Numerical Modelling and Satellite Remote Sensing as Tools for Research and Management of Marine Fishery Resources

Chapter · September 2014

DOI: 10.1007/978-3-319-06326-3_18

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Chapter 18
Numerical Modelling and Satellite Remote Sensing as Tools for Research and Management of Marine Fishery Resources

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Abstract This chapter outlines the use of modelled and satellite remote sensing (SRS) data in supporting the research, technology-development and management of marine fishery resources. The value of such methods used in marine fisheries management is emphasized. State of art techniques in fisheries resource management utilizing numerical models, and SRS, separately and jointly, are described here. Numerical models are useful for studying fish and other aquatic invertebrate larval transport. SRS data are used to locate fish stocks, locate areas of reef stress and delineate areas of high productivity in the wake of cyclone paths. Coupling SRS with models helps to manage fishery resources on an ecosystem scale, generate potential fishing zones (PFZ), forecast ocean state (OSF), detect meso-scale features such as eddies and track cyclones threatening coastal resources. Modelled, SRS and *in situ* data sets in combination can be used in the estimation of potential fishery resources in the exclusive economic zone (EEZ), which in turn can help in fishing fleet management. Hence, there is a huge scope for application of numerical modelling and SRS in marine fisheries research and management.

18.1 Introduction

Data collection in an oceanic environment is tedious and expensive. So as to enable wide use of *in situ* data, various organizations are hosting their databases on World Wide Web (Table 18.1). But often marine fisheries research and management lack *in situ* environmental time series data (Platt et al. 2007). Both modelled and Satellite Remote Sensing (SRS) data validated for time and space can be used to fill such gaps. Implementation of complex numerical models is frustrated by lack of

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C.W. Finkl and C. Makowski (eds.), *Remote Sensing and Modeling: Advances in Coastal and Marine Resources*, Coastal Research Library 9,
DOI 10.1007/978-3-319-06326-3_18,

Table 18.1 Various organizations maintaining world wide web databases on fish resources

Organization	Web address
Central Marine Fisheries Research Institute	http://cmfri.org.in/annual-data.html
Commission for the Conservation of Southern Bluefin Tuna (CCSBT)	http://www.ccsbt.org/
Conservation of Arctic Flora and Fauna (CAFF)	http://www.grida.no/prog/polar/caff
Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR)	http://www.ccamlr.org/
Food and Agriculture Organization of the United Nations (FAO)	http://www.fao.org/
Indian National Centre for Ocean Information Services (INCOIS)	http://odis.incois.gov.in/
Indian Ocean Tuna Commission (IOTC)	http://www.iotc.org/English/index.php
Inter-American Tropical Tuna Commission (IATTC)	http://www.iattc.org/
International Commission for the Conservation of Atlantic Tunas (ICCAT)	http://www.iccat.int/
International Council for the Exploration of the Seas (ICES)	http://www.ices.dk/
International Pacific Halibut Commission (IPHC)	http://www.iphc.washington.edu/
International Whaling Commission (IWC)	http://www.iwcoffice.org/
North Atlantic Salmon Conservation Organization (NASCO)	http://www.nasco.int/
North Pacific Anadromous Fish Commission (NPAFC)	http://www.npafc.org/
North Pacific Marine Science Organization (PICES)	http://www.pices.int/
North-East Atlantic Fisheries Commission (NEAFC)	http://www.neafc.org/
Northwest Atlantic Fisheries Organization (NAFO)	http://www.nafo.int/
Secretariat of the Pacific Community (SPC)	http://www.spc.int/
Western and Central Pacific Fisheries Commission (WCPFC)	http://www.wcpfc.int/

data inputs whereas simple models ignore some complexities in the marine ecosystem. As a result model outputs have not been analysed to the extent they deserved. In case of SRS, algorithms for data retrieval vary spatially and temporally depending on the nature of optical constituents present, especially in coastal waters. But modelled and SRS data can permit at least qualitative inferences when we address some of the major unresolved questions in fisheries biology. With the advent of improved computing facilities and SRS, last two decades have seen increased activity in both ecosystem modelling and ocean biology from space (Chassot et al. 2011). The results are used for operational and applied marine fisheries research (Stuart et al. 2011). This chapter discusses some of the applications and illustrates them with particular case studies.

18.2 Numerical Models and Their Potential Application to Marine Fish and Invertebrate Larval Transport

The benefit of numerical modelling is that the necessary state variables can be simulated at each grid point of the study domain. Advanced techniques such as finite element mesh and curvilinear contours have made modelling of irregular coastline easier and decreased the complexities involved in formulating the numerical equations.

Biological processes such as fish larval transport can be modelled based on a clear understanding of the physics of a water body. Knowledge of local hydrodynamics is a pre-requisite to modelling coastal processes, given that physical drivers such as tides and currents control them. There is a major role of diffusion and related physical processes in dispersal and recruitment of marine populations (Okubo 1994). Tidal flows can move larvae passively in peak tidal velocities (Levin 1990; Gross et al. 1992). Physical processes influence the distribution of larval fish on a variety of scales, ranging from few meters to thousands of kilometers (Bruce et al. 2001; Hare et al. 2002). There are few larval transport studies in the coastal waters in particular regions (Moser and Smith 1993; Oliver and Shelton 1993; Grothues and Cowen 1999; Hare et al. 2001). Two related studies are discussed in the following section.

18.2.1 Fish Larval Transport Modelling as an Example of Bio-physical Processes

The basic idea in fish larval transport studies is to characterise the passive movement of larvae during the planktonic larval duration (PLD) phase of the species studied. During the pelagic larval phase, the larvae may be dispersed or retained in passive response to physical forcing (Cowen and Sponaugle 2009). It is a phase that larvae are considered as "poorswimmers" (Leis et al. 2006) because the hydrodynamic (HD) forcing on them exceeds their swimming ability. There are various HD models to provide the spatial and temporal current patterns. Digitized bathymetry maps are used for defining the study domain. Inputs such as tide and wind are given in the model as the major physical forcings driving the current. Simulation will produce the HD variables as output at every grid point for the time interval required. The currents generated in these models can be validated using observed data at certain grid points to ascertain the model accuracy.

