Chapter 6

Ocean-Colour Radiometry and Fisheries

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The food requirements of an expanding human population have increased the pressure on fisheries resources. In the last half century the world fish harvest has increased more than four-fold from 20 million tonnes in 1950 to 95 million tons in 2004 (FAO Fisheries Department, 2007). However, the number of overexploited or depleted stocks has increased, and the capture fishery production has, in fact, declined or remained static since 2000, reflecting over-harvest in many regions (Hilborn *et al.*, 2003). Better fisheries management, through a deeper understanding of marine ecology, is needed to maximize the utility of living marine resources now and into the future. A major challenge for fisheries scientists is distinguishing fluctuations caused by human activities (such as overexploitation, habitat alteration and pollution) from natural environmental variability. Over 100 years ago with the formation of the International Council for the Exploration of the Seas (ICES), the fundamental question of what drives the interannual variability of fish stocks was first posed, and still has not been adequately resolved (Kendall and Duker, 1998; Bakun and Broad, 2003; Anderson *et al.*, 2008).

In the broadest sense, fisheries science encompasses not just commercial fish stocks, but all living marine resources, including efforts to help recover threatened and endangered species. Satellite data can be used to characterize the habitat and ecosystem properties that influence marine resources at large temporal and spatial scales, and high temporal and spatial resolution. There are two primary ways that ocean-colour data are used for fisheries management. One is to monitor the environment, with a view to better understand ecosystem processes or stock biology. The other is to locate populations of fish, with a view to increase fishing efficiency or enhance conservation by mitigating human interactions. Additionally, ocean-colour data are used to monitor a number of issues that impact fisheries, such as harmful algal blooms and coastal pollution, which are discussed in further detail elsewhere in this volume.

6.1 The Oceanic Food Web

Satellite chlorophyll provides an index of phytoplankton biomass, which is the base of the oceanic food web, as depicted in simplified form in Figure 6.1. The relationship between satellite chlorophyll data and a specific fish stock depends upon the number of linkages between phytoplankton and the higher trophic level. For some species, such as anchovies and sardines, which eat phytoplankton at some points in their life cycle, the linkage can be direct (Ware and Thomson, 2005), whereas for other species there are many trophic levels in between, and the relationship can be quite non-linear. There can also be spatial disconnects between satellite measurements of the ocean surface and demersal and deep-water species. Nonetheless, chlorophyll is the only

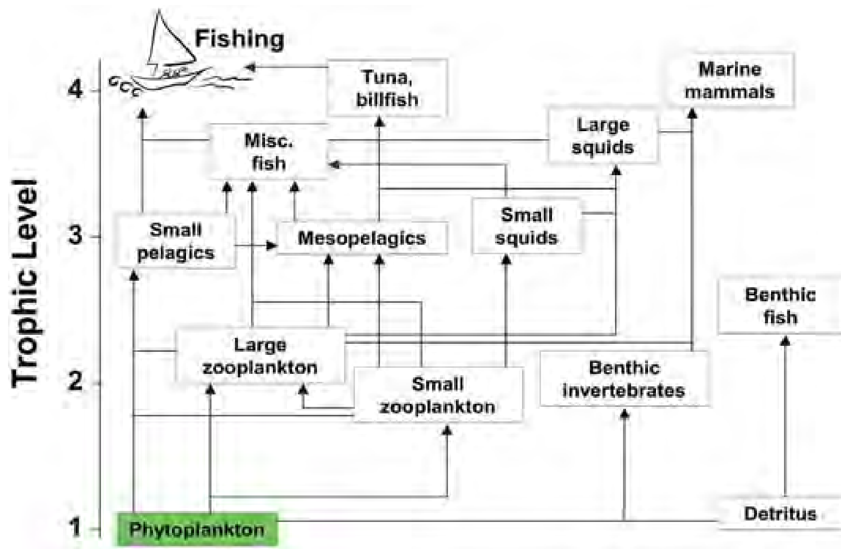

Figure 6.1 Simplified oceanic food web, showing the varying complexities in the linkages between phytoplankton, measured by satellite ocean-colour data, and higher trophic levels. Modified from Pauly and Christensen (1995).

biological component of the marine ecosystem accessible to remote sensing, and as such it provides a key metric to measuring ecosystems on a global scale. Satellite chlorophyll measurements are the primary component in algorithms to calculate the primary productivity (PP) of the ocean. Global PP measurements, in conjunction with fish catch statistics and food web models, such as shown in Figure 6.1 can be used to estimate the carrying capacity of the world's fisheries. In the open ocean 2% of the PP is needed to support the fishery catch, but in coastal regions the requirement ranges from 24-35%, suggesting that these systems are at or beyond their carrying capacity (Pauly and Christensen, 1995), which is cause for concern as the bulk of the world's fish catch comes from coastal areas. In a similar manner, discrepancies between the values of satellite derived PP and reported fish catches have been used to demonstrate spurious trends in global fish catches as reported by the Food and

Agriculture Organization (FAO) of the United Nations (Watson and Pauly, 2001). In this instance satellite ocean-colour data provide an important objective baseline against which to gauge data that can have socio-economic biases.

