Remote Sensing in Fisheries and Aquaculture

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Remote Sensing in Fisheries and Aquaculture

Edited by:
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Chapter 1

Introduction to SAFARI

Nick Hardman-Mountford, Alida Bundy, Nicholas Dulvy, and Trevor Platt

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sa·fa·ri (sə-fär′ē): Noun *a journey* (Swahili).

1.1 Introduction

The Earth is a blue planet, with three quarters of its surface area covered by water. For many reasons, society needs to keep an eye on conditions in the ocean, but this is not a simple task. Its vast size is a fundamental obstacle, as is our inability to inhabit the ocean for more than the briefest periods. The undertaking is complicated by the dynamic nature of the marine environment: unlike the terrestrial environment, ocean waters move rapidly in three dimensions. The conventional platform for observing the ocean, the ship, has enabled great advances in our understanding of the oceans, but has many limitations, foremost that it can observe only a single point in the ocean at any one time. Only by using instruments carried on spacecraft (satellites) can we hope to observe the whole ocean surface at a frequency high enough to detect change in the ocean.

The scope of earth observation by satellite remote sensing, as applied to the ocean, is very broad. It covers the physical system (surface temperature, winds, surface height, surface waves, ice cover and soon, surface salinity), as well as the ecosystem and water quality (both from ocean colour) and surveillance. All of these are relevant to fisheries and aquaculture. Their importance will only increase as we try to understand how aquatic systems, and the fisheries that depend on them, will be affected by the suite of processes known collectively as climate change. In this volume we show how the outputs from an array of remote-sensing methods can be applied in the context of fisheries research, operations and management for the benefit of society at large.

1.2 Remote Sensing and Ocean Ecosystems

Fish are part of the ecosystem; so is the seawater medium in which they live, along with its physical and chemical characteristics such as temperature and nutrients;

so are the planktonic organisms upon which they feed; and so are the fishing activities which exploit them. The source of energy for the ecosystem is the sun. In aquatic systems, the solar input is captured and made biologically available by the photosynthetic pigments within phytoplankton. It is because the phytoplankton act in this way, to couple the ecosystem to its source, that we consider them to be the basis of the aquatic food chain. It is this fundamental attribute, the presence of pigments in phytoplankton, that enables us to map the colour of ocean waters, hence the abundance of phytoplankton. This is achieved by satellites equipped with sensors able to measure the visible spectrum of light (ocean-colour radiometry).

Phytoplankton are characterised also by their vulnerability to environmental fluctuations. The productivity, biomass, size-distribution, community composition and seasonality are all determined by the ambient physical conditions, which vary on hourly, daily, seasonal and interannual timescales. The environment in the surface layer of the ocean, where phytoplankton prosper, is affected in the short term by changes in the weather, and in the longer term by changes in the climate (where climate is the long-term average weather conditions). We know that the Earth's climate is undergoing change and it is inevitable that the ocean will experience a corresponding change (see Chapter 2 for a fuller discussion of ecosystem variability and climate change in relation to fisheries).

The phytoplankton will certainly be affected, but in ways that we cannot easily predict. We also know that the weather varies from year to year. In particular, for temperate latitudes, the weather in the spring, which determines the phase of the seasonal cycle of phytoplankton, varies interannually, for example with respect to wind stress and cloud cover. This means that variability in the timing of the principal outburst of phytoplankton growth in the spring is, in part, determined by the weather. The significance is that the phytoplankton produced during the spring outburst form an important food source for the larvae of many fish and invertebrates that reproduce in the spring. The food has to be available in the right quantity and quality, at the right place, and at the right time if the larvae are to have any chance of survival. Implicit in this view is the belief that the sea is not everywhere a uniformly-hospitable environment for the growth of larval fish. Because the base of the aquatic food chain is hostage to the weather and the climate, in so far as they modify the environment in the surface layer of the ocean, it is certain that environmental fluctuations will propagate through the phytoplankton to higher trophic levels. There may be conservative tendencies that act to smooth perturbations as they flow from phytoplankton through the food chain, but these are not strong enough to obliterate the effect of environmental variability on recruitment of exploited stocks. It is only the development of satellite remote sensing of ocean colour that has now provided data at the required resolution in time and space to enable such links between the physical and biological aspects of the environment to be elucidated, as will be shown in Chapter 3.

1.3 Remote Sensing Contributions to Fish Harvesting, Assessment and Management

The value and significance of fisheries resources to humanity makes responsible management essential. However, previous attempts to manage stocks either on a single or multi-species basis, taking account only of their population dynamics and ignoring environmental variability, have failed systematically, sometimes with catastrophic consequences. For example, in the early 1970s, a combination of overfishing and environmental change led to the collapse of the Peruvian anchoveta fishery. As well as having disastrous economic consequences, the collapse resulted in the starvation of millions of seabirds and mammals that feed on this small plankton-feeding fish. The widespread recognition of these failings has led to the development of a series of principles, guidelines and policies that have collectively become known as either the Ecosystem Approach, Ecosystem-based Fisheries Management (USA) or the Ecosystem Approach to Fisheries (Europe) (Pikitch *et al.*, 2004; ICES, 2005). This new paradigm is embedded in the general structure of sustainable development, which requires that the actions of current generations do not compromise the needs of future generations. Hence, although the details vary between management regions, the broad thrust of the Ecosystem Approach is to maintain the health of marine ecosystems alongside appropriate human use for the benefit of current and future populations (WSSD, 2002; ICES, 2005). The Ecosystem Approach can therefore be described as: *a comprehensive, integrated management of human activities, based on the best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take action on influences which are critical to the health of the marine ecosystem, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity.* The approach explicitly recognises that fisheries are not just biological entities but have ecological, social and economic dimensions as well. Although fishing and fisheries have a variable contribution to the economic growth of nations, it is increasingly recognised that fishing fleets are often the dominant local economic activity in coastal areas with few other income opportunities.

A major limitation to operational implementation of the Ecosystem Approach for fisheries management has been the sparse availability of information on the state of the wider ecosystem structure and processes, for example the timing and magnitude of the spring phytoplankton bloom in temperate latitudes, or the intensity of upwelling in Eastern Boundary Current regions. Some nations have invested much money and effort in routinely monitoring their fish populations to underpin stock assessment approaches to fisheries management. Implementation of the Ecosystem Approach, however, requires a much wider information-base for decision making. Furthermore, operational delivery of information on the status of the ecosystem requires all spatial regions to be sampled at high frequency (at least daily for some applications, e.g. the detection of harmful algal blooms). Additional sampling from ships and moored instruments are clearly important for providing this information, but such a sampling programme alone would be inadequate to provide the spatial and temporal resolution required for such applications, as well as prohibitively expensive. Thus, to address this limitation we need to consider alternative sampling platforms.

Remote sensing from satellites has revolutionised our view of the surface of planet Earth, on land, in the atmosphere and in the sea. As well as the many scientific advances made possible from these sensors, the data they provide have been applied operationally for weather forecasting and military planning. Therefore, it would be of utmost value if they could also provide operational information useful for the sustainable management of ocean ecosystems. Certainly, time series of greater than 10 years have been gathered for ocean surface measurements of visible (ocean colour) and infra-red radiation and sea surface height, providing information on, for example, chlorophyll concentrations, sea surface temperatures and ocean currents. Ocean-colour data is particularly relevant to ocean ecosystems: chlorophyll provides a measure of phytoplankton biomass, i.e. the base trophic level of the ecosystem. The standing stock of phytoplankton biomass at any particularly time integrates the impact of both top-down (e.g. zooplankton grazing) and bottom-up (i.e. environmental forcing) processes, so contains a very large amount of ecosystem information, much of which has not yet been exploited. Other coloured (light absorbing or light scattering) constituents of seawater can also be detected, such as coloured dissolved organic material and sediments. Sea surface temperature captures many physical processes and has a fundamental role in regulating the ecosystem. Sea surface heights can be used to derive information on mesoscale circulation and sea state. Variability at these scales is important for many ecosystem processes (e.g. Lasker windows for first-feeding larvae).

1.4 A Framework for the Application of Remote Sensing to the Ecosystem Approach

1.4.1 Indicators

For remote sensing to contribute to the ecosystem approach, it needs to address the requirements of stakeholders on operational time and space scales. Thus there is an imperative for scientifically robust measures that are easily interpretable with reference to specific objectives. Such measures have been termed ‘indicators’. They can be defined as:

> *“A variable, pointer or index. Its fluctuation reveals the variations in key elements of a system. The position and trend of the indicator in relation to reference points or values indicates the present state and dynamics of*

> *the system. Indicators provide a bridge between objectives and action"* (FAO, 1999).

According to UNEP (2003), indicators serve four basic functions: simplification, quantification, standardisation and communication. They summarise complex and often disparate sets of data and thereby simplify information. They should be based on comparable scientific observations and statistical measures. They also need to provide a clear message that can be communicated to, and used by, decision makers, stakeholders and the general public (see Chapter 7 for more information on communication with stakeholder communities).

Table 1.1 The purpose, fit within the Driver-Pressure-State-Impact-Response (DPSIR, see Section 1.4.3) and basic statistical properties of some candidate indicators.

Indicator	**Purpose**	**DPSIR**	**Statistical Property**
Fisheries stock status (within or outside safe biological limits)	Operational (fisheries) management[1]	Pressure	Quantitative, continuous, composite
Average depth of North Sea fish assemblage	Surveillance (of climate change)[2]	State	Quantitative,continuous, composite
Mean size of fish community	Surveillance (of fishing effects)[3]	State	Quantitative, continuous, composite
Phytoplankton colour	Surveillance (of hydroclimatic forcing)[4]	State	Quantitative, continuous, component
Ratio of *C. finmarchicus/ C. helgolandicus*	Surveillance (of changing climatic conditions)[5]	State	Quantitative, continuous, component

1. Piet & Rice (2004); 2. Dulvy *et al.* (2008); 3. Jennings *et al.* (2002); 4. Edwards *et al.* (2001); 5. Reid *et al.* (2003)

Indicators are employed for a wide range of purposes, from broad-range surveillance to more specific operational management. Because they are targeted to specific objectives, they provide interpretation at a higher level than the ecosystem measurements alone, so should normally constitute a transformed value, based directly or indirectly on a measured variable. Transformations can range from simple statistical aggregations in space or time to high-level integration for providing a comprehensive, multivariate measure of an entire aspect of the system. They can be qualitative or quantitative: ranging from binary (on/off), to ordinal (three or more states) or continuous (Table 1.1). They can be component indices (timing of spring bloom, species richness) or composites (average size of fish community or average depth of the fish assemblage).

A key consideration in the choice of indicators is their interpretability. In this regard, it is recommended that an indicator be specific to a single pressure (climate change) rather than to a combination of other pressures (exploitation, invasive species etc); that its responsiveness to the pressure be appropriate and known, and that the sensitivity of the indicator to a change in the pressure be appropriate relative to background environmental variability (Rice, 2003; Rice and Rochet, 2005).

1.4.2 Objectives

The selection of an indicator that is fit-for-purpose can be undertaken only in the context of the vision, goals and specific objectives of the management system under consideration. This has lead to a scientific consideration of what ecological objectives might look like and what exactly society might want from the marine environment. In Canada, the mission of the Department for Fisheries and Oceans is, "*to manage Canada's oceans and major waterways so that they are clean, safe, productive and accessible… and to ensure sustainable use of fisheries resources and facilitate marine trade and commerce*". The UK vision is for "*clean, healthy, safe, productive and biologically diverse oceans and seas*". Within this broad vision there is a range of possible specific operational objectives that might contribute to achieving this vision, such as "*Ensure zooplankton and phytoplankton remain within limits specified by taking account of natural population dynamics and trends*", or "*Ensure fish and cephalopod populations, species and communities are diverse, productive and resilient to environmental change*" (Rogers *et al.*, 2007).

For novel ecosystem indicators derived from remotely-sensed data to become operationally useful, it is essential that they are tested and validated to ensure they are fit for their intended purpose. Existing indicators should also be quality controlled and regularly validated to ensure they remain relevant. In many cases, indicators will be used for management decisions without complete certainty in their interpretation, so they should be accompanied by a statement of their known uncertainty levels and the reliability with which they can be used.

1.4.3 DPSIR framework

The broad framework of an Ecosystem Approach is centred on the DPSIR (Driver-Pressure-State-Impact-Response) framework for evaluating environmental quality (see Figure 1.1). This framework seeks to outline the cause-effect relationships between human activities and the quality and quantity of ecosystem services and the societal response in the form of changes in policy, awareness and behaviour (OECD, 2003). DPSIR frameworks include the following elements in some form:

1. Drivers include high level social, economic or environmental issues such as human population growth or rapid changes in fuel prices.
2. Pressure is a more specific and direct measure of the expression of the driver for the part of the system of interest (e.g. fishing pressure and intensity or nitrogen input).
3. State refers to the current social, economic or biological status of the part of the ecosystem of interest (chlorophyll concentration, spawning stock biomass of target fish population, fishers in economically active employment) and these are usually the focus of societal concerns.
4. Impact is the consequence of the pressure on the state (e.g. 10% increase in the

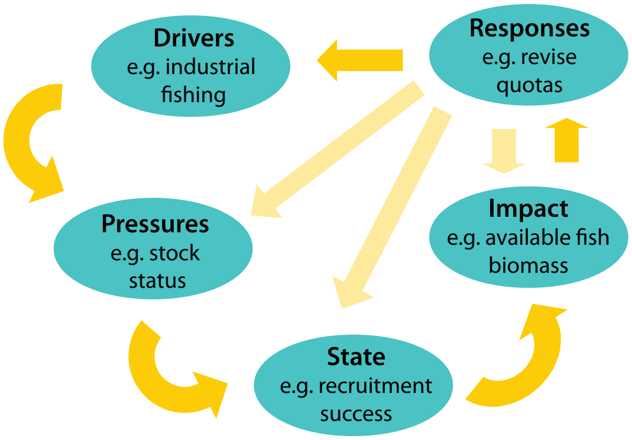

Figure 1.1 The DPSIR cycle, showing examples of different types of indicators.

number of threatened species, spawning stock biomass is 5% below the limit reference point, increased frequency and magnitude of harmful algal blooms (HABs).

5. Response is the management action required to return the part of the system of interest back within the bounds constrained within the system reference points or specified limits.

Most indicator development has taken place within the DPSIR framework, indeed most indicators have been proposed to cover only the ecological state with a few available for pressure and response (Rogers and Greenaway, 2005). Hence, in Europe at least, the focus of the Ecosystem Approach has narrowed to considering only the more tractable pressure-state-response part of the wider DPSIR framework.

1.4.4 Baselines and reference conditions

Changes detected in an indicator are uninformative unless placed in a spatial, temporal and ecosystem context. The FAO (1999) guidelines on indicators state that their fluctuation should reveal key elements of a system, while the position and trend of indicators in relation to reference points or reference directions should indicate the present state and dynamics of the system (Jennings and Dulvy, 2005). We also need to know the circumstances (e.g. geographic extent) to which the reference condition applies and the levels of naturally occurring variability around the reference point.

Target reference points refer to the desired state (and hence pressure), e.g. in a single species fishery this might be attainment of maximum sustainable yield. A limit reference point is an undesirable state where risks rapidly become unacceptable such as species extinction (or non-recovery), or persistent HABs. Often there may be insufficient knowledge to set defensible target and limit reference points, in such cases it may be easier to ensure the state or pressure trajectory move in an appropriate reference direction, e.g. increase in the average size of the fish community (Jennings and Dulvy, 2005).

Ideally, we would like to know what the environment should be like in the absence of human impacts and how far from this baseline it has deviated. This requires knowledge of variability levels in the pre-impacted state of a system, necessitating the collection of considerable data covering long time periods. As this is not always feasible, an alternative approach has been to use current conditions to define the reference level. This can be adequate for the evaluation of future change, but gives no information on past status, so is insufficient if restoration is a target. It must be used with care as it can lead to shifting baseline syndrome (Pauly, 1995), where the perception of 'good' conditions shifts from pristine to degraded. For further discussion of environmental baselines see Hardman-Mountford *et al.* (2005). For remote sensing applications, time series of greater than 10 years have been measured for the majority of sea-surface sensor types (temperature, colour, height, winds). Maintaining these time series with sufficient capability to continue observing ecosystem properties and accuracy to detect climate-related changes is an operational imperative.

1.5 Earth Observations and Societal Benefits

The benefits to society from marine ecosystems are wide-ranging and substantial, extending far beyond the commercial returns and food contribution from fisheries and aquaculture activities. In an attempt to understand the 'value' of these benefits, it has become popular to discuss ecosystems as providers of 'goods and services': market terminology which (perhaps) enables the spectrum of users of the oceans to comprehend its importance (see Beaumont *et al.*, 2007; 2008 for a fuller description of this approach). These services include provisioning (e.g. food supply), regulating services (e.g. carbon fixation by the ocean), cultural services (e.g. recreational use of the oceans) and supporting services (e.g. habitats that provide nursery grounds for young fish and invertebrates) (UNEP, 2006).

Provisioning (i.e. the products obtained from ecosystems, such as food) is the ecosystem service most directly related to fisheries and aquaculture. Fish provide 20% of the world's protein and are the main source of protein for over a billion people. The extraction and cultivation of fish directly provides around 41 million jobs (FAO, 2007), and indirectly employs 162 million people (UNEP, 2006). Clearly, society, and those employed, will benefit if these jobs are maintained.

Marine and freshwater ecosystems are, however, undergoing rapid change due to resource depletion, pollution, habitat destruction, biodiversity loss and climate change. These all threaten the ecosystems and, from a socio-economic viewpoint, the goods and services which they provide. Within this context, how can remote sensing contribute to the better regulation of human impacts on the ecosystem and sustainable use of natural resources?

Fishing is a spatial activity and remotely-sensed data is spatial in nature. This is particularly relevant when spatial management measures are used, such as marine protected areas or seasonal closures. Spatial mapping of fishing vessels can be used directly for management operations and enforcement. The application of remote sensing to aid spatial detection of various species has made promising advances. For example, satellite-tagged tuna and turtles have both been shown to track ocean fronts (Royer *et al.*, 2004; Polovina, 2005). Such knowledge can aid management by improving understanding of the behaviour and distribution of these species, useful for managing exploitation effort and helping to reduce bycatch of non-target species. This may be of particular relevance to species at risk. Chapter 4 focuses on the remote sensing applications for fisheries management.

An alternative approach to the use of remote sensing is being applied in several countries, including India, Japan and Peru, that are using it to help fish harvesters locate target species through the detection of hydrographic features, such as fronts (e.g. Saitoh *et al.*, 1986; Nayak *et al.*, 2003). This approach has the advantages of improving the efficiency of the catch, reducing fuel use and thereby greenhouse gas emissions, as well as potentially reducing bycatch. It has, however, raised concerns of increasing the potential for over-exploitation of fish stocks and implementation clearly needs to be considered alongside other conservation-based management tools, such as quota systems. These approaches are discussed further in Chapter 5.

Remote sensing can also be applied usefully to aquaculture. Approaches include providing information on where to base fish and shellfish farms by taking account of factors such as water quality, transport of nutrients and sea surface temperature (e.g. Pérez *et al.*, 2003). The detection of harmful algal blooms (HABs) is essential for both fishing and aquaculture operations: remotely-sensed maps of chlorophyll-*a* concentration and SST can help quick detection (e.g. Stumpf *et al.*, 2003) and understanding the formation of HABs (e.g. Tanga *et al.*, 2006). Remote sensing applications in marine aquaculture are reviewed in Chapter 6.

1.6 Scope and Structure of the Report

The SAFARI project, under whose umbrella this monograph is produced, is a contribution to the work of the Group on Earth Observations (GEO) and is sponsored by the Canadian Space Agency. GEO seeks to enhance, promote, coordinate and quantify the benefits to society of investment in Earth observation. It is structured around various societal benefit areas. The particular focus for SAFARI is the societal value of applying Earth observations to the sustainable management of fisheries and aquaculture. In this area, as in all GEO societal-benefit areas, we hope to advance the use of Earth observation data from the research domain to the operational domain.

In the following chapters, we document what has been achieved so far and speculate on what lies in the future. We aim to convince the reader that Earth observation data have a very rich potential in fisheries and aquaculture. It is an intellectually challenging field, whose *raison d'être* is much enhanced by its undoubted value to society.

Chapter 2

Climate Change, Ecosystem Variability and Fisheries Productivity

Nicholas Dulvy, Emmanuel Chassot, Johanna Heymans, Kimberly Hyde, Daniel Pauly, Trevor Platt and Kenneth Sherman

Climate-driven variation on the timing and location of phytoplankton blooms has profound effects on the number of larval fish and invertebrates surviving and recruiting each year, and ultimately on the structure and dynamics of marine ecosystems. The spring phytoplankton bloom is the only source of food for many fish and invertebrate larvae. The degree of spatial and temporal overlap of the spring phytoplankton bloom with the timing and spatial distribution of the spawning of eggs into the surface waters has a strong influence on larval fish survival (Hjort, 1914; Cushing, 1990; Mertz and Ayers, 1994; Platt *et al.*, 2003). Eggs and larvae develop in the planktonic zone of the water column for 1 to 2 months before descending to the seabed habitat. Fish and invertebrate larvae have sufficient yolk stores to survive for only a small fraction of the total time spent developing in the surface waters. Larvae starve and die unless they are spawned into, or transported into, a patch of phyto- and zooplankton that is sufficiently large and productive enough to sustain their development. The variable pattern of fish and invertebrate recruitment to juvenile stages is modulated by physical forcing of phytoplankton and ultimately, this environmental variability has a measurable effect on recruitment of new individuals to exploited stocks and the productivity and biomass of higher trophic levels. Remote sensing of ocean colour has finally provided data at the resolution in time and space necessary to elucidate the linkages between climate-driven changes in the marine environment and the dynamics of fish and ecosystem productivity. In this chapter we focus on large-scale year-by-year variability in the physical environment and consider how this influences fish and invertebrate production. In particular we consider the likely effect of climate change on ocean temperature and productivity and highlight emerging approaches toward understanding the consequences for global fisheries yields.

2.1 Climate Change, Ocean Temperature and Productivity

2.1.1 Sea surface temperature

The global temperature has risen by 0.6°C in the past 100 years (IPCC, 2007). Over the last 25 years, most of the 64 Large Marine Ecosystems (LMEs) have warmed. Only two have cooled; the Pacific upwelling regions of the California and the Humboldt Current LMEs (Sherman *et al.*, 2009; Belkin, 2009). The warming trends span from 0.08 to 1.35°C for the Patagonia Shelf and the Baltic Sea LMEs respectively. The rapid warming of the Baltic and North Sea has been verified with daily temperature records from light ships and annual fisheries research vessel records showing that the Baltic and adjacent parts of the North Sea have increased by at least one degree, with the greatest increase in summer temperatures of ~1.6°C in the past 25 years (MacKenzie and Schiedek, 2007; Dulvy *et al.*, 2008). Mid to high-latitude LMEs are experiencing the fastest warming (>0.6°C over 25 years), with greatest warming occurring in the North Atlantic (e.g. Figure 2.1). This is consistent with the observation of rapid climate change in the Arctic resulting in rapid heat penetration into Atlantic waters through the deep convention patterns characteristic of this ocean (Barnett *et al.*, 2005).

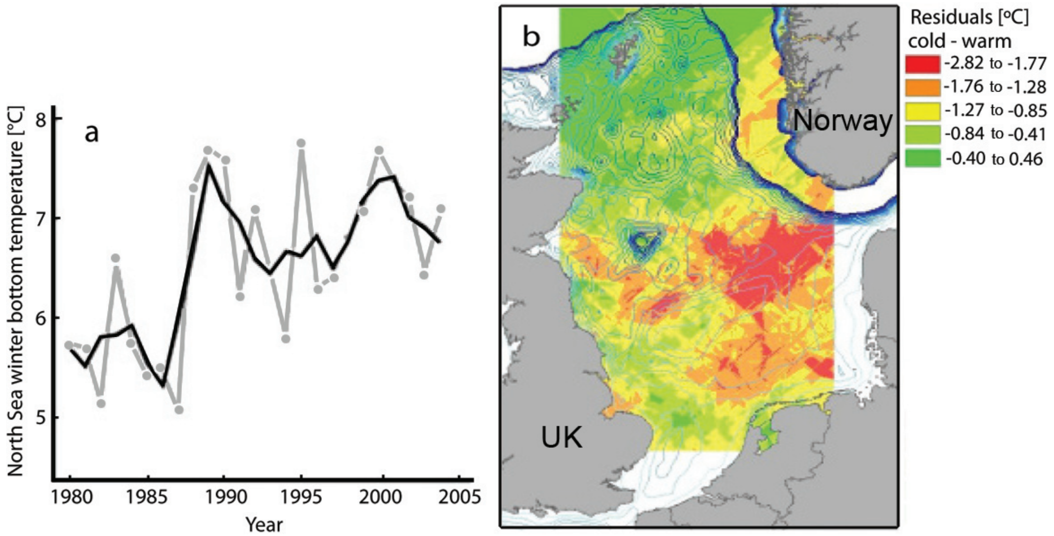

Figure 2.1 (a) The change in average North Sea winter bottom temperature over time (grey line), with a three-year running average (black line). Redrawn from Dulvy *et al.* (2008). (b) Spatial variation in the warming of North Sea summer bottom temperature. The warming was calculated as the temperature difference between a cold period (1983 to 1987) and a warm period (1990 to 2003) (Dulvy and Stelzenmüller, unpublished data).

2.1.2 Ocean productivity

The relationship between climate change and future ocean primary production is likely to be a key determinant of fish and fisheries production (Cushing, 1982). Metabolic scaling theory suggests that the balance between primary production and respiration will be profoundly affected by rising temperatures, with respiration rates increasing more than production rates (López-Urrutia *et al.*, 2006). Consequently metabolic models predict that the epipelagic ocean biota will capture 4 gigatonnes of Carbon per year less by 2100, representing 21% less CO_2 being captured (López-Urrutia *et al.*, 2006). At present there is considerable uncertainty in empirical measures of the effects of climate change on global primary production and the regional variation of these effects. The declines in production predicted by metabolic theory are consistent with coupled ocean biogeochemical and general circulation models (GCM). These models that predict climate change will lead to more nutrient-depleted conditions in the ocean surface, which will favour small phytoplankton at the expense of larger diatoms (Bopp *et al.*, 2005).

Global ocean chlorophyll concentration has varied considerably over the past 25 years, declining since the 1980s, followed by an increase between 1998 and 2000, and a subsequent decline in response to climatic forcing. Recent comparisons of two datasets, CZCS (1979 to 1986) and SeaWiFS (1998 to 2002) ocean-colour observations, suggest the world ocean average chlorophyll concentration has declined by 6% since the 1980s (Gregg *et al.*, 2003). Nearly 70% of the global decadal decline occurred in northern high latitudes corresponding with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans (Gregg and Conkright, 2002; Gregg *et al.*, 2003). Mid-ocean gyres exhibited limited changes (Gregg and Conkright, 2002) or declining concentrations (Antoine *et al.*, 2005). There is further heterogeneity among regions. Sea surface warming in the northeast Atlantic is accompanied by increasing phytoplankton abundance in cooler regions and decreasing phytoplankton abundance in warmer regions (Richardson and Schoeman, 2004). Sea temperature increases have led to an 80% decrease in macrozooplankton biomass since 1951 in waters off southern California (Roemmich and McGowan, 1995). More recently, since 1998 global chlorophyll concentration increased following a strong El Niño year in 1998, the increase persisted until a La Niña in 2000 whereupon global chlorophyll concentration decreased. These changes are largely attributed to changes in surface temperatures and stratification associated with the ENSO cycle and the multivariate ENSO index (Behrenfeld *et al.*, 2006).

Insight into the future is provided by an analysis of six coupled 'atmosphere-ocean global circulation models' (AOGCMs) which indicate that primary production may increase very little, 0.7 to 8.1% by 2050, relative to a pre-industrial state (Sarmiento *et al.*, 2004). However, the level of confidence in this prediction is low, mainly due to large increases in the intertropical areas (Antoine *et al.*, 2005).

However this slight increase at the global scale belies marked differences in the responses of regions and biomes. The AOGCMs predict reduction in the area of permanently stratified low productivity waters in the subtropical gyres (Sarmiento *et al.*, 2004). This pattern has already been observed in ocean-colour estimates, which suggest that during this time there was a 15% increase in the size of the ocean's most oligotrophic waters with chlorophyll concentrations <0.07 mg chl m^{-3} (Polovina *et al.*, 2008). The Atlantic Ocean has exhibited the greatest increase in the size of its oligotrophic gyre which is expanding by 4.3% yr^{-1}. This is consistent with predictions of increased heat content and vertical stratification in mid-latitudes due to global warming.

2.2 Fisheries Oceanography: Linking Physical Oceanography, Phytoplankton and Fish

The recent advent of global, systematic, daily, fine-scale estimates of primary production from satellites has created unprecedented opportunities to predict abundance, biomass and production of fish and other higher trophic level crustaceans, molluscs, reptiles, birds and mammals. Integrating data across ecological scales and from low to high trophic levels remains challenging and requires the combination of a range of field observations and the development of new collaborations between theoreticians, field scientists and model developers (Platt *et al.*, 2007; Cury *et al.*, 2008). There are four broad approaches available to estimate the production and biomass of fish and other high trophic level organisms from primary production: statistical models, size spectra models, energy mass-balance models and 'end-to-end' or 'physics-to-fish' ecosystem models. The statistical approach relies on relationships derived from analyses of ecosystem properties at large spatial scales. The other three approaches are mechanistic founded in physical, chemical and ecological laws and principles.

2.2.1 Statistical links from plankton to fish

Detailed links have been uncovered between environmental variability and the population dynamics and catches of exploited species of octopus, shrimp, pelagic fish, eels and Pacific salmon. These studies provide greater insight into the mechanisms linking physical oceanography to phytoplankton production and the production of higher trophic levels. Here we focus on the invertebrate examples but point the reader toward some other examples (Cole, 1999; 2000; Hardman-Mountford *et al.*, 2003; Mueter *et al.*, 2005; Bonhommeau *et al.*, 2008). In the northwest Gulf of St. Lawrence the sea surface temperature and surface chlorophyll-*a* concentrations, estimated through remote sensing at the time of larval emergence of the northern shrimp (*Pandalus borealis*), were correlated with larval survival and the subsequent cohort abundance (Ouellet *et al.*, 2007). Chlorophyll concentrations were positively related to larval survival, and absolute temperature negatively correlated to larval survival. However greatest larval survival was correlated with the greatest rate of warming. The subsequent carapace length of young northern shrimp is heavily influenced by the initiation, timing and intensity of the spring bloom (Fuentes-Yaco *et al.*, 2007). Catches of octopus (*Octopus vulgaris*) in the coastal water of northwest Spain exhibited strong relationships with wind structure and upwelling. The percentage of days of upwelling (offshore Ekman transport >500 m^3 s^{-1} km^{-1}) in spring and summer (April to September) two years prior were positively related to octopus catches (Otero *et al.*, 2008). The strength of upwelling was positively correlated with remotely-sensed estimates of primary production. Octopus larvae hatch at the end of summer through early autumn during the end of the upwelling and peak of primary productivity. Strongest upwelling, leading to enhanced primary productivity, during this period had greatest positive effects on the catches of octopus two years later.

A prevailing view in ecology is that bottom-up processes control the abundance and biomass of high trophic level organisms, notably through the level and variability of primary production at the base of the food web. Primary production, combined with assumptions on the number of trophic levels in food chains and the loss of energy from one trophic level to the next (transfer efficiency), has long been viewed as a good indicator of the global production of capture fisheries (Ryther, 1969). At large spatial scales, primary production has been shown to be broadly correlated with fish yields (Iverson, 1990). Positive relationships between primary production (or annual mean chlorophyll-a concentration used as a proxy for primary production) and long-term average fishery catches have been described for 9 fisheries areas in the mid-latitude region of the northwest Atlantic (Frank *et al.*, 2006), 11 fisheries areas in the northwest Pacific (Figure 2.2) (Ware and Thomson, 2005), 14 European

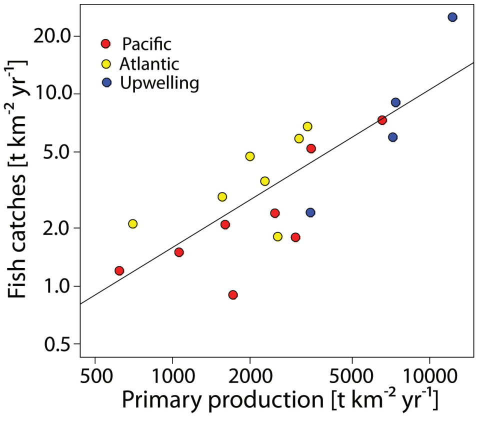

Figure 2.2 The relationship between fishery landings (catches) and primary production in a range of large marine ecosystems (Redrawn from Ware, 2000). Approximately 1 mt km^{-2} yr^{-1} of fish catch is derived from 1000 mt km^{-2} yr^{-1} of primary production.

ecoregions (Chassot *et al.*, 2007) and 1000 exploited fish and invertebrates (Cheung *et al.*, 2008a).