This HD input, along with the physical forcings, is applied to larval transport models to deduce the dispersion pattern of larvae. Simulation results provide information on the retention of larvae (as concentration of larvae) at every grid point (Cowen and Sponaugle 2009). A common strategy employed in this kind of model is to predict the maximum likelihood of retention of investigated species based on habitat attributes (Guisan and Zimmermann 2000; Moisen et al. 2006; Elith and Graham 2009). During breeding seasons, the areas of maximum likelihood retention of larvae can be demarcated as nursery grounds or marine protected areas for aiding larval survival.

Numerical modelling of fish egg dispersion at the Patos Lagoon estuary in Brazil was carried out by Martins et al. (2007). A similar study combining observational data with a two-dimensional numerical model product has been carried out to determine the fate of fish eggs released in a semi enclosed basin (Grinson et al. 2011a). Fish eggs were treated as passive particles in the model, and were released from probable spawning sites identified during exploratory surveys. Areas with retention of larvae above 30 % were demarcated as nursery areas. Model simulation of eggs from different spawning sites showed varying dispersal patterns. About 80 % of the particles were retained in the basin for all the three seasons studied. Complete retention of particles occurred in the southern part of study domain. A small quantity is flushed out at the northern boundary. This could be the reason for more fish larvae in the southern part. Trawler catches from scientific surveys show a higher abundance of adult fish in the southern part compared to the north. Marine protected areas (MPA) in this study region are demarcated based on ecologically significant factors such as the presence of corals and mangroves. The areas of maximum likelihood of retention of fish larvae differentiated by the numerical model reasonably corraborated with the MPA (Grinson et al. 2011a). Therefore, this sort of simulation can also help as a decision support tool in rightly demarcating the MPA.

Similar experiment was carried out along an open coastal region (Grinson 2011). HD model results were validated with measurements (Fig. 18.1a–c). The modelled and predicted tidal levels showed very good match with no phase difference. The modelled u and v-velocities agree well with the measured current velocities. The larval tracks have a uniform pattern of dispersal southwards and they aggregate near the southern boundary during all the seasons (Fig. 18.1). We can infer that the hydrodynamics of the region promote occurrence of fish assemblages in the southern part of study domain. This is consistent with earlier field studies from this region (Rivonker et al. 1990) which have shown that the fishing grounds are spread over the southern part of the region without any seasonal change in the pattern.

The scale and predictability of fish larval dispersion or retention remain unknown, largely due to measurement difficulties. Utilization of high-resolution biophysical model allows multiple releases of virtual eggs, thus making each individual simulation equivalent to observations of numerous dispersal events.

18.2.2 Modelling Larval Transport and Settling Areas in Case of Bio-fouling Organisms from Ballast Waters

Biofouling by barnacles poses a major threat to fishing, navigation, tourism and port-related activities. The life cycle of barnacles includes a pelagic larval phase. Therefore, the methodology used for modelling dispersal of larval fish can be applied for larval barnacles. The scale of dispersal depends on movement of the water masses, larval behaviour and duration of pelagic stages (Table 18.2). This is characteristic of oceanic diffusion with a positive correlation between time and spread (Pineda 2000).