There is growing awareness that the long-standing approach to fisheries management which focuses on a specific species is inadequate (Browman and Stergiou, 2005; Sherman *et al.*, 2005). Interactions with other species, complex predator-prey dynamics, and temporal and spatial variability in physical aspects of the ecosystem all need to be incorporated into an ecosystem-based approach to management. Although not all of these aspects can be addressed by satellite data, the high spatial and temporal resolution of satellite ocean-colour data make it an efficient tool to characterize and monitor marine ecosystems to better manage them. For example, satellite-derived primary productivity is one of the indicators used in the assessment of Large Marine Ecosystems (LME) (Sherman *et al.*, 2005).

6.2 Recruitment

A fundamental issue in fisheries oceanography is understanding how environmental variability affects annual recruitment, the number of new individuals entering a stock. Most fish have planktonic larval stages that are strongly influenced by ocean circulation and can have narrow ranges of optimal thermal conditions. Availability of a suitable food source is important for successful recruitment and hence many fish reproduce near the seasonal peak in phytoplankton abundance. A long-standing hypothesis in fisheries has been that recruitment success is related to the degree of timing between spawning and the seasonal phytoplankton bloom, the Cushing-Hjort or match-mismatch hypothesis (Cushing, 1990). This hypothesis has been difficult to address with traditional shipboard measurements that have limited spatial and temporal resolution, but with satellite ocean-colour data, interannual fluctuations in the timing and extent of the seasonal bloom can be clearly seen. In an application on the Nova Scotia Shelf, the timing of the spring bloom determined from satellite ocean colour was compared with available *in situ* data on larval survival of haddock, an important commercial fish species. Comparison of these two independent data sets indicated that highly successful year classes of haddock are associated with exceptionally early spring blooms of phytoplankton (Fig. 6.2), confirming the match-mismatch hypothesis (Platt *et al.*, 2003). A comparable study has also documented a relationship between the timing of the spring bloom and the growth rate of shrimp (Fuentes-Yaco, 2007). These studies demonstrate that it is possible to separate ecosystem-associated variability in fish stocks from other components, such as human exploitation or predation effects. The satellite-derived time series permits the extraction of value-added products, in this case the timing of the seasonal biological cycle.

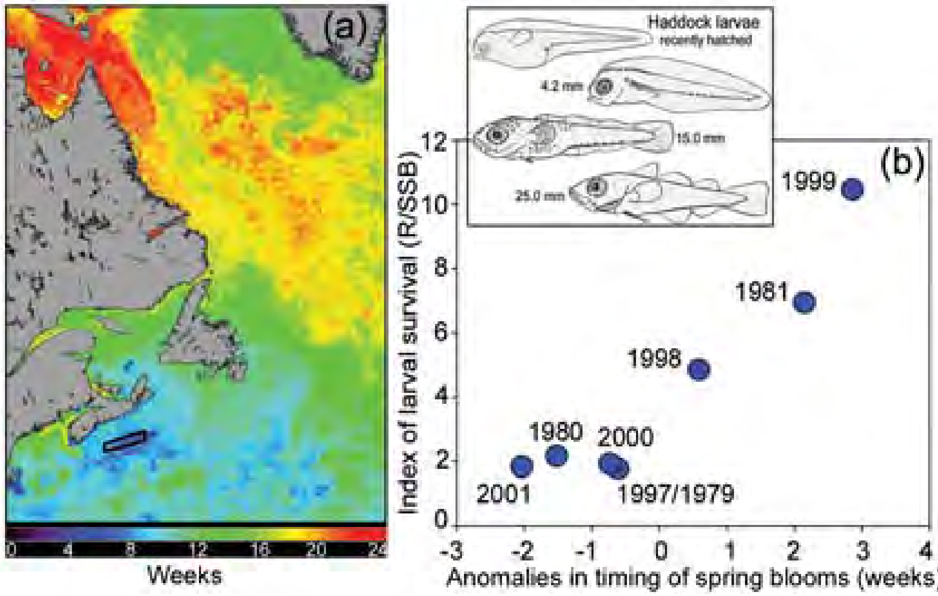

Figure 6.2 (a) Timing of the maximum phytoplankton biomass in the NW Atlantic from February to July, derived from SeaWiFS climatology (1998-2001). Units in weeks; blue indicates early spring bloom (March), red indicates late spring bloom (July). Image provided by César Fuentes-Yaco, Dalhousie University, Canada. (b) Relationship between larval haddock survival index (normalized to recruitment) and local anomalies in bloom timing. Data from the continental shelf off Nova Scotia (see black rectangle on map) for the periods 1979-1981 and 1997-2001, adapted from Platt *et al.* (2003).