In the northwest Atlantic, higher production in the south was associated with higher fisheries yields. Such correlations might overlook the long history of exploitation on these ecosystems, which combined with the large spatial scale of the analysis may obscure any top-down predatory control of fish and other secondary production (Frank *et al.*, 2006). Less productive northerly systems with lower fisheries yields exhibited collapses of predator populations in response to fishing. This is largely due to the lower intrinsic rates of population increase of larger-bodied predator populations at lower temperatures (Myers *et al.*, 1997). In less productive areas, declining predator numbers could result in increased primary production. This would be mediated by reduced predation on mesopredatory fishes which would in turn increase predation on, and reduce, zooplankton abundance (Frank *et al.*, 2006). Untangling the effects of fishing and climate on plankton variability remains a challenging task as both forcing factors can act simultaneously upon ecosystem structure (Greene and Pershing, 2007). Although less productive systems are more vulnerable to fisheries mediated top-down control, ultimately primary production sets a top limit to the long-term average of higher trophic level production or food web carrying capacity (Frank *et al.*, 2006; Chassot *et al.*, 2007). These limits can be used to understand the primary production required to support fisheries and the sustainability or the ecological footprint of fisheries.

2.2.1.1 Measuring the footprint of fisheries based on remote sensing

Ecological footprints represent the effective ecosystem area appropriated by fishers and others in the form of ecosystem products and services. Ecological footprints are measured as the ratio between the ecological productivity of the ecosystem and human consumption (Wackernagel and Rees, 1996). The advent of satellite remote sensing has enabled fisheries scientists to calculate the primary production required to support fisheries based on phytoplankton-based ecosystems and the footprint of coral-reef fisheries.

The footprint of plankton-based fisheries, which make up the bulk of the world fish catch, has yet to be estimated. However the ‘primary production required’ (PPR) to sustain the food pyramid upon which the animals feed, which are caught by global fisheries in different ecosystem types (coastal, shelf, upwelling, oceanic), has been calculated for the early 1990s (Pauly and Christensen, 1995). The PPR of fisheries depends on their trophic level of the constituents of the catch: far more primary production is required to produce one metric tonne of a high-level trophic fish (e.g., tuna), than of a low level-trophic fish (e.g., sardine) because the transfer efficiency from one trophic level to the next is typically 10% in the ocean (Pauly and Christensen, 1995; Ware, 2000). Thus, to calculate the primary productivity of a given tonnage of fish catch, we need the average ‘trophic level’ (TL) of the fish, an assumption about 'trophic efficiency' (TE), the catch biomass and the equation below from Pauly and Christensen (1995):

$$\mathrm{PPR} = \mathrm{catch} \cdot (1/\mathrm{TE})^{\mathrm{TL}-1}, \tag{2.1}$$

or assuming a TE of 10%:

$$\mathrm{PPR} = \mathrm{catch} \cdot 10^{\mathrm{TL}-1}. \tag{2.2}$$

To refine the broad ecosystem types used by Pauly and Christensen (1995), the catch data used were from the Sea Around Us Project, which has spatialised the statistics submitted to the Food and Agriculture Organization (FAO) of the United Nations into 0.5 degree cells and regrouped them by Exclusive Economic Zones (EEZ) and Large Marine Ecosystems (LME) (Watson *et al.*, 2004). To date these 'nominal' landings exclude discarded bycatch, illegal and other unreported catches, as these have been estimated for only a few countries (Zeller *et al.*, 2007; Zeller and Pauly, 2007). Trophic levels for the fish and invertebrate taxa in the FAO statistics were derived from time- and location-specific diet composition studies (`www.fishbase.org` and `www.sealifebase.org`). Global estimates of primary production were derived from remotely-sensed SeaWiFS data, and made available on a monthly basis in the form of an annual cycle (October 1997 to September 1998), with a spatial resolution of 9 km. These data, thus, represent only approximately the primary production of specific years and the average primary production over the period from which catch data are available (1950 to 2004) (for more details see: `www.seaaroundus.org`). In order to facilitate comparisons between EEZs and LMEs, the maximum PPR was calculated from the mean of the 5 years with the highest values.

The primary production required to support the fisheries within various EEZs ranges between 1 and 2% for the Australian EEZ, and up to 60 to 80% for the Icelandic EEZ. The EEZ of Mauritania is fished by distant water fleets from European and Asian countries, along with the relatively small Mauritanian fisheries. Together these fleets appropriate between 15 and 20% of the observed primary production (Figure 2.3).

The maximum primary production required to support the fisheries of most of the large marine ecosystems is less than 20%, with 30 LMEs having PPR below 10% (Figure 2.4). Of these, 16 are Arctic, Antarctic and Australian LMEs. On the other hand, a few LMEs have unrealistically high PPR values (> 50%). These high values may be due to: (1) the assumptions and data used for implementing the method itself (e.g. the use of SeaWiFs global remote-sensing data from one year to derive annual primary production, and taken as representative of all years since 1950); (2) over-reported landings, e.g., catches that were reported from an area, but were caught elsewhere (Watson and Pauly, 2001); and (3) massive range extension in periods of peak abundance, or migration of targeted species, especially feeding migrations, extending beyond the limits of an LME. This occurs in the Kuroshio LME where sardine, for a few years, greatly expanded their range; and some of the

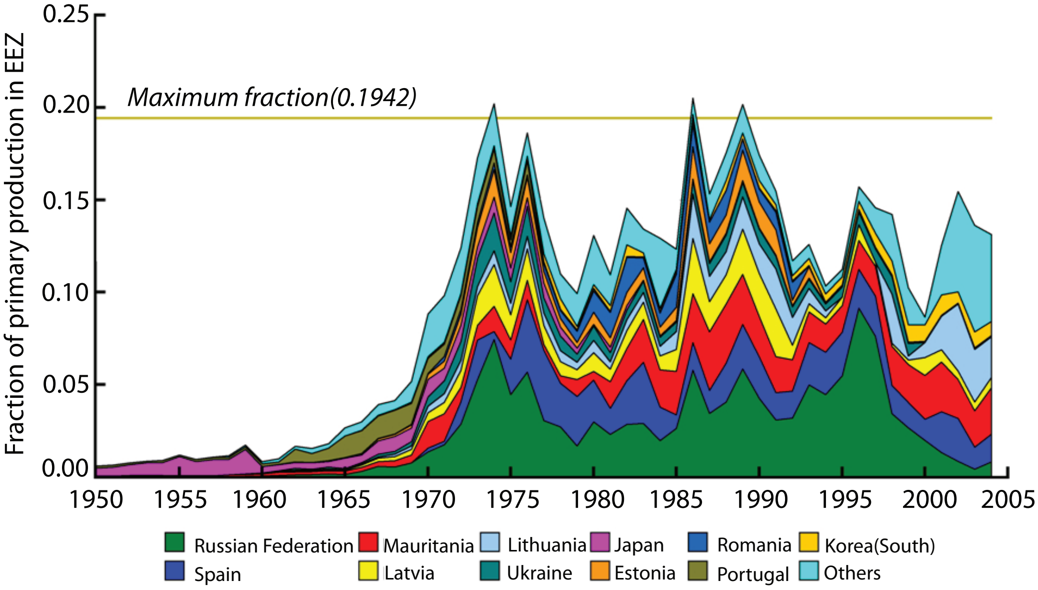

Figure 2.3 The primary production required (PPR) by the fisheries operating in the exclusive economic zone of Mauritania, northwest Africa. In this ecosystem, distant-water fleets from Europe and east Asia appropriate most of the primary production (as embodied in catches), leaving little for Mauritanians; a maximum PPR of nearly 20% was taken in the early 1970s and late 1980s.

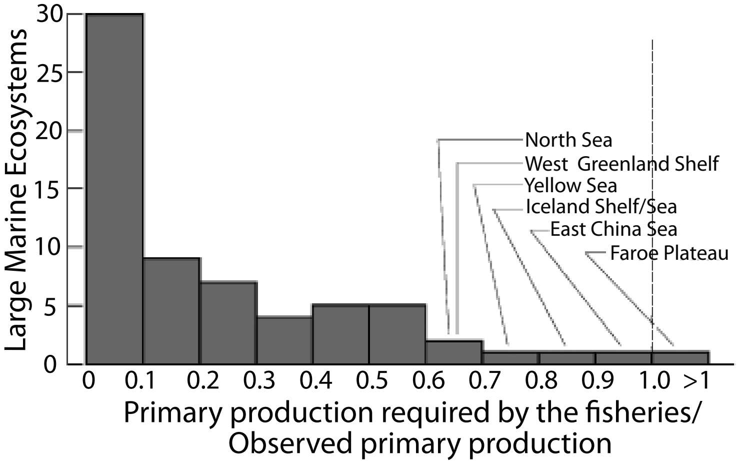

Figure 2.4 The distribution of the maximum primary production required (PPR) to support fisheries in the World's 64 large marine ecosystems (LMEs). The majority of LMEs have maximum PPR <20%; some LMEs have unrealistically high values (>60%), due to catch over-reporting, and/or boundaries that fail to encompass the entire distribution range of important species.

smaller LMEs of the north Atlantic where cod and other groundfish may be fished in a LME, but feed in another. Problems in the estimation of primary production will occur throughout the world, however, and it is likely to be small and hence not the cause of the pattern in Figure 2.4. While this approach can provide insight into the amount of primary production required to support fisheries, further work is required to determine what proportion of primary production can be sustainably removed each year without compromising ecosystem resilience and integrity, i.e. the ecological footprint or 'fishprint' of plankton-based fisheries.

The global extent of coral reefs has recently been measured accurately for the first time, by combining aerial photography and satellite sensors, enabling the calculation of the first estimates of the footprint of coral reef fisheries (Spalding and Grenfell, 1997; Spalding *et al.*, 2001). The ecological footprints of the coral reef fisheries of 49 island nations were calculated; this represents ~41% of the world's coral reefs. The human consumption of coral reef fishes, molluscs and crustaceans was estimated from the nominal fisheries landings reported to the UN FAO, and sustainable fisheries production was assumed to be 5 metric tonnes km^{-2} year^{-1}. It was estimated that total landings of coral reef fisheries are currently 64% higher than can be sustained. Consequently, the area of coral reef appropriated by fisheries exceeds the available effective area by ~75,000 km^{2}, or 3.7 times the area of Australia's Great Barrier Reef (Newton *et al.*, 2007). The size of the footprint was greater in nations with higher human population densities per unit area of coral reef (Figure 2.5).

As human populations grow so will their ecological footprint increase from 1.64 to 2.7 by 2050, and the area appropriated exceeds the available area by 196,000 km^{2} (Figure 2.6). There are key assumptions which will require further work to refine the footprint estimate (Newton *et al.*, 2007), including: revised coral reef habitat area definitions and estimates (Andréfouët *et al.*, 2006), better estimates of coral reef fisheries landings (Zeller *et al.*, 2006; Zeller *et al.*, 2007) and a better understanding of sustainable yields of coral reefs (Halls *et al.*, 2006; McClanahan *et al.*, 2008). However, it is becoming increasingly clear that this first estimate of the footprint of coral reef fisheries may be underestimated. Adding more coral reef habitat to the world's oceans is not a feasible management option. However these footprints, for the first time, provide an indication of the scale of the challenge facing tropical island nations – which is to sustain the livelihoods of an increasing number of people while ensuring the continued resilience and productivity of coral reefs.

2.2.1.2 Observed primary production and the changing fisheries catches of Large Marine Ecosystems

A key concern is how the predicted and observed changes on ocean productivity have affected fisheries catches. To answer this question researchers are examin-

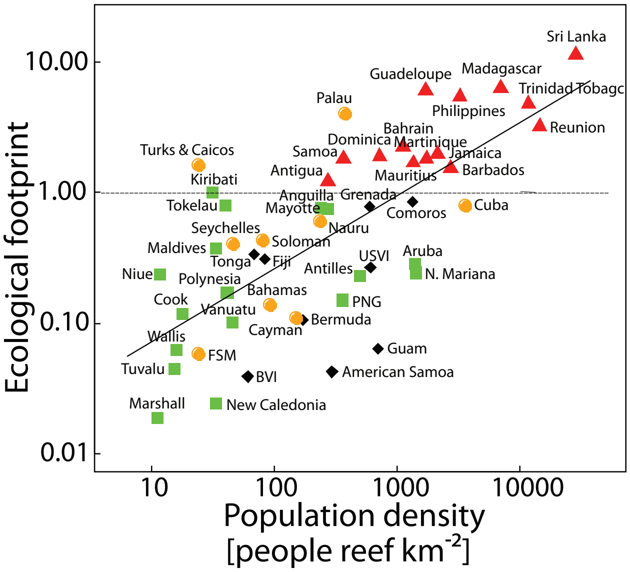

Figure 2.5 Densely populated islands have unsustainable coral reef fisheries footprints. There is a positive relationship between human population density per unit area of island coral reef ecological footprints. Island reef fisheries status is represented by four colours: green squares – underexploited, orange circles – fully exploited, red triangles – overexploited, black diamonds – collapsed. The line represents the least squares regression model $\log_{10} Y = -1.59 + 0.53(\log_{10}$ persons per km^2 coral reef). The dashed line represents an ecological footprint = 1 for a maximum sustainable yield of 5 tonnes km^{-2} yr^{-1} (redrawn from Newton *et al.*, 2007).

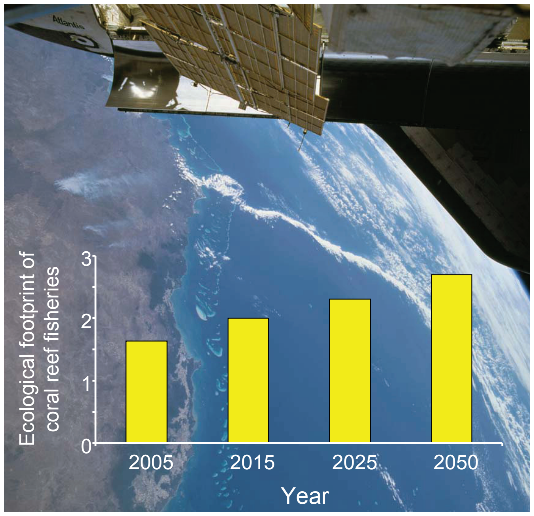

Figure 2.6 The increase in the ecological footprint of coral reef fisheries of 49 island nations as human population size grows. In 2005 the area of coral reef appropriated by fisheries exceeded the available effective area by ~75,000 km^2, or 3.7 times the area of Australia's Great Barrier Reef. The background is the Great Barrier Reef, Queensland, Australia as seen from the space shuttle Atlantis (Photo courtesy of NASA).

ing changes in primary production and fish catches at the scale of Large Marine Ecosystems (LME) (Sherman *et al.*, 2007; Sherman *et al.*, 2009). Over the last ten years there was no consistent trend in primary productivity, and of the 63 LMEs examined, the annual primary production trends of only four LMEs were significant. Primary productivity declined in one LME (Bay of Bengal), and increased in three others (Hudson Bay, Humboldt Current and Red Sea) (Sherman *et al.*, 2009). Monthly and annual means of primary production estimates were derived from satellite-borne data of NOAA's Northeast Fisheries Science Center, Narragansett Laboratory calculated from modeled chlorophyll and light attenuation profiles derived from satellite chlorophyll and photosynthetically active radiation (PAR) measurements using the 'ocean productivity from absorption of light' (OPAL) model.

The effects of warming on global biomass yields were non-uniform in relation to any persistent global pattern of increasing or decreasing yields. The response of global fisheries yields to warming trends varied by LME clusters. Both increasing and decreasing fishery trends were observed in fast-warming, moderate-warming and slow-warming LMEs. The results, however, are complicated by increased fishing effort that has led to exploited and overexploited fish stocks, driven by the fish protein and food security needs of many developing countries. Increasing fisheries biomass yields were observed in half (31) of the LMEs while decreasing trends were detected in the remaining 32 LMEs (Sherman *et al.*, 2009). A clear example of increasing fisheries yields in response to warming climate is in the Norwegian Sea, Faroe Plateau and Iceland Shelf LMEs. These three LMEs account for 5% of the world marine fisheries yield and are influenced by bottom-up forcing of increasing zooplankton abundance and warming hydrographic conditions in the northern areas of the north Atlantic. Here stocks of herring, blue whiting and capelin are benefiting from an expanding prey field of zooplankton (Beaugrand *et al.*, 2002; Skjoldal and Saetre, 2004; Hjermann *et al.*, 2007). The productivity and fisheries of these LMEs are benefiting from the increasing strength of the sub-Polar gyre bringing warmed waters to the northeast Atlantic. In contrast, the warmer water from the sub-Polar gyre is contributing to decreasing production and fisheries yields in the relatively warmer southern LMEs of the northeast Atlantic (the North Sea, Celtic Biscay, and Iberian Coastal LMEs). In these southern Europe fast-warming LMEs, the mean annual marine fisheries biomass yields have decreased due to over exploitation but may also be suffering from declining abundance levels of warm water zooplankton (Valdés *et al.*, 2007) and northward and deepening distribution of fishes (Perry *et al.*, 2005; Dulvy *et al.*, 2008).

2.2.1.3 Future climate change impacts on fish and fisheries distributions

If the distribution of fish change, how will the distribution of fisheries catches change? Using a bioclimatic envelope modelling approach and assuming a 2.5°C temperature rise, the geographic distribution of the yellow croaker (*Larimichthys* *polyactis*) was predicted to move northwards, with the area of occupancy increasing, expanding out from the China Sea and invading Japanese waters (Cheung *et al.*, 2008b). The fisheries productivity remains unchanged (assuming the distribution and quantity of primary production are unchanged), however the geographic distribution of potential catches changes markedly (Figure 2.7). Currently, most of the catch is taken by China and South Korea, but under the climate-shifted scenario, catch potential would increase – particularly in Japan and North Korea (Cheung *et al.*, 2008a).

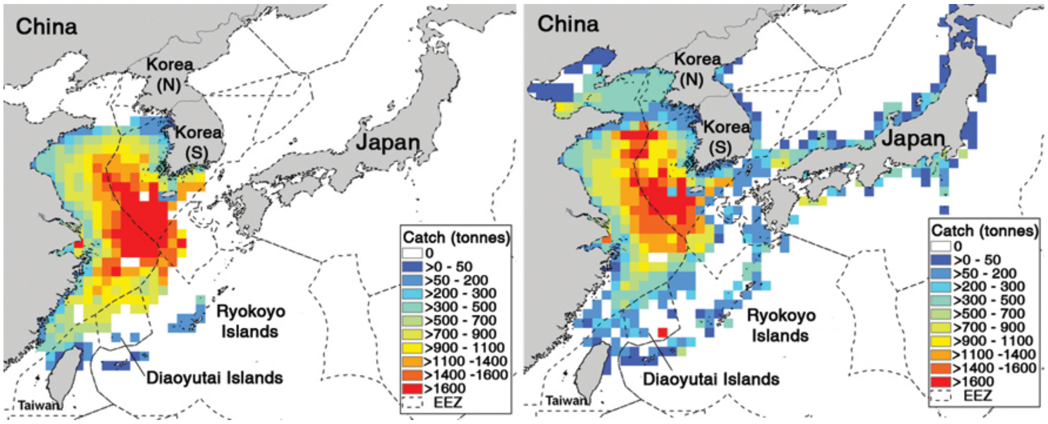

Figure 2.7 (a) Current (early 2000s) and (b) climate-shifted distributions of the small yellow croaker (*Larimichthys polyactis*). The current distribution was generated from the method described by Close *et al.* (2006). The climate-shifted distribution was predicted by a dynamic bioclimate envelope model described by Cheung *et al.* (2008a), under a hypothetical increase in average global ocean temperature of 2.5°C. (Adapted from Cheung *et al.*, 2008a).

2.2.2 Size spectra

Static size spectra models can be used to predict equilibrium abundance and biomass of animals in the sea from three variables and two parameters: (i) primary production, (ii) phytoplankton size distribution, (iii) sea surface temperature, (iv) predator-prey mass ratio, and (v) transfer efficiency (Figure 2.8). The advent of satellite remote sensing allows time-integrated measures of primary production and sea surface temperatures across the globe on small spatial scales. Most oceanic primary production (~90%) is accounted for by remote-sensing estimates; except seasonally-icebound high latitude areas and areas dominated by non-planktonic production such as coral reef, kelp forest, seagrasses and microphytobenthos (Duarte and Cebrián, 1996). The size distribution of phytoplankton cells depends upon local productivity. The most productive areas occur in shallow, well-mixed, inshore, shelf systems and coastal upwelling zones. These support very large phytoplankton cells (>100 μm in diameter) which can often form large gelatinous colonies that can be grazed directly by herbivorous fish. Offshore oceanic oligotrophic zones are mainly dominated by nano- and picoplankton (5 to 25 μm and <5 μm in diameter, respectively) (Agawin *et al.*, 2000; Marañón *et al.*, 2001; 2007). Biological rates increase with temperature in a manner described by the Boltzmann factor or Van't Hoff-Arrhenius equation $e^{-E/kT}$, where E is the activation energy of metabolism (0.63 eV), k is Boltzmann's constant (8.62 x 10^{-5} eV K^{-1}), and T is temperature in Kelvin (°C + 273) (Brown *et al.*, 2004). In the sea, predators are typically between 300 and 1000 times heavier than their prey (Cushing, 1975; Jennings, 2005; Brose *et al.*, 2006). The relatively limited predator-prey mass ratio arises from allometry; the size of mouth parts of fishes and many other marine predators increase in a fixed proportion to total body size. A fundamental consequence is that only larger organisms can catch and consume larger prey. This limits the number of trophic levels that can be supported: the larger the phytoplankton cells at the base of the food chain, the shorter the food chain (Ryther, 1969; Jennings and Warr, 2003). Longer food chains are less efficient and less productive than shorter food chains because energy is lost at each trophic level due to low transfer efficiency. Between 5 and 15% of energy in each trophic level is lost due to respiration and excretion, or transport out of the ecosystem (Pauly and Christensen, 1995; Ware, 2000).

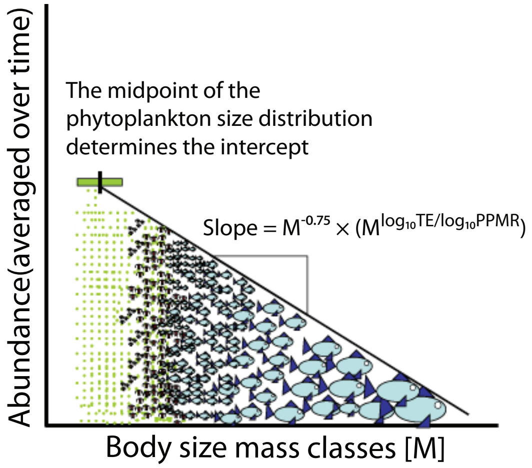

Figure 2.8 The pelagic size spectrum of time-averaged abundance in each body mass class. The slope of the body mass (M) size spectrum is a function of transfer efficiency (TE) and predator-prey mass ratio (PPMR). The height of the intercept, or start of the spectrum, depends on primary production which also determines the phytoplankton size distribution at the start of the size spectrum. This pelagic spectrum consists of phytoplankton, zooplankton and fish. In reality benthic and pelagic invertebrates (jellyfish, squid, crabs, worms) occupy intermediate size classes and mammals and sea birds occur in the largest size classes.

A static or equilibrium size spectra approach has been used to estimate global fish production and biomass, in the absence of fishing, using remotely-sensed estimates of primary production on a 36 km^2 scale. Based on an estimate of total primary production of 4.1 x 10^{11} mt yr^{-1}, the global biomass of marine animals (> 10^{-5} g wet weight) is 2.6 x 10^9 t and annual production is 1.1 x 10^8 mt (Jennings *et al.*, 2008). Globally, the areas of highest fish biomass and production were found in upwelling areas and mid-latitude shelf seas. The total biomass of fish > 10 g in these areas was 5.3 x 10^8 mt with a production of 1.1 x 10^8 mt (Figure 2.9).

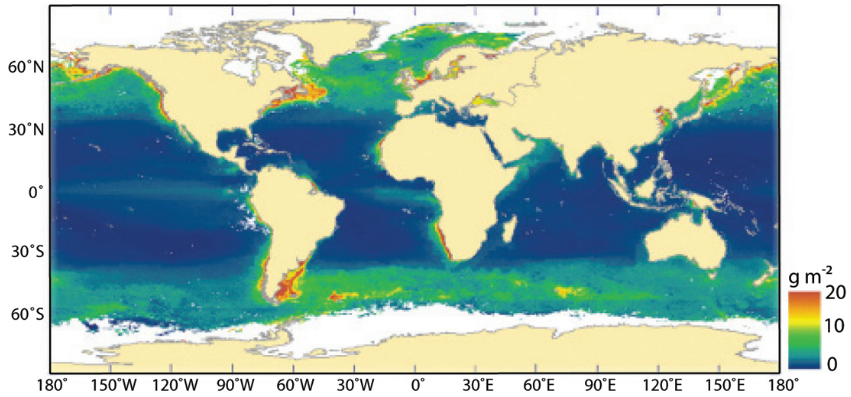

Figure 2.9 The global distribution of marine teleost fish biomass. Primary production estimates were not available for the areas shown in white. (Adapted from Jennings *et al.* 2008).

Although this approach is simple to implement and requires few parameters, it is sensitive to the expected range of transfer efficiencies and predator-prey mass ratios. Further refinement requires new research into trade-offs between transfer efficiencies and predator-prey mass ratio and how these parameters vary across environments. At present the approach can only provide size-based outputs for large functional groupings, (e.g. bony fish and elasmobranchs), further fundamental work on the partitioning of the energy niche and the optimal distribution of life histories by size and energy availability is required to predict species abundances from size spectra (Jennings *et al.*, 2008). Currently, dynamic size spectra models are being developed to utilize new measurements of the size distribution of primary production (Hirata *et al.*, 2008) and provide predatory feedback to phytoplankton production to derive more realistic estimates of local fish biomass and production. (Blanchard *et al.*, 2009).

2.2.3 Energetic mass-balance models

The flow of energy through ecosystems can be described by various food web models, such as Ecopath with Ecosim and ecological network analysis. Ecopath with Ecosim models rely on balancing the production and biomass of functional groups of organisms based on their feeding relationships and the efficiency of energy transfer between trophic levels (Figure 2.10) (Polovina, 1984; Pauly *et al.*, 2000).

Ecological network analysis incorporates analytical techniques for studying the

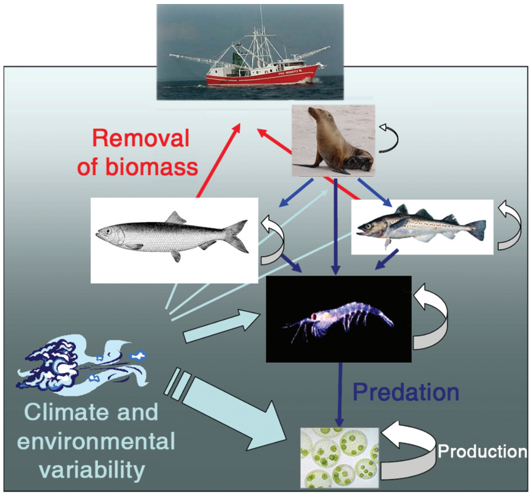

Figure 2.10 An Ecopath mass balance 'box' model of a marine ecosystem. Production is represented by the size of the curved arrow; energy transfer up through the food web through predation is shown by blue arrows and energy removal by exploitation shown in red arrows. The whole ecosystem is embedded within the effects of climate change and environmental variability, with greatest, most direct effects at lowest trophic levels, largely mediated through the effect of environmental variability on phytoplankton production.

indirect trophic effects and the structure of recycling pathways (Ulanowicz, 1986). Specifically, the indirect trophic effects and energy and/or nutrient recycling due to changes in primary production can be described with ecological network analysis in the dynamic simulation of the Ecopath with Ecosim suite (Christensen *et al.*, 2005). Ecopath models have been used for a range of issues including calculating the primary production required to support global fisheries catches (Pauly and Christensen, 1995) and evaluating the relative importance of climate change and fishing in determining the dynamics of high trophic level species (Guénette *et al.*, 2006). The effect of environmental variation on an ecosystem is readily seen in the changes in the total systems throughput of that system. The total ecosystem throughput is the total amount of energy flowing through the ecosystem, from low to high trophic levels via predation and decomposition pathways and is therefore affected by environmental variability (Ulanowicz, 1986).

For example, in the Gulf of Alaska, the total ecosystem throughput (Figure 2.11a, b) is driven by the changes affected on the primary production of the ecosystems by the Aleutian Low Pressure system and the sea surface temperatures as described by the Pacific Decadal Oscillation (Heymans *et al.*, 2005). The Pacific Decadal Oscillation positively influences ecosystem throughput in southeast Alaska and has a negative influence in the western and central Aleutian Islands. However, when the direct effects of the environmental drivers are removed, the effects of the changes in flow structure can be observed. Specifically, the 'average mutual information' is a network analysis index which measures the degree of organization of the fluxes of energy and matter among ecosystem compartments of functionally-similar species (Ulanowicz and Abarca-Arenas, 1997).

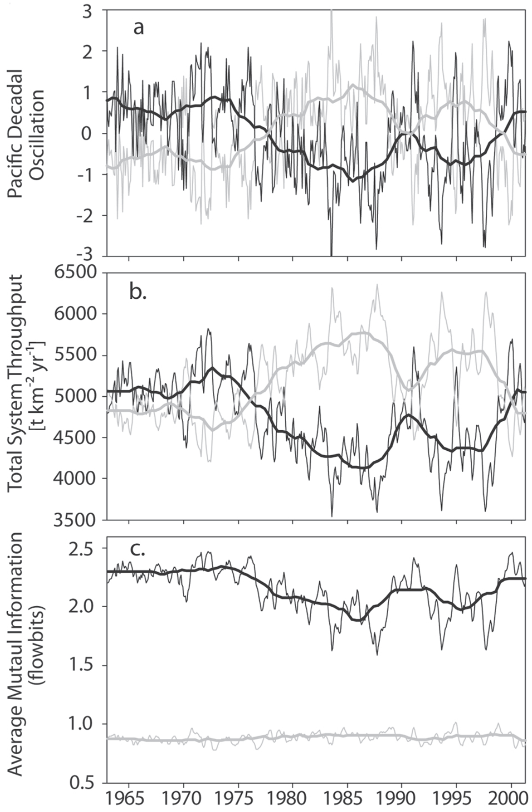

Figure 2.11 (a) Pacific Decadal Oscillation (PDO) of the Aleutian islands (black) and southeast Alaska (grey); (b) changes in total ecosystem throughput; (c) average mutual information. (Adapted from Heymans *et al.*, 2007).

We can see that in two different ecosystems in the Gulf of Alaska (the western and central Aleutian Islands and southeast Alaska) the average mutual information was very different and did not relate directly to the environmental driver (Figure 2.11c). The reduction in large predators (Steller's sea lions) in the Aleutian Islands simplified the pathways for energy and matter flow in the ecosystem after the regime shift in the late 1970s, while no such simplification was experienced in southeast Alaska, where most species increased over the study period.

2.2.4 End-to-end models

End-to-end models aim to (i) represent all ecosystem components, from the abiotic components and the biological food web, (ii) integrate physical and biological processes at different scales, (iii) two-way interactions and feedback, and (iv) account for the dynamic forcing of climate variability and other human impacts acting through multiple pathways and trophic levels (Travers *et al.*, 2007; Cury *et al.*, 2008). The models are founded on first principles and aim to represent accurately the dynamic physical forces affecting oceans (wind, tides, currents, and light penetration) and their effects on primary and secondary production. These models usually consist of linked or coupled models that use some form of hydrodynamic model to drive a biogeochemical model to provide primary production and zooplankton production to higher trophic levels (Lehodey *et al.*, 1997; Megrey *et al.*, 2007).

The simplest biogeochemical models focus on the pelagic environment and include some plankton functional groups, for example, nutrient-phytoplankton-zooplankton dynamics models such as ROMS-NPZD (Regional Ocean Model System-NPZD), NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography), POL-GCOMS (Proudman Oceanographic Laboratory-Global Coastal Ocean Modeling System) and DGOM (Dynamic Green Ocean Model) (Le Quéré *et al.*, 2005; Kishi *et al.*, 2007). The more complex models include coupled benthic-pelagic habitats and include benthic functional groups and sediment chemistry, for example, ERSEM (European Regional Seas Ecosystem Model) (Allen *et al.*, 2001; Siddorn *et al.*, 2007). The key challenge is to convert the output of the biogeochemical or 'low trophic level' models into fish and higher trophic levels, and eventually to feed predation from higher trophic levels back into low trophic level models (Travers *et al.*, 2007).