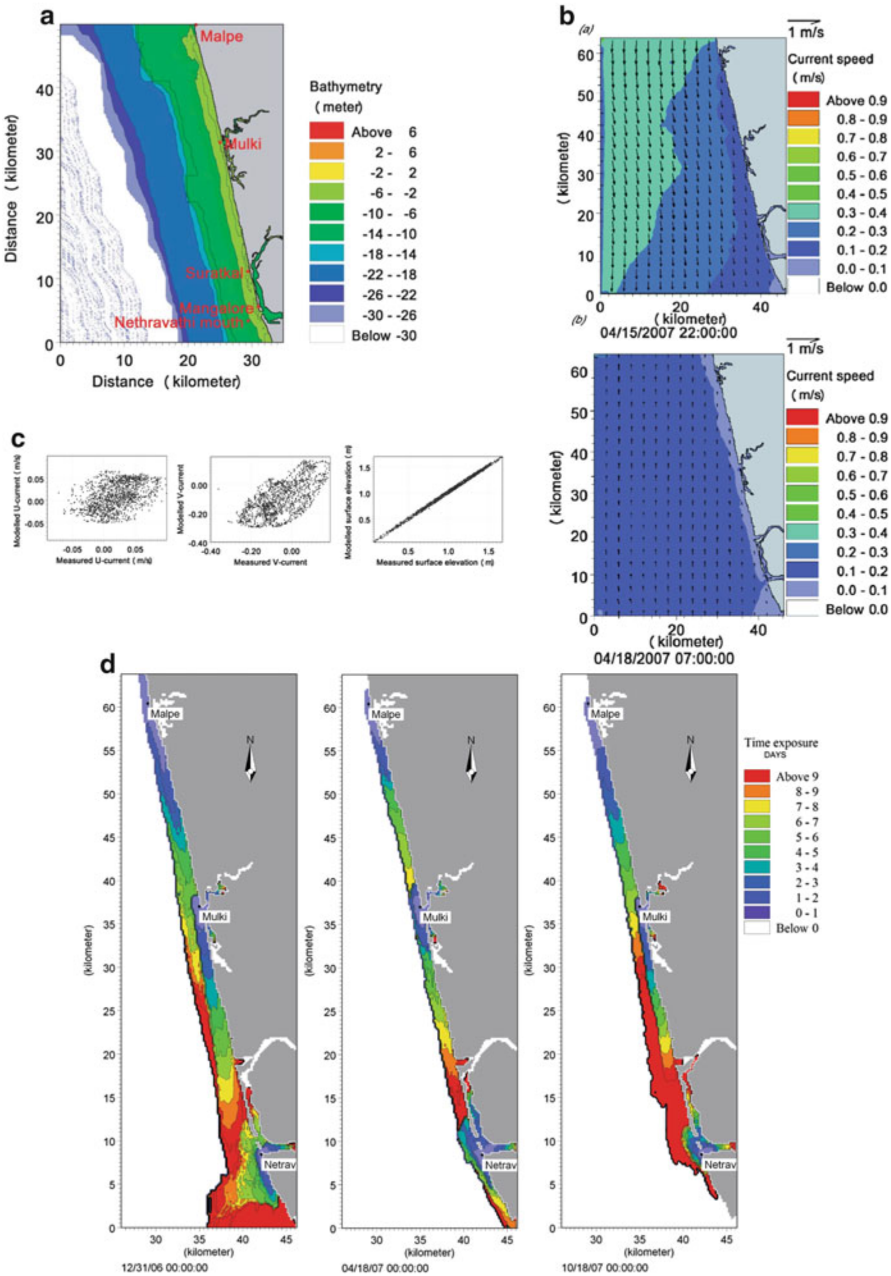

Fig. 18.1 Mangalore open coastal waters (**a**), HD modelling (**b**), HD validation (**c**) and fish larval transport indicating their aggregation towards southern boundary of the domain (**d**), which is a traditional fishing ground

Table 18.2 Distance traversed by barnacles for different pelagic larval duration scales as calculated by Pineda (2000)

Pelagic larval duration	Distance traversed
Few hours	100–1,000 m
1–2 days	1 km
7–14 days	10–20 km
10–15 days	20–30 km
1–2 months	50–100 km
1 year	1,000 km

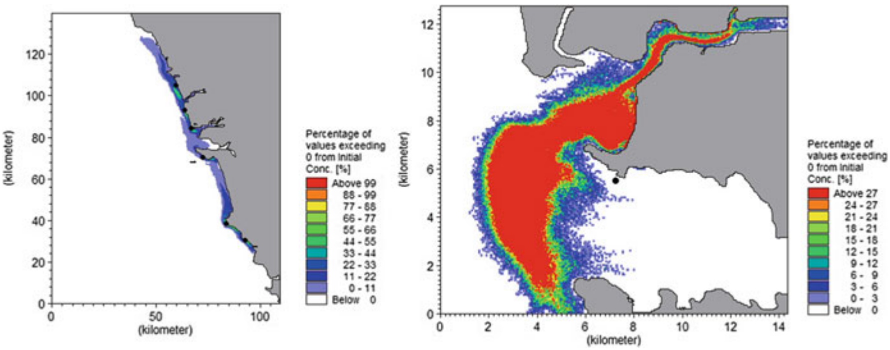

Fig. 18.2 Barnacle larval transport modelling carried out in an open coast of Goa and in Mandovi-Zuari estuary

An application was worked out to estimate the extent of larval spread of barnacles from ballast water sources in different seasons. In the case-study discussed below, the larval dispersal and retention of barnacles in an estuarine mouth was examined (Gaonkar et al. 2012; Grinson et al. 2013a). There is a spatial and temporal variation in the larval dispersal pattern from different spawning sites. Northern spawning sites of the study domain contributed larvae to the estuary during December and May. But, with the reversing wind and current, southern spawning sites contributed larvae to the estuary in October. Larval transport is southward during December and May, reflecting the predominant wind direction. In October the larvae spawned at northern sites were transported to the north and as consequence are lost from the estuary. Larvae spawned at remaining sites in October might be transported either to the north or the south, depending on the timing of the reversal in winds. The net transport in October is usually to the north (Fig. 18.2).

Numerical simulations of larval dispersal have limitations arising from the simplicity of the model in its biological and ecological aspects. Rates of settling, natural mortality, predation and reproductive output may vary with season and with location. For example, higher temperatures can lead to early metamorphosis of larvae, leading to earlier settlement than at lower temperatures. Heavy rainfall result in lower salinity and increased land runoff leading to turbidity which increases larval mortality. Therefore, the results of the simulations can be interpreted as maximum dispersal

Table 18.3 Geo-physical databases useful to fishery scientists

Website	Parameters
http://218.248.0.134:8080/OCMWebSCAT/html/controller.jsp	SST, Chl-a, WS and WD
http://cersat.ifremer.fr/data/products/latest-products	WS and WD
http://oceandata.sci.gsfc.nasa.gov/readme.html	SST, Chl-a, PP
http://odis.incois.gov.in/index.php/remote-sensing-data	Aerosol, Chl-a, fog, humidity, SST, Kd-490 and wind
http://podaac.jpl.nasa.gov/CoreMeasurements	SST, SSS, OCC, SSH, SSHA, WS and WD
http://www.aviso.oceanobs.com/en/data/products.html	SSH, Wind and wave
http://www.eumetsat.int/website/home/Data/Products/Ocean/index.html	SST, Wind
http://www.src.com/mm5/MM5_Main_Page.html	WS and WD

OCC ocean currents and circulation, *SSHA* sea surface height anomaly; Kd-490- diffuse attenuation coefficient of down-welling irradiance at 490 nm

and survival rates. However, this study did provide some basis for the observed variations in larval abundance, settlement and recruitment of barnacles which represent the major biofouling agent from ballast waters.

18.3 Geo-physical Datasets from SRS in the Context of Marine Fisheries Research and Management

SRS datasets are often used in empirical or semi-analytical validated models, either to extrapolate regional datasets in space or to generate derived geo-physical products. A simple example for this can be the summation of thermal signals from different wavelengths for generation of SST. In a similar way, some of the most useful and relevant environmental properties in fisheries research such as sea surface salinity (SSS), WS and WD, sea surface height (SSH), chlorophyll-a (Chl-a) and Chl-a derived primary production (PP) are available online as processed and unprocessed geo-physical datasets (Table 18.3). These datasets can be used to advantage in various fisheries research and management programmes. A few such case studies are illustrated in this section.