6.3 Harvesting

Locating and catching fish is becoming more challenging as easily accessible fish stocks dwindle. As search time increases, so does cost. Satellite data can help to increase the efficiency of fishing efforts by identifying oceanographic features that are sites of fish aggregation and migration such as temperature fronts, meanders, eddies, rings and upwelling areas (Laurs *et al.*, 1984; Fiedler and Bernard, 1987; Chen *et al.*, 2005). Fishermen have been using SST from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar orbiting satellite for the past 20 years. Fishermen also use remotely-sensed ocean-colour maps at sea to guide fishing effort. Thermal or colour gradients often indicate sites of high biological productivity. Temperature is also an important factor determining the distribution of fish, as different species have different preferred temperature ranges.

To be of practical use to the fishing industry, satellite ocean-colour data must be available in a near-real time basis. There are differences between countries in how satellite data is disseminated to users. While in some countries, notably Japan and India, the national fisheries agencies are actively involved with helping to increase the efficiency of their fishing fleets. NOAA Fisheries in the USA is not allowed to provide services such as distributing 'fish finding maps' that would compete with commercial interests. For example, the SeaWiFS satellite is privately owned, and its chlorophyll data is only available on a real-time basis to commercial subscribers. Clients of the service company can receive custom-tailored maps of ocean colour, as well as other oceanic properties derived from satellite data, directly onboard their fishing vessel. In contrast, data from the Indian IRS-P4 ocean-colour sensor (in conjunction with satellite SST from AVHRR) is used operationally to produce maps of potential fishing zones (PFZs).

6.3.1 Potential Fishing Zones: The Indian Experience

Methods for locating potential fishing zones (PFZ) in India 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, Narain *et al.* 1990) known to be conducive to fish aggregation. This approach has the

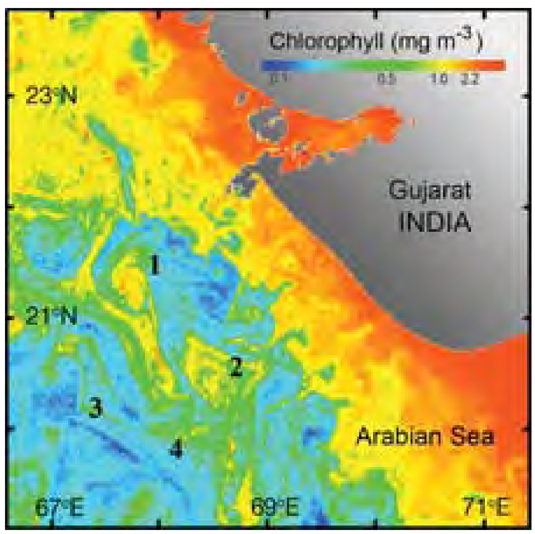

Figure 6.3 Chlorophyll image of northwest India on 29 February 2006 generated from the Indian OCM sensor. Oceanic features such as cyclonic eddies (1 and 2 on the image) and fronts (3 and 4) are known to be productive sites and are hence relevant for fishery exploration (Credit: R.M. Dwivedi, Indian Space Research Organisation, India).

basic limitation that SST images provide data on the temperature of the surface skin only (upper ten microns). Heating of sea surface, particularly in equatorial and tropical waters during summer, gives rise to strong stratification of the water column, preventing arrival of cool nutrient rich waters from deeper layers to the surface. This, in turn, inhibits appearance of SST gradients in the satellite imagery. For this reason, SST images are not always adequate for identification of potential fishing zones. Another problem with detection of thermal features is that surface frontal structures may be perturbed by prevailing surface winds or currents of even moderate magnitude (Dwivedi *et al.*, 2005).