At present there is no generic model for converting dynamics at low trophic levels to dynamics at higher trophic levels relevant to fisheries. There are some important case studies of location-specific population dynamic models that provide the proof of principle. They focus on the dynamics of low-trophic level pelagic fish, such as Pacific herring (*Clupea harengus pallasi*) and Pacific saury (*Cololabis saira*) (Ito *et al.*, 2004; Megrey *et al.*, 2007). There are still difficult theoretical and practical challenges associated with end-to-end models including data availability, the coupling of submodels based on different formalism and discretization methods, the representation of major ecological processes such as excretion and egestion that can generate feedbacks between components, and the integration of different trophic level components characterized by distinct spatio-temporal scales and functional complexity (deYoung *et al.*, 2004). The development of such integrative models is a key challenge for assessing the combined impacts of fishing and climate changes on marine ecosystem structure and functioning (deYoung *et al.*, 2004; Cury *et al.*, 2008). The synoptic character of satellite data makes them particularly suitable inputs for end-to-end models and for model evaluation through data assimilation techniques, for instance (Kuroda and Kishi, 2004).

While the approaches to end-to-end modelling of population dynamics are tailor-made and context-specific, they have the advantage that they explicitly capture the role of biodiversity in the emergence of alternative trophic pathways which may emerge, such as climate-forced shift between sardine and anchovy dominated states

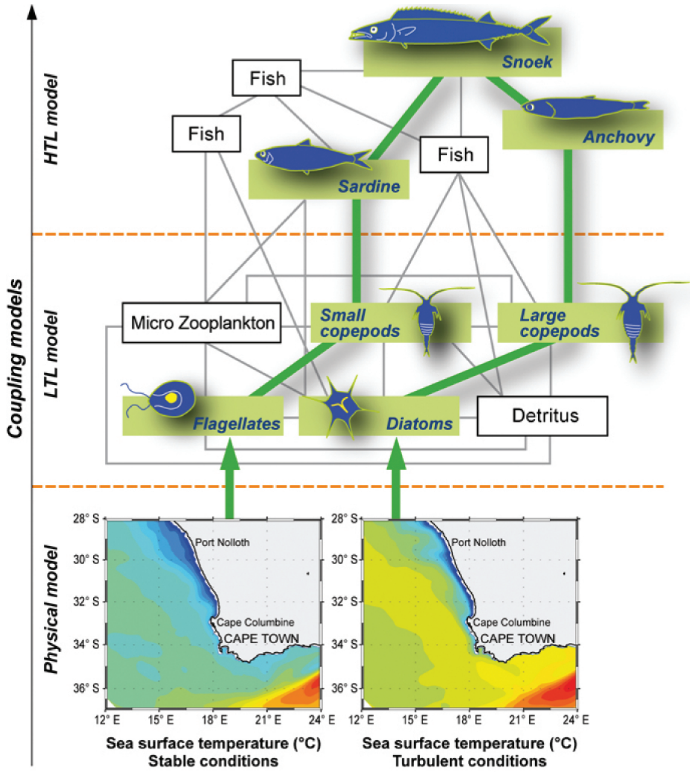

Figure 2.12 End-to-end models can be built by coupling physical atmospherically forced hydrodynamic models to models of lower trophic levels (pelagic and benthic) to high trophic level fish production models (Cury *et al*., 2008). The boxes represent key species or groups of species, the lines represent the trophic interactions (pathways) and the arrows represent the forcing of hydrodynamic models on the lower trophic level model. (Adapted from Cury *et al*., 2008).

(Cury *et al*., 2008). One pragmatic way of extending the approach to an end-to-end model of higher trophic level ecosystem dynamics might be to link a low trophic level hydrodynamic-biogeochemical model to either size spectra models or Ecopath with Ecosim models (Figure 2.12).

2.3 Concluding Remarks

After a century, fisheries oceanography is coming of age. The combination of rapid theoretical development, collaborative and integrative modelling efforts, and in particular, the accumulation of a sufficiently long global time-series of remotely-sensed ocean colour and sea surface temperatures allow hypothesis testing at large spatial scales and rapid model development and validation. The development of cross-trophic level models linking phytoplankton to fish production is timely given the urgent need to understand and predict the effects of global climate change on marine ecosystems.

Chapter 3

Remote Sensing Applications in Stock Assessments

Peter Koeller, Kevin Friedland, César Fuentes-Yaco, Guoqi Han, David Kulka, Jay O'Reilly, Trevor Platt, Anne Richards and Maureen Taylor

3.1 Introduction

Satellite remotely-sensed data are now widely used in fisheries oceanography (Santos, 2000), but their use in stock assessments is just beginning. In fact, the incorporation of environmental data of any kind into stock assessment models has rarely been achieved successfully, for several inter-related reasons. First, assessments have traditionally taken classical single species approaches which deal only with the numeric population dynamics of the stock under review – the fish stock as 'bank account', with principal (abundance), interest (growth), deposits (recruitment) and withdrawals (natural and fishing mortality) determined by research vessel surveys and fishery (catch, effort) data. Second, the environmental factors forcing change to the 'bank account' are complex, poorly understood and difficult to measure, consequently they have largely been excluded from traditional assessment models, greatly limiting their accuracy and effectiveness.

The advent of the 'Ecosystem Approach to Fisheries' (EAF) has given new impetus to research on the environmental factors influencing fish stock dynamics, and urgency to their inclusion as an integral part of the assessment process. It is particularly important to develop an understanding of the factors determining recruitment of commercially important fish and shellfish stocks, for two reasons: first, the adverse effects of fishing cannot be separated from 'normal' environmentally-driven changes unless the latter is thoroughly understood. Second, environmental factors modify underlying stock-recruitment relationships, arguably the most important information necessary to define reference points and achieve fisheries sustainability.

Until recently, defining stock-recruitment relationships and identifying the environmental factors modifying them have been the 'holy grail' of fisheries research, largely unresolvable with traditional oceanographic methods because of the complex, large and small spatial scale, and long and short-term temporal processes involved. Satellite data, particularly ocean colour (chlorophyll-*a* concentration), sea surface temperature (SST), and altimetry have now made these objectives achievable – the results are eminently suitable for incorporation into stock assessments within an ecosystem-based assessment and management framework.

It is fortuitous that the ocean surface data obtainable from satellites are also those most desirable (and now most readily available to researchers) for studying larval survival and recruitment to the adult, fishable population. Many commercially important species in the open ocean release pelagic larvae near the surface where they are most likely to obtain nourishment of suitable size and quality during this critical life history stage, either directly in the form of phytoplankton (measured by ocean colour) or as micro or meso-zooplankton which develop almost immediately from the primary producers. In temperate latitudes the annual spring bloom, while driven primarily by the seasonal solar radiation cycle, is modified by local factors, particularly surface temperature, which influences water column stability and the nutrients available for phytoplankton growth. Differences in the annual 'average' surface temperature cycle, also measured by satellites at previously unattainable temporal and spatial scales, modify the 'average' phytoplankton bloom conditions to which commercially important species have adapted their reproductive cycles. These differences can lead to a mismatch between, for example, the timing of larval release and the spring phytoplankton bloom required for their survival, resulting in weak year classes. Conversely, on occasion conditions during larval release can be 'ideal', resulting in exceptional year classes. These exceptional conditions and events are of particular interest to fisheries biologists because it is the resultant strong year classes upon which the fisheries depend. Understanding these processes will lead to improved and longer term fisheries forecasts i.e. for the period between birth and capture, which for some species can be as much as a decade. The case studies in this chapter all demonstrate the essential role of remotely-sensed data in recruitment research.

3.2 Northern Shrimp (*Pandalus borealis*)

3.2.1 Recruitment on the eastern Scotian Shelf

The rise of cold-water shrimp (*Pandalus borealis*) to ecological and economic importance over much of its vast circumpolar range has variously been attributed to concurrent decreases of their groundfish predators, predominantly cod; and large-scale environmental forcing manifested by changes in the North Atlantic Oscillation (Parsons and Colbourne, 2000; Lilly *et al.*, 2000; Koeller, 2000; Worm and Myers, 2003). Both factors were probably involved. The release of predation pressure must have contributed significantly to recent increases in shrimp abundances, but the importance of environmental factors in shrimp population dynamics, particularly to larval survival after spring hatching, has been known for some time. Dow (1964) first made the key observation that shrimp catches in the Gulf of Maine were indirectly related to spring surface temperatures at a lag of 4 years, the approximate time from hatching to their recruitment to the fishery. In other words, cooler spring surface temperatures are associated with improved survival of the pelagic larvae. These and similar observations by others are at odds with laboratory larval rearing experiments which tend to show the opposite i.e. better survival at warmer or increasing temperatures. The mechanism behind these relationships remained obscure until recently (Koeller *et al.*, 2009). Studies in the Gulf of Maine, the Gulf of St. Lawrence and on the Scotian Shelf continue to explore the underlying processes using satellite data.

Ouellet *et al.* (2007) found that in the Gulf of St. Lawrence the larvae of successful shrimp year classes tend to hatch during springs where colder SSTs were followed by rapid warming of the surface layers. They also noted that sea surface temperatures (SST) were indirectly related to upper water column stability, which in turn influences spring phytoplankton bloom dynamics. Specifically, water column instability (low spring SSTs) promotes mixing of nutrients from deeper layers to the euphotic zone during spring storm events, resulting in sustained and higher phytoplankton production during larval development. Rapid warming following hatching results in faster growth rates, which favours survival, in accord with laboratory studies. Results obtained in the Gulf of Maine and the Gulf of St. Lawrence were tested on the Scotian Shelf by focussing on a very large year class, hatched in the spring of 2001. The parents of this year class produced the most eggs in the 12 years of observations (Figure 3.1). On this basis alone one would expect greater larval survival. However, bottom temperatures during egg development and surface conditions during hatching were such that these more abundant larvae were released in the most favourable conditions. Surface temperatures in the spring of 2001 were indeed cooler, resulting in a later than average bloom, followed by rapid warming

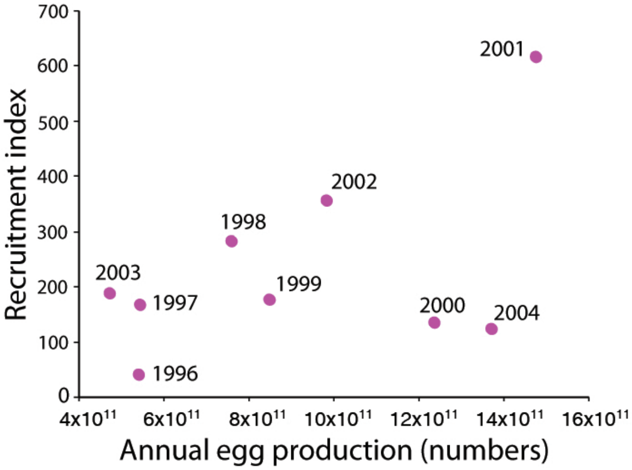

Figure 3.1 On the Scotian Shelf, the exceptionally large 2001 year class was produced from the largest annual egg production, eggs which were incubated from summer 2000 to spring 2001.

(Figure 3.2 top). The hatch was also later than usual, consequently both bloom and hatch were closer than average to the rapid surface warming period – temperatures were 4°C or greater within about a week after hatching was complete. In contrast, during 1999 (Figure 3.2 bottom) surface temperatures were warmer than average, probably contributing to the much earlier bloom that year. Coincidentally, the earlier hatch matched the earlier bloom. However, both events occurred much earlier than the rapid warming period – temperatures > 4°C were not reached until a month after hatching was complete, despite warmer than average surface temperatures. Moreover, the number of eggs produced was less than average.

What caused the large difference in hatching times in these two years? Bottom water temperatures on the Scotian Shelf are at times strongly influenced by incursions of cold water from the Labrador current, which moves southward along the continental shelf and spills over into the deep shrimp holes where females incubate their eggs. Bottom water temperatures during the two egg incubation periods examined here were strongly influenced by the Labrador current. During the 1998 to 1999 incubation, bottom temperatures were rising quickly as the effects of the 1997 to 1998 cold water incursion waned. Shrimp eggs were subjected to rising temperatures, resulting in a shorter incubation period and an early hatch. During the 2000 to 2001 incubation temperatures were falling again as the Labrador current returned, resulting in a longer incubation period and a later hatch of the shrimp eggs.

Results from the Scotian Shelf suggest that both surface and subsurface processes must match to produce a large year class. In 2001 the good match between egg hatching time and favourable surface temperature/food availability resulted from two different, apparently unrelated environmental influences on two different life history stages: the Labrador current's influence on egg development and hatching times; and atmospheric influences on surface water temperatures, bloom timing and larval survival.

Satellite data have been pivotal in elucidating the near surface processes important to northern shrimp recruitment on the Scotian Shelf. These data sets will be essential if matches of larval release with surface conditions are to be estimated, and the results formally incorporated into the assessment/management process. Future studies, especially those using satellite altimetry, will also be valuable in determining the importance of surface water movements in the retention of larvae within suitable settling habitats during the crucial spring pelagic larval phase, as described for white hake in Section 3.4.1 below.

3.2.2 Recruitment in the Gulf of Maine

The northern shrimp (*Pandalus borealis*) is at the southern limit of its distribution in the Gulf of Maine, where it is most abundant in the relatively cool waters of the western portion of the Gulf (Haynes and Wigley, 1969). Richards *et al.* (1996;

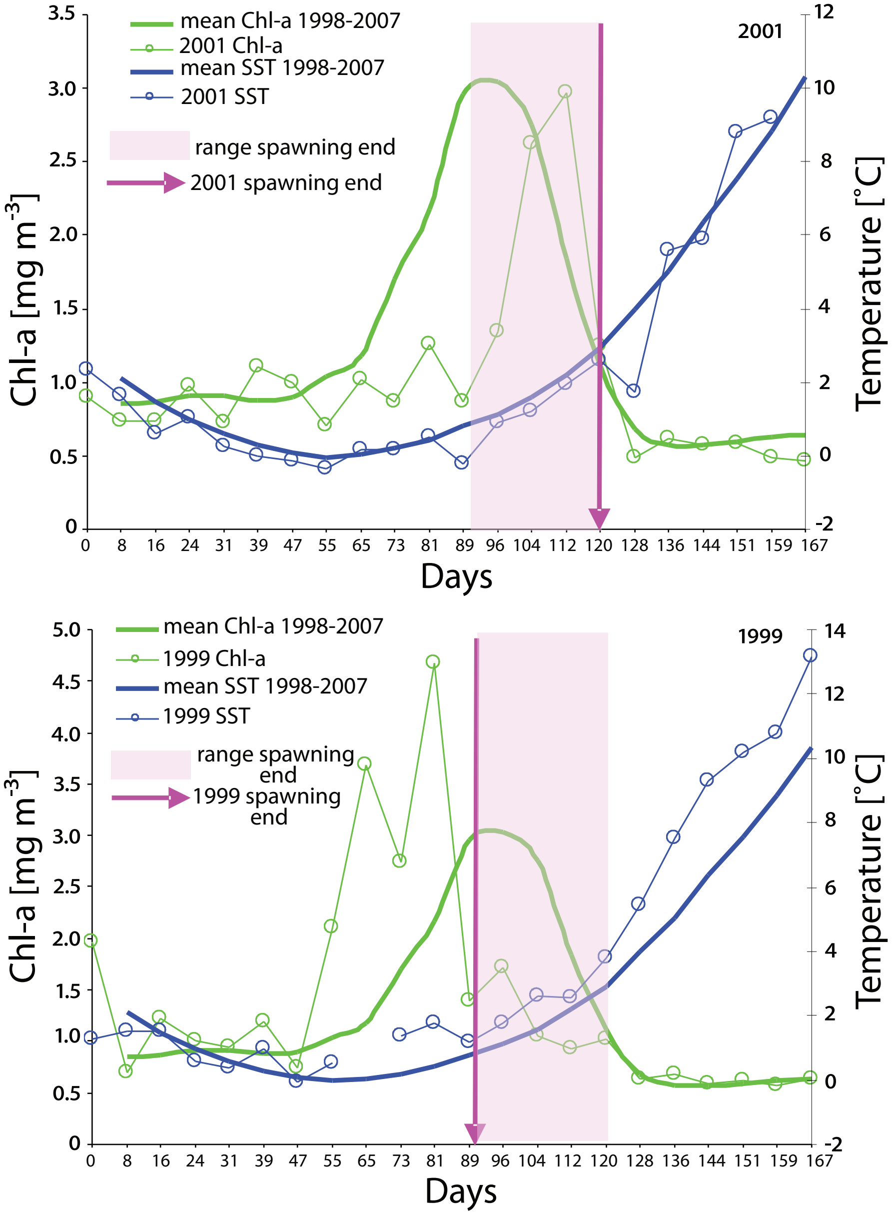

Figure 3.2 In 2001 (top) satellite-derived sea surface temperatures on the eastern Scotian shelf were cooler than average, contributing to a late spring bloom. In addition, egg hatching was completed later than usual, resulting in a match between hatching and satellite-derived bloom times. Because both events occurred later in the spring, they were closer in time to the rapid atmospherically-induced warming of surface water, conditions favoured by the young larvae – sufficient food and warmer water promote faster growth. In 1999 (bottom), spring surface temperatures were warmer than average, contributing to a much earlier spring bloom on the eastern Scotian shelf. Coincidentally, the hatch was also completed earlier. Although hatch and bloom matched quite well, both were farther removed from the period of rapid warming. Moreover, the number of eggs produced that year was below average (Figure 3.1) – fewer eggs hatched under less than favourable conditions and the year class was not spectacular.

2004) demonstrated the importance of temperature and also spawning stock size in determining year-class strength. SSTs during the larval period had a significant negative influence on recruitment, i.e. colder temperatures produced higher recruitment. Although the inverse temperature effect seems intuitively correct based on the species circumpolar distribution and decreased abundance in southern latitudes, most laboratory studies show positive effects of warmer water on survival within the range of temperatures in the Gulf of Maine (Nunes, 1984; Stickney and Perkins, 1977; Wienberg, 1982; Ouellet and Chabot, 2005). This suggests that the mechanisms underlying the spring surface temperature effect are more complex than direct effects of temperature on shrimp physiology or survival. A possible explanation is that ocean temperatures affect the timing of the northern shrimp hatch relative to the timing of the winter/spring phytoplankton bloom. While embryonic development rate is strongly influenced by temperature, bloom timing in coastal waters of the Gulf of Maine depends primarily on solar radiation and the intensity of PAR (photosynthetically active radiation) in the upper mixed layer of the ocean (Townsend and Spinrad, 1986). Because hatch timing and bloom timing are tied to different forcing mechanisms, they have the potential to be decoupled, setting the stage for a mismatch between the appearance of larvae and their food. This is the classic 'match/mismatch' hypothesis of Cushing (1975; 1990), which states that survival of larvae depends on the spatial and temporal alignment of larvae and their prey.

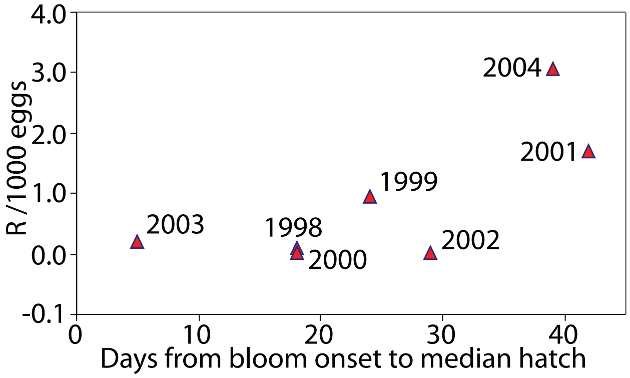

Figure 3.3 Survival of northern shrimp larvae in the Gulf of Maine vs. the offset in timing of the bloom and the hatch (median hatch date). Survival was estimated as the number of juvenile shrimp (abundance at age 1) per 1,000 eggs produced.

The match/mismatch hypothesis is currently being tested by comparing timing of the phytoplankton bloom with timing of the shrimp hatch. Timing of the bloom is estimated from high resolution SeaWiFS images, and hatch timing is derived from the proportion of egg-bearing females in the landings. The offset in timing of these two processes is compared to annual estimates of shrimp survival derived from fishery-independent surveys. The relationship suggests that shrimp survival is better when the hatch lags the bloom onset by ~40 days (Figure 3.3). Our working hypothesis is that a relatively early bloom leads to development of a rich zooplankton population which provides the preferred prey of later stage shrimp larvae (Rasmussen *et al.*, 2000).

The results of this project could have direct implications for fishery management of northern shrimp in the Gulf of Maine. Because the fishery is prosecuted almost exclusively on egg-bearing females, conservation measures that allow sufficient escapement of spawners are critical to sustaining the population. Satellite data could be used to develop indicators for timing of the shrimp hatch (using SSTs) and bloom onset (from chlorophyll concentrations). This would provide a prediction of survival conditions in the current year, which could be used to make management adjustments, particularly if poor survival is predicted.

3.2.3 Latitudinal-spatial differences in growth on the Newfoundland-Labrador shelf

Fuentes-Yaco *et al.* (2007) used satellite data from SeaWiFS to characterize the spring phytoplankton bloom on the Newfoundland-Labrador shelf. Characteristics included: maximum observed chlorophyll-*a* (intensity); time when biomass first exceeded a threshold value of the maximum (initiation); time when the maximum intensity occurred (timing); and the period during which the biomass remained above the threshold (duration) (Figure 3.4). The results showed significant links between bloom intensity, timing and carapace length of various shrimp life history stages, implying a direct influence of bloom characteristics on growth, as elaborated by Koeller (2006).

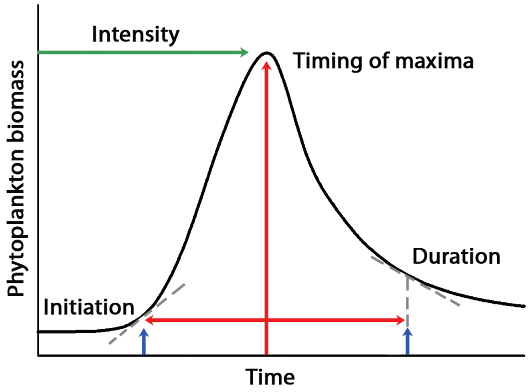

Figure 3.4 Ecological indices that characterise the phytoplankton bloom: i) intensity, or maximum chlorophyll-*a* concentration (estimate of phytoplankton biomass), ii) bloom initiation, time when the slope of the phytoplankton biomass curve exceeds a defined threshold value, iii) time when the phytoplankton bloom reaches its maximum amplitude, and iv) duration, the time when the slope of the declining portion of the biomass curve reaches a threshold value.

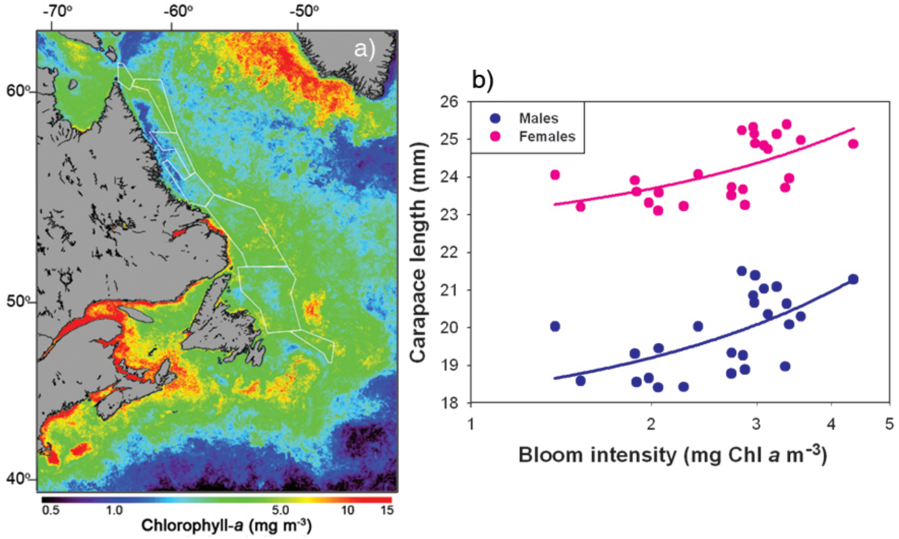

Figure 3.5 (a) Climatology of maximum chlorophyll-*a* concentration and (b) relationship between the chlorophyll-*a* maximum and the carapace length for male and female shrimp on the Newfoundland-Labrador shelf. The lines represent significant non-linear regressions ($p<0.001$).

Figure 3.5a represents the average (6 years) climatology of bloom intensity on the Newfoundland-Labrador shelf, showing persistent, identifiable high phytoplankton concentrations in the northern and southern extremes, bracketed by relatively weak values in the central areas. Figure 3.5b shows the association between bloom intensity and the carapace length of male and female shrimp; similar results were found for all shrimp life history stages by year (Fuentes-Yaco *et al.* 2007). Clearly, the phytoplankton bloom characteristics influence shrimp size and growth in this area. This association of satellite data with the growth of a marine species, a first in fisheries oceanography, could help answer some important fisheries questions, for example, the cause of the decrease in size and growth of Newfoundland shrimp (Koeller *et al.*, 2007) which has a major economic impact in this fishery.

3.3 Haddock (*Melanogrammus aeglefinus*)

3.3.1 Recruitment and the spring bloom on the Scotian Shelf

As is the case for northern shrimp (see previous section), variability in food supply for larval fish species is also related to the timing of the spring phytoplankton bloom relative to the timing of spawning (Cushing's match/mismatch hypothesis).

Only with the advent of remotely-sensed data on ocean colour did fisheries oceanographers have access to a sampling method adequate to address this hypothesis at the appropriate scales of time and space. An early test examined the haddock *Melanogrammus aeglefinus* on the continental shelf of Nova Scotia and examined the variance in recruitment as related to fluctuations in the properties of the spring bloom i.e. amplitude, initiation, time of maximum, and duration (see Section 3.2.3).

Data from the CZCS, POLDER and SeaWiFS missions were used to characterise the bloom. Data on haddock recruitment came from a thirty-year series of abundance trawl surveys. In this series, two years (1981 and 1999) produced exceptional year classes, which were found to correspond to years in which the spring phytoplankton bloom was exceptionally early (Platt *et al.*, 2003 - see also IOCCG 2008). Anomalies (deviations from the local climatology) in larval recruitment (normalised to spawning biomass) were highly correlated with anomalies in the timing of the spring bloom (Figure 3.6), indicating that early blooms favour higher haddock recruitment. These observations could not have been made without the use of satellite data.

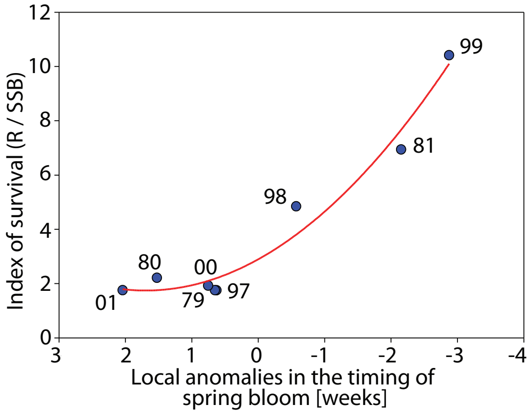

Figure 3.6 Index of haddock survival on the Scotian Shelf (recruitment index normalised by spawning stock biomass) versus satellite-derived anomalies in the timing of the spring phytoplankton bloom.

This study also argued for the persistence of a trophic link between phytoplankton and fish, such that fluctuations in the phytoplankton, mediated by environmental variability, could be detected as fluctuations in larval survival. For fish species with a protracted spawning period, such as haddock, an early spring bloom would confer enhanced survival on those larvae produced early in the spawning period. The importance of environment for fish was brought into focus.

3.3.2 The relationship between the fall phytoplankton blooms and recruitment on Georges Bank

In recent years, the depleted haddock stock on Georges Bank has responded to more stringent management measures with increased recruitment and stock size, at least partially due to a larger spawning stock. Indeed, seventy years of careful monitoring shows that the relationship between spawning stock and recruitment (measured as numbers of age 1 fish) is positive (Brodziak *et al.*, 2006). However, as in almost all stock-recruitment (s-r) plots, the relationship for Georges Bank haddock is noisy, which is attributed to inter-annual variability in the environmental factors modifying the underlying s-r pattern.

Friedland *et al.* (2008; 2009) found no evidence for the common hypotheses concerning the environmental factors influencing marine fish recruitment, including: variability in the retention of eggs and larvae in the spawning and nursery areas; the timing of haddock spawning; the growth of larvae and juveniles; the availability of preferred food resources; and, the timing of the spring bloom. In particular, none of these factors were associated with the exceptional 2003 recruitment event on Georges Bank. Instead, they found evidence that in this area the most important environmental factor determining haddock recruitment is the magnitude of the fall phytoplankton bloom, via its effect on the reproductive condition of females the year before they spawn.

The fall bloom, which occurs most years on Georges Bank, is localized over the shallow portion of the Bank. In some years it lasts for several months, while in others it may not develop at all. The fall bloom can be characterized in a number of ways, including a computed statistic called 'magnitude' (Friedland *et al.*, 2008) – the weekly sum of chlorophyll concentrations estimated from the SeaWiFS colour sensor. Magnitude reflects both the concentration and the duration of elevated chlorophyll levels. The magnitude of the fall phytoplankton bloom the year prior to spawning was highly correlated with subsequent recruitment (Figure 3.7). This correlation has led to the 'parental condition hypothesis', which suggests that the fall bloom affects recruitment through enhanced feeding conditions for adults and the resultant increase in the quantity and quality of their reproductive output.

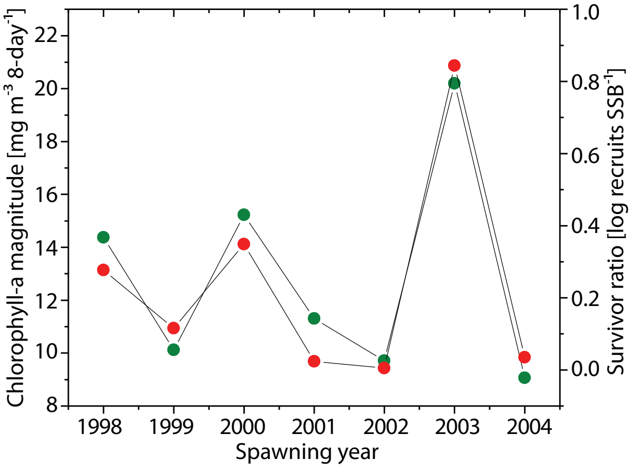

Figure 3.7 The magnitude of the fall bloom on Georges Bank the year before spawning (green dots), and the survivor ratio of the year class spawned during the spawning year for the Georges Bank stock of haddock (red dots). Chlorophyll magnitude is a bloom index that reflects the concentration and duration of the fall phytoplankton bloom. The survivor ratio is the ratio of recruitment to spawning stock size, which corrects for the spawning stock size effect.

The linkage between the fall bloom and haddock recruitment is dependant on food web processes of the Georges Bank ecosystem and the feeding ecology of haddock. The system is fueled by photosynthesis in the upper water column, but the benthic community, where haddock live, is fed by the sinking of bloom products to the bottom (Witte *et al.*, 2003), where they are consumed by the detritivorous organisms haddock feed on, including brittle starfish, *Ophiuroidea* spp., amphipods, and polychaetes (Garrison and Link, 2000). In contrast, cod are more piscivorous feeders, which may partly explain why cod recruitment has not improved despite management measures – its recruitment appears to be unrelated to the fall bloom on Georges Bank. Further test of the parental condition hypothesis will require measurements of haddock condition and fecundity for comparison with bloom conditions. Such analyses would be impossible without satellite data.

3.4 White hake (*Urophycis tenuis*)

3.4.1 Recruitment of juveniles on Grand Bank

The white hake population on the Grand Banks has undergone large fluctuations in abundance since the 1970s. The Labrador current, which carries cold Arctic water along the shelf edge, has strong seasonal and inter-annual variability in water volume transport (Han and Tang, 1999), which may impact the biology of commercially important fish species in the area, including the distribution of white hake. The potential impacts of the Labrador Current on the extremely successful recruitment of white hake juveniles in 1999 were explored using satellite altimetry data and ocean modelling.

A computer model (Han *et al.* 2008) was used to reconstruct monthly ocean circulation patterns during the period of interest, including the exceptional recruitment year 1999. For 1999, satellite altimetry was used in conjunction with the model to empirically reconstruct water circulation. Long-term mean current patterns were calculated by averaging the model's monthly circulation patterns across years. Subsurface currents were incorporated assuming that either, surface and subsurface anomalies were the same (invariant), or they were vertically linear with zero bottom current. Compared with the model-derived climatological mean currents (Figure 3.8a), the reconstructed 1999 monthly means (Figure 3.8b) have a weaker along-slope Labrador Current and increased on-bank flow on the southwestern Grand Bank edge. This has important implications for the early life history of white hake, in particular the retention of larvae in favourable areas.