18.3.1 SRS Chlorophyll Data Providing Cues on Fish Stock Variability

Variations between years in the seasonal cycle of SRS Chl-a have been implicated in fluctuations in fish stock variability (Platt et al. 2003). In this section we describe the results of an analysis of Chl-a with Indian oil sardine in the coastal waters of

India. Fishing effort in the coastal waters of India changed little in the period 1998–2006, with 238,772 fishing craft in 2005 (CMFRI 2005) in comparison with 239,000 craft in 1997 (Sathiadhas 2006). Thus, the variability in sardine landings during the study period, despite steady fishing effort, indicates that other factors such as environment or food to the sardines are involved. A correlation analysis between available environmental factors (SST, sea bottom temperature, surface salinity, surface dissolved oxygen, bottom dissolved oxygen, pH, nutrients, chlorophyll, zooplankton, rainfall, multivariate El Niño Southern Oscillation index, coastal upwelling index, and derived SST) and sardine catch from the study area emphasised the high significance of chlorophyll compared with other environmental factors in explaining the variability in sardine catch (Krishnakumar and Bhat 2008). Using their fine branchial apparatus, sardines feed predominantly on phytoplankton and zooplankton. In a given area, Chl-a is a good index of the food availability to sardines. Summer surface Chl-a from the study area lies in the range 0.1–5 mg/m^3, and can be very high, from 5 to 10 mg/m^3, during bloom periods (Raghavan et al. 2006). Given the wide dynamic range of chlorophyll concentration in the coastal waters of southwest India and the dominant role of chlorophyll as a determinant of variability in sardine stocks, it seems likely that much will be gained in studying this link in detail.

Algal bloom in the study area often occurs during upwelling. Upwelling in the waters of the southwest coast of India (5–15°N latitude) and the variability in local physical parameters drives changes in the chlorophyll concentration (Smitha et al. 2008). Physical processes affect not only the magnitude of the plankton biomass, but also its species composition (Huntsman et al. 1981), which may in turn affect larval fish feeding and survival (Lasker 1975; Simpson 1987). According to the Hjort-Cushing match-mismatch hypothesis (Hjort 1914; Cushing 1974, 1990), the survival rate of fish larvae is a function of the match between timing of hatching of eggs and initiation of spring phytoplankton bloom. The advent of SRS provides information at the appropriate temporal and spatial scales for testing this hypothesis (Platt et al. 2007). With SRS, it is possible to characterize the spring bloom objectively based on the timing of initiation, amplitude and duration. The statistical moments of all of these properties, and their inter-annual variation, can be calculated and the results used to analyze the effect of ecosystem fluctuations on exploited fish stocks (Platt et al. 2003).

The case study presented below deals with the interannual variability of Indian oil sardine (*Sardinella longiceps*) stock in the southwest coastal waters of India and its relationship with the phytoplankton bloom characteristics computed from SRS, with a view to explain larval survival and interannual variability at the synoptic scale (Grinson et al. 2012).

The life cycle of sardines includes an active breeding season from May to September. This coincides with the high chlorophyll concentration seen during May to September every year (Fig. 18.3). Thus, we find a probable connection between the life history of sardines and phytoplankton bloom dynamics. This supports the finding that the fish itself times its breeding and adjusts its migration

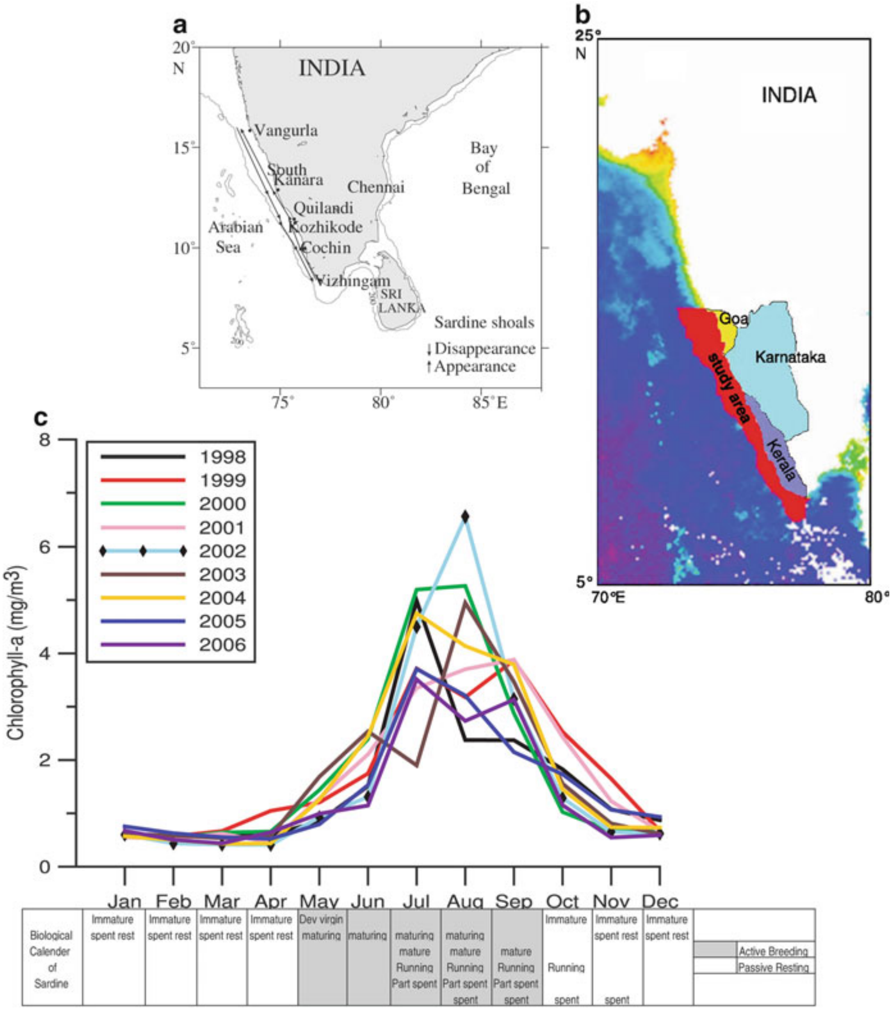

Fig. 18.3 Indian oil sardine migration (**a**), and SeaWiFS satellite chlorophyll (**b**) peaks utilized for explaining the trophic link between the upwelling bloom biology (**c**) and sardine interannual variability along the south west coastal waters of India (Source: Grinson et al. 2012)

to exploit the productive southwest monsoon period. In this study, magnitude of the bloom during initiation month is selected for characterization of bloom, which naturally falls in the month of May every year. May is the most critical month for sardines because both bloom initiation and the beginning of sardines' active breeding phase occur during this month. A delay in the initiation of bloom in the area results in a delay in the onset of suitable conditions for survival of sardine larvae (Grinson et al. 2012).

