

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

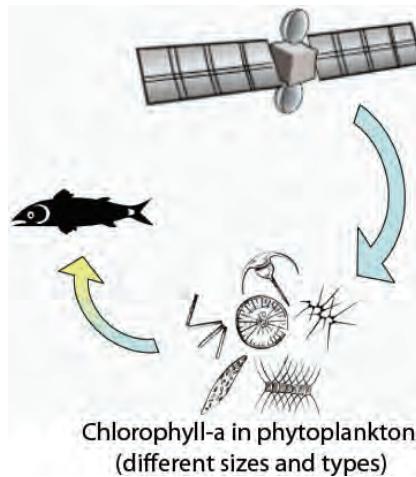


Figure 4.1 Schematic showing simplified pathway between fish populations and properties that can be inferred from satellite ocean-colour data, such as phytoplankton type and size. There can be many different levels in the link between phytoplankton and the top of the trophic food chain. See also Figures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

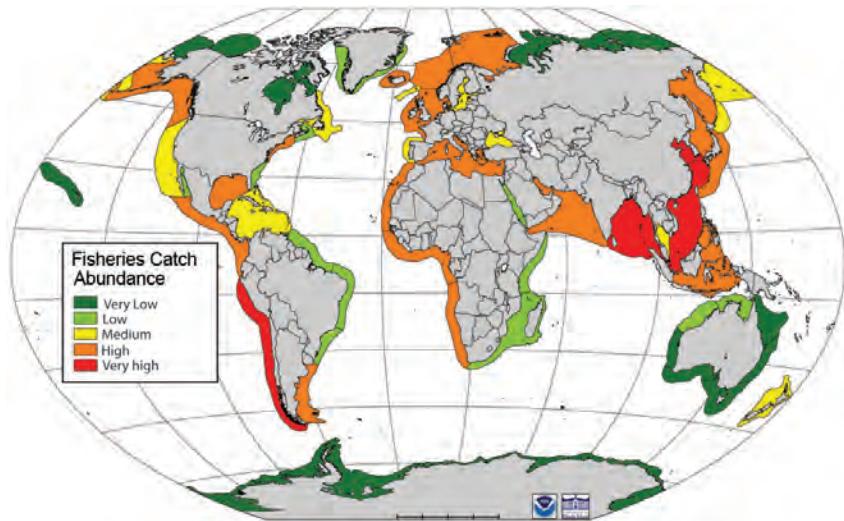


Figure 4.2 Outline of the 64 Large Marine Ecosystems of the world showing fisheries catch abundance for 2000-2004 (adapted from <http://www.lme.noaa.gov/>).

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.

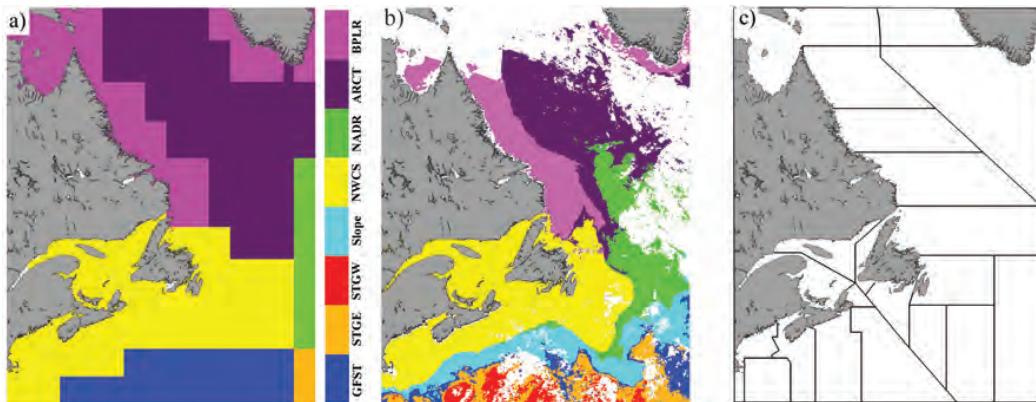


Figure 4.3 Ecological partitions of the northwest Atlantic Ocean, (a) static partition according to Longhurst (1998); (b) dynamic partition according to Devred *et al.* (2007), for 16 to 31 October 2001; (c) static partition of the Northwest Fisheries Organisation (see Halliday and Pinhorn, 1990). Figure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

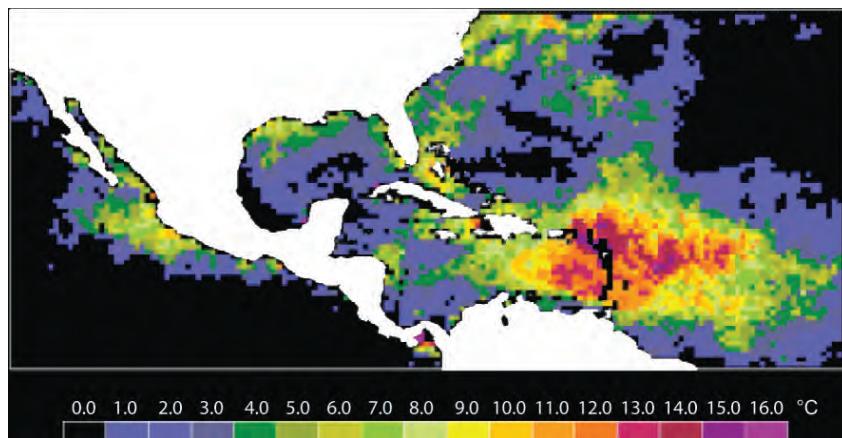


Figure 4.4 Map of an unusual heating in the Caribbean for the summer of 2005 when a massive bleaching event occurred. Results are presented as anomalies of sea-surface temperature (SST) above the expected summer-time maximum, over a one week period, expressed as ‘Degree Heating Weeks’ (DHWs). One DHW 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 $99 \text{ g C m}^{-2} \text{ y}^{-1}$ (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