A simulation tracked the pelagic eggs, larvae and juveniles in the monthly-mean circulation fields, as per Werner *et al.* (1993) and Berg (1993). Release locations and timing of the simulated, passively-drifting particles were determined by examination of white hake ovaries taken during groundfish trawl surveys and available data on the distribution of pelagic and newly settled juveniles. Spawning females were found

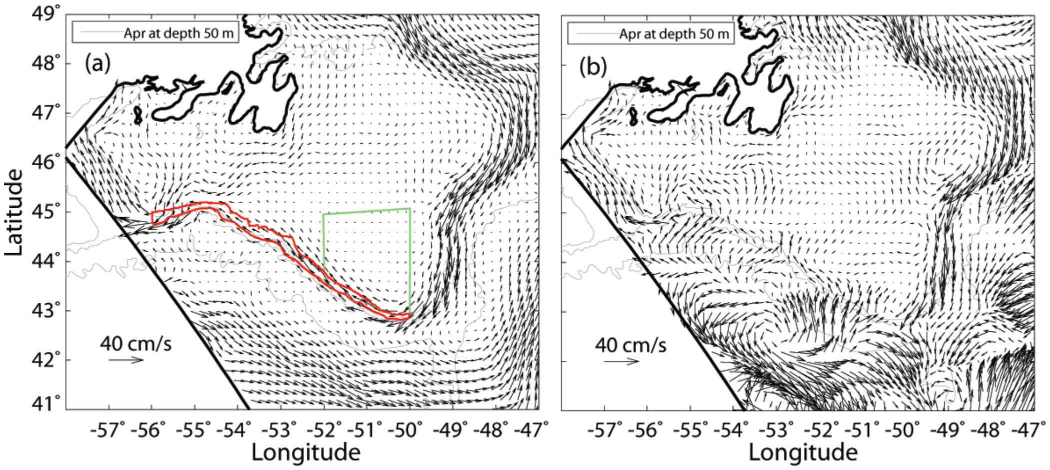

Figure 3.8 The circulation patterns at a depth of 50 m in April: (a) modelled climatology. The horizontal extent of eggs at the start of tracking (red) and the nursery area on the SW Grand Bank (green) are also depicted. (b) 1999 circulation reconstructed using satellite altimetry and model.

during April-May along the southwest slope; summer observations were not available and the full extent of the spawning period is unknown, but no mature fish were observed in October, suggesting that spawning is completed by the fall (Kulka *et al.*, 2005). Pelagic young of the year, probably born in spring/summer, were observed to concentrate over the shallow part of the southern Bank in August-September (Kulka *et al.*, 2005) and newly settled juveniles, largely separated from older components of the population, were also observed on the bottom in the same area. This is also the warmest location on the outer Grand Banks and appears to constitute a nursery area (Figure 3.8a).

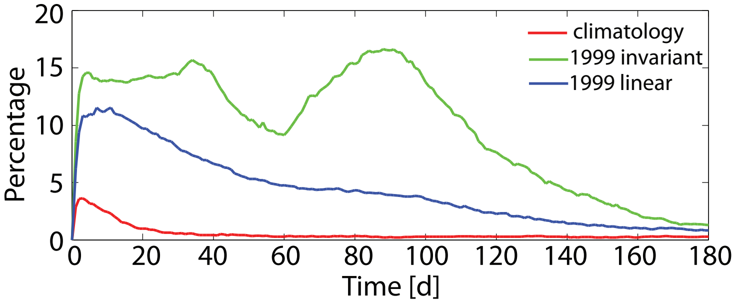

Figure 3.9 The temporal evolution of the percentage of particles within the nursery area on the Grand Banks showing the 50 m release for a normal year under the climatological monthly-mean circulation fields (red) and for 1999 under the assumptions of depth-invariant (green) or linearly decreasing (blue) current anomalies. The simulated particles were released on April 1 and tracked for six months.

The simulation showed that the number of eggs and larvae reaching the nursery ground in 1999 are much higher than in a normal year (Figure 3.9). Clearly the circulation pattern in 1999, including a reduced along-slope Labrador Current and increased on-bank flow, provided a much better transport and retention mechanism for the eggs and larvae to reach and remain in the nursery area (Figure 3.8). Survey data indicates that the number of spawning females in 1999 was not significantly different from other years. However, SeaWiFs ocean-colour data indicated that the spring bloom in the vicinity of the nursery ground in 1999 was a few weeks earlier than normal which could have affected recruitment as described in Section 3.3.1 above and by Platt *et al.* (2003). Sea surface temperatures were also significantly warmer in 1999, favourable for survival and growth. Again, this study would not have been possible without the availability of satellite data.

3.5 Concluding Remarks

The case studies in this chapter all emphasized exceptional events – they are only able to do so because the necessary data are available at the spatial and temporal scales at which they occur – none of these findings would have been possible without satellite data. Three of the studies concerned three different stocks of the circumpolar northern shrimp species, *Pandalus borealis*, currently one of the most important wild fishery resources in the world. It is also perhaps the species most suitable for studying the 'match-mismatch' theory (Cushing, 1990) of biological and physical processes because its life history is so finely tuned to the local spring bloom event in the North Atlantic – timing of larval hatching parallels latitudinal changes in the timing of the solar cycle and phytoplankton bloom (Figure 3.10, Koeller *et al.*, 2009). Independent studies in the Gulf of Maine and the Scotian Shelf (Sections 3.2.1 and 3.2.2) come to broadly similar conclusions, indicating that the approach is sound and the findings more widely applicable than just to the individual study areas. Although research is ongoing and the refined results are some time away from direct use in assessments, for example, in calculating the probability of a good year class under current environmental conditions, some findings are already applicable as general management considerations. Greater variability of bloom timing on the Scotian Shelf coupled with the strong sub-surface influences on hatching times (see Section 3.2.1) suggests that good matches resulting in the strong year classes are less likely to occur there. It is these strong year classes on which the fisheries depend. Consequently, a more precautionary approach to management of this stock may be indicated. A third study (Section 3.2.3) demonstrated a link between shrimp growth and satellite observations, a first in fisheries research – clearly the usefulness of satellite imagery is not limited to recruitment research.

Two studies on haddock in adjacent stocks concentrated on two quite different aspects of the recruitment process, one on how spring bloom characteristics influence larval survival, the other on the apparent influence of the fall bloom on

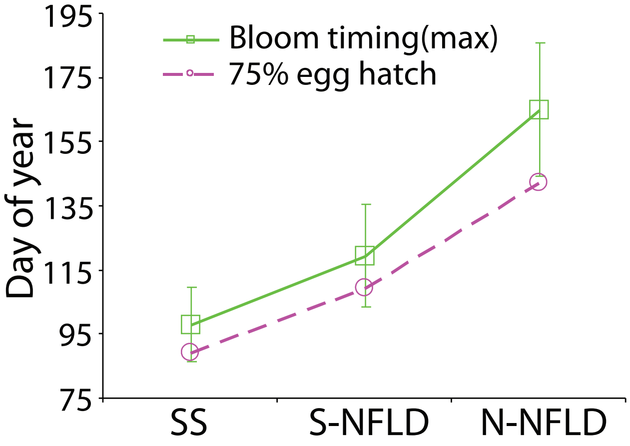

Figure 3.10 The satellite-derived timing of the spring bloom varies with latitude according to latitudinal differences in the solar cycle. Egg hatching of *P. borealis* coincides with the spring bloom at all latitudes within its wide geographical range. Shown – average bloom timing and 75% completion of hatching time on the Scotian Shelf (SS, 45°N), southern Newfoundland (S-NFLD, 50°N) and northern Newfoundland (N-NFLD, 58°N).

parental conditions, which in turn determines the robustness of their offspring. Finally, a study of white hake recruitment illustrated the use of satellite data in studying the other major factor determining pelagic larval survival – their retention in areas with suitable habitat by surface currents (Sinclair, 1987). Satellite altimetry is used to characterise surface currents during the critical pre-settlement phase and to demonstrate that a successful year class likely resulted from exceptionally strong retention of larvae and juveniles in an area where conditions were more favourable to their survival.

It should be noted that the works highlighted in this chapter were not intended to be exhaustive regarding the use of satellite data in stock assessments and current assessment-related research – rather they are illustrative of the varied applications of satellite data in this field, and of the significant progress being made, more or less directly because of their availability. Note also that the examples given all happen to be from the northwest Atlantic – this is not to say that all, or even most, similar applications are from this area. For example, recent work with Pacific sardine and northern anchovy in the California Current uses remotely-sensed data to define spawning habitat (Reiss *et al.*, 2008). Current work (unpublished) is using physical oceanographic and seasonal primary production data from satellites to investigate their temporal relationship to larval birth dates, larval growth rates, and reproductive success of these species. Clearly the increasing importance and use of satellite data in fisheries oceanography and fish stock assessment is a global phenomenon.

Chapter 4

Remote Sensing Applications to Marine Resource Management

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4.1 Introduction

The continuity, global coverage, and high temporal and spatial resolution of satellite data make them an important tool for monitoring and characterizing the habitat and ecosystems that influence marine resources. Remotely-sensed variables such as sea-surface temperature (SST), sea-surface height, ocean colour, ocean winds and sea ice, characterize critical habitats that influence marine resources. Most of the physical features that are important to ecosystems, such as ocean fronts, eddies, convergence zones, river plumes and coastal regions, cannot be resolved adequately without satellite data. Similarly, satellite data are crucial for resolving the timing of processes such as upwelling, harmful algal blooms (HABs), seasonal transitions and El Niño events. Satellite ocean colour is particularly important, since it is the only remotely-sensed property that directly measures a biological component of the ecosystem. For example, chlorophyll derived from ocean colour data can be used to observe changes in the timing and magnitude of the phytoplankton blooms that can affect future fish populations via recruitment (Platt *et al.*, 2003; Friedland *et al.*, 2008), to classify the productivity of the oceans (Pauly and Christensen, 1995; Sherman *et al.*, 2005), to detect interannual differences in the frontal structures that are important to fisheries (Polovina *et al.*, 2001; Bograd *et al.*, 2004) and to map the spatial extent of the part of the ocean experiencing reduced productivity during El Niño events (Wilson and Adamec, 2001). This Chapter shows some specific examples of how satellite data have been applied to improve the management of fisheries.

4.2 Fisheries Management: Changing the Paradigm

Traditionally, fisheries management strategies have focussed on a single species in relative geographic isolation. However, neither one fish species, nor its fishery, exist in isolation. Both the fish and its fishery are embedded in an interacting network of plants, animals (including humans) and non-living components. Thus, there is growing recognition that an integrated approach is needed: one that considers the cumulative impacts from various sources, and from potentially conflicting uses, to manage the entire ecosystem, and one that moves beyond political boundaries. A key conceptual difference between an ecosystem-based approach to management and conventional approaches is the focus on sustainability of all components of the ecosystem, not just those that are targeted by fisheries. The need for this broader approach, which demands a better understanding of the structure and function of the entire ecosystem, has become apparent as many fisheries, including some closely managed ones, have declined when management has tried to treat the target species in isolation. Factors such as fisheries, pollution, coastal development, harvest pressure, predator-prey and other ecological interactions, and watershed management all need to be taken into account (Sherman *et al.*, 2005; Ruckelshaus *et al.*, 2008). A variety of systems have been developed to define different ecosystems or provinces in the ocean. The large marine ecosystem (LME) concept is widely used in the coastal ocean (Sherman and Alexander, 1986; Sherman, 1991; 1993; Duda and Sherman 2002; Sherman and Hempel 2008), and a number of different approaches have been used to define ecological provinces within the open ocean (Ryther, 1969; Sieburth *et al.*, 1978; Longhurst, 1995; Platt and Sathyendranath, 1999; Devred *et al.*, 2007; Spalding, *et al.*, 2007).

The availability of global coverage of SST and chlorophyll from satellites has been instrumental in classifying marine ecological regions. The world's oceans have traditionally been poorly sampled using shipboard sampling, partially due to the inherent logistical difficulties involved with shipboard sampling of such vast areas, and also due to the fact that the ocean is highly dynamic, making many oceanic features impossible to resolve adequately either temporally or spatially with shipboard sampling. Oceanographic satellite data solves many of these problems, and the amount of satellite oceanographic data available has expanded tremendously in recent years. The challenge, however, is in interpreting the relationship between the fundamental satellite measurement, i.e. the amount of chlorophyll-a in the surface ocean, and the higher trophic levels (Figure 4.1).

4.2.1 Large marine ecosystems

Large marine ecosystems (LMEs) are regions of the world's oceans encompassing areas from river basins and estuaries to the seaward boundaries of continental shelves and the outer margins of the major ocean current systems. The physical

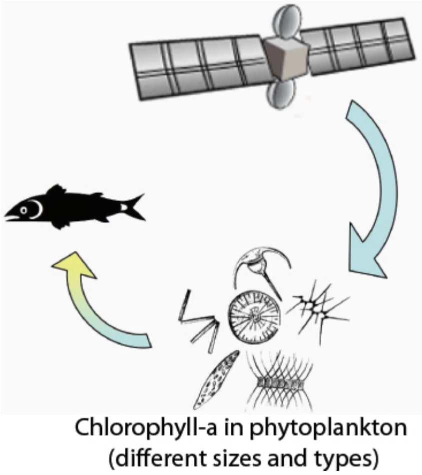

Figure 4.1 Schematic showing simplified pathway between fish populations and properties that can be inferred from satellite ocean-colour data, such as phytoplankton type and size. There can be many different levels in the link between phytoplankton and the top of the trophic food chain. See also Figures 2.10 and 2.12.

extent and boundaries of the LMEs are based on bathymetry, hydrography, productivity and trophic relationships (Sherman and Alexander, 1986; Sherman, 1991; Sherman *et al.*, 2007; Sherman and Hempel, 2008). Within the boundaries of the 64 LMEs (Figure 4.2) are the highest levels of global primary production and 80% of the world's annual fisheries yield (Garibaldi and Limongelli, 2003; Sherman *et al.*, 2009). However, overfishing, destruction of marine habitats, and accelerated pollution loading has dramatically reduced the biomass and diversity of the coastal ocean to a point that ecosystems are being severely degraded, and the dependency of coastal communities on marine resources for livelihoods and protein is being threatened (Duda and Sherman, 2002).

The LME concept is a strategic approach for resource managers to characterize ecosystems and develop management approaches that can provide a basis for cooperation among the different countries managing a shared ecosystem. The LME management approach has developed a 5-module methodology with indicators of (i) productivity, (ii) fish and fisheries, (iii) pollution and ecosystem health, (iv) socioeconomics, and (v) governance to analyze ecosystem-wide changes (Sherman and Hempel, 2008). The productivity module is especially important, as primary productivity is related to the carrying capacity of an ecosystem for supporting fish resources and fisheries (Pauly and Christensen, 1995). Using satellite chlorophyll and SST data the primary productivity of the LMEs can be calculated at a high spatial resolution, and its seasonal and interannual variability can be monitored. Satellite data provide a large-scale physical and biological context to understand better the changes in fish stock populations. A crucial component of the satellite

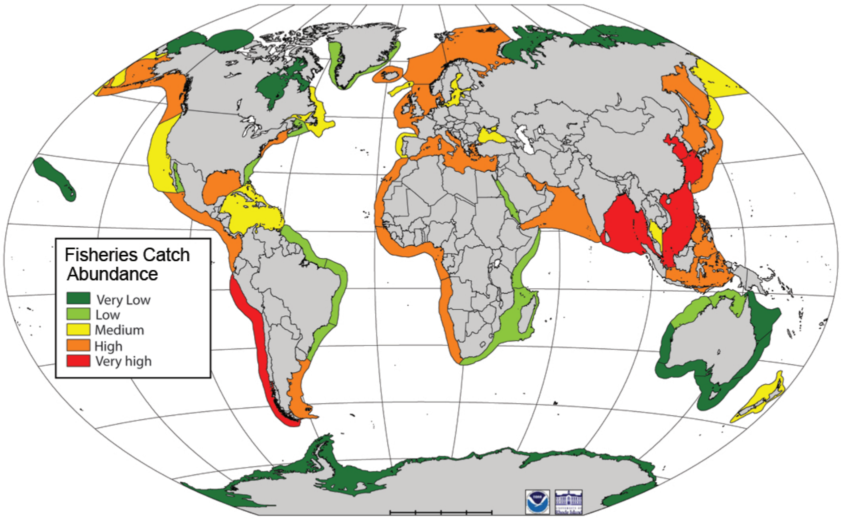

Figure 4.2 Outline of the 64 Large Marine Ecosystems of the world showing fisheries catch abundance for 2000-2004 (adapted from `http://www.lme.noaa.gov/`).

data is the time-series, which provides a baseline from which significant anomalies from the climatological seasonal cycles can be determined, as well as long-term increases or decreases in different ecosystem variables. For example, satellite SST and chlorophyll, and their spatial and temporal trends, are some of the key indicators in the biannual advisory reports produced on the current status of the northeast U.S. LME (`http://www.nefsc.noaa.gov/omes/OMES/`).

4.2.2 Open ocean provinces

Many LMEs fall within the coastal waters (see Figure 4.2) where primary productivity is generally higher than in the open gyres. However, to manage fisheries on a global scale requires a methodology for defining the boundaries of the large open-ocean ecosystems. The simplest system is a box defined by lines of longitude and latitude, but for fisheries management it is imperative that the distribution of both the fish stock and its key habitat are also taken into account (Halliday and Pinhorn, 1990). And for an ecosystem-based approach to management, information about the ecological structure and the physical environment also needs to be utilized.

A seminal classification of global marine ecological provinces was developed by Longhurst (1995; 1998; 2007), who used satellite chlorophyll data, in conjunction with other datasets, to delineate rectilinear regions in the ocean with similar physical and biological seasonal patterns. However, ecological provinces are not fixed temporally, but rather have significant seasonal and interannual variability. Recently Devred *et al.* (2007), using ocean-colour data, developed a method to determine the instantaneous boundaries of marine ecological provinces (Fig 4.3). From this analysis, not only is the climatological position of the provinces determined, but also their seasonal and interannual variability.

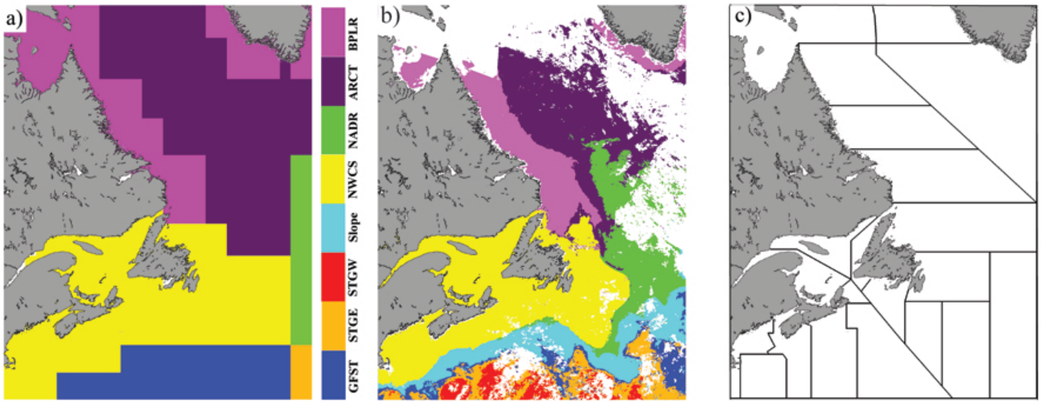

Figure 4.3 Ecological partitions of the northwest Atlantic Ocean, (a) static partition according to Longhurst (1998); (b) dynamic partition according to Devred *et al.* (2007), for 16 to 31 October 2001; (c) static partition of the Northwest Fisheries Organisation (see Halliday and Pinhorn, 1990). Figure modified from Platt and Sathyendranath (2008).

A related approach to defining oceanic provinces is on the basis of the dominant type of phytoplankton population. Typically, smaller phytoplankton (nanoplankton) dominate in the ocean gyres, and larger phytoplankton (microplankton) dominate in coastal areas (Ryther, 1969). These different ecosystems also have differing numbers of average trophic levels. For example, Ryther (1969) assigned a representative number of five trophic levels in oceanic provinces, three in coastal provinces and one and a half in upwelling provinces. The short food chain in the upwelling zones, where a majority of the world's fish yield comes from, implies a better ability to relate satellite-derived measurements of chlorophyll to fish production. But even in oligotrophic environments the food web relevance of nano- and picophytoplankton, through microbial food webs, has been shown to be a crucial issue for local and regional fisheries (Mousseau *et al.*, 1989; Rossi *et al.*, 2006; De Figueiredo *et al.*, 2007).

Various methods have been proposed to identify phytoplankton size classes from phytoplankton absorption characteristics that are retrievable from ocean-colour data (Ciotti *et al.*, 2002; Devred *et al.*, 2006; Uitz *et al.*, 2008). Vidussi *et al.* (2001) used a number of pigment biomarkers to classify natural populations of phytoplankton according to the fractions of pico-, nano- and microphytoplankton present. Uitz *et al.* (2006) used these indices of phytoplankton to demonstrate common patterns relating chlorophyll concentration with phytoplankton size structure: the general trend is for phytoplankton size classes to shift from picophytoplankton-dominated waters under oligotrophic conditions towards predominance of microphytoplankton with increasing chlorophyll concentration. Since chlorophyll concentration is readily available from remote sensing, this provides a method to estimate probable phytoplankton size class structure from satellite-derived chlorophyll data. Nair *et al.* (2008) have reviewed the use of ocean-colour data to obtain information on phytoplankton size class, and Brewin *et al.* (2009) have compared various methods for estimating phytoplankton size class structure from satellite data.

Cell size is an important predation criterion, since most fish larvae are visual predators, but phytoplankton biomass and composition also play a role in food web dynamics. For example, a diet composed exclusively of diatoms can negatively affect both the growth and survival of some fish larvae and the hatching and reproduction of copepods, which are an important food source for the early larval stages of many carnivorous species (Hunter, 1981; Kleppel *et al.*, 1991; Kleppel, 1993; Ban *et al.*, 1997; St. John *et al.*, 2001). Upwelling systems alternate between being dominated by sardines or anchovies, and it has been suggested that changes in the phytoplankton community structure are involved, with dinoflagellates supporting a sardine regime, and diatoms supporting an anchovy regime (Cury *et al.*, 2008). These results argue for an approach to fisheries applications of ocean-colour data that is based not only on the total concentration of chlorophyll-a, but also on phytoplankton composition.

For the classification of ecological provinces to be useful for fisheries management, it is necessary to first show that distributions of pelagic biota do in fact follow the same patterns and boundaries. Despite the large disparity between the temporal and spatial resolution of fish population data relative to that of satellite data, a mirroring of the pattern of defined ecological provinces has been observed at higher trophic levels. The distribution of species of tuna inferred from long-line catch statistics shows a partitioning along Longhurst's province boundaries (Royer and Fromentin, 2007; Corbineau *et al.*, 2008). For example, yellowfin tuna dominate in the provinces of the western tropical oceans; the tropical provinces with shallower thermoclines are the domain of bigeye tuna in the Pacific and the Atlantic, while albacore tuna dominate in the central gyral provinces of each ocean basin, and bluefin tuna are largely restricted to the higher latitude provinces (Fontenau, pers. comm.). Such concordance must be made with caution, for other factors — such as administrative restrictions on long-lining in certain areas — may easily confuse the result.

4.2.3 Marine managed areas

Marine managed areas (MMAs) are an important aspect of ecosystem-based approaches to fisheries management. MMAs range in overall management approach from marine reserves, which are relatively rare 'no-take' areas that prohibit all extractive uses, to more common 'multiple use' areas, such as marine sanctuaries and marine protected areas, where a variety of activities are managed to ensure the sustainability of the marine resources. Both chlorophyll and turbidity from ocean-colour satellites are key indicators of oceanographic habitat that are used in the biogeographical assessment of waters within marine sanctuaries. Areas of consistent upwelling, and the locations of persistent fronts, both features of biological importance, can be determined using satellite SST data, for use in coastal management (Stegmann *et al.*, 2006). Delineating upwelling and frontal areas, and the seasonal expansion and contraction of their boundaries have been used in designing strategies for identifying the locations of new MMA regions and in monitoring their effectiveness (Alpine and Hobday, 2007).

4.2.4 Coral reef monitoring

Coral reef ecosystems support a high diversity of coral, fish, and benthic species, with corals forming the structural and ecological foundation of the reef system. Coral reefs are sensitive to their environment (temperature, light, water quality, and hydrodynamics), and as a result of both anthropogenic and climate impact (Kleypas *et al.*, 2001), they are among the most threatened coastal ecosystems worldwide (Pandolfi *et al.*, 2003; Hoegh-Guldberg *et al.*, 2007). Corals have a symbiotic relationship with a microscopic organism, zooxanthallae, which provides the corals with oxygen and a portion of the organic compounds they produce through photosynthesis. When stressed, many reef inhabitants expel their zooxanthallae *en masse*. The polyps of the coral are left bereft of pigmentation and appear nearly transparent on the animal's white skeleton, a phenomenon referred to as coral bleaching.

Severe bleaching events can have dramatic long-term effects on the coral. Recovery rates appear to differ with species, and the time required to attain full recovery of symbiotic algae varies from as little as two months to as much as one year. When the level of environmental stress is high and sustained, the corals may die. Since the late nineteen eighties, coral bleaching related to thermal stress has become more frequent and more severe. High SSTs associated with the 1997 to 1998 El Niño caused bleaching in much of the world's oceans, particularly in the Indian Ocean and in the western Pacific. Other major bleaching events occurred around the Great Barrier Reef and northwestern Hawaiian Islands in 2002, and in the Caribbean in 2005 (Figure 4.4).

With the capability of providing synoptic views of the global oceans in near-real-time and the ability to monitor remote reef areas, satellite remote sensing has become a key tool for coral-reef managers and scientists (Mumby *et al.*, 2004; Maina *et al.*, 2008; Maynard *et al.*, 2008). Since 1997, NOAA has been producing near-real-time, web-accessible, satellite-derived SST products to monitor globally the conditions that might trigger coral bleaching from thermal stress. Currently NOAA's Coral Reef Watch Program provides operational products such as SST anomalies, bleaching HotSpot anomalies, Degree Heating Weeks (see Figure 4.4), and Tropical Ocean Coral Bleaching Indices to the global coral reef community (Strong *et al.*, 2006). These products provide an effective early warning system globally, but are not always accurate in predicting the severity of a bleaching event at the regional

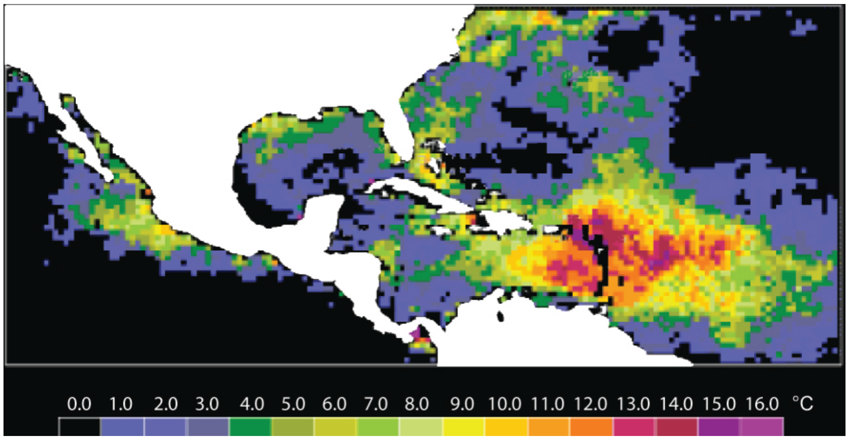

Figure 4.4 Map of an unusual heating in the Caribbean for the summer of 2005 when a massive bleaching event occurred. Results are presented as anomalies of sea-surface temperature (SST) above the expected summer-time maximum, over a one week period, expressed as 'Degree Heating Weeks' (DHWs). One DHW is equivalent to one week of SST greater than expected summertime maximum by 1°C. DHWs greater than 10 indicate the existence of high and persistent SST, with a high probability that coral reefs may be undergoing severe bleaching, and possible mortality.

scale (McClanahan *et al.*, 2007; Maynard *et al.*, 2008). CSIRO's ReefTemp project produces satellite-derived bleaching risk indices specifically for Australia's Great Barrier Reef (Maynard *et al.*, 2008).

4.2.5 Use of remote sensing within an ecosystem-based approach to management

Most of the coastal fishery resources within the Lesser Antilles are fully exploited or overexploited (especially those of higher commercial value), and the demand for fish (including pressures from tourism and recreation fishing) continues to grow. As a result, both fishers and the governments in the region are actively working to expand their fisheries. In line with current thinking, the governments of the region opted to pursue this expansion under the framework of management using an ecosystem-based approach to fisheries.

The countries involved requested assistance from the Food and Agriculture Organization (FAO) to help with the development of the data, information systems and models necessary to assess the status of the regional pelagic ecosystem and associated fisheries. They also requested recommendations toward implementing an ecosystem-based approach to management. The result was the Lesser Antilles Pelagic Ecosystem (LAPE) project. The project compiled new and published scientific information needed to provide the scientific basis for recommendations towards ecologically-sustainable development of the pelagic fisheries in the Lesser Antilles.

The project integrated information about fisheries, primary production, trophic relationships and other ecological factors using the Ecopath model (Christensen *et al.*, 2005) to estimate the flows of energy to, and within, the pelagic community. At the base of this trophic model was the estimation of primary production for the LAPE project study area. Primary production was computed on a synoptic scale for the LAPE area from satellite chlorophyll data, in conjunction with field measurements made during the LAPE project (Platt *et al.*, 2008). Annual mean primary production was quite low for the LAPE area, approximately 99 g C m^{-2} y^{-1} (Figure 4.5a). The highest primary production was found in the southern-most areas, adjoining the coast of Venezuela and Trinidad. These areas have enriched nutrient supplies driven by the outflows of the Orinoco and, to a lesser extent, Amazon Rivers. Primary production increased in summer months and decreased in the winter, as a result of seasonal variation in chlorophyll concentration, solar irradiance and both photosynthetic and biomass profile parameters (Figure 4.5b). Seasonal variation in river outflows is also suspected to impact the annual pattern in both chlorophyll concentration and primary production (Muller-Karger and Aparicio Castro, 1994).

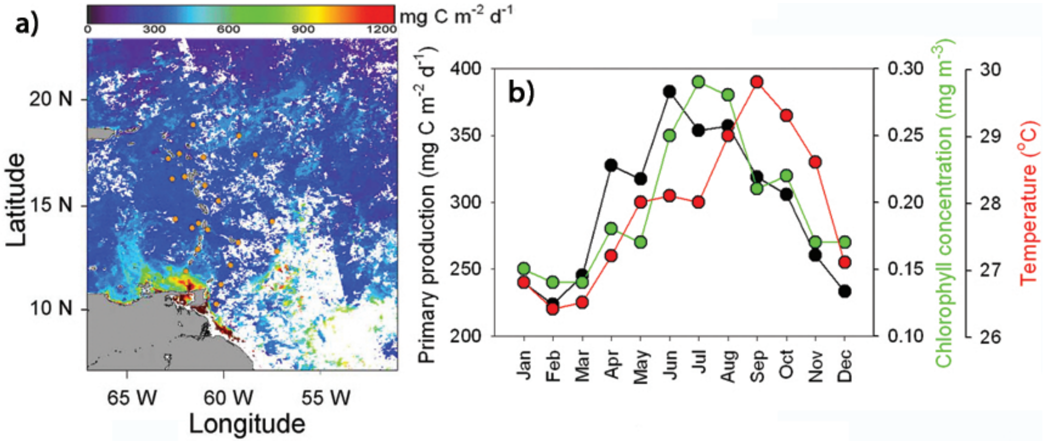

Figure 4.5 (a) Primary production map for May 2006 for the LAPE study area. Parameters are heterogeneously assigned using the Nearest-Neighbour Method (Platt *et al.*, 2008). The sampling stations of the photosynthetic parameters are superimposed. (b) Seasonal cycle of primary production (black), sea-surface temperature (red) and chlorophyll-*a* concentration (green) estimated from remote sensing in 2006.

The LAPE is a relatively low productivity ecosystem and many of the important commercial fisheries within it depend on species that migrate from other areas. Thus a substantial fraction of the biomass available in the area is imported and derived from primary production elsewhere. These species are also subject to fisheries in the other parts of their ranges and effective management for these fisheries will require inclusion of LAPE fisheries in the relevant international fisheries bodies e.g. International Commission for Conservation of Atlantic Tunas.

4.3 Marine Hazards

Because of the synoptic and frequent measurements, satellite remote sensing in the visible provides effective means to monitor marine hazards such as harmful algal blooms (HABs), oil spills, and turbidity events, which can all be serious threats to marine ecosystems. Since these hazards often (although not always) have unique optical signals compared to their surrounding environment, they can be monitored with remote sensing.

4.3.1 Harmful algal blooms

Harmful algal blooms (HABs) are blooms of toxin-producing algae that can have negative impacts on humans, marine organisms or coastal economies. HAB events can result in the closure of shellfish beds and beaches, extensive fish kills, death to marine mammals and seabirds, and alteration of marine habitats (see Chapter 9 in IOCCG, 2008, and Chapter 6, this volume, for examples). As a consequence, HAB events adversely affect commercial and recreational fishing, tourism, and valued habitats, creating a significant impact on local economies and the livelihood of coastal residents. Advanced warning of HABs increases the options for managing these events and minimizing their harmful impact on society.

