

$$K(490) = 0.022 + 0.088 \left[ \frac{L_w(443)}{L_w(555)} \right]^{1.491} \text{ m}^{-1}$$ (1)

A large number of CZCS data sets were processed using this algorithm and root mean square (rms) errors in $K(490)$ estimates from CZCS data was less than 20% based on direct comparison with in situ radiometric profiles (Mueller 1993b). More recently SeaWiFS project of NASA has been providing the diffuse attenuation coefficient at 490 nm, $K(490)$, as one of the standard ocean data product. SeaWiFS is using a revised $K(490)$ algorithms based on the work of Mueller and Tree (1996). The above aspects are dealt in detail in chapter 5.

1.9 Exploration of living marine resources in the Arabian sea through integrations of ocean color with SST

Exploration of fishery resources using remote sensing technique makes use of food chain principle and identification of feeding grounds. It is established that thermal or colour gradients formed due to oceanic fronts indicate sites of high biological productivity. In order to overcome problems while using SST gradients for locating fishery resources in the Indian waters, two more approaches were developed and tested in the coastal waters of West Coast of India. In the first approach, SST (sea surface temperature) contours were overlaid on chlorophyll image of corresponding date. This enabled identification of common frontal structures from the composite product. These sites were selected as priority fishing zones for the forecasts. Besides, certain merits of ocean colour signature were realized through study of ocean colour pattern with multi date SeaWiFS chlorophyll
images. It was due to penetration of visible radiation below surface to one attenuation length and frequent Repeatability of the satellite data. Exclusive use of ocean colour pattern formed second part of the modified approach for fish location. The improvements due to additional information from ocean colour include capability of prediction of oceanic features, studying history of the features, identification of biological fronts in the deep sea waters etc. Also, the features like non-toxic diatom bloom and internal waves were identified in the Northern Arabian Sea from OCM chlorophyll images and field-testing was carried out to observe response of fish. Main purpose of this paper is to highlight these merits of ocean colour for improving an approach for fish location. Knowledge of instantaneous availability of food is to be extracted from the satellite data and hence, time is a constraint. Therefore, on-line reception of OCM and AVHRR data in near real time was arranged. An experiment was designed for validation of the fishery forecasting approach. Integrated forecasts were generated within 24 hours of satellite over pass and disseminated to collaborating agencies for follow up fishing operation. Verification of the experimental forecasts were found superior in terms of rate of success and magnitude of fish catch. The validation experiment was carried out for three years covering different seasons during 1999-2001. Summary of feedback received shows 70-90 per cent success rate (reliability) of forecasts and 70-200 per cent increase in catch. In comparison to this, earlier SST based approach for the forecast yielded 50 per cent success rate and 40-50 increases in catch. The approach has been operationalised and currently is being used to generate nation-wide fishery forecasts. The above aspects are dealt in detail in chapter 6.
1.10 Phytoplankton bloom monitoring in the offshore water of northern Arabian Sea using IRS-P4 OCM satellite data

Ocean colour, remote sensing is widely recognized tool for monitoring the optically active biogeochemical parameters like phytoplankton I pigments (e.g. chlorophyll), suspended I particulate matter and yellow substance. Measurements of ocean colour and the fate of I light in the ocean are extremely useful for describing biological dynamics in surface waters (Yentsch, 1960; Lorenzen, 1972; Smith et al. II 1989); thus the oceanographic community has, made a substantial commitment to remote sensing of ocean colour from space (Aiken et al. 1992; Mitchell, 1994). The central Arabian sea has been found productive than sub-tropical gyre elsewhere, and the area north of 20°N to be richer than the central Arabian sea (Bansc, 1984). The results from the Indian Joint Global Ocean Flux Studies (JGOFS) cruise, during February - March 1995, also revealed the evidence of high productivity in the northern Arabian sea. (Bhatlathiri et al. 1996). The above aspects are dealt in detail in chapter 7.

1.11 Comparison between the OCM detected chlorophyll and suspended sediments with in-situ measurements

An algorithm was developed at SAC to carry out atmosphere correction on the OCM radiances and for the estimation of ocean water constituents. For the validation of retrieval algorithms, sea truth campaigns were conducted over the seas around India on board the research vessels Sagar Kanya, Sagar Dhwani and Samudra Kaustubh. Measurements carried out on the oceanic and atmospheric parameters on the cloud free days during the cruises were compared with the OCM retrievals. The procedure for
atmospheric correction and the estimation of ocean constituents are described in chapters 1 and 2 respectively. In this chapter we discuss the comparison between the OCM detected chlorophyll and suspended sediments concentrations with in-situ measurements conducted synchronous with satellite overpass. The above aspects are dealt in detail in chapter 8.

1.12 Primary productivity of north west coast of India

Almost all organic matter on which marine life depends for food is synthesized from carbon dioxide and nutrients by autotrophs through photosynthesis. This process is called Primary Production. In marine waters, organisms like phytoplankton and bacteria produce organic matter (carbohydrate) from carbon dioxide and water in presence of chlorophyll by using light energy; The rate of production of organic matter by autotrophs is known as primary productivity. It is measured as the quantity (usually mass) organic matter synthesized by phytoplankton or bacteria from inorganic substances within unit volume or area of water in unit time. It is an important parameter for understanding biology and general ecology of the sea water. Knowledge of this parameter is useful for studying variability of biological activities of the sea water across seasons and years in the region of interest. The study can be extended to fishery exploration and stock assessment. New production, which is primary production associated with arrival of inorganic nitrogen compound in euphotic zone due to upwelling, is another important parameter, which can be derived from total primary production. It can be utilized to estimate potential of seawater in removing carbon dioxide from atmosphere. Modeling of the phytoplankton production requires inputs from satellite ocean color and ship data.
One of the major inputs like integrated chlorophyll can be derived from surface chlorophyll obtained from remote sensing ocean color data and ship measured inputs like shape parameters of the vertical chlorophyll profile. Other inputs like P-I parameters and diffuse attenuation coefficient for downwelling light (Kd) can be obtained from ship measurements. Seasonal primary production is estimated for the waters of Northwest coast of India with implementation of photosynthesis-light model (Platt et al., 1982, Platt and Satyendranath, 1993). Remote sensing model of primary production has obvious advantage of computation of this parameter periodically at close spatial interval and at basin scale. Analytical model for mixed layer production as developed by Platt and Satyendranath (1993) has been implemented for the Arabian Sea waters and using IRS P4 OCM data. The above aspects are dealt in detail in chapter 9.