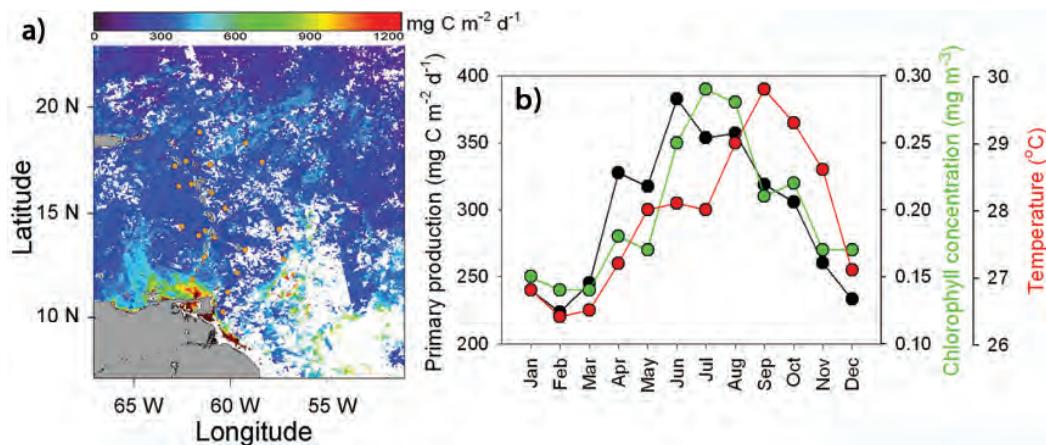


Figure 4.5 (a) Primary production map for May 2006 for the LAPE study area. Parameters are heterogeneously assigned using the Nearest-Neighbour Method (Platt *et al.*, 2008). The sampling stations of the photosynthetic parameters are superimposed. (b) Seasonal cycle of primary production (black), sea-surface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

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).

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

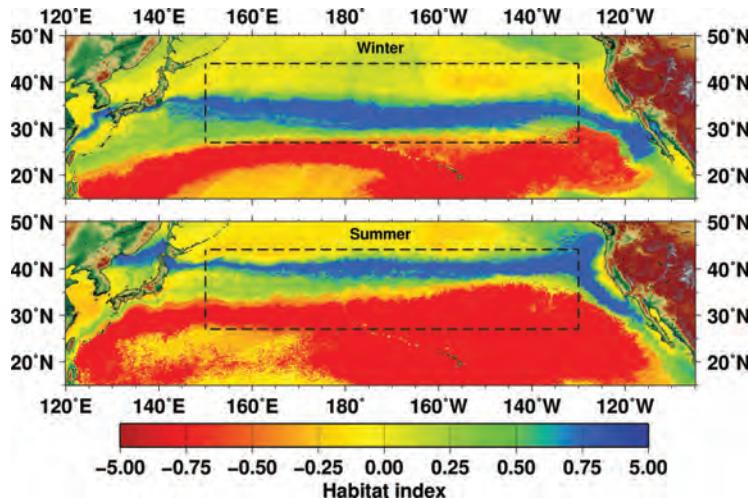


Figure 4.6 Seasonal climatological habitat map for pelagic loggerhead sea turtles in the north Pacific based on Pathfinder SST, SeaWiFS chlorophyll and 3 magnetic variables. Blue areas represent a high probability of finding loggerhead sea turtles. Modified from Kobayashi *et al.* (2008).

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

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.

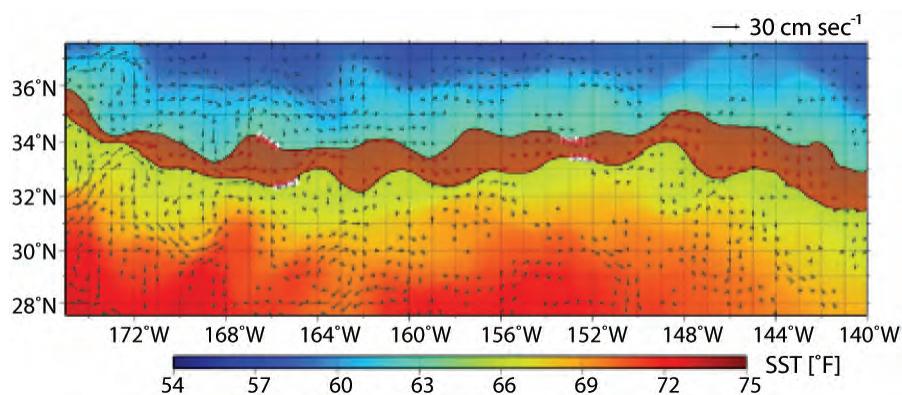


Figure 4.7 The TurtleWatch product. SST represented as a colour background, geostrophic currents estimated from satellite altimetry shown as black arrows, and the zone with the highest probability of bycatch of loggerhead sea turtles is shown in brown (defined as the area between 63.5°F and 65.5°F).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