Because of the large spatial scale and high frequency of observations needed to assess bloom location and movements, ocean-colour satellite data are a key component in HAB forecasting. ‘New’ blooms can be identified by a chlorophyll anomaly method that accounts for the complex optical properties in coastal waters that can confound some satellite chlorophyll algorithms (Stumpf *et al.*, 2003; Tomlinson, *et al.*, 2004). For some coastal waters with high amounts of organic matter, fluorescence data from the MODIS satellite has the potential for providing a better estimate of the bloom extent (Hu *et al.*, 2005). However, because persistent blooms can escape detection, and not all high chlorophyll features are HABs, definitive identification of a HAB generally requires *in situ* water sampling. Despite these limitations, satellite ocean colour has proven an effective tool to monitor HABs, which is done operationally in the U.S. by NOAA and in Europe by the Nansen Environmental and Remote Sensing Centre

4.3.2 Oil spills

Synthetic Aperture Radar (SAR) data has been the most useful satellite sensor for operational oil spill detection because of its wide coverage, high spatial resolution, and its ability to measure both through clouds and at nighttime (Fingas and Brown, 1997; 2000; Liu *et al.*, 2000; Brekke and Solberg, 2005). However, the temporal repeat of SAR data is poor outside of the polar regions, and there is a narrow window of sea states (winds of 1.5 to 6 m s^{-1}) where the method is effective at detecting oil spills (Hu *et al.*, 2003; Brekke and Solberg, 2005). Coarse spatial resolution, cloud cover issues and the need for visible light have generally restricted the usefulness of ocean-colour data for oil spill detection (Fingas and Brown, 1997, 2000; Hu *et al.*, 2003). However, recent work with the MODIS 250-m resolution imagery (MODIS has two bands at 250 m resolution) has demonstrated the utility of medium-resolution ocean-colour radiometry data to detect relatively large oil spill slicks in turbid waters because of the near daily coverage (Hu *et al.*, 2009). These MODIS bands were designed for land applications, but they are very promising for coastal monitoring applications since their high spatial resolution allows detection of such features in the coastal ocean.

4.3.3 Turbidity events

Turbidity or sediment resuspension events, often caused by storms or high winds, can be easily recognized from ocean-colour imagery because of the high backscattering signals of the suspended sediments (Acker *et al.*, 2004; Hu and Muller-Karger, 2007). For example, after the passage of Hurricane Dennis in July 2005, significant sediment resuspension covered nearly the entire west Florida shelf. Such turbidity events, followed by algal blooms resulting from elevated nutrients, can lead to hypoxic conditions resulting in benthic mortality (Adjeroud *et al.*, 2001). MODIS 250-m data have been used to estimate turbidity and sediment concentrations at higher spatial resolution (Hu *et al.*, 2004; Miller and McKee, 2004; Chen *et al.*, 2007), extending such applications to moderately sized estuaries.

4.4 Protected Species Research and Management

In the late 1980s, field programmes monitoring monk-seal pup survival, sea-bird reproductive rates, and reef-fish densities in the northwestern Hawaiian Islands indicated ecosystem changes had occurred. However, due to a lack of oceanographic data at relevant space and time scales, it was difficult to construct comparable environmental indicators, or envision how environmental variation might be coupled with the higher trophic-level changes (Polovina *et al.*, 1994). The launch of the SeaWiFS ocean-colour sensor in 1997 allowed assessment of basin-wide biological variability across the Pacific. From SeaWiFS imagery, it was shown that during the winter, the boundary between the cool, high surface chlorophyll, vertically-mixed water in the north and the warm, low surface chlorophyll, vertically stratified subtropical water in the south (Polovina *et al.*, 2001) was located at the northern atolls of the Hawaiian Archipelago (Kure, Midway and Laysan Atolls). This boundary has been termed the 'transition zone chlorophyll front' (TZCF) (Polovina *et al.*, 2001).

In some years the TZCF remains north of these northern atolls throughout the year, while in other years the TZCF shifts far enough south during the winter to encompass these atolls with higher chlorophyll water. The ecosystem of the northern atolls is more productive when the TZCF is in a more southerly location relative to its long term winter position, and vice versa. Specifically during a winter when the TZCF was shifted south of its average position, monk seal pup survival 2 years later increased (Baker *et al.*, 2007). The 2-year time lag probably represents the time needed for enhanced primary productivity to propagate up the food web to monk seal pup prey. Should management action, such as a head start program, be developed to improve pup survival, a 2-year forecast based on satellite ocean colour can be used to predict the years when low survival is likely and hence when management intervention is needed.

4.4.1 TurtleWatch, a tool to reduce turtle bycatch in the longline fishery

A pelagic longline fishery based in Hawaii occasionally catches several species of sea turtles, with the threatened loggerhead sea turtle (*Caretta caretta*) historically accounting for the majority of the turtle bycatch. Since 1997, Argos-linked transmitters have been attached to loggerhead sea turtles caught and released by longline vessels (Polovina *et al.*, 2000) to characterize migration and forage areas of loggerheads, with the ultimate aim of spatially separating the fishery from the loggerheads. In recent years the number of tracked turtles has been augmented by releasing hatchery-reared loggerheads provided by the Port of Nagoya Aquarium, Nagoya, Japan. To characterize turtle habitat it is necessary to place the tracks within an environmental context. Satellite SST, ocean colour, altimetry, and wind data have all been important in defining the oceanographic habitat of turtles within the north Pacific (Polovina *et al.*, 2000; 2004; 2006; Kobayashi *et al.*, 2008), allowing

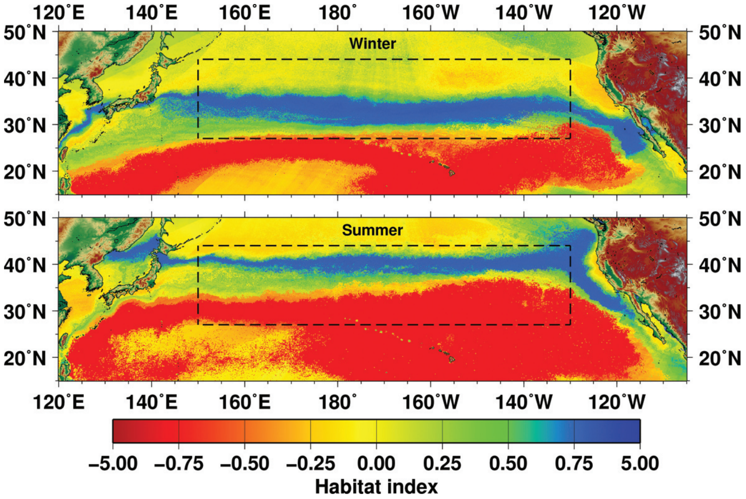

Figure 4.6 Seasonal climatological habitat map for pelagic loggerhead sea turtles in the north Pacific based on Pathfinder SST, SeaWiFS chlorophyll and 3 magnetic variables. Blue areas represent a high probability of finding loggerhead sea turtles. Modified from Kobayashi *et al.* (2008).

determination of seasonal habitat maps (Figure 4.6).

It is now possible to predict the areas with a high probability of loggerhead and longline interactions, by combining information on loggerhead habitat accrued from analyzing turtle track data, environmental satellite data, and fisheries and fisheries bycatch data (Howell *et al.*, 2008). In 2006, NOAA released an experimental product called TurtleWatch (see Howell *et al.*, 2008 and `www.pifsc.noaa.gov/eod/turtlewatch.php`), which uses satellite oceanographic data to map, in near-real time, areas with a high probability of loggerhead and longline interactions, so that fishers can avoid them.

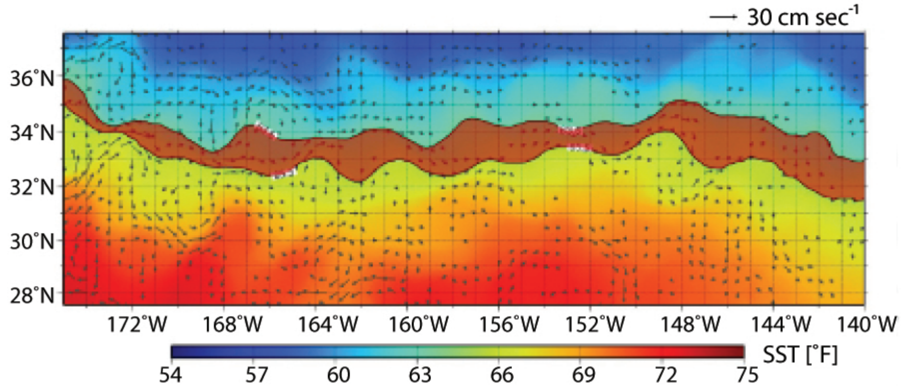

Figure 4.7 The TurtleWatch product. SST represented as a colour background, geostrophic currents estimated from satellite altimetry shown as black arrows, and the zone with the highest probability of bycatch of loggerhead sea turtles is shown in brown (defined as the area between 63.5°F and 65.5°F). Longline fisheries should be restricted from these areas to lower bycatch rates.

This information benefits both the turtles and the fishers, who operate under strict limits on the number of turtle interactions allowed. The area of the highest probability of loggerhead bycatch, hence the area the fishers should avoid, represents the area between the 63.5 and 65.5°F isotherms (Figure 4.7). The TurtleWatch tool is generated and distributed daily in near-real time since the zone with the high probability of loggerhead bycatch is a temporally-dynamic feature. The TurtleWatch product is also provided to fishers onboard, via the GeoEye commercial fisheries information system.

4.4.2 Right whale forecasts

With fewer than 400 individuals left, the north Atlantic right whale (*Eubalaena glacialis*) is one of the most endangered whale populations (Kraus *et al.*, 2005). This population spends much of its time in U.S. and Canadian waters, with the winter calving grounds off of Florida, Georgia, and South Carolina, and feeding grounds in the Gulf of Maine. The recovery of this population is limited by high mortality, especially due to ship strikes and entanglements in fishing gear. Because its habitat overlaps with lucrative fishing grounds and shipping lanes of major U.S. ports, reducing mortality is politically and economically challenging (Kraus *et al.*, 2005). The current management strategy involves limiting adverse impacts by requiring modifications to fishing gear or vessel speeds in regions and time periods when whales are likely to be present. Thus, all management options require knowing when and where whales are likely to be. The question is how to identify these likely regions within a dynamic ocean environment?

A new approach to locating right whales combines synoptic information from satellites with a model of the right whales' main prey. Right whales feed on small crustaceans called copepods, especially the large and abundant species *Calanus finmarchicus*. High numbers of whales are typically found in regions of high copepod concentrations (Pendleton *et al.*, 2009). Many important rates in *Calanus*'s life cycle can be estimated using satellite data. The time required for an egg to develop into an adult is related to temperature, with shorter generation times in warmer water. Chlorophyll, which is a proxy for phytoplankton, the main food of *Calanus*, determines how quickly a female copepod can produce eggs. By combining the rate information derived from satellite data with reconstructions of the ocean currents from a computer model, estimated maps of *Calanus* abundance can be produced and related to right whale distributions (Pershing *et al.*, 2009a,b). An initial test of this system forecasted that, due to the cold winter in 2008, the *Calanus* population would be delayed, and that whales would arrive on their main spring feeding ground east of Cape Cod three weeks later than normal. While a full analysis of the data is underway, it appears that the whales arrived close to when the model predicted. These forecasts are currently being expanded to include a wider area of space and time and will soon be able to incorporate observations of both copepods and whales.

4.5 Concluding Remarks

Given that many of the capabilities of ocean-colour data are still being actively researched, much of this potential has yet to be incorporated in an operational way into fisheries management. For example the ability to assess phytoplankton size, functional type and physiology from ocean-colour data is a relatively recent development in remote sensing, and many of the methods are yet to be validated extensively. However, satellite ocean-colour data has been instrumental in documenting how the recruitment mechanism can transfer phytoplankton fluctuations up the food chain to higher trophic levels (Platt *et al.*, 2003; Friedland *et al.*, 2008; and Chapter 3 of this volume). These observations serve as key examples of how phytoplankton variability is a crucial component of the pelagic ecosystem, and a measure of its temporal and spatial variability should be incorporated into ecosystem-based management (Watson *et al.*, 2003; Levin *et al.*, 2009).

Chapter 5

Remote Sensing Applications to Fish Harvesting

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5.1 Introduction

Fish have been an important food source for mankind since before recorded history, and it is anticipated that this will continue in future generations. Sustainable practices in fisheries are one of the most critical issues that should be promoted by the fishing industry through effective fisheries management. Results of fisheries landings on a global scale indicate that the capture fishery production has declined or remained static since 2000, reflecting over-harvest in many regions (Hilborn *et al.*, 2003). This is a key issue of global concern for the sustainable use of fishery resources. Climate or oceanic environmental change can also influence the abundance of fish (Cushing, 1982) so it is important to take into account both over-exploitation as well as changes in climatic/oceanic conditions in an effort to address sustainability of fisheries resources. The Food and Agricultural Organization (FAO) of the United Nations (1995) has developed the 'Code of Conducts for Responsible Fisheries', that describes, in detail, guidelines for fisheries management.

Effective management of fisheries requires both the implementation of regulations and the reliable reporting of fish catch by local fishermen. Oceanographic information on pelagic fisheries is also important for effective and sustainable fishing practices, which in turn can help maintain the fishing industry. It is essential to make the fishing industry more economically viable, and to raise the awareness of fishermen in an attempt to conserve marine resources, thus promoting a sustainable fishery. This Chapter deals with examples of how local governments, fisheries scientists and local fishermen can work together toward the realization of effective and sustainable fisheries management.

Satellite remote sensing for fisheries has been developing since the 1980s and its effectiveness at synoptic scale and synchronized observation has been demonstrated in scientific literature (e.g. Saitoh *et al.*, 1986; Feidler *et al.*, 1987; Podestá *et al.*, 1993; Semedi *et al.*, 2002; Kiyofuji and Saitoh, 2004; Zainuddin *et al.*, 2004). Simpson (1992) described the necessary components and processing methodologies of satellite remote sensing for fisheries and provided an overview of an operational fisheries system.

Exploration of fishery resources using remote sensing technology is based on the principle of identification of feeding grounds where fish tend to aggregate. Thermal or chlorophyll fronts often indicate areas of high biological productivity, and hence a high probability of finding fish. This chapter presents specific case studies of remote sensing applications to fish harvesting in three different areas: the west coast of India, the western North Pacific (Japan) and the western Indian Ocean.

5.2 Using Remote Sensing for Profitable Fishing: Techniques for Indian Waters

It is possible to locate fish-feeding grounds from SST or chlorophyll images generated from satellite data through detection of oceanic features or gradients. Thermal or colour gradients, arising from circulation of water masses, often indicate areas of high biological productivity. Generally, the thermocline acts as a barrier to the transport of nutrients from deeper water to the euphotic zone. However, if physical processes lead to upwelling, nutrients enter the euphotic zone. As a result, productivity of the surface waters is enhanced. In satellite images this phenomenon is manifest in the form of frontal structures.

Methods for locating potential fishing zones (PFZ) from satellite data were developed initially through detection of SST gradients revealed by oceanic features such as fronts, eddies and upwelling (Lasker *et al.*, 1981; Laurs *et al.*, 1984; Maul *et al.*, 1984; Xingwei and Baide, 1988; Kumari and Nayak, 2000). However, this method has the limitation that remotely-sensed SST represents only the surface skin of the water column. Heating of the sea surface, particularly in equatorial and tropical waters during summer, gives rise to strong stratification of the water column, preventing transport of cool nutrient-rich waters from deeper layers to the surface. This, in turn, inhibits the appearance of SST gradients in the satellite image. Therefore, SST images are not always sufficient for identification of PFZs. Another problem in using SST as an indicator is that surface frontal structure is perturbed by prevailing surface winds or currents, even of moderate magnitude.

Unlike thermal sensors, the ocean-colour sensors can detect signals from below the surface due to the greater penetration of visible radiation, and this characteristic can be exploited to predict occurrence of oceanic features such as diverging fronts and eddies using time series of chlorophyll images. It also enables detection of variations in biomass concentration at different stages of ecosystem development. Three methods have been developed and validated for forecasting PFZs in the coastal waters off the west coast of India, and are described in detail in the following section.

5.2.1 Method 1: Location of PFZ sites using integrated chlorophyll and SST

Generally, chlorophyll and SST images are expected to reveal common gradients in waters away from coastal regions due to the inverse correlation between the two properties. Cool waters detected in SST images are indicators of the presence of higher concentrations of nutrients. Corresponding to this, the signature of high chlorophyll water can be seen clearly in an ocean-colour image. Based on this coupling of biological and physical processes, experimental forecasts were generated taking into account common gradients in the chlorophyll-SST composite images (Solanki *et al.*, 2000). High catches were observed in the vicinity of thermal as well as colour gradients. Forecasts made with this approach were successful, and positive comments were received from the fishermen.

5.2.2 Method 2: Use of additional information from ocean colour

Comparison of SST and chlorophyll images reveal several additional frontal structures in chlorophyll images, which can sustain fish populations (Dwivedi *et al.*, 2005). The second method makes use of these colour gradients. Relatively sparse thermal gradients are a feature of SST images in tropical waters during summer, as a result of rapid warming of surface waters. Figure 5.1a shows a chlorophyll image from 17 November 2003 with an anti-clockwise rotation of the water mass. The

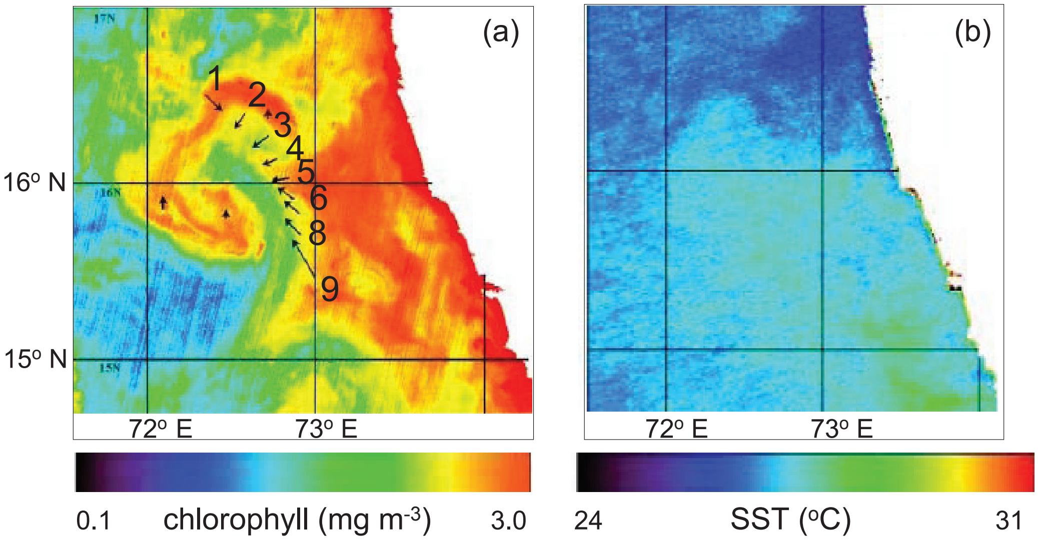

Figure 5.1 Not only the core, but also the streamer of an eddy causes aggregation of fish. The example shown is of a chlorophyll image (a) from Oceansat-1 OCM and an SST image (b) from AVHRR data, for waters off the Goa coast and vicinity, west coast of India (17 November 2003). The SST image does not show the signature of the eddy as well as the corresponding chlorophyll image. Arrows numbered 1 to 9 indicate fishing tracks.

corresponding SST image (Figure 5.1b) does not reveal this rotational motion very clearly, and furthermore the core of the eddy is not detectable in the image. Fish tended to aggregate along the streamer of the eddy (fishing tracks 1 to 9 in Figure 5.1a), with higher catches being reported for this area, in the range 109 to 903 kg hr^{-1} (compared with the mean of 64 kg hr^{-1}).

5.2.2.1 Importance of history of oceanic features

Chlorophyll images can reveal information about frontal structures, but the selection of the appropriate colour gradient is important for fisheries applications. It requires studying the *history* of oceanic features from a time series of ocean colour images (Figure 5.2). In these images an increasing trend of chlorophyll was found from 16 to 18 January 2000 (Figures 5.2a, b). Correspondingly high fish catches (79 kg hr^{-1}, which is greater than the sum of the local mean plus standard deviation) were recorded for 18 January. A diverging front marked with an arrow can be seen in the chlorophyll image of 18 January (Figure 5.2b). This peculiar structure can also be seen at different stages of formation in the next two images. Subsequently,

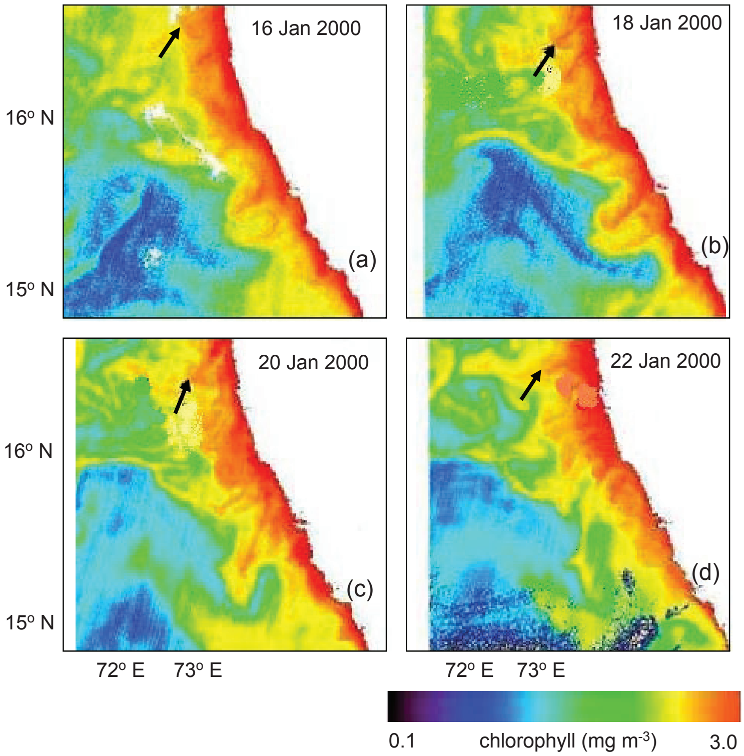

Figure 5.2 Illustration of the use of the 'history of colour gradients' for generating fishery forecasts. Time series of chlorophyll images from the Indian OCM sensor for the waters off the Goa coast, west coast of India (16, 18, 20 and 22 January 2000).

chlorophyll showed a decreasing trend from 18 to 20 January (Figure 5.2c) resulting in a lower catch. The decreasing trend of chlorophyll observed from the multi-date images indicates the decay of circulation of water masses resulting in decreased productivity. The report of low fish catches from this water mass reflects the dispersion of fish, which had aggregated for feeding. Low fish catches might also be attributed to local overfishing (e.g. Maury and Gascuel, 2001).

5.2.2.2 Prediction of oceanic features using ocean colour

Early studies of multi-date SeaWiFS chlorophyll images indicated the possibility of short-scale prediction of development of an eddy through observation of a rotating water mass at different stages in serial images. The SST-based approach cannot be used for eddy prediction because SST images only reveal signatures of eddies when the cold, nutrient-rich water from deeper layers arrives at the surface. Enhancement in productivity due to upwelling below the surface starts once the high-nutrient waters enter euphotic zone. Also, enhanced photosynthesis continues even after the surface expression of upwelling in SST images disappears. Changes in the signature due to circulation below the surface can be picked up in ocean-colour images. The prediction of features from time series of ocean-colour images can be used for efficient fishery exploration, and can compensate for time loss through fishing in non-productive areas. This approach of using advanced knowledge of the formation of features was implemented using multi-date OCM chlorophyll images. The results of experimental fishing obtained from the predicted sites are shown in Figure 5.3. A potential rotating water mass is indicated with an arrow Figure 5.3a. Confirmed evidence of eddy formation can be seen in Figure 5.3b. The follow-up fishing operation conducted on 20 February with bottom-trawl fishing returned a

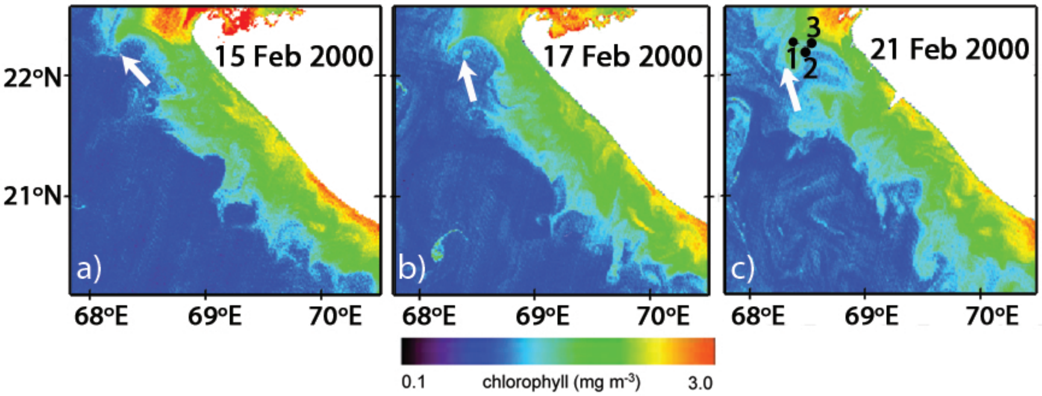

Figure 5.3 Time series chlorophyll images for NW coast of India (15, 17 and 21 February 2000) captured by the Indian OCM sensor, showing the development of oceanic features used to provide information for PFZs. Numbers 1, 2 and 3 indicate fishing areas.

significant increase in fish catch.

5.2.2.3 Exploration of oceanic resources using ocean colour, a case study

Coastal waters in shallow shelf regions usually remain under heavy fishing pressure and there is a need to reduce the fishing load to ensure sustainability of living resources. One approach is to divert fishing efforts to oceanic waters. This was not feasible until operational ocean-colour sensors were available in the late 1990s. The biological-physical coupling as observed in coastal waters may not always be as strong in oceanic waters, so the observed thermal gradients in the SST image may or may not be associated with the enhanced production. Non-toxic algal blooms, *Noctiluca millaris*, with unusually-high chlorophyll concentrations (>2 mg m^{-3}) occur every year in deep waters off the northern Arabian Sea between January and March (see Gomes *et al.*, 2008). High productivity during the winter monsoon is attributed to winter cooling and convective mixing. An attempt was made to observe how fish respond to these algal blooms. Unusually high tuna catches (hooking rates) were obtained from the outer edge of bloom patches in offshore waters beyond the Indian continental shelf. These high hooking rates indicate that the high primary production associated with the bloom provides a rich feeding ground for the fish, and as long as anoxic conditions do not arise, the bloom can support a fishery. Availability of food in abundance at the primary level provides a necessary condition for faster development of the food web. As these events persist for a long period of time, the developed food chain is sustained and the probability of good fish catches increases.

5.2.3 Method 3: Inclusion of wind vectors to update PFZ locations

Oceanic features indicative of PFZs may shift by the time fishermen receive forecasts. The expected shifts (s, in km day^{-1}) were computed with the help of a time series of wind speed (w, in m s^{-1}) and direction derived from QuikSCAT-SeaWinds data (Solanki *et al.*, 2005) using the following empirical relationship:

$$s = 1.36(w) + 1.7422; r^2 = 0.82 \tag{5.1}$$

Locations of PFZs were modified according to predicted feature shifts. Figure 5.4 shows a typical product generated overlaying wind vectors on a chlorophyll image. The forecasts were made available to collaborating agencies for verification through fishing operation (Solanki *et al.*, 2005; 2008). Success rate (reliability of the forecasts) improved with wind-integrated forecasts yielding consistent positive feedback in more than 80% of the cases.

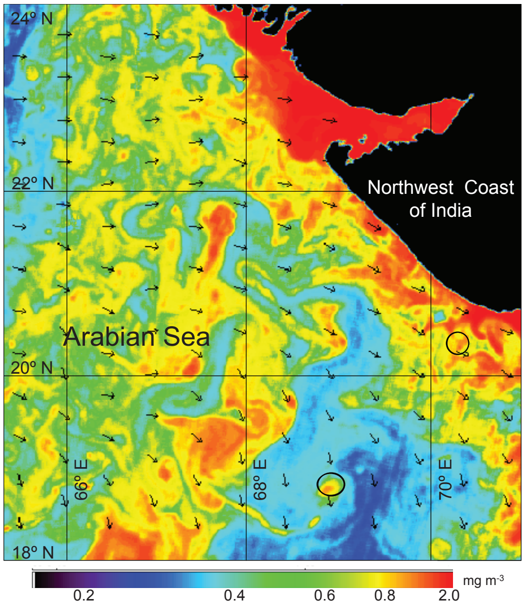

Figure 5.4 Location of PFZs updated to account for shifts in the gradient using time series wind data from QuikSCAT. Circles indicate potential fishing zones.

5.2.4 Validation of fishery forecasts

Experimental fishery forecasts generated using the three above-mentioned methods, which evolved through iterated improvement, were validated with planning and controlled fishing operations in near-real-time mode.

Verification of the experimental forecasts with inclusion of ocean colour indicated a 70 to 80% success rate (reliability) of the forecasts and 70 to 200% increase in catch. This is an improvement over the earlier SST-based approach, which yielded 50% success rate and 40 to 50% increase in catch. The integrated approach has been transferred to the Indian National Centre for Ocean Information Services (INCOIS) for operational nation-wide implementation.

Spatial shifts in the gradient, indicative of PFZs, were computed using a time series of wind vectors and an in-house developed algorithm (Solanki *et al.*, 2005; 2008). Locations of the PFZs were updated accordingly. It was found that the reliability of the forecasts improved to 82 to 85% with the inclusion of wind in the forecasting approach.

In summary, an integrated approach for PFZ identification has been developed using ocean-colour and SST data from operational sensors. Selection of frontal structures, common in SST and chlorophyll images, has provided consistent positive feedback. However, frontal structures common in both SST and chlorophyll images are relatively few in number. There are many more features detectable from a chlorophyll image for which there is no matching counterpart in the corresponding SST image. Selective use of additional features from ocean-colour data enabled identification of those potential fishing zones which could not be detected from corresponding SST images. The capability of ocean colour radiometry to 'see' deeper into the water column than SST technology allows ocean-colour data to reveal more features of relevance to fisheries than SST data.

5.3 Experimental analysis of skipjack tuna fishing grounds in the Kuroshio region, northwest Pacific

5.3.1 Skipjack tuna fisheries in the Mie prefecture

The Mie prefecture is located on the east coast of the Kii peninsula (Honshu Island, Japan). About 140 km of its coastline faces the Kumano-nada Sea (northwestern Pacific Ocean). There are 73 fishing ports along the coast. About twelve thousand fishing boats, including small outboard motor boats, operate in the coastal and offshore regions. Total fish catch of the prefecture was 188 thousand tonnes in 2006, one third of which was skipjack tuna (*Katsuwonus pelamis*), indicating the importance of this species for the Mie fishermen. Although the fishing industry accounts for only 0.4% of the total economic production of this prefecture, it has its own fisheries research institute, which provides information on oceanic conditions to local fishermen.

Two methods of catching skipjack tuna are used in Japan: one is the offshore rod-and-line fishing method which uses relatively large boats (50 to 450 tonnes with 10 to 30 fishermen), and the other is coastal trolling line fisheries which uses small boats (3 to 5 tonnes with 1 to 2 fishermen). The former involves 10 to 50 day cruises from the mother port, while the latter consists of one-day cruises. Both types have shown interest in the potential fishing grounds related to oceanic conditions. The relationships between fishing grounds and oceanic conditions have been investigated by local scientists (Nishimura, 1987; Takeuchi and Nakaji, 1998; Kuno *et al.*, 2001). The definition of good fishing grounds for fishermen include not only a high density of fish schools, but also a short distance from the mother port. The maximum possible distance for small fishing boats is about 100 km. When the location of the skipjack tuna fishing ground is too far, the fishermen switch to other target fish. Oceanographic information can inform the fishermen on a daily basis what type of fish to harvest, and where the fishing grounds are located.