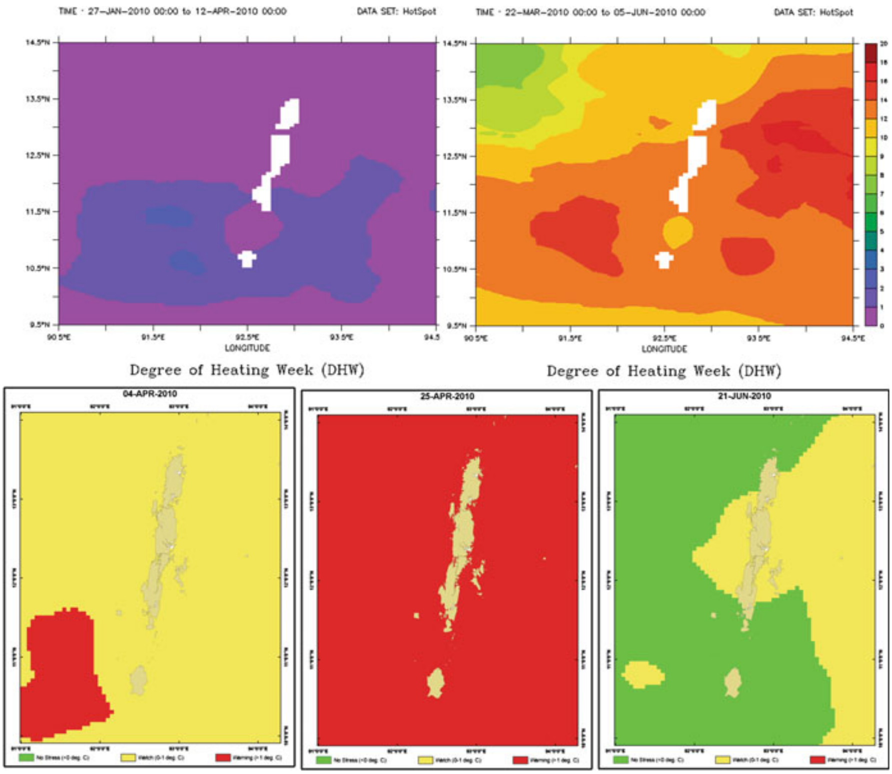

Fig. 18.4 HS and DHW generated during the bleaching events in 2010 in Andaman Sea indicating the stress levels reefs faced (provided as advisory by INCOIS)

18.3.2 Reef Health Advisories Using SRS Derived SST

Globally, there are several instances of mass coral bleaching incidents leading to heavy reef mortality (Krishnan et al. 2011). The application of SRS provides synoptic views of the global oceans in near-real-time for monitoring the reef areas (Liu et al. 2003; Bahuguna et al. 2008; Mahendra et al. 2010). SST during night time is an important parameter for assessment of the thermal conditions inducing the bleaching. SRS provides SST information during day and night routinely, facilitating the development of a coral reef bleaching warning system to generate early warning advisories/bulletins in near real time. The estimation of monthly maximum mean using night time SST climatology retrieved using NOAA, AVHRR is used for generating reef health advisories to eliminate the effect of solar glare and reduce the variation in SST caused by the heating during day time. Threshold hotspot (HS) and daily heating week (DHW) values for a region are calculated the advisory (Mohanty et al. 2013). Depending on the intensity of HS and DHW there can be advisories such as ‘no stress’; ‘watch’; ‘warning’ and ‘alert levels-I & II’ which progressively indicate the severity of a potential bleaching event. Based on this study INCOIS offers reef stress advisories (Fig. 18.4) to alert the reef managers to take appropriate measures to reduce the damage caused to reefs during bleaching events.

18.3.3 SRS Data for Cyclone Tracks Creating Productive Fishing Grounds

Even though cyclones are devastating, there are some positive effects of cyclones on the fishery. Study of the effect of tropical cyclones on biological processes has gained momentum in the recent past. In thermally-stratified coastal waters, cyclones trigger the breaking up of nutrient-depleted surface waters and bring in nutrient-rich sub-surface waters inducing sudden algal blooms and enhancing the regional scale PP. The effect of physical forcings on PP, its variation and associated hydrography in the southwestern Bay of Bengal during the southwest monsoon (July) and post-cyclone period (November) of 1999 was studied by Madhu et al. 2002. In the postcyclone period, the combined effects of well-mixed coastal waters and freshwater injection from the land runoff associated with the cyclone brought nutrients to the mixed layer, which enhanced PP. Potentially, such enhancement of PP results in improving the regional fishery. But cyclone tracks alone will not provide the information on enhanced PP. SRS is able to detect the environmental changes caused by tropical cyclones. Geo-physical data sets from SRS are useful in such studies for indicating possible productive fishing grounds after a lag following the cyclone (Rao et al. 2006).

18.3.4 Demarcation of Ecological Provinces in Support of an Ecosystem Approach to Fisheries Management

Globally, the ecosystem approach to fisheries management (EAFM) is preferred as a basis for sustainable management of fish stock (Garcia et al. 2003b). In this context, it is useful to have a spatial structure for global oceans defined on the basis of ecological provinces rather than geo-political considerations. There are various approaches for classifying the global oceans into ecological provinces (Ekman 1953; Margalef 1961; Yentsch and Garside 1986; Cushing 1989; Fanning 1992; Sathyendranath et al. 1995). The classification by Longhurst et al. 1995 is the most comprehensive, identifying some 50 biogeochemical provinces globally (Longhurst et al. 1995). Some other methodologies require huge data sets for demarcating ecological provinces (Hooker et al. 2000; Li et al. 2004; Alvain et al. 2005; Sherman et al. 2011). But there is lack of *in situ* data to support these approaches. As oceanic realms are dynamic, there are logistic issues in sampling.

Consequently, SRS data are very useful to classification protocols. PP derived from SRS can be a very useful input as PP provinces subsume many oceanographic forcing mechanisms on synoptic scales (Platt and Sathyendranath 2008). These ecological provinces are useful in fisheries management as the physical processes and the ecosystems in each province support characteristic fisheries different from those in nearby provinces (Stuart et al. 2011). Beyond static partitioning, there is a further goal for dynamic bio-geography at regional scales that would incorporate complexities of a dynamic marine environment and their effect on the phytoplankton. SRS will be an invaluable source of inputs in case of such partitioning. Changes in spatial extent of the ecological provinces arising from temporal variations in physical forcing can be captured in a SRS climatology of ocean colour.

18.4 Coupling Modelled and SRS Data for Effective Fishery Management

So far in this chapter, we have discussed the usage of environmental data sets from models and SRS for various aspects in fisheries research and management. But lack of environmental time series data sets pointed to the need for more data. Coupled with SRS, numerical modelling is an alternative tool to generate environmental and biological datasets, which can help to mitigate problems arising from data gaps. Some relevant case studies are described below.

18.4.1 Trophic Modelling Using SRS Data as an Ecosystem Approach to Fisheries Management

Trophic levels in the marine ecosystem are similar to those in terrestrial systems starting with primary producers and ending in scavengers. But, the trophic structure in marine systems is web like, rather than a linear food chain. Fishing often alters the ecosystem structure. Trophic webs will respond differently to fishing depending on whether the target species is a predator or prey species. Single-species fish stock-assessment models ignore food web interactions. Ecosystem based fish stock assessment is offered as another option. EAFM models often resort to SRS-based PP as an input for forcing at the base of the food web to investigate energy transfers and biomass in an ecosystem without fishing, from lower to upper trophic levels (Chassot et al. 2011).

18.4.2 Generating Potential Fishing Zones (PFZ) and Their Dissemination Along with Ocean State Forecasts (OSF)

Identification of PFZ involves an understanding of oceanic processes and interaction of hydro-biological parameters (Desai et al. 2000). The forage base and the physical gradients of temperature and Chl-a help the predatory fish to locate their prey and the same cues are used by fishermen. A number of studies have examined the use of SRS as an aid to locate more productive fishing areas (Waluda et al. 2001). Indian Remote Sensing Satellite P4 Ocean Colour Monitor (IRS P4 OCM) derived chlorophyll concentration and National Oceanographic Aerospace Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) derived SST images have been used to characterise the relationship between the biological and physical variables in coastal waters and it was observed that chlorophyll concentration and SST were inversely correlated with each other (Solanki et al. 1998). The relationship between these two parameters was estimated by a clustering technique called ARNONE (NCAER 2010) and the matching features were selected for generating integrated PFZ forecasts from the composite images on the basis of latitude and longitude (Solanki et al. 2005; NCAER 2010).

Validation of studies of PFZ forecasts have shown that the forecast may lead to substantial increase in fish catch (Solanki et al. 2001, 2003; Nayak et al. 2003). PFZ forecasts in near-real time indicating the likely availability of fish stocks for the next 2 days are disseminated in the Indian EEZ by INCOIS (Fig. 18.5) to about 225 nodes for operational use (Nayak et al. 2003). A significant increase in total catch by following PFZ forecasts has been documented from ANI (Grinson et al. 2011b, 2013b).

18.4.3 Detection of Meso-scale Features Such as Eddies and Fronts That May Indicate Productive Fishing Grounds

Oceanographic features such as eddies, currents and meanders are pervasive features in the world's oceans. These conspicuous hydrographic features influence the horizontal and vertical distributions of the chemical (e.g. nutrients), physical (e.g. SST) and biological (e.g. Chl-a) properties in pelagic systems (Yoder et al. 1981; Seki et al. 2001). Eddies have been found to be localized regions of higher PP leading to aggregation and development of forage species base communities. The presence of mesoscale eddies and their detection by the fishing fleet is an important factor in fishery performance, leading to increased catch per effort for most pelagic species (Laurs and Lynn 1977; Laurs et al. 1984). The influence of mesoscale processes at fronts, such as the formation of rings,