5.3.2 Skipjack fishing ground analysis using SST and ocean colour

Western Pacific skipjack tuna spawn off the eastern Philippines and in the north Mariana region, and the juveniles stay at these lower latitudes during their immature stages. After maturation, most of the population migrates north up to the Oyashi–Kuroshio frontal zone, reaching the coast of Japan. After feeding in these areas, they return south for spawning. The northward and southward migrations are called the feeding and spawning migrations respectively. Small-boat fishermen in the Mie prefecture target the northward migration of the school, which is influenced by the meandering of the Kuroshio Current. Fifteen coastal skipjack tuna trolling-line fishermen participated in a fishing ground experiment in 1997 and 1998, reporting fish catch information including the fishing-ground position measured by onboard GPS, size of the fish catch, fish species and sea-surface temperature (SST). Spatial and temporal distribution of tropical tunas are characterised by fish congregating in schools, and schools gathering into concentrations or aggregations (see Ravier *et al.*, 2000). These aggregations are referred to as 'fishing grounds'. The research vessel, *Asamamaru* was also used in this experiment. Although fishing boats collect oceanographic and fish-catch data every day, they go only to areas of high fishery potential, therefore data from these locations are biased, unlike research vessels, which operate along regular observation lines and do not rely on commercial fishing grounds.

AVHRR data from NOAA were received at the Mie Prefecture Fisheries Research Institute (Figure 5.5a), and processed into SST maps, while chlorophyll concentration maps were obtained from OCTS and SeaWiFS sensors. Satellite SST and chlorophyll data were compared with *in situ* measurements of temperature recorded by the fishing boats and chlorophyll concentrations measured on-board the RV *Asamamaru*. Skipjack fishing grounds were superimposed on the SST and chlorophyll maps on a daily basis.

In Figure 5.5 the warm Kuroshio Current (red) and cold coastal waters (blue) are clearly visible in the study area. The SST data indicate that the coastal area of Kumano-nada was covered by cold water. The SST distribution usually changes seasonally, with temperatures increasing in the coastal waters during spring. In 1997, however, the increase in temperature was later than usual, so skipjack tuna were not found in these waters. Instead, fishing grounds were formed on the edge of the Kuroshio Current. The effectiveness of using SST data for predicting potential skipjack fishing grounds is apparent. Water temperature at the site of fish catches was between 19°C and 21°C, which is 1 to 2°C lower than the appropriate SST (20 to 23°C) for skipjack in Tohoku waters (Uda, 1960). Average monthly SST at the fishing grounds in the Kumano-nada in spring ranged from 19.7°C to 20.7°C, and remained fairly constant throughout the fishing season, as well as between years (Table 5.1).

In Figure 5.6 skipjack fishing grounds in the Kumano-nada were overlaid on an OCTS chlorophyll image from 25 April 1997, which corresponds to the SST data in Figure 5.5c. No skipjack fishing grounds were observed in coastal waters with chlorophyll concentrations greater than 1 $\mu\text{g}\,\text{l}^{-1}$, while small catches were obtained from areas with concentrations less than 0.1 $\mu\text{g}\,\text{l}^{-1}$ (dark-blue in the figure). Optimal fishing grounds were concentrated in the Kuroshio waters near the ocean-colour front, with the chlorophyll concentrations ranging from 0.2 to 0.5 $\mu\text{g}\,\text{l}^{-1}$.

When the weather is calm and the skin surface layer of the water is heated by the strong solar radiation, the contrast in SST between coastal waters and the

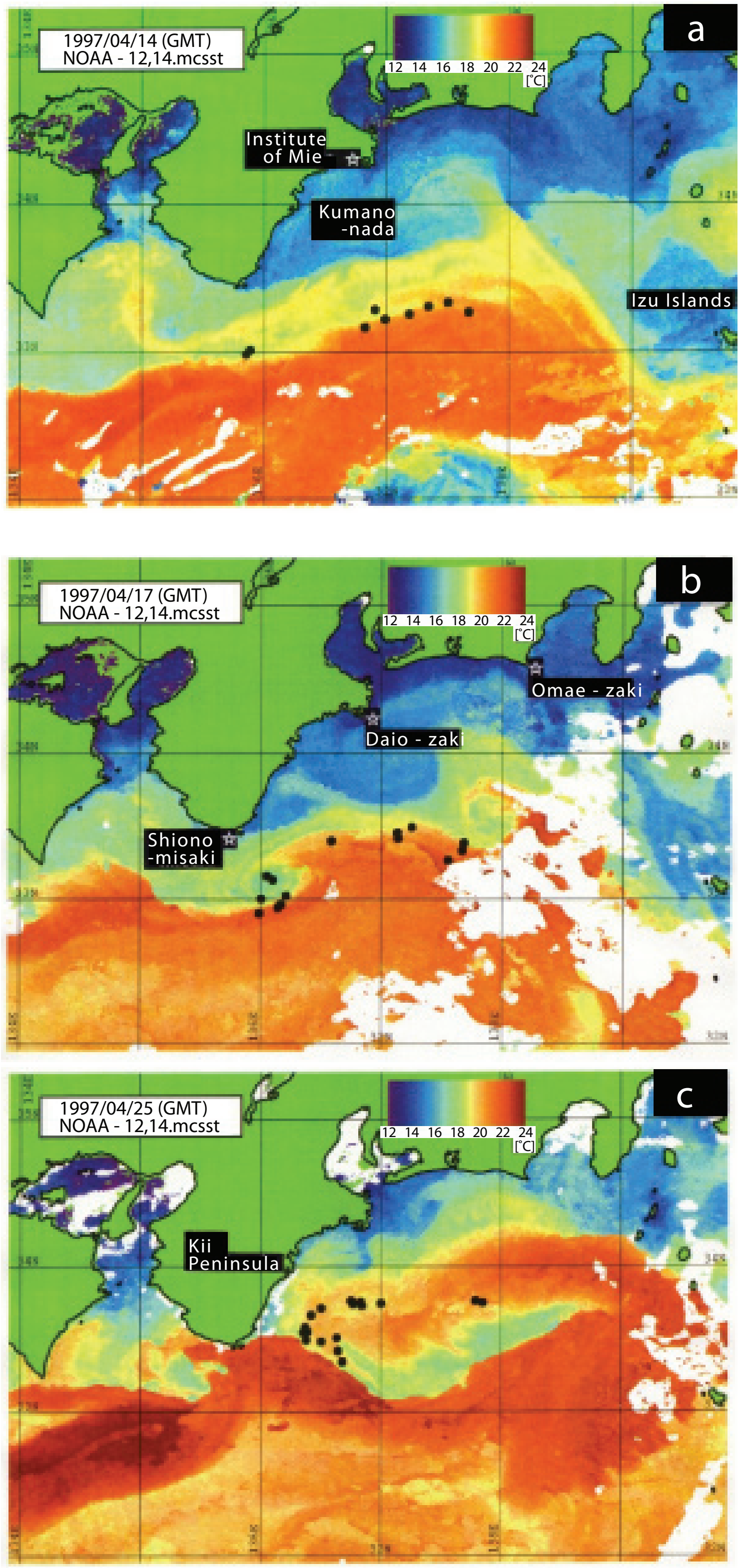

Figure 5.5 NOAA/AVHRR sea surface temperature (SST) images for the SE coast of Honshu Island, Japan (Mie prefecture) for 14, 17 and 25 April 1997. Black circles represent the trolling-line skipjack fishing grounds.

Table 5.1 Monthly average sea surface temperature (°C) at the trolling-line skipjack fishing grounds in the Kumano-nada in spring. The total number of fishing grounds is given in parentheses.

Year	1997	1998
Feb.	– (0)	20.7 (37)
Mar.	19.9 (30)	19.9 (113)
Apr.	19.7 (241)	20.0 (291)
May	20.6 (89)	19.9 (36)
Average	19.9 (360)	20.0 (477)

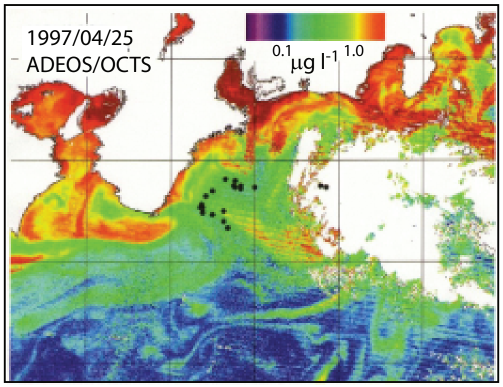

Figure 5.6 Chlorophyll concentrations off the southeast coast of Honshu Island, Japan captured by the OCTS sensor onboard ADEOS on 25 April 1997. The trolling-line skipjack fishing grounds are indicated with black dots.

Kuroshio Current becomes subtle. For example, in Figure 5.7 (left) it can be seen that even though the northern edge of the Kuroshio extends eastwards from the Cape Shiono-misaki, the difference in SST between the coastal region of the Kumano-nada and the Kuroshio is relatively small. No significant patterns can be seen in the coastal area. Therefore, it is difficult to detect the distribution of water masses from SST images alone. On the other hand, the corresponding chlorophyll image (Figure 5.7 right) clearly shows an intrusion of the Kuroshio waters and a small eddy of coastal waters. The low chlorophyll Kuroshio waters are shown in purple ($< 0.1\ \mu$g chl l^{-1}), while the coastal waters have higher chlorophyll concentrations. *In situ* oceanographic observation by RV *Asamamaru* recorded surface chlorophyll-*a* concentrations of 0.32 μg l^{-1} for coastal waters and 0.16 μg l^{-1} for offshore waters. It is evident from Figure 5.7 (right) that the skipjack fishing grounds were formed along the edges of the ocean-colour front between the coastal and offshore waters.

Comparison of the location of skipjack trolling-line fishing grounds with OCTS

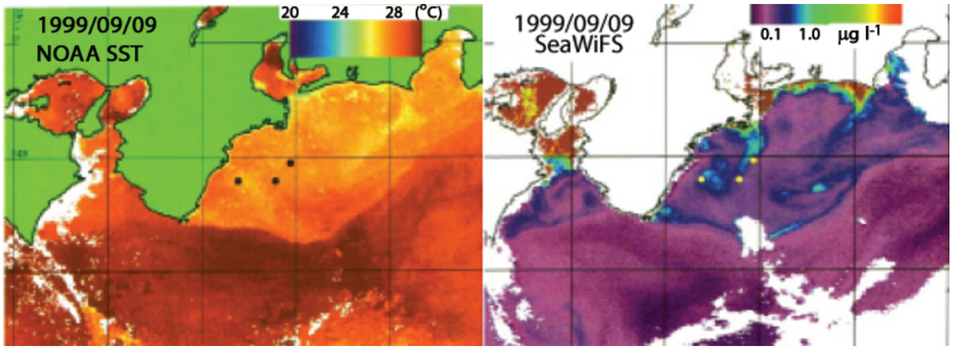

Figure 5.7 AVHRR sea surface temperature image (left)and SeaWiFS chlorophyll concentration (right) on 9 September 1999. Location of skipjack tuna caught by the RV 'Asamamaru' are indicated by black dots on the SST image and yellow dots on the chlorophyll image.

ocean-colour imagery lead Tameishi (1997) to conclude that ocean-colour fronts may have a greater effect on skipjack fishing-ground formation than SST fronts. Ocean-colour sensors can detect information from deeper layers than satellite SST data collected by an infrared radiometer (Matsumura, 1991; Matsumura and Shiomoto, 1993), and are thus more effective in predicting fishing grounds. The skipjack fishing grounds are found to be in a narrow range of sea-surface temperature, which varies with season and area. Future analyses on fishing-ground formation must be done for each fish species for all seasons and areas. Ocean-colour data are very useful for identification of fishing grounds, especially when strong summer solar radiation heats up the surface-skin layer of the ocean, redendering the SST data less effective.

5.4 TOREDAS Remote Sensing GIS Information Service

Over the past ten years, GIS (Geographical Information System) has been recognized as an important tool for visualizing and analyzing the spatio-temporal distribution of fisheries resources. GIS is a powerful tool for archiving, management, analysis and display of biological information (Al-Garni, 1996) and its use has increased extensively in land-based research. Recently, GIS has been widely adopted in fisheries and oceanographic research (Nishida *et al.*, 2001; 2004).

In this section, a newly developed ubiquitous fisheries information system and service for Japanese waters is described, with the perspective of responding to sustainable development of fisheries resources. Target species for this research and development are the Japanese common squid (*Todarodes pacificus*), Pacific saury (*Cololabis saira*), skipjack tuna (*Katsuwonus Pelamis*), and albacore tuna (*Thunnus alalunga*), which are a popular and important food source in Japan. Previous scientific research has shown that these target species are distributed widely, and migrate around the islands of Japan. Four different areas were selected for each target species including the Sea of Japan for the Japanese common squid, the Kuroshio and Oyashio regions for saury and skipjack tuna, the Kuroshio extension area for albacore tuna and the area around the island of Hokkaido for both the Japanese common squid and saury.

5.4.1 System overview

A system was developed to provide and transfer information to the public via the internet and using satellite connections, to support fishing operations or resource management. The system is composed of four fundamental elements:

- a data acquisition system,
- a database,
- an analysis module and
- a GIS system (WebGIS as well as onboard GIS).

The important goals of the system are to (1) develop the system for near-real time data transfer via the internet and satellite connections during fisheries operations; (2) to estimate or predict optimal fishing areas based on scientific findings; and (3) to provide high value-added fisheries oceanographic information (Kiyofuji *et al.*, 2007).

5.4.1.1 Data acquisition element and database

Chlorophyll concentration, SST, cloud mask, and sea ice products are processed in near-real time for support of fisheries activities. MODIS chlorophyll-*a* concentrations for Case 1 and Case 2 waters at 1-km resolution are estimated using the MODIS bio-optical algorithm (Clark, 1997; Carder *et al.*, 1999). SST is processed for daytime as well as nighttime (Brown and Minnett, 1999) and sea ice is processed for daytime only. All processed data are sent to the database server via FTP.

5.4.1.2 Analysis module

The ERDAS IMAGINE software is used for data analyses and image processing, and Fortran 77 or IDL (Interactive Data Language) for extracting and calculating contours, gradients and anomalies. ArcGIS is used for conversion from raster to vector data formats. These software packages are applied and integrated, for example, during estimation of potential fishing areas.

The products processed in the analysis module constitute a hierarchical structure from Level 1 to Level 5, which is produced in phase from simple to complex processing. Level 1 products are raster image data such as SST and chlorophyll-*a* concentration. Level 2 is defined as single image processing, resulting from the calculation of average SST or SST gradients from an SST image, or extraction of high chlorophyll-*a* concentrations. Level 3 is the resulting product of overlaying Level 1 and Level 2 data. Level 4 products comprise fishing ground areas estimated from algorithms developed in the Laboratory. Level 5 products are a one- or two-day forward prediction of fishing ground formation. Display of the extracted parameters described above is shown in the next section.

These procedures run automatically, so that the fishermen can receive information in near-real-time through communication by satellites (maritime satellite internet services and digital packet communication services) and S-band digital multimedia broadcasting service (S-DMB). Using satellite communication services, users can generate all products dynamically such as overlaying, measuring distance from the nearest port or fishing grounds using the onboard GIS. This service is called TOREDAS (Traceable and Operational Resource and Environment Data Acquisition System). Users can also receive several types of marine data (SST, chlorophyll-*a* concentration, currents, position of Kuroshio axis, etc.) and weather information as broadcasts using the S-DMB service. These systems can help to support effective fishing activities by minimizing searching time for fishing grounds as well as providing distances to the nearest landing port.

5.4.1.3 GIS system

The output from the analysis module is designed to be web-based and requires an internet connection for planning the fishing operation before leaving the port (WebGIS), or satellite connections during offshore fishing activities (onboard GIS, Figure 5.8). The WebGIS service was developed using ArcIMS. It provides dynamic

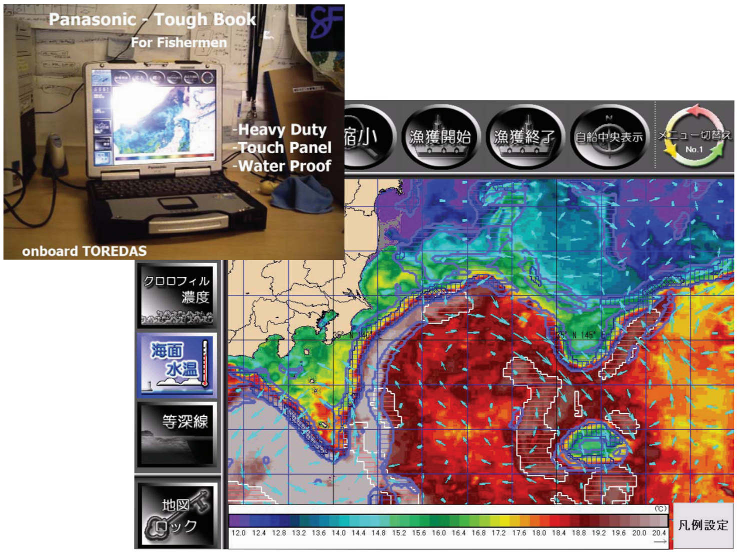

Figure 5.8 On board PC system and display of an SST image from the onboard-GIS showing an estimated potential fishing ground (grey polygon) and SST fronts (blue lines).

maps and GIS data via the Internet. Access to the area of interest is restricted and users need to be registered. Once logged in to the WebGIS, users can select the images at different temporal scales i.e. daily, weekly, weekly moving-averaged, and monthly composites. After selecting the temporal scale, users may see the latest version of image. The user can also enlarge and reduce the size of an image, move to an area of interest, and measure distances from places such as ports to a pre-determined fishing location.

An operational method was also developed to assess the fishing operation on board. The function of the onboard GIS is to display, overlay, measure distances to the nearest ports or fishing grounds, search the nearest fishing areas from the current fishing position, and link with a GPS (Global Positioning Systems). Before fishing, fishermen can get the latest information such as images and estimated fishing area, and once they go offshore, they can get information via satellite connection. The most important information received while offshore in near-real-time is the estimated fishing areas located along the Kuroshio warm-core and around the isolated Kuroshio cold-core ring, shown in Figure 5.8. All data are transferred successfully within 30 seconds, indicating that access to this information is possible during fishing operations.

5.4.2 Perspectives

The TOREDAS system was developed specifically for fishermen to facilitate the use of satellite data in conjunction with GIS. Further developments are being considered regarding the development of sustainable fishing activities and management of resources using this system.

An abundance of satellite data, e.g. SST or ocean chlorophyll, is accumulating in tandem with the advantages brought about by modern technology. Satellite data is one of the several sets of data necessary for analyzing spatial and temporal relationships between resource distribution and the oceanic environment. However, the frequency of use in fisheries research is still low, primarily because the processing and analyses procedures are complicated. Moreover, detailed analyses such as spatial statistics or geostatistics need to be included for better estimation of fishing area formation (Kiyofuji *et al.*, 2005). Hence, developing robust methodologies is still a relatively unexplored field of research. Recent studies employing statistical models such as ‘generalized additive models’ and ‘generalized linear models’ for detecting optimum habitats for pelagic species is one such direction to determine more accurate estimates of fishing grounds (Zainuddin *et al.*, 2007; 2008). In the near future, research and development factoring in spatio-temporal analysis techniques should be included for better assessment of stocks within a multi-species approach (Mugo *et al.*, 2008). This could also add a new scientific perspective and field of fisheries science.

In June 2006, a company known as SpaceFish LLP (`http://www.spacefish.co.jp/`)

was established to promote the TOREDAS fisheries information service. Recently, a 'vessel management system' function was added to the onboard TOREDAS allowing the system to monitor the trajectories of each fishing vessel. Figure 5.9 shows an example of the trajectories of the Pacific saury fishing fleet. This figure clearly illustrates that the fishing vessels navigate directly to the fishing grounds from the mother port, resulting in a reduction of fuel consumption by about 30% after introduction of the TOREDAS system in fishing operations. To complement the vessel management system function, especially for squid and saury vessels, the TOREDAS system was enhanced to display remotely-sensed night-light images from fishing vessels. Night time fishing lights are known to be good proxies for location of fish grounds, primarily for vessels using high-powered lights to attract saury and squid schools. Spatial comparisons of proxy fishing locations and fishing grounds predicted by the TOREDAS system have the potential to improve predictions. An example of such comparisons as displayed by the onboard TOREDAS is shown in Figure 5.10. This particular feature also has a great potential to expand the capacity to monitor fishing effort.

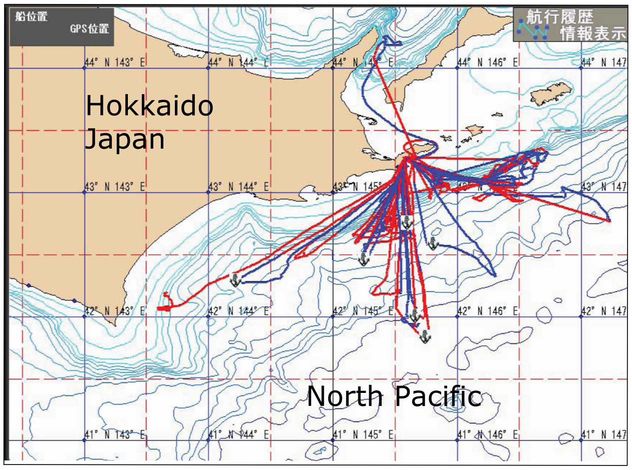

Figure 5.9 Trajectories of Pacific saury fishing fleets showing a direct approach to fishing grounds from the mother port off eastern Hokkaido, Japan for the period from 1 September to 30 October 2006.

Stock management methods based on an ecosystem approach is gaining momentum on a global scale. The TOREDAS system and service can contribute to the development of such methodology in Japan, or at least take the first step towards it. As a result, the system will contribute to reduced fuel consumption and time spent searching for suitable fishing areas, which will foster effective fisheries by reducing input costs and improving energy efficiency.

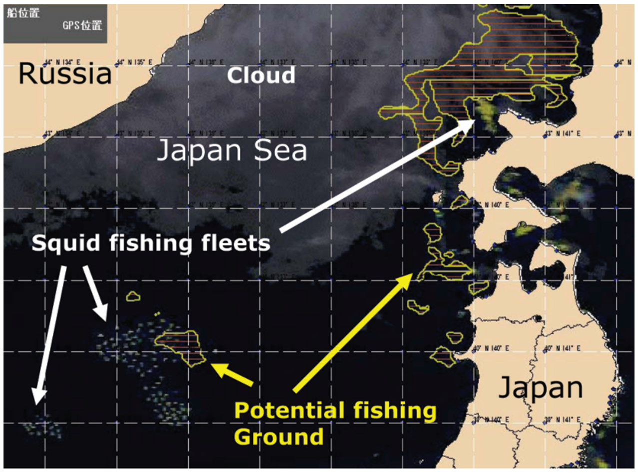

Figure 5.10 Night-light image in the Japan Sea showing location of the high-powered lights on fishing vessels, and the potential fishing grounds as estimated by the TOREDAS system on 3 October 2008.

5.5 Tuna Purse Seine Fisheries of the Indian Ocean

Global annual catches of the principal market tuna species have increased steadily since the beginning of the 1950s, reaching more than 4 million tonnes in the early 2000s (Majkowski, 2007). The tropical yellowfin (*Thunnus albacares*), skipjack (*Katsuwonis pelamis*), and bigeye (*Thunnus obesus*) tunas represent a major part of the world tuna catch and are exploited in the three oceans, mainly by long-line and purse seine fisheries (Fonteneau, 1997). Purse seine has become the major tuna fishing gear since the late 1970s, with a rapid development in the western Indian Ocean by France and Spain in the mid-1980s (Stéquert and Marsac, 1989). Different fishing modes are considered in purse seine fisheries, e.g. ‘fish aggregating devices’ (natural or artificial) and sets/schools of fish (may be associated with whales). The size of the catch harvested during a fishing trip depends firstly on the ability of the fishing master to detect tuna schools or tuna concentrations, and secondly on the success in capturing the fish with the purse seine. The role of detection in purse seine fishing is especially important when the set is made on a free school since the search requires a number of indices to guide the fishing master. On the other hand, the location of tuna schools associated with fish aggregating devices is more predictable when the fish aggregating devices are equipped with radio-range beacons. The relation between the spatial patchiness of tuna and the dynamics of oceanic water masses, features, and processes, as well as topography, has been exploited by fishermen to detect tuna schools. Remote sensing data have been used for a long time in tuna fisheries to improve fishing efficiency and increase catches, starting in the late 1970s in the eastern Atlantic Ocean with METEOSAT-1 (a geostationary satellite). SST maps were received on-board the fishing vessels by fax. Currently, the

French purse-seine fishery of the western Indian Ocean is utilising state-of-the-art remote sensing applications for fish harvesting.

5.5.1 Ecological justification for the use of remote-sensing data in tuna fisheries

Tropical tunas are highly migratory apex predators of the open ocean, with a spatio-temporal distribution strongly related to the environment (Lehodey *et al.*, 1997). In the last few decades, several analyses based on fishery data, ultrasonic telemetric data, and archival tagging data have provided valuable insights into the relationships between tuna population dynamics and environment. In particular, temperature, salinity, oxygen, and prey availability have been shown to affect local tuna abundances, diving behaviour, horizontal movements, and migration schemes from local to meso- and basin-scale (Block *et al.*, 1997; Brill *et al.*, 1999, Maury *et al.*, 2001, Zainuddin *et al.*, 2008). Tuna are active and opportunistic predators that feed mainly during the day in the epipelagic layer of the ocean. Within the oligotrophic tropical waters of the open ocean, they constantly swim in search of prey concentrations to fulfill their high energetic requirements (Stéquert and Marsac, 1989). Hydrological structures that favour chlorophyll concentrations potentially associated with tuna prey have been used by fishermen as indicators of potential zones of tuna abundance. More generally, quasi-geostrophic systems, such as domes and equatorial thermal ridges and non-geostrophic systems, such as equatorial divergences and coastal upwelling, have been identified as enrichment systems where tuna are often concentrated to feed (Stretta, 1991). The advent of remote-sensing data revealed a synoptic view of the dynamics of oceanic water masses, allowing the detection of enrichment areas, and more recently, of mesoscale oceanographic features such as upwelling filaments, fronts, and eddies that can be related to tuna schools (Kumari *et al.*, 1993; Royer *et al.*, 2004). As an example, a major tuna concentration located within an area of 3,500 nautical square miles gave rise in February 2005 to more than 20,000 tonnes of catch, mainly yellowfin, and was related to a strong phytoplankton bloom observed at the edge of an anticyclonic eddy 12 days previously (Fonteneau *et al.*, 2008). Information about oceanographic features derived from satellites has now become easily accessible to fishing masters and is used daily by most purse seiners as a major tool for detecting tuna concentrations.

5.5.2 Commercial remote sensing products for tuna fishing fleets

Commercial products derived from satellite imagery for fish harvesting have rapidly expanded in the last decade and currently include, in addition to meteorological and SST maps, sea-level anomaly data that allow visualizing surface currents and temperature fronts, ocean-colour data, temperature data based on microwave imagery, and subsurface temperature maps (provided through ocean models such as MERCATOR). Two major world companies, CLS (CatSat system) and Orbimage (now GeoEye), dominate the market and provide satellite information in the form of processed data files (taking one to a few days) sent by email to the fishing vessels. Remote-sensing data files are used as layers with computerized navigation and geographic information systems that allow fishermen to visualise maps and store the data in a user-friendly way. In particular, maps of chlorophyll-*a* concentration, used as a tracer of oceanographic features, are analysed both to predict the drift of fish aggregating devices with currents, and to search for enrichment areas, assuming a time delay of 2 to 8 weeks between a phytoplankton bloom and a potential tuna concentration. The major differences between companies providing Earth imagery products are related to the types of satellites and sensors used, the spatio-temporal resolution of the data, and the service of data analysis which may or may not provide the location of potential tuna fishing grounds. Remote-sensing data have contributed to improving the fishing efficiency of tuna purse seiners by increasing the probability of detecting and exploiting tuna concentrations, in conjunction with several other factors such as vessel size, fish aggregating devices, bird radars, and echo-sounders (Gaertner and Pallares, 2002). The use of remote-sensing data is embedded within a spatio-temporal framework characterized by a constant evolution of the scale at which information for detecting the resource is provided to the fishing master, driving eventually to the success of the fishing set (Figure 5.11).

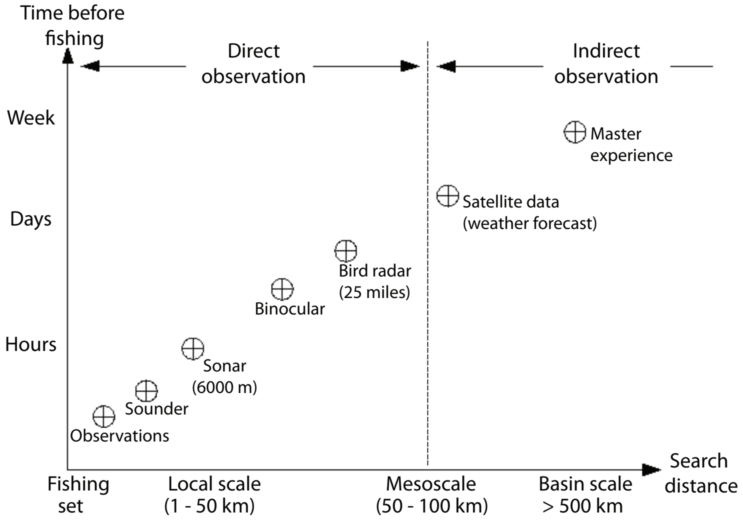

Figure 5.11 Spatio-temporal scales of the major tools used in the tuna purse seine fishery of the Indian Ocean to detect tuna schools.

Remote-sensing data are now available to most of the purse seiners, whatever their country of origin. There is, however, a high variability between fishing vessels, strategies and tactics, and the use of satellite information varies greatly between fishing masters and fishing trips. When used, basin-scale maps of SST, chlorophyll and surface currents generally enable the fishermen to define at least large marine areas with a low probability of high tuna concentrations. Fishing vessels arriving first in areas with high, local, and transitory concentrations are generally the most efficient.

Although most of the world's highly migratory tuna and tuna-like species are becoming fully or over-exploited (Maguire *et al.*, 2006), the increasing efficiency of tuna fishing fleets through the development of technological factors such as those derived from remote-sensing data raises problems of overcapacity, erosion of economic return, and inadequate management of tuna stocks. In addition, these factors are difficult to include in the estimate of fishing efforts when quantifying vessel fishing power, potentially biasing stock assessments and eventually leading to conservation issues related to world tuna species.

5.6 Concluding Remarks

The application of remote sensing to fish harvesting has been characterized, quite unfairly, as a sophisticated avenue to overfishing. In conjunction with many other technological improvements (radars, sonars, etc.), tools based on remotely-sensed data have developed progressively over time, and have been used widely to increase fishermens' ability to detect marine resources. This is particularly true for pelagic fishing in open-sea ecosystems where pelagic resources are closely associated with environmental features at different spatio-temporal scales, from basin- to local scale. Nevertheless, it would be quite improper to hold remote sensing responsible for overfishing, since changes in fishing power and fleet capacity are inexorable and are also related to a number of economic and technological factors. It is the responsibility of fishing authorities to manage fisheries in a sustainable manner through the use of quotas and other such tools. Within the limitations set by the managing authorities, remote sensing can be extremely valuable to fisheries by increasing efficiency through saving time and fuel consumed in searching, particularly in periods characterized by increasing petrol prices and associated costs for fishing industries. Such tools are also useful for artisanal fisheries, such as in Indian waters, where remote sensing products can be used to support fishing activities through the identification of PFZs.

Looking to the future, one hopes that all fisheries, including high-seas fisheries conducted outside territorial waters, will be managed on an ecosystem basis. Here also, remote sensing can help as it affords an excellent way to develop objective ecosystem indicators that can be applied in operational mode as an aid to rational management (Platt and Sathyendranath, 2008; IOCCG, 2008). Used wisely, remote sensing is one of the keys to sustainable fisheries, not an agent of their destruction.

Chapter 6

Remote Sensing Applications in Marine Aquaculture

Jon Grant, Cedric Bacher, Joao G. Ferreira, Steve Groom, Jesus Morales, Cristina Rodriguez-Benito, Sei-ichi Saitoh, Shubha Sathyendranath and Venetia Stuart

6.1 Introduction

Many aquaculture species (e.g. bivalves, shrimp) are suspension-feeding and derive nutrition from natural particles, the most nutritious being phytoplankton. Dense populations of cultured shellfish are thus food limited by seston depletion, and an understanding of the growth and production of these animals requires an understanding of their food source. Given the importance of phytoplankton to this process, remote sensing of ocean colour is an obvious research area, although little work has been conducted on this topic relative to aquaculture. In addition to food requirements, ocean colour may be used to detect biophysical conditions for shellfish growth, particularly turbidity, which is deleterious for some species such as scallops.

There is tremendous potential for remotely-sensed ocean colour to be applied to fish and shellfish farming, and the examples below hint at this promise. Specifically, these applications include:

- identification of high-chlorophyll zones for farm site selection;
- identification of unfavourable locations for farm sites because of unfavourable temperature, turbidity, or potential development of harmful algal blooms;
- characterization of boundary conditions for ecological modelling (e.g. production capacity);
- ground-truthing of model results, particularly spatial model output;
- quantification of seston depletion by suspension-feeder grazing; and
- parameterization of primary production in fish farm models.