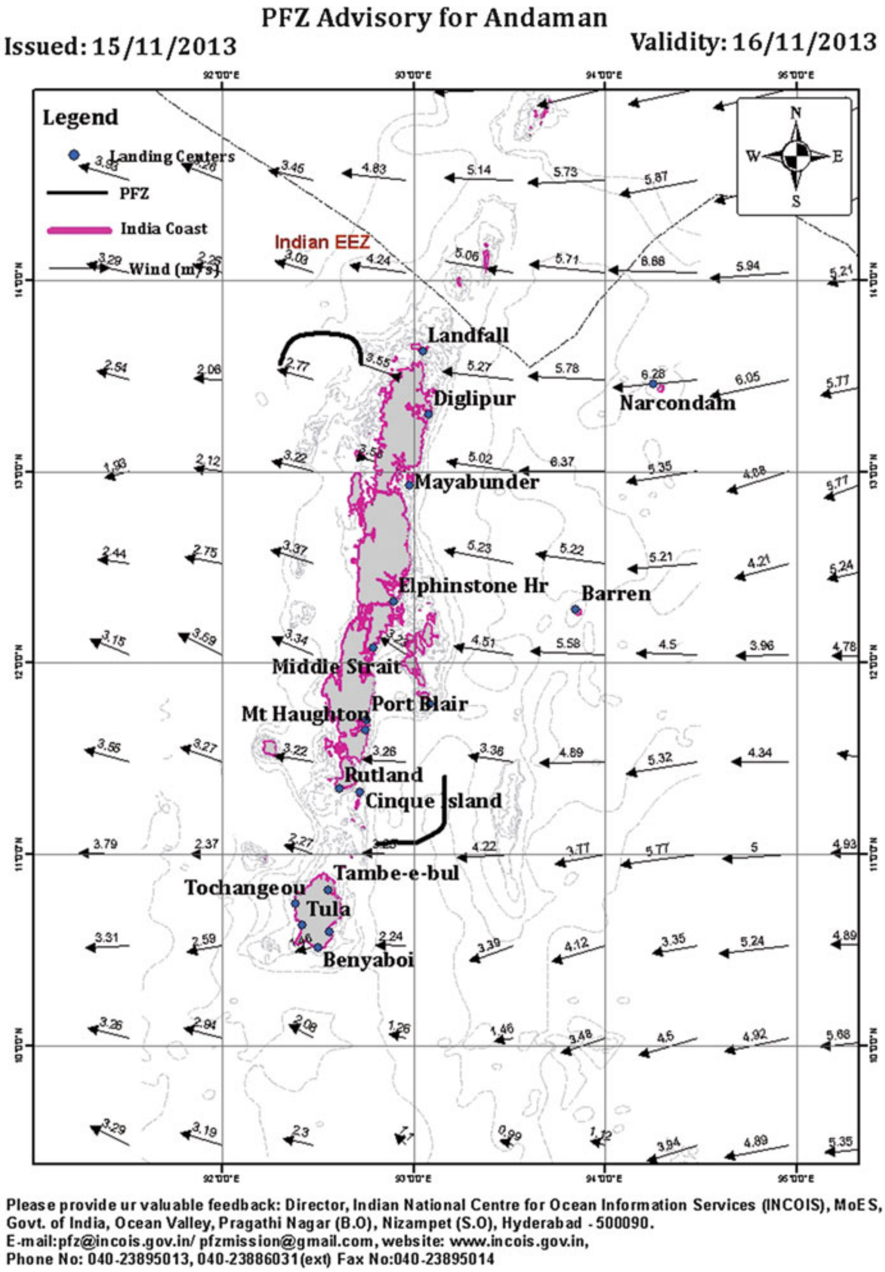

Fig. 18.5 An INCOIS PFZ imagery for Andaman group of islands

meanders and streamers arising or breaking off from these dynamic current systems, has also been shown to be important in shaping the distribution of pelagic fish and shellfish (Waluda et al. 2001). Studies linking the physical oceanographic processes with fish have been carried out around the major boundary currents and related mesoscale processes, such as in the fishing grounds associated with Kuroshio frontal regions (Yokouchi et al. 2000), mesoscale eddies and pelagic fisheries off Hawaiian waters (Seki et al. 2001), upwelling and longline fishery of Portuguese waters (Santos et al. 2006), Atlantic tuna and Gulf of Mexico circulation (Block et al. 2005), oceanographic conditions of spawning grounds of bluefin tuna in the NE Indian ocean (Matsuura et al. 1997), bluefin and frigate tuna spawning along the Balaeric archipelago (Garcia et al. 2003a) and tuna exploitation near the mesoscale processes near the Sechelles (Fonteneau et al. 2006).

The chlorophyll-SST based advisories depend on the surface manifestation by algal blooms and thermal fronts which result from eddies and upwelling. Using altimetry data however, one would be able to follow the evolution of feature from inception to maturation and dissipation with time. There is a time lag between physical upwelling of nutrients to the ocean surface and development of phytoplankton blooms, and subsequently the aggregation of planktivorous and piscivorous fish. Altimetry data helps to identify the fish-aggregating meso-scale features from the outset giving valuable time to forecast and exploit the consequences. Difficulties in getting cloud free imageries sometimes limits the scope of this approach. Altimetry data, especially the SSH have been useful to study the physical oceanography and mesoscale circulation. Advances in SRS altimetry are making it possible to extend the information to the coastal areas where the fishermen are most active. Inputs from the altimetry data on the mesoscale features can be used to augment the PFZ advisories and also provide data during cloud cover.

18.4.4 Forecasting Cyclones and Ocean State to Reduce Impacts on Coastal Fisher Folk and Resources

Apart from elucidating the areas of likelihood of fish/shellfish distributions during the PLD phase, the wind models used for generating wind inputs in simulation of physical process can be utilized for studying cyclone tracks. Fisheries is one of the sectors with high occupational hazard. The extent of direct mortality caused by storms at local or regional scales is severe (Gardner et al. 2005; Done 1992). OSF derived as products of numerical models are provided as input to fishermen to mitigate this risk. OSF provides wave and swell height as well as period, WS as well as wind direction (WD), Tsunami and rough sea warnings and coastal current details. To ensure safe navigation and operations at sea, and to forewarn the fishermen community, INCOIS started the OSF service in 2005 by issuing forecasts 7 days in advance and at three hourly intervals, with daily updates. Fishermen utilize these forecasts to guide their daily operational activities and to ensure safe

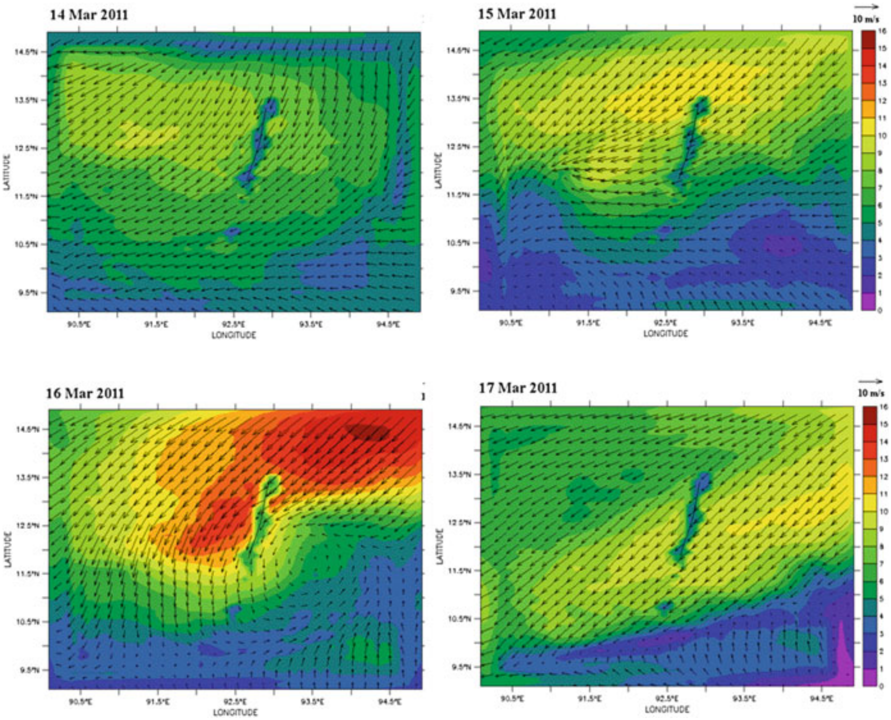

Fig. 18.6 Tropical cyclone wind climatology modelled using WRF for studying the reef damages in Andaman Sea

navigation. Though international agencies such as National Centres for Environmental Prediction (NCEP), USA and European Centre for Medium-Range Weather Forecasts (ECMWF) and UK issue sea state forecasts based on models such as WAVEWATCH III and WAM, these forecasts are for the open ocean. The INCOIS model provide accurate location-specific forecast in the coastal waters using high resolution local bathymetry, and tuning them using observed wave measurements. Real-time and on-line validation of the forecast products is disseminated through various means by INCOIS (Nair et al. 2013).

Cyclones also render coastal resources vulnerable. The ecological effects of cyclones on coral reefs have been reviewed by Harmelin-Vivien (1994). Tropical storms cause severe damage to the reefs; their impacts include the removal of reef matrix, scouring and fragmentation (Rogers and Fish 1991; Done 1992), deposition of loosened material onto beaches above sea level or transporting it into deeper sub-reef environments (Done 1992). The reefs in Andaman and Nicobar Islands (ANI) suffered severe damage following a tropical cyclone in the Bay of Bengal off Myanmar coast during 13–17 March 2011 (Krishnan et. al. 2013). The investigation exposed the vulnerability of the reefs to oceanographic features which generally remain unnoticed unless they directly affect the life or the property of coastal inhabitants. The wind tracks of cyclone were generated using weather research and forecasting (WRF) models (Fig. 18.6) which clearly indicated the passage of cyclone where reefs suffered damage.

18.4.5 *Estimation of Potential Fishery Resources of an Exclusive Economic Zone (EEZ) for Fishing Fleet Management*

Global marine fish production increased from less than 20 million tons per year in early 1950s to average around 90 million tons per year during the last decade. If the unreported and discarded catches are also taken into account, the global catches will be around 120 million tons per year (Dirk and Pauly 2005). The general trend in shortfall from traditional fishing grounds in the EEZ's of developed countries is compensated by the increasing exploitation of resources in developing countries (Pauly and Watson 2003). The United Nations Convention on the Law of the Sea (UNCLOS) bestows the coastal states with the right to exploitation and responsibility for management of fishery resources of their EEZs. Observations are of paramount importance for managing the resources, and there is a need to establish acccurate catch data collection systems. Fish captured are considered to reflect fish abundance in coastal waters. From marine fish catch data, we can estimate the potential harvestable fish by plotting the catch effort curve, and estimate the maximum sustainable yield (MSY). But, mere post-mortem analysis of landed fish may lead to imperfect estimates as fish catch data without geotags of catching locations may not provide samples representative of the stock in the sea. Therefore, an estimate of harvestable fish based on *in situ* water productivity, taking into account the tropho-dynamics in the EEZ may afford very useful complimentary information.

Chlorophyll, which is an index of algal biomass (ML^{-3}) present in a water column (L) is a prerequisite for primary production and subsequent fish production ($ML^{-2}\ T^{-1}$) which is the annual rate of production of fish biomass per unit area of sea bed. The importance of the potential link between PP and fish was understood decades ago (Ryther 1969), but the advent of SRS Chl-a and modelled PP data sets now available on global and meso-scale prompted policy planners to utilize this for estimation of fishery potential in the EEZ. Past studies relied on *in situ* datasets resulting from different sampling and processing methods and were generally characterized by low spatiotemporal sampling coverage. SRS Chl-a data are now basic to cross-trophic-level analyses of ecosystem production, structure, and function because of the easy and free availability of a wide-ranging, high resolution, and consistent sampling framework (Platt et al. 2007) at a reliable accuracy.

18.5 Overview

This chapter has reviewed some recent advances in numerical modelling, SRS and their coupled applications in marine fisheries research and management. Globally, there is considerable potential for phytoplankton data to serve in future as a proxy for estimation of fish biomass. Usually, investigations in fisheries biology lack environmental time series or other biological data sets (Longhurst and Wooster 1990; Madhupratap et al. 1994). Data from SRS, numerical modelling and their combinations can lead to robust conclusions. Numerical simulation is an attempt to supplement the existing decision support systems. The biological relevance of numerical modelling and SRS at present is restricted to a few operational activities in fisheries. But the issues are complex and there are many uncertainties. The role of coastal processes in fish and shell fish production and dynamics deserves further investigation with improved time series sampling of early life stages in marine organisms. But in the years to come, numerical modelling, SRS and their coupled usage will provide major technological advances supporting operational fisheries research and management.

Acknowledgement This chapter was written during the fellowship offered by NAIP, Indian Council of Agricultural Research for my PML visit with Dr. Trevor Platt as my mentor. My previous research associations with Dr. Vethamony at NIO, Goa, Dr. Dam Roy and Dr. Krishnan at CARI, Port Blair, Dr. T. Srinivasakumar and Dr. R.S. Mahendra at INCOIS and A. Anand at RRSC, Nagpur are reflected in this chapter. I acknowledge the support from Dr. B. Meenakumari, DDG (Fisheries), ICAR, India and Dr. A. Gopalakrishnan, Director, CMFRI, India and the ChloRIFFS project which sponsored this work.

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