This chapter will examine the use of remote sensing in fish and shellfish farming with an emphasis on ocean-colour applications. A few examples of case studies are presented; others undoubtedly exist. A number of recent studies have used imagery from various high-resolution commercial satellites (e.g. QuickBird, SPOT-5, Landsat and RADARSAT) for aquaculture applications such as mapping mussel farms (Alexandridis *et al.*, 2008). Other applications using this type of imagery will be referred to briefly in the sections below.

6.2 Site Selection

Remotely-sensed data have been used in near-shore aquaculture site selection for more than 20 years (Kapetsky *et al.*, 1987; Kapetsky and Aguilar-Manjarrez, 2007). Historically, satellite images have been used in two different ways:

- as survey tools prior to field work (see Edwards, 2000) and,
- as input data for GIS analysis for the preparation of suitability maps for regional planning or for aquaculture facilities design (Giap *et al.*, 2003; Buitrago *et al.*, 2005).

Site selection for near-shore aquaculture sites has been routinely based on the use of multispectral images from high spatial-resolution sensors (e.g. Landsat, Spot) which more recently have been complemented with the application of new sensors such as Aster or IRS LISS/PAN (Dwivedi and Kandrika, 2005). The use of remotely-sensed imagery for aquaculture site selection in the open sea (e.g. fish cages, mollusc rafts or long-line systems) is much more recent. In contrast to land-based aquaculture planning where a few high spatial-resolution images are used, site selection in open seas requires extensive use of medium-resolution images (e.g. AVHRR, SeaWiFS, MODIS and QuikSCAT) for the analysis of the seasonal and interannual variability of the highly-dynamic characteristics of the marine environment, and also for the determination of environmental patterns and trends of potential aquaculture sites, or for the preparation of aquaculture suitability maps. Thus, the study for site selection of seabream and seabass cages near the Canary

Table 6.1 Criteria for fish-cage site selection and environmental monitoring in Spain, in the Mediterranean Sea (adapted from JACUMAR, 2008).

Variable	Good	Medium	Bad
Coastal exposition	Partial	Sheltered	Non-sheltered
Wave height (m)	1 to 3	< 1	> 3
Water depth (m)	> 30	15 - 30	< 15
Water current speed (cm s^{-1})	> 15	5 - 15	< 5
Pollution level	Low	Medium	High
Max. Temperature (°C)	22 - 24	24 - 27	> 27
Min. Temperature (°C)	12	10	< 8
Salinity (average)(L’)	25 - 37	15 - 25	< 15
Salinity fluctuations (L’)	< 5	5 - 10	> 10
Dissolved oxygen (%)	100	70 - 100	< 70
Turbidity/Suspended solids	Low	Moderate	High
Sediment type	Sand or gravel	Mixture	Mud
Water classification	Oligotrophic	Mesotrophic	Eutrophic
Fouling	Low	Moderate	High
Predators	No	Few	Abundant

Islands (Spain) made extensive use of sea-surface temperature (SST) data (NOAA-AVHRR) for the identification of suitable culture temperatures in the region (Pérez *et al.*, 2003). A different approach was followed by Travaglia *et al.* (2004) for the inventory and monitoring of milkfish cage culture in Philippines, which was based on ERS-2 and RADARSAT radar imagery.

The preparation of GIS-based suitability maps for aquaculture site-selection using remote-sensing imagery as input data is based on previously established water quality and culture criteria (Ross *et al.*, 1993). Table 6.1 summarizes the Spanish protocol for the identification of suitable zones for installation of aquaculture cages in the Mediterranean Sea as an example (JACUMAR, 2008).

Another set of criteria for the selection of suitable sites for intensive farming of aquaculture species in offshore waters includes waste dispersal, because severe water or sediment quality problems, associated with fish cage, mussel, or pearl farming has been observed in Ireland, Japan and Greece (Chamberlain *et al.*, 2001; Yokoyama, 2002; Yokoyama *et al.*, 2004; Pitta *et al.*, 2005). Table 6.2 provides some examples of published water-quality criteria for different aquaculture species, including a number of suitable satellite sensors for the evaluation of the selected water-quality criteria. In this context, water-quality monitoring of marine aquaculture areas using ocean-colour and altimetry sensors is an important application of remote sensing.

Table 6.2 Some examples of satellite sensors used for offshore aquaculture site selection.

Species/ Group	**Culture Technique**	**Country**	**Potential RS Sensors**
Salmon	Cages[1]	Scotland	AVHRR
Oysters	Rafts[2]	Venezuela	AVHRR, SeaWiFS, MODIS, MERIS, ATSR
Bivalves	Onshore, offshore[3]	Australia	AVHRR, SeaWiFS, MODIS, MERIS, ATSR, QuikSCAT
European seabream	Cages[4]	Spain	AVHRR
Scallops	Hanging[5]	Japan	SeaWiFS, MODIS, AVNIR

1. Ross *et al.* (1993); 2. Buitrago *et al.* (2005); 3. PIR (2000); 4. Pérez *et al.* (2003); 5. Radiarta *et al.* (2008).

6.3 Parameterizing Primary Production in Norwegian Fjords

The upper reaches of some Norwegian fjords have high bivalve-shellfish-culture potential, but are in narrow locations with high cliffs, in essence poor locations for remote sensing. Progressing seaward to the coast are areas that can be observed via satellite, but due to the length and complexity of fjord geometry, these areas may be quite distant from a culture site of interest. In this context, a major research question concerns the applicability of both primary production and chlorophyll data obtained offshore by satellite ocean colour to inshore regions. Using archived data on measurements of chlorophyll and primary production from various Norwegian fjords, satellite data is being used to examine the relationship between these data and chlorophyll and primary production data from offshore in the coastal North Sea. These measurements can be compared with measurements made inshore within various fjord systems to determine whether chlorophyll-specific production can be extrapolated from areas where satellite coverage is more reliable, to fjords where aquaculture is practised.

This has led to a qualitative assessment of coastal environments that are likely to be coupled inshore-offshore, a complex problem controlled by coastal circulation, upwelling, river input and other physical and geochemical variables. A prime example where extrapolation is likely to be successful are the Magdalen Islands in the Gulf of St. Lawrence, eastern Canada. The Grande Entrée Lagoon is a shallow bay used for mussel culture, and intended for further aquaculture development (Grant *et al.*, 2007b). Since the inlet leads to the open Gulf, the lagoon is closely linked to nearshore waters, so that the boundary conditions used in models of carrying capacity can be reliably obtained from time series of ocean colour. Further studies are ongoing to determine how this linkage can be utilized to benefit initialization of carrying capacity models.

6.4 Case Studies

6.4.1 Food resources for Japanese scallop culture

Culture of scallops via suspension and bottom seeding is an important fishery activity in northern Japan. Drawing together biophysical, logistical, and other limiting data, Radiarta *et al.* (2008) undertook constraint mapping of scallop culture areas in Funka Bay, to quantify site selection. The biophysical data consisted of SST, chlorophyll (OC4v4), turbidity (water-leaving radiance at 555 nm), and bathymetry, using MODIS data for SST and SeaWiFS for the two water quality variables. Logistical considerations included positive variables such as distance to wharves, and negative variables such as river mouths. These data were also obtained from satellite images (visible and NIR). There are few examples of constraint mapping applied to aquaculture, and their application was made more quantitative by a weighting scheme for the relative importance of environmental variables. Results indicate that 88% of the bay area is suitable for scallop culture, and that 56% of this area had a high score in suitability rating. This type of thematic mapping, employing data from a variety of remote sensors coupled with decision support through GIS spatial analysis, provides more rigour and insight in aquaculture planning.

Mustapha and Saitoh (2008), attempted to relate scallop fisheries and aquaculture success to the spring bloom and its coincidence with departure of ice and wind stress along the Hokkaido coast. Ice concentrations were obtained via passive microwave data and chlorophyll with SeaWiFS. Although interannual variation in these interactions were observed, their relationship to scallop production has not yet been examined. Radiarta and Saitoh (2008) examined temporal variation in chlorophyll, turbidity, and temperature in Funka Bay, Japan. These data were used to explain seasonal trends in the spring bloom and relate them to scallop production. It is obvious however, that a time series of chlorophyll, turbidity, and temperature can be generated by this approach, which would provide the boundary conditions for simulation models of the ecosystem. This is particularly useful in cases where there is not much field data for model parameterization. However, it is more readily applied to Funka Bay, a large open system of ~50 km length, than the smaller scale and more complex coastline of the Magdalen Islands discussed above.

6.4.2 The SPEAR project

The SPEAR project (Sustainable options for PEople, catchment and Aquatic Resources) was a European Commission project within their programme for international cooperation with developing countries (Ferreira *et al.*, 2008). Its goals included sustainable management of Chinese aquaculture for shellfish, finfish, and seaweeds. Using a variety of remote-sensing data (Landsat, MODIS, MERIS, AVHRR) the watersheds, land use, and marine culture areas in Sanggou Bay (Yellow Sea) and Huangdun Bay (south of Shanghai) were characterized. Remotely-sensed data from MODIS and MERIS were used to examine the distribution of chlorophyll and turbidity for the regions offshore of the bays. A focus on web-based data provision increased data availability (`http://www.biaoqiang.org/gis`), although not all data layers are currently available on the web. In addition, Google Earth was investigated as a display avenue. A series of approaches were developed to assess the carrying capacity and impacts for these systems (e.g. Xiao *et al.* 2007; Sequeira *et al.* 2008), and the remote-sensing data generated will allow more detailed modelling of urban eutrophication and its interaction with aquaculture. Although the results are still being analyzed, the wealth of GIS, web-based mapping, modelling and remote-sensing expertise applied to this research indicates that it is not just an initial application of ocean colour to aquaculture, but a benchmark for progress in this research area.

6.4.3 Mussel culture modelling in the bay of Mont St. Michel

The bay of Mont St. Michel, France, is an important culture area for mussels and oysters. This coast is macrotidal (14 m range) and mussels are grown on an intertidal shellfish bed. Scientists from IFREMER have conducted studies of the production potential in the bay in order to predict the carrying capacity for existing sites, as well as potential new sites (Thomas *et al.*, 2006).

Phytoplankton chlorophyll provides the main input to a bioenergetic model of mussel growth, using the ‘dynamic energy budget’ approach. In this approach, the mussel ingestion equation is a function of chlorophyll. SeaWiFS data at 1-km resolution were used to derive chlorophyll using the OC4 algorithm of O’Reilly *et al.*, (1998). Since macrotidal systems are typically turbid, it was necessary to adjust the algorithm for suspended particles such as sediment and detritus. Extensive field sampling provided an exceptional ground-truthing database. According to Gohin *et al.* (2005), the water-leaving radiance at 555 nm is related to turbidity, so this relationship was used to correct chlorophyll values.

SeaWiFS data were extracted over 358 pixels of the bay every day between March 2003 and November 2004. Despite the relatively low spatial resolution, a gradient of chlorophyll was observed in the bay from east to west (Figure 6.1). Although the data did not reach the edge of the coastline in many cases, it covered the culture areas and provided adequate representation of food conditions both spatially and temporally. Forced by chlorophyll and additional satellite-derived temperature data, the 'dynamic energy budget' model of mussel growth was used to project mussel growth scenarios. First, satellite data were used to test model predictions against measured mussel growth in five zones corresponding to cultivated areas. Secondly, the mussel growth model was applied to all the pixels to assess site potential at a wider scale. Predicted growth trajectories as well as a map of mussel wet weight showed consistent agreement with growth observations from the field. This study provides the first example of a cultured shellfish growth model coupled to ocean-colour input.

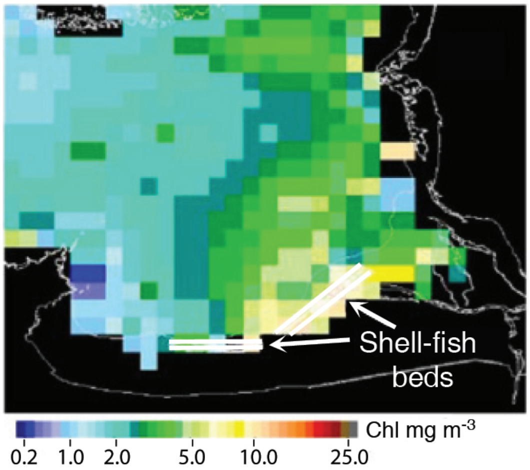

Figure 6.1 An example of the monthly average of chlorophyll derived from SeaWiFS for May 2004 in the bay of Mont St. Michel, France. The distance across the entire image is ~33 km.

6.4.4 Seston depletion in dense mussel cultures, eastern Canada

Depletion of phytoplankton by successive lines of hanging culture is thought to be evidence of resource limitation. However, detection of the process is difficult due to high temporal and spatial variability in phytoplankton fields. In addition, a high ambient chlorophyll concentration is required to see a significant reduction due to suspension-feeding. Moreover, the effect may be localized in isolated farms, such that extensive farmed areas must produce a persistent depletion effect in order to be detected. If the footprint of phytoplankton removal is substantial, ocean-colour is an ideal tool for its documentation, as shown in the example above.

In another study of remote sensing applied to seston depletion, Grant *et al.*, (2007a) used the CASI airborne hyperspectral remote sensing instrument to observe a gradient of chlorophyll through a densely-cultured area of Tracadie Bay, Prince Edward Island, Canada. These observations are a snapshot of a rapidly-evolving seston field, so the dynamics of the process must be characterized. First, the gradient in chlorophyll was documented geostatistically, confirming that there was loss of phytoplankton through the farm (Figure 6.2). Next, a numerical model was run with relevant circulation and tracers to show that abiotic diffusion processes alone would not account for that magnitude of particle loss. Subsequent studies (Grant *et al.*, 2008) document this farm-scale process as part of a larger pattern of chlorophyll reduction by suspension feeding in the bay.

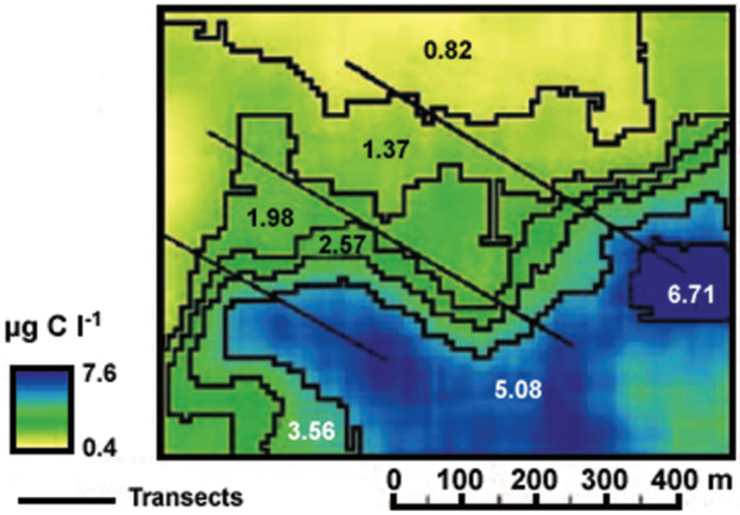

Figure 6.2 Seston depletion through a mussel lease in eastern Canada. A pulse of chlorophyll expressed in μg C l^{-1} appears in blue, with current direction from lower right, to upper left. There is rapid reduction in chlorophyll as it proceeds through the farm which occupies most of the image. Adapted from Grant *et al.* (2007a).

6.4.5 Harmful algal bloom in Cardigan Bay, eastern Canada

Remote sensing is particularly useful to study phytoplankton dynamics in areas around aquaculture sites on a routine basis. Ideally, one would also like to determine whether or not the phytoplankton are harmful. This would only be possible by remote sensing if the harmful algae had some spectral optical characteristic that could be used to distinguish them from other types of phytoplankton. Only a small number of harmful or nuisance algal blooms, such as *Trichodesmium* and *Gymnodinium*, have such characteristics that could be exploited in remote sensing. In the absence of such traits, the primary usefulness of remote sensing in this context is as a tool for systematic and sustained observations of algal dynamics in the vicinity of aquaculture sites. When remote sensing indicates rapid changes in algal biomass, this could trigger a more detailed *in situ* observation to classify the types of algae involved, and determine potential harm, if any, to aquaculture.

A case study from Cardigan Bay of Prince Edward Island (Canada), served to illustrate the potentials and limitations of remote sensing for monitoring harmful algal blooms. An incidence of shellfish poisoning from blue mussels (*Mytilus edulis*) cultured in the area, leading to tragic loss of human lives as well as substantial commercial losses to the aquaculture industry, was reported for the first time in the autumn of 1987 (Addison and Stewart, 1989). The source of the neurotoxin domoic acid, responsible for the incidence, was traced to a diatom, *Pseudo-nitzschia multiseries* (Bates *et al.*, 1989). Initial scientific investigations into the problem focused on understanding the physiology of the toxin-producing algae, and on *in situ* sampling to understand the spatial and temporal variability in the distribution of the algae in the field. *In situ* observations, however, lack the peripheral vision provided by remote sensing, thus limiting the extent of such surveys in time and in space. These early studies revealed that *Pseudo-nitzschia multiseries* has both benign and toxigenic strains. Furthermore, the toxigenic strains produce the toxin only during the senescent phase of their life cycle (Subba Rao *et al.*, 1990).

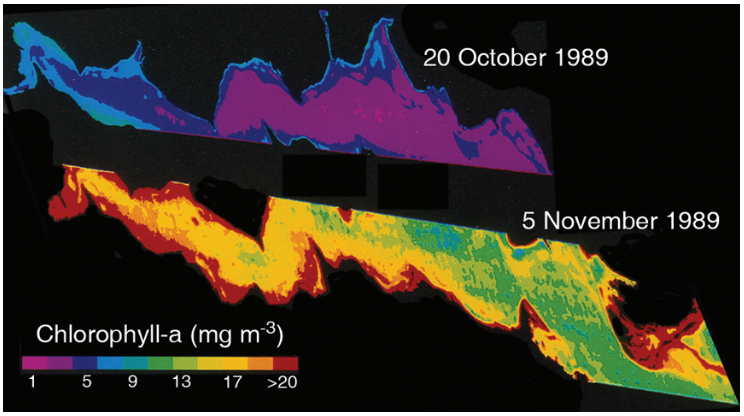

Figure 6.3 Distribution of pigments in the lower reaches of the Cardigan River, Prince Edward Island, Canada on 20 October 1989 and 5 November 1989, generated from the CASI airborne remote-sensing imager. Both maps are plotted using the same colour code for chlorophyll concentration. Adapted from Sathyendranath *et al.* (1997).

When there was another occurrence of the toxigenic *Pseudo-nitzschia* in Cardigan Bay, a remote-sensing experiment was mounted on a crisis basis. The experiment demonstrated the utility of remote sensing as an efficient and cost-effective tool to map the growth and areal extent of the bloom (Figure 6.3). But the experiment also served to illustrate that a judicious mix of *in situ* and remote-sensing observations serve the needs of aquaculture better than either method in isolation. Sathyendranath *et al.* (1997) could not find any absorption characteristics in toxigenic strains of *Pseudo-nitzschia multiseries* that could be used to distinguish them from the benign strains, which would limit the potential for identifying the toxic strain by remote sensing. They therefore concluded that it would be difficult to propose a standard protocol for remote sensing of toxic algal blooms, and suggested that protocols would have to be tailored to meet the problems associated with different types of toxic blooms. The ready application of remote sensing in this context remains the day-to-day monitoring of changes in the concentration and distribution of phytoplankton in the vicinity of aquaculture centres. A ground-based 'toxin-watch' could be activated whenever remote sensing indicates rapid changes in algal conditions.

6.4.6 Monitoring harmful algal blooms in southern Chile

Southern Chile is characterized by an archipelago of pristine waters with a multitude of channels, bays, fjords and islands, providing an ideal area for salmon farming and other types of aquaculture (Figure 6.4). Over the past few years the aquaculture industry in this region has grown exponentially, and today Chile is one of the largest producers of farmed salmon, in addition to a rapidly expanding shellfish culture industry. These ideal conditions for aquaculture also lead to favourable conditions for the development of harmful algal blooms (HABs). Phytoplankton blooms are most common in warm, calm, stratified waters such as found in estuaries or coastal inlets that are subject to increased nutrient loads, often from human activities. Not

Figure 6.4 A salmon fish farm located in the Aisén Region of Chile (Region XI) showing two sets of 12 cages per module. Credit: Mariscope Chilena 2008.

surprisingly, this area of Chile has been subjected to an increased incidence of HABs over the past few years. HABs have direct and indirect impacts on fisheries resources, coastal aquaculture economies, as well as public health. Dense algal blooms can lead to severe oxygen depletion of the water through decomposition of the bloom, potentially killing caged fish that are unable to escape the affected area. Some harmful algal species also produce potent toxins that can cause illness or death in organisms higher up in the food chain, including a number of life-threatening syndromes in humans. For example, in 2002 an extensive *Alexandrium catenella* bloom was responsible for 73 cases of paralytic shellfish poisoning and two deaths in southern Chile through consumption of contaminated mussels. Currently, HAB activity routinely impacts the aquaculture industry in southern Chile every year throughout the spring and summer months.

In recent years, satellite ocean-colour radiometry (OCR) has provided an effective tool to monitor the distribution and progression of these blooms in one of the remotest parts of Patagonia. Mariscope Chilena (Oceanography Branch) initiated the application of satellite data in this area to monitor phytoplankton biomass remotely. Imagery from the MERIS and MODIS-Aqua sensors revealed the extent of the toxic *Gymnodinium chlorophorum* blooms that occurred in southern Chile in 2004 and 2005 (Figure 6.5). Hatfield Consultants and ESA, in parallel with Mariscope Chilena, developed an information framework for future near-real-time data integration, to improve management and monitoring of aquaculture facilities (the Chilean Aquaculture Project). The products delivered under this project included daily composites of chlorophyll-*a* concentration (from merged MERIS and MODIS imagery); SST from MODIS; transparency (Secchi depth) from MERIS reflectance; and suspended particulate matter from MERIS.

Mariscope Chilena has since developed an operational early warning system to detect conditions that favour the development of HABs. They identified the most critical areas in which the risk of HABs is higher, and have developed an interdisciplinary database to ingest near-real-time satellite data in conjunction with *in situ* measurements and meteorological information. The satellite data are used to identify areas where strong thermal fronts originate and where nutrients and phytoplankton are retained. These areas provide phytoplankton with optimal conditions for growth, and are thus at risk for the development of dense algal blooms. Using this interdisciplinary information, Mariscope Chilena are now able to provide an early warning to aquaculture companies in the areas affected by potentially-harmful algal blooms, on an operational basis. This service is still at the proof-of-concept stage, and is still under investigation, although it is of high interest to the insurance companies.

Advanced warning of HABs provides aquaculture companies with enough time (in the order of days) to make contingency plans to mitigate damage to their farms. An advance warning of only four days is sufficient response time to minimise the effects of a harmful algal bloom, for example by delaying the release of young

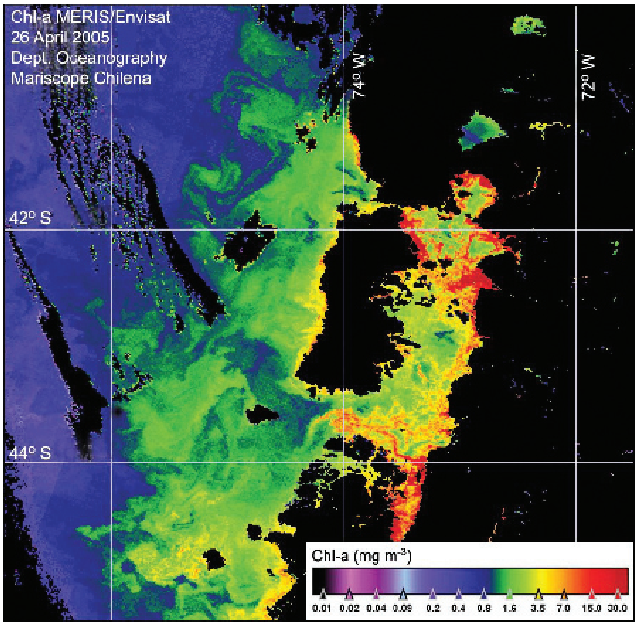

Figure 6.5 An extensive bloom of the dinoflagellate *Gymnodinium chlorophorum* in southern Chile, captured by the MERIS sensor on 26 April, 2005. Image data provided by the European Space Agency under the Category 1 Project 1336.

salmon into cages. Data from OCR thus play a critical role in the development of forecasts for potentially harmful algal blooms, which in turn help to improve the efficiency of the aquaculture industry as a whole. Furthermore, OCR data are also of tremendous value for determining the most appropriate areas for fish and shellfish growth. Location of aquaculture sites is one of the most important aspects for the shellfish industry, since it can have dramatic impacts on shellfish growth rates.

6.5 Concluding Remarks

Two issues remain outstanding in the application of satellite ocean colour to shellfish aquaculture. The first is resolution – many culture sites are below the spatial detection of single pixels, for example small estuaries and bays less than 1 km wide. This situation is alleviated to some extent by using MODIS 500 m resolution for pigments or 250 m resolution for turbidity and MERIS full-resolution (300 m) images. In addition, pixels near land are often missing due to either atmospheric correction and/or Level-2 flags in standard ocean-colour products. This may be alleviated by using Level-0 processing with custom atmospheric correction (Hu *et al.*, 2000). A second issue is proximity – is it possible to utilize remote sensing data from a nearby location, e.g. near-shore waters beyond an inlet, as discussed above? The proximity of boundary conditions to aquaculture farms is important since suspension-feeding can affect water quality and particle load, making boundary conditions less independent from culture conditions.

Beyond boundary conditions, ocean colour may be applied to ground-truthing of model output. Spatial models produce maps of variables such as chlorophyll which are difficult to verify except by towed vehicles (Grant *et al.*, 2008). Time series of remotely-sensed variables are especially useful since seston fields are highly variable and may require averaging for comparison to model output.

In addition to models, there is a fundamental need to assess the biophysical requirements of shellfish in order to define potential culture areas. Although a number of variables are important, several are available through remote sensing, namely temperature, salinity, chlorophyll and turbidity. It should be emphasized that ocean colour has great potential in characterizing biophysical requirements. Turbidity and chlorophyll are available as ocean colour products from NASA, and temperature is readily available as discussed above. Salinity may be obtained from ocean colour as a function of CDOM (Binding and Bowers 2003), and in future from ESA's Earth Explorer Soil Moisture and Ocean Salinity (SMOS) mission and NASA's Aquarius mission (scheduled for launch in 2009 and 2010 respectively). Ground-based measurements have been used to produce suitability maps for aquaculture based on these biophysical requirements, e.g. British Columbia provincial government (`http://ilmbwww.gov.bc.ca/cis/projects/sarp/vanisl.htm`). This is clearly an application of remote sensing with great potential for shellfish aquaculture.

Chapter 7

Building Links with the Fishing, Aquaculture and Management Communities

Alida Bundy, Gary Borstad, John Field, Steve Groom, Nicolas Hoepffner, Chuanmin Hu, Vivian Lutz and Cara Wilson

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7.1 Introduction

Globally, fish are an important source of protein, and fisheries and aquaculture are critical to food security in many countries. Effective sustainable management of these fisheries is required at national and international levels so that fish stocks can contribute to meet global nutritional needs. At the international level, marine resource management has moved on from a single species stock assessment and management approach to a more holistic 'Ecosystem Approach to Fisheries' (EAF), or variations on the theme (FAO, 2003; Garcia *et al.*, 2003; Daan *et al.*, 2005; Pitcher *et al.*, 2008). EAF still includes single species stock assessment but is expanded to minimally include the wider impacts of fishing on the ecosystem, the role of the environment on species dynamics, the impacts of other activities and the engagement of stakeholders in the processes leading to decision making (Rice, 2008).

Remote sensing of the ocean is relatively new, but is now being applied globally to many areas of ocean resource use and management. The scale of remote-sensing data makes it suitable for local, regional, national and international studies, with applications to ecosystem approaches to fisheries (Polovina and Howell, 2005; Platt and Sathyendranath, 2008), including the role of the environment on species dynamics, the wider impacts of fishing or other activities on the ecosystem, and more directly in relation to fisheries assessment, management and operations, for example, to generate maps of potential fishing zones (PFZs) for the fishing community (Solanki *et al.*, 2005). Other applications include ecological and process studies of the ocean (Ware and Thomson, 2005; Chassot *et al.*, 2007), climate change, and marine aquaculture. However, the scope of remote sensing is far greater. Wider applications may include coastal issues, oil and gas development, marine protected areas and others.

There is a strong consensus that Earth observation data could play a major role in providing the appropriate information to support fishery management. Operation costs of resource management could be lowered significantly by the availability of improved information on the environmental variables controlling the condition of marine resources through remote sensing. The traditional means to collect marine data by sea-based systems is expensive and time consuming. As a result, the derived information available to key users is often incomplete and inadequate. Despite the potential of satellite data to dramatically improve the monitoring of marine waters and its resources, several constraints to its use have been identified by the operational community, such as inadequate data access and an inadequate system of analyzing and disseminating this information to the communities outside of the research community. The challenge is to develop better links between the remote sensing world and the communities who can use this data, e.g., scientists, the fishing and aquaculture industries, managers and policy makers. These are the people who have the questions and applications that remote sensing can address.

Many applications of remote sensing data use SST, chlorophyll, and sea surface height. Global coverage of satellite-derived time-series of these data extend back at least a decade. The continuity, global coverage, and high temporal and spatial resolution of these datasets make them an important tool for monitoring and characterizing marine ecosystems. However, the huge scale of this data can be a challenge, even to building links with scientists. There are a number of reasons why remote sensing data can be challenging to use:

- Satellite data can be difficult to access, manipulate and process, particularly for people who have never used it before.
- Work required to get relevant parameters can be cumbersome, ie:
  - primary productivity from chlorophyll;
  - front locations from SST fields;
  - climatologies required to generate anomalies;
  - rigorous ‘data mining’ needed to match up satellite data with telemetry records;
  - ‘one-stop’ satellite data shopping desired.
- People are too busy with their regular workloads to find time to familiarize themselves with new analyses.
- Time-series of satellite data are relatively short compared to many fisheries datasets.

The most direct way to overcome these problems are to form interdisciplinary research teams to address key questions (e.g., Platt *et al.*, 2003; Fuentes-Yaco *et al.*, 2007; Chassot *et al.*, 2007; Friedland *et al.*, 2008; Koeller *et al.*, 2009), where remote sensing scientists team up with fisheries scientists. However, there is a limit to this process, and more questions and issues need to be addressed than there are remote sensing scientists to answer them. In the United States, NOAA is developing novel ways to build these linkages, such as training workshops and facilitating data use and access (Section 7.1.1).

This interdisciplinary approach to research can also extend into management of resources. In Florida, USA, the case of the management of industry wastewater in 2003 presents an example of how the various stakeholders, including managers, policy makers, fishing community, scientists, and the general public worked together to address an emergency situation whereby there was a high risk that 1.2 billion gallons of acidic and phosphate-rich wastewater would spill into the nearby Tampa Bay estuary (Section 7.1.2). Remotely-sensed data played a critical role in the successful management of this emergency situation by providing information about currents and possible dispersal sites, and the subsequent monitoring of dispersal of phosphate-rich water which could potentially cause harmful algal blooms.

In some cases, specific tools have been developed that connect scientists and resource managers to satellite data, at the local, national and international level. At the local level, for example, Borstad Associates have developed the Satellite Image Portal to provide a simple, accessible interface for users of Earth observation image data (Section 7.1.3). Its focus is on secondary products of interest to scientists and managers in fisheries and aquaculture sectors. At the national level, the Indian National Centre for Ocean Information Services (INCOIS), provide 'Potential Fishing Zone' (PFZ) advisories to the Indian fishing community. The PFZ advisories are generated using satellite-derived sea surface temperature and ocean-colour data, which fishermen use to maximize efficiency in locating their catch (`http://www.incois.gov.in/Incois/advisory_pfz_main.jsp`, see Chapter 5 for further details). The Netherlands Agency for Aerospace Programs (NIVR) funds projects through its 'User Support Programme', whose objectives include support for users of Earth observation data and the development of new applications for scientific research, industrial and policy research, and operational use. They partially funded a project which used remotely-sensed chlorophyll-*a* maps derived from MERIS, together with *in situ* data collections and bio-physical modelling, to detect and characterize harmful algal blooms in Dutch coastal waters. The outcome of the project is a prototype system that combines near-real-time forecasting with MERIS and a bio-physical model.

Managing wild populations requires estimates of their abundance. A relatively simple use of remotely-sensed imaging data is being evaluated by biologists of the Marine Mammals Management office (Washington, USA), who are responsible for ensuring that Pacific walrus in Alaska remain within an optimum sustainable population range and that they continue to be a healthy, functioning component of the Bering and Chukchi Seas ecosystems. They are exploring the use of QuickBird high-resolution satellite imagery as a tool for population monitoring of the Pacific walrus, since Pacific walrus are sufficiently large to be detected individually by high-resolution satellite imagery (`http://www.csc.noaa.gov/crs/rs_apps/issues/quickbird_walrus.htm`).

7.1.1 Building links with resource scientists and managers in the USA

In the United States NOAA has been working on developing linkages between the remote sensing community and fisheries scientists, managers, and policy makers. In 2005 NOAA started holding satellite courses specifically designed for marine resource managers. These courses have two primary benefits. In addition to the primary goal of educating managers about the availability of satellite data, and showing them how to access and utilize the data, the courses provide a better understanding of users' needs and requirements, allowing those needs to be better addressed. There are a number of ways that the accessibility of available satellite data can be enhanced, for example, by data transport procedures that allow data to be subset spatially and temporally, and by client-side applications that directly import satellite data streams into the software traditionally used by resource managers. For example, many marine resource managers use ArcGIS products as decision support tools, however importing satellite data into ArcGIS has traditionally been a cumbersome process at best. To address this problem, NOAA had an ArcGIS extension developed which allows users to browse existing on-line catalogs of satellite data, subset them spatially and temporally, and bring them directly into ArcGIS, resulting in a significant savings of time and energy (tool for importing satellite data in ArcGIS: `www.pfeg.noaa.gov/products/EDC/`). Another example is the process of matching up environmental satellite data with telemetry records of tagged animals to better understand and characterize their habitat. Mining global datasets of satellite chlorophyll, SST or SSH for the synoptic values associated with a telemetry track is a daunting task for most marine biologists unaccustomed to working with large satellite datasets. However, utilizing the data transport capabilities of THREDDS catalogs and OPeNDAP servers, simple scripts (for R and Matlab) have been written to automate this process and are being distributed to marine biologists (`http://coastwatch.pfel.noaa.gov/xtracto/`.

7.1.2 Remote sensing and the management of waste water

The case of the management of industry wastewater in Florida, USA in 2003 presents an example of how the various stakeholders worked together to address an emergency situation.

In early 2001, a phosphate fertilizer plant claimed bankruptcy and left 1.2 billion gallons of acidic and phosphate-rich wastewater unattended in open-air holding ponds, threatening to spill into the nearby Tampa Bay estuary as the ponds gained volume with seasonal Florida rains. Such a disaster occurred in December 1997 when the spill of 50 million gallons of the acidic wastewater from another plant into the Alafia River killed over 1 million fish and severely damaged local wetlands.

The Florida Department of Environmental Protection (FDEP) implemented various methods to manage the wastewater and impending danger to the estuary. Yet, heavy rainfall was expected throughout 2003, forcing FDEP to find fast solutions. In the process of converging on a best solution, FDEP consulted with environmentalists, fishermen, resource managers, and the general public as well as scientists, and obtained an emergency permit from the U.S. Environmental Protection Agency (EPA) to discharge the wastewater into the Gulf of Mexico using barge operations, after treatment (to meet all EPA standards). From 20 July to 30 November 2003, about 248 million gallons of treated wastewater were discharge into the Gulf through 35 barge trips.

Satellite remote sensing played two important roles for this emergency management. Before the dispersal, satellite data were instrumental to help outline the area where the barge would discharge the water (Figure 7.1). This was through the analysis of real-time satellite data to determine the position of the Loop Current, a strong oceanic current that can quickly carry water and materials away. During and after the dispersal, satellite data provided timely and accurate information to evaluate the potential adverse impact of the wastewater discharge on the coastal water environment (e.g., would the discharge stimulate harmful algal blooms?).

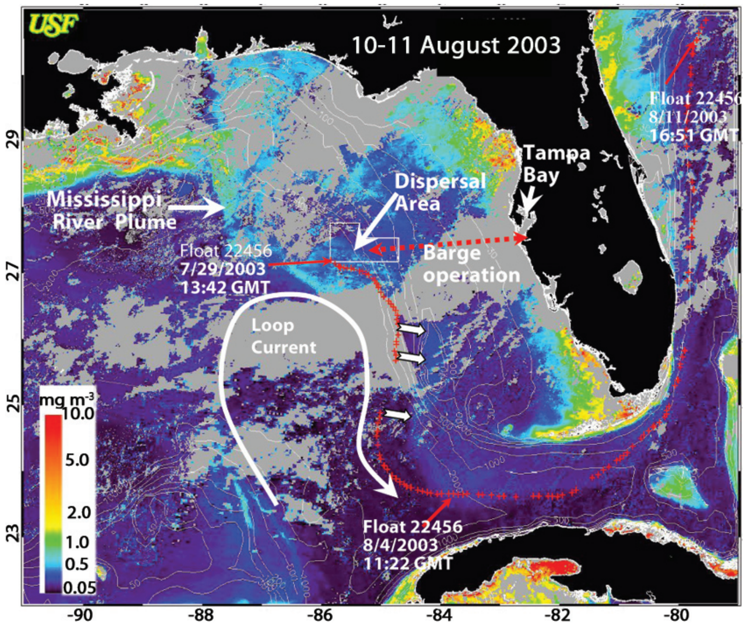


Figure 7.1 MODIS chlorophyll-*a* concentration for 10 to 11 August 2003, when ~27-million gallons of treated wastewater was dispersed in the Gulf of Mexico beginning on 20 July 2003. Overlaid on the image is the track of one Argo drifter (small red crosses) that drifted with the Loop Current. The Loop Current movement direction is indicated by the white arrows.

Over the course of the dispersal operation, satellite data were analyzed daily to examine satellite chlorophyll concentrations and ocean-colour patterns, which were compared with historical conditions during similar periods (Hu and Muller-Karger, 2003). The results showed that there were no anomalous variations in chlorophyll on the west Florida Shelf or waters near the Florida Keys. There was no evidence of enhanced biological activity near or downstream of the discharge area due to the immediate water advection and dilution through the Loop Current. There were only a few cases where increases in chlorophyll concentration (0.01 to 0.02 mg m^{-3}) were detected in a limited area downstream of the dispersal location. These increases were negligible, and indeed could only be detected by MODIS satellite imagery and not by shipboard instruments.

It is clear that the successful management of this emergency situation could only have been achieved through collaborative efforts between the various stakeholders including managers, policy makers, fishing community, scientists, and the general public. Satellite remote sensing plays a significant operational role in monitoring our marine environment and in helping make management decisions.

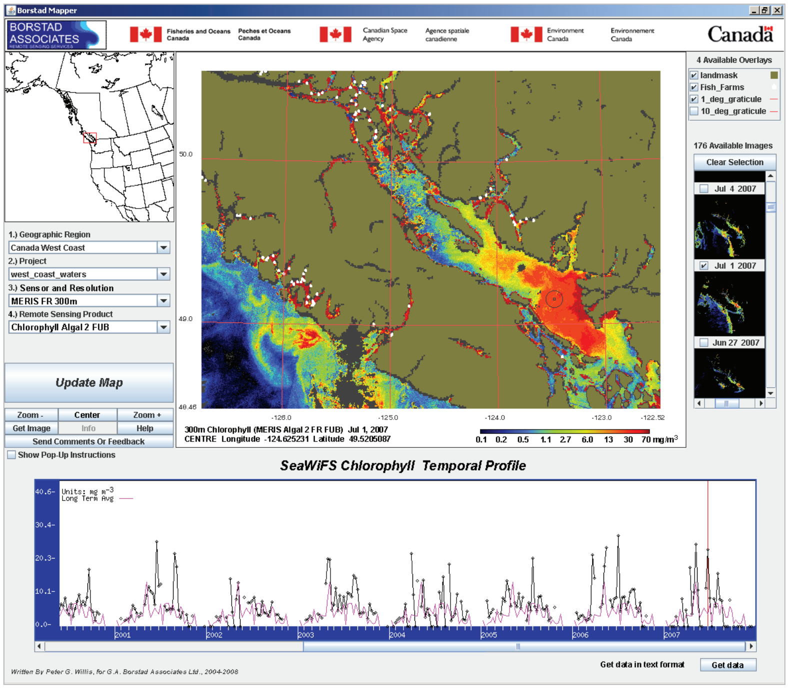
7.1.3 Borstad Associates/GRIP geographic data portal

The Borstad Associates Ltd./GRIP geographic data portal was designed to provide a simple, accessible interface for users of Earth observation image data. It uses a GIS interface and currently provides 9-km, 8-day CZCS, SeaWiFS and MODIS imagery for the global northwest hemisphere (0 - 90°N, 0 - 180°W), as well as 1-km and 300-m daily MODIS and MERIS imagery for the west coast of Canada, Newfoundland and the Great Lakes (Figure 7.2). The focus is on secondary products of interest to scientists and managers in fisheries and aquaculture sectors, and includes chlorophyll, SST, $nL_w(551)$, K_{490}, and MERIS estimates of yellow substances and total suspended material.

In order to provide data in a timely manner to the user community, the imagery is automatically downloaded and processed on-site daily, with 1-km MERIS reduced resolution data available same day, and SeaWiFS and MODIS with a 2 to 4 week lag. MERIS Full Resolution (FR) products are of greatest interest to the aquaculture industry, since their 300-m spatial resolution provides usable information within the narrow inlets where the majority of British Columbia fish and shellfish farms are located.

Of additional interest to the scientific community is the interactive ‘Temporal Profiler’, which returns time series of chlorophyll, SST, $nL_w(551)$ or K_{490}, for the currently selected image location. Data values are retrievable in ASCII format by mouse click. Other tools under development include a ‘Temporal Transect Profiler’, which at present generates contour plots of chlorophyll along a user selected spatial transect over time, and ‘Temporal Animations’ of SeaWiFS chlorophyll imagery.

At present the most common users of the geographic data portal are oceanographers and fisheries scientists interested in coastal and ocean climate related phenomena. As MERIS high resolution imagery becomes increasingly available, the site is attracting more interest from aquaculture operators and managers. This type of usage is expected to increase now that MERIS FR imagery is accessible in near real



1.) Geographic Region: Canada West Coast
2.) Project: west_coast_waters
3.) Sensor and Resolution: MERIS FR 300m
4.) Remote Sensing Product: Chlorophyll Algal 2 FUB

300m Chlorophyll (MERIS Algal 2 FR FUB) Jul 1, 2007
CENTRE Longitude -124.625231 Latitude 49.5205087

4 Available Overlays
☑ landmask
☑ Fish_Farms
☑ 1_deg_graticule
☐ 10_deg_graticule

176 Available Images
☐ Jul 4 2007
☑ Jul 1 2007
☐ Jun 27 2007

☐ Show Pop-Up Instructions

Written By Peter G. Willis, for G.A. Borstad Associates Ltd., 2004-2008

Figure 7.2 GIS interface for the Borstad Associates Ltd./GRIP Geographic Data Portal.

time.

Development is continuing on the project, with support from the Canadian Space Agency via the Department of Fisheries and Oceans and Environment Canada, and from Borstad Associates Ltd. It is anticipated that the Earth observation data currently available will soon be supplemented with additional oceanographic data, including winds, currents, and possible links to ARGO buoy data or AVHRR imagery. The Image Portal can be accessed at `http://www.borstad.com/grip.html`.

7.2 Network, Capacity Building and Coordination

As discussed in this monograph, satellite data can be an invaluable means of estimating chlorophyll-*a* for monitoring of harmful algal blooms, aiding fishing operations, fisheries management and coastal zone management. However, many potential users, particularly in developing countries, do not have the infrastructure to download and process, or even view, the data. Similarly, in-water sampling of chlorophyll-*a* to validate the satellite images is also very limited. Furthermore, networking and capacity building are needed to share experience on the exploitation of satellite data to support fishing and aquaculture management.

Two main factors influence the extent to which satellite ocean-colour information is used in fisheries studies: the reliability and the availability of these data. To improve the reliability of the satellite chlorophyll (a proxy for phytoplankton abundance), more bio-optical and biological studies are needed in the world's various seas and oceans. This will allow the validation of the satellite products with high quality *in situ* data, and the regional adjustment of the algorithms used to estimate the quantities of interest. This is particularly true for many coastal areas where sparse *in situ* data are available for validation of satellite information. The second factor, the availability of data, has also been mentioned as a limiting factor in the use of remote-sensing data in fisheries oceanography (Podestá, 1997). There have been great advances since the beginning of the ocean-colour era, but despite the free availability of large volumes of data, as noted above, these are often not in a user-friendly format for the non-specialist.

Tools to handle geographical or spatial data have developed rapidly within the last decade and are becoming very useful in the study of marine ecosystems regarding database creation, monitoring, mapping and visualization. For example, GIS enables the integration of data from multiple and disparate sources, and also provides an excellent platform to communicate results of scientific studies to a wider community including the policy makers.

Networks provide an efficient way to tackle both aspects of data distribution. A network with centres performing biological oceanographic studies in different countries, allows *in situ* data to be gathered in a unified database from distant places, and also helps enhance studies carried out at each centre through the commitment of the members to share data, resources and especially expertise. Belonging to a network generates a sense of participating in something larger than one's own individual study at a local site; it also enhances local results by bringing them into a larger regional and ultimately global picture.

7.2.1 Antares network

An example of such a network is the Latin American Antares (Figure7.3), which was fostered by the IOCCG and the Partnership for the Observation of the Global Oceans (POGO). The network was built on ongoing initiatives in different countries in the Americas, including both remote sensing and *in situ* observations. At the moment around 30 researchers from 7 countries, including local scientists from Latin America and consultants from North America, are members of the network. It is proposed to link *in situ* data from the time series stations with remote sensing observations, creating an integrated database for scientific, educational and management purposes. Antares has a website (`http://www.antares.ws`) where satellite information (daily images and ASCII data) of sea surface temperature and chlorophyll (from MODIS obtained from NASA and processed at the Institute of Marine Remote Sensing, University of South Florida) is openly and freely delivered in an easy to use format. Future work should promote the growth of the network, incorporating new centers from different countries in the region, as well as strengthening the *in situ* time

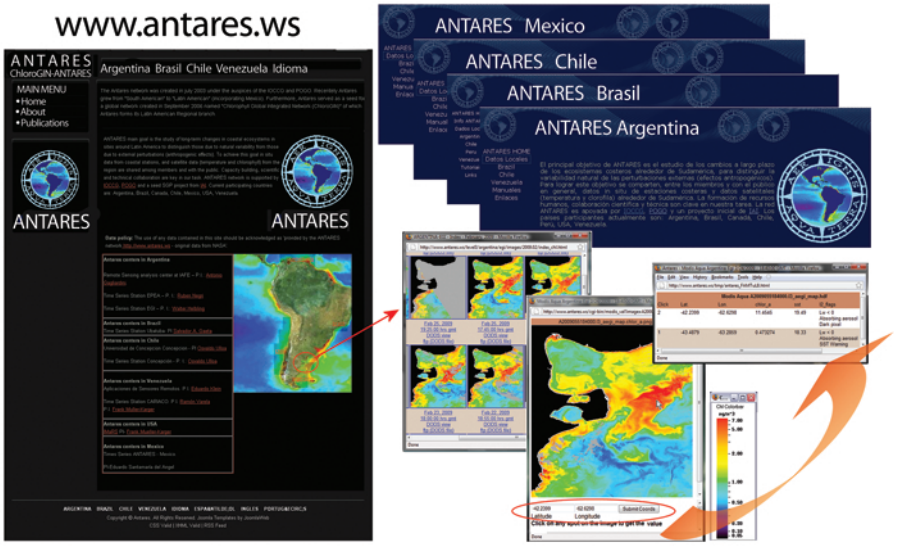


Figure 7.3 Screenshots of the main ANTARES portal (left) and the regional web sites of member countries (upper right) containing local information. Level-2 mapped MODIS chlorophyll-*a* and SST products for selected areas (grey areas in the map) are available in HDF and ASCII format. Images can be downloaded via FTP, and data for individual pixels can be retrieved by specifying the coordinates or clicking on the image via a user-friendly interface (lower right).

series stations, and the facilities offered from satellite information through the website. At the moment at least five research groups in Argentina are starting to use satellite information provided on the Antares website for their research on the distribution and abundance of hake, red Patagonian shrimp, anchovy, king crab, and other coastal commercial fish species.

7.2.2 ChloroGIN network

The Antares network was extended to create the Chlorophyll Global Integrated Network (ChloroGIN) which was established in September 2006. A model for providing remote-sensing data via regional 'centres of excellence' as well as protocols for *in situ* calibration and validation of the satellite products was developed. Satellite data are processed at a number of regional centres and supplied via the internet to a network of end users in developing countries

In South Africa, the ChloroGIN network is used mainly for monitoring harmful algal blooms (HABs) and issuing warnings about potential harmful blooms several days beforehand. This is very helpful for the oyster and mussel mariculture industry and also for rock lobster stock management. In the latter case, the resulting decay of blooms causes a reduction in oxygen concentration of coastal waters which in turn can result in lobster migrations, or even large-scale walkouts onto the shore, with disastrous consequences for the lobster industry.

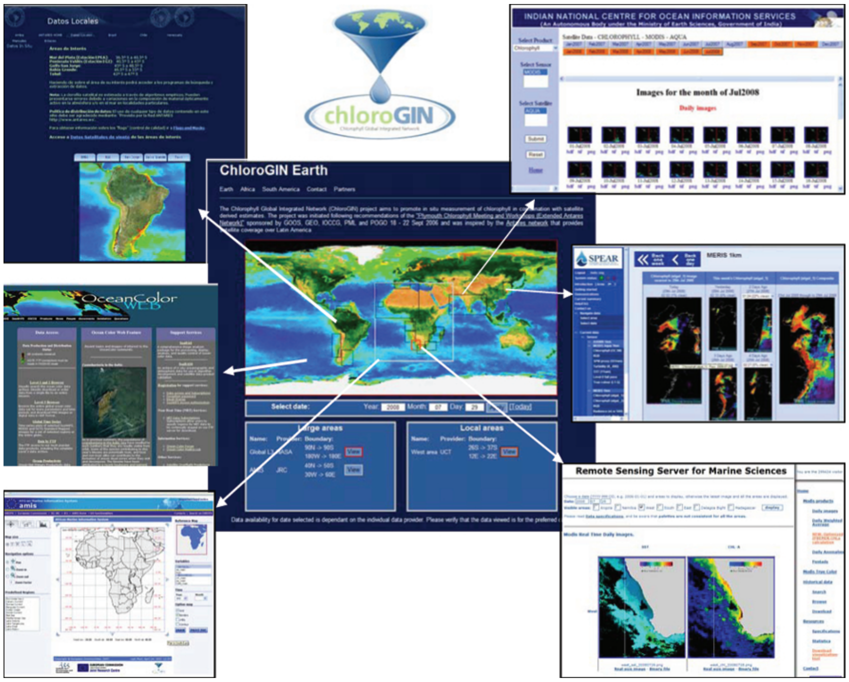


Figure 7.4 ChloroGIN portal (centre) with shots of the websites of various regional and global data providers.

ChloroGIN has created a web-portal (Figure 7.4) that provides links to existing suppliers of regional and global data in South Africa, Latin America, India, the UK, the USA and the EC Joint Research Centre (see `http://www.chlorogin.org/world/`). These provide regular chlorophyll-*a* images and associated products such as SST and other variables (daily, weekly or bi-weekly, depending upon each region's needs and conditions). The web page shows a number of regional areas and mouse clicking within any one will link to the regional data provider's web site. These include, notably, the Indian PFZ information and the South African coastal monitoring for HABs. Clicking outside a regional box provides a link to global chlorophyll-*a* from NASA.

Although still at an early stage, ChloroGIN is already providing a focal point for development of international collaboration, networking and capacity building. As an example, ChloroGIN partners from Africa and Europe are participating in a European Framework project called DevCoCast (GEONETCast applications for and by Developing Countries). GEONETCast is a system whereby environmental data can be distributed at low cost, to and from developing countries with poor internet infrastructure, using satellite based Digital Video Broadcast technology. DevCoCast is using the GEONETCast concept to provide satellite data on chlorophyll-*a*, other ocean-colour products and SST from MODIS, AVHRR and MERIS from regional data providers in South Africa and Europe to countries in Africa (Namibia, Tanzania,

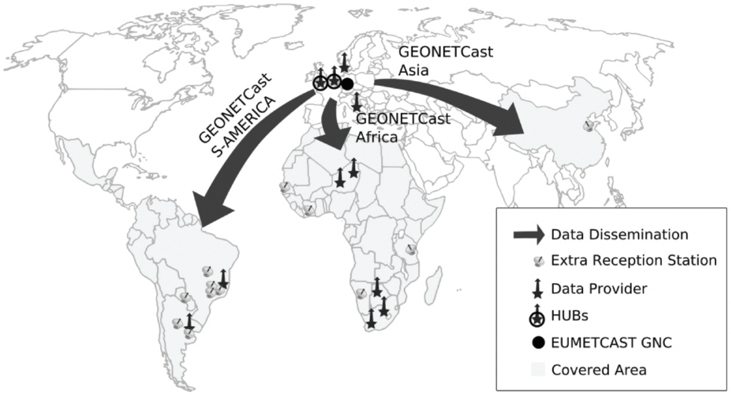


Figure 7.5 DevCoCast data flow diagram

Ghana and Senegal), South America (Brazil) and Asia (China). It will also improve the infrastructure by installing a number of GEONETCast receivers at marine science institutes (see Figure 7.5).

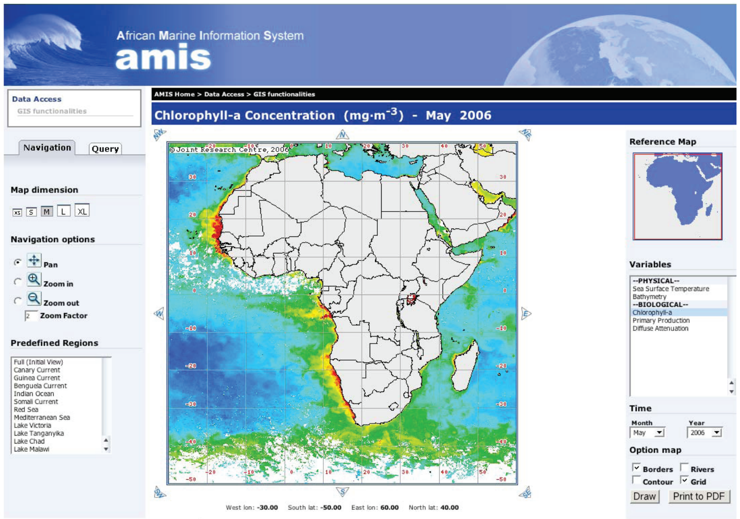
Looking to the future, another aim of ChloroGIN is to develop tools to support fisheries and aquaculture management including the integration, comparison and analysis of satellite data with *in situ* samples and numerical model forecasts as well as derived products such as current or bloom frontal locations, and positions of blooms in relation to territorial or province boundaries. Two systems are the JRC-AMIS system and the InterRisk system.

7.2.3 The African Marine Information System

The African Marine Information System (AMIS, `http://amis.jrc.ec.europa.eu/`) was recently developed as part of the European Commission – Joint Research Centre 'Observatory for Sustainable Development' (`http://acpobservatory.jrc.it`). It was established under the EU sustainable development strategy (CEC, 2002) to provide the user community at large with appropriate bio-physical information to conduct water quality assessment, resource monitoring and climate change studies in the coastal and marine waters around Africa.

AMIS is a simple and easy-to-use mapping tool application, developed for the publication and dissemination of African marine information via the web (Figure 7.6). The system relies mostly on Earth observation data from optical and thermal sensors processed according to standard (i.e. space agency-related) and in-house peer-reviewed algorithms. It includes:

- provision of continuous, detailed and accurate information on relevant marine biophysical parameters as derived from optical, and infrared satellite sensors;
- generation of indicators for global diagnostics of the coastal state and analyses of changes in marine ecosystems;



● Pan
Zoom Factor: 2
Variables: Chlorophyll-a
Month: May
Year: 2006
☑ Borders ☐ Rivers
☐ Contour ☑ Grid
West lon: -30.00 South lat: -50.00 East lon: 60.00 North lat: 40.00

Figure 7.6 Screen shot of the AMIS internet webpage.

- optimization and implementation of an interdisciplinary system of marine resource information and analysis (GIS) to enable decision makers and the public to make full and lasting use of this information.

At present, the user can automatically generate maps, scatter plots, histograms, and time series in a format ready for publication. AMIS applications range from water quality management, monitoring issues that can impact on the ecosystems and resource distribution (e.g. HABs, coastal pollution) to climate studies, examining interactions between marine resources and major forcing variables. The system is extremely fast and simple, resulting in a very practical and useful high level user application.

7.2.4 InterRisk

InterRisk (Interoperable GMES Services for Environmental Risk Management in Marine and Coastal Areas of Europe) is a European Framework project that is building systems to demonstrate web-based integration of various data types from different countries and suppliers in order to better manage coastal pollution events. Since it is web-based, it only requires a browser (such as Internet Explorer) as opposed to specialist and expensive local software. The system includes near-real-time satellite data that can be inspected for high chlorophyll-*a* events (possibly related to eutrophication or HABs) and compared to long-term means and standard deviations from 10 years of SeaWiFS data. The system will also allow, *inter alia*, comparison of satellite data to model forecasts or *in situ* measurements of phytoplankton, overlaying of depth contours, maps of Exclusive Economic Zones, location of bathing beaches, juvenile fish nursery beds, LME boundaries or Longhurst provinces. The

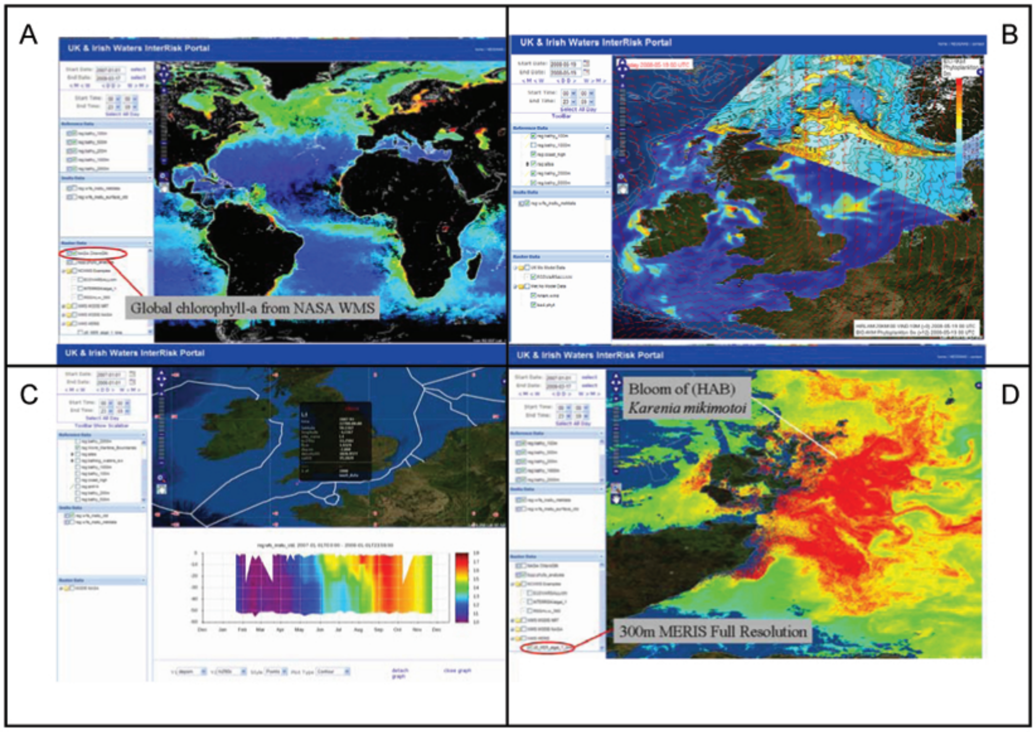


Figure 7.7 Screenshots of the PML InterRisk portal (see `http://www.npm.ac.uk/rsg/projects/interrisk/`). a) global coverage with NASA MODIS chlorophyll-*a* overlaid with bathymetry; b) integration of phytoplankton model output from the UK and Norwegian Met Offices, modelled surface winds, and *in situ* moorings (PML); c) density plot of *in situ* temperature with depth for station L4 south of Plymouth also showing EEZ boundaries; d) MERIS 300 m chlorophyll-*a* image showing a bloom of the harmful *Karenia mikimotoi* around the Orkney Islands July 2006.

system is shown in Figure 7.7 with various screenshots showing data integration, comparison and web-based plotting of *in situ* data sets.

7.3 Looking into the Future

Tremendous strides have been made in satellite remote sensing over the past few decades. What is striking is that the first global ocean-colour image took many months of processing to achieve. Now these are produced routinely, every day. Initially, very different processes were involved in generating ocean colour and sea surface temperature images, but now we have the tools to produce such images, and composite images, on the same scales and integrate them with other remotely-sensed observations (e.g. wind vectors and altimetry). It is becoming relatively easy to incorporate these into models and predict the movement of oceanic features such as fronts, eddies or upwelling that can be used for fish harvesting and management purposes. Remotely-sensed data provides information to calculate objective ecosystem indicators that can be applied in operational mode as an aid to rational management of the oceans (Platt and Sathyendranath, 2008; IOCCG 2008). With the growing time series of data, the information provided by these ecosystem indicators will improve. Thus information and software will become more widely available, user friendly, and accessible to managers rather than just to specialist remote-sensing scientists. This volume contains many examples of applications of remote sensing for the benefit of society, illustrating the advances that have been made. We can expect to project similar rapid developments into the future. This latter point is fundamental since remote sensing provides a global vision in an era of climate change and highly impacted and deteriorating marine ecosystems (Halpern *et al.*, 2008; Bundy *et al.*, 2009; Shin *et al.* 2009). As we move nationally and internationally through agreements such as those forged at the 2002 World Summit on Sustainable Development to anticipate, ameliorate and combat these global impacts, remotely-sensed ecosystem indicators give insight into the state and rate of change of the world's oceans and ocean ecosystems.

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Acronyms and Abbreviations

ADEOS	Advanced Earth Observing Satellite (Japan)
ARGO	Collection of small, drifting oceanic robotic floats deployed worldwide
AMIS	African Marine Information System
AOGCM	Atmosphere-Ocean Global Circulation Models
ASCII	American Standard Code for Information Interchange
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced High Resolution Radiometer
AVNIR	Advanced Visible and Near Infrared Radiometer
CASI	Compact Airborne Spectrographic Imager
CDOM	Coloured Dissolved Organic Matter
ChloroGIN	Chlorophyll Global Integrated Network
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CZCS	Coastal Zone Colour Scanner
DGOM	Dynamic Green Ocean model
DHW	Degree Heating Weeks
DSPIR	Driver-Pressure-State-Impact-Response
EAF	Ecosystem Approach to Fisheries
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
ERS-2	European Remote Sensing satellite
ERSEM	European Regional Seas Ecosystem Model
ESA	European Space Agency
FAO	Food and Agricultural Organization
FDEP	Florida Department of Environmental Protection
FR	Full Resolution
FTP	File Transfer Protocol
GCM	General Circulation Model
GEO	Group on Earth Observations
GIS	Global Information Systems
GPS	Global Positioning System
HAB	Harmful Algal Bloom
HDF	Hierarchical Data Format

IDL	Interactive Data Language
IFREMER	Institut Francais de Recherche pour l'exploration de la Mer
INCO-DEV	International Cooperation with Developing Countries
INCOIS	Indian National Centre for Ocean Information Services
IOCCG	International Ocean Colour-Coordinating Group
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
Landsat	Earth-observing satellite missions jointly managed by NASA and the U.S. Geological Survey
LAPE	Lesser Antilles Pelagic Ecosystem
LME	Large Marine Ecosystem
MERIS	Medium Resolution Imaging Spectrometer
MMA	Marine Managed Area
MODIS	Moderate Resolution Imaging Spectroradiometer
NEMURO	North Pacific Ecosystem Model for Understanding Regional Oceanography
NOAA	National Oceanic and Atmospheric Administration
NPZD	Nutrient-Phytoplankton-Zooplankton dynamics
OCM	Ocean Colour Monitor
OCR	Ocean Colour Radiometry
OCTS	Ocean Colour and Temperature Scanner (Japan)
OPAL	Ocean Productivity from Absorption of Light
OPeNDAP	Open-source Project for a Network Data Access Protocol
PAR	Photosynthetically Active Radiation
PDO	Pacific Decadal Oscillation
PFZ	Potential Fishing Zone
PML	Plymouth Marine Laboratory
PPMR	Predator-Prey Mass Ratio
PPR	Primary Production Required
QuikSCAT	Quick Scatterometer (NASA)
RADARSAT	Canada's remote sensing satellite
SAR	Synthetic Aperture Radar
S-DMB	S-band Digital Multimedia Broadcasting service
SeaWIFS	Sea-viewing Wide Field-of-View Sensor
SPEAR	Sustainable options for PEople, catchment and Aquatic Resources
SSH	Sea Surface Height
SST	Sea Surface Temperature
TE	Trophic Efficiency
THREDDS	Thematic Realtime Environmental Distributed Data Services
TL	Trophic Level
TOREDAS	Traceable and Operational Resource and Environment Data Acquisition System
TZCF	Transition Zone Chlorophyll Front