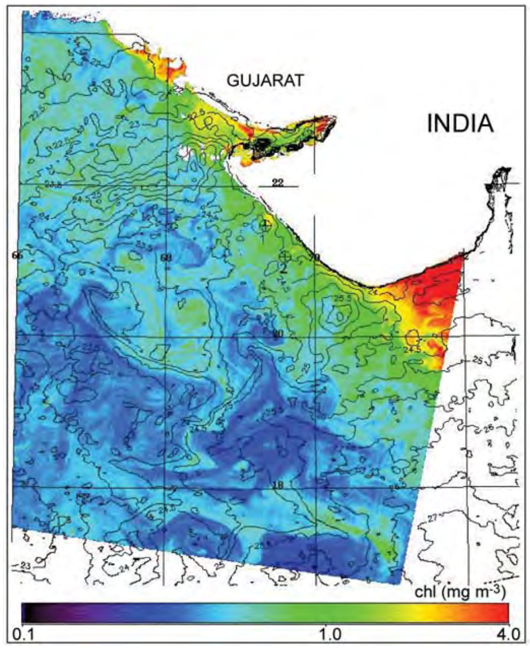

Figure 6.4 An example of a chlorophyll map overlaid with SST contours, for detection of Potential Fishing Zones (PFZ). The chlorophyll image was captured by India's IRS-P4 OCM sensor on 29 February 2000 off the west coast of India (Credit: Space Applications Centre, Indian Space Research Organisation, India.)

Unlike thermal sensors, ocean-colour sensors can detect signals from below the surface due to penetration of visible radiation down to one attenuation depth (typically metres to tens of metres), and thus have advantages over the SST-based approach for fishery applications. One of the benefits of water penetration capability of visible radiation is that it provides the ability to predict occurrence of oceanic features such as diverging fronts and eddies (Fig. 6.3). These features are known to be the most reliable indicators of potential fishing zone (Laurs *et al.* 1984). It also enables detection of variations in biomass in a column at different stages of feature development in serial chlorophyll images. This advantage was exploited to develop the ability to anticipate formation of oceanic features such as eddies, at least two days before their actual occurrence. Verification of the experimental forecasts with inclusion of ocean colour proved superior to those using SST alone in terms of rate of success and magnitude of fish catch. Secondly, chlorophyll images, unlike those of SST, reveal many more frontal structures, given the penetration capability of visible radiation. Moreover, unlike SST, the ocean-colour front detected from chlorophyll image is a true biological front and hence, relevant to exploration for fish.

Two approaches are routinely used by the Indian National Centre for Ocean Information Services (INCOIS) to identify potential fishing zones. In the first approach,

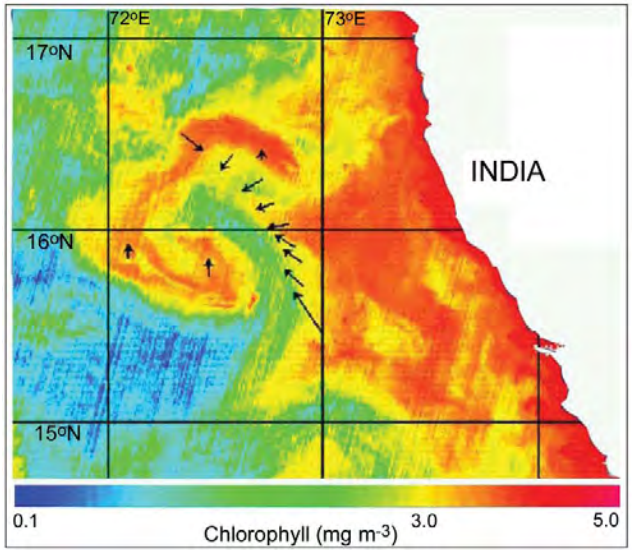

Figure 6.5 This image shows chlorophyll concentrations off the west coast of India, captured by India's OCM sensor onboard the Oceansat-1 satellite on 17 November 1999 . Arrows indicate areas where fishing was conducted (Credit: Space Applications Centre, Indian Space Research Organisation, India).

SST contours derived from NOAA-AVHRR data are overlaid on chlorophyll images generated from the Indian OCM sensor, to enable identification of matching features revealed by corresponding gradients (Solanki *et al.* 2000) (Fig. 6.4). This method has provided consistent positive feedback, although frontal structures common in both SST and chlorophyll images are generally few in number. There are many more features detectable from a chlorophyll image for which there is no matching counterpart in SST images, so the second approach uses satellite chlorophyll data alone, especially when relatively sparse thermal gradients are detected in SST imagery (Fig. 6.5). Selective use of these additional features from ocean-colour imagery has successfully enabled identification of potential fishing zones, and is a major contribution to the improved fishery forecast in Indian waters. Nayak *et al.* (2003) carried out a cost benefit analysis to assess the impact of using satellite PFZ forecasts on fish catch. The benefit-to-cost ratio (*i.e.* value of the fish catch vs. cost of fishing and generating PFZ charts) was found to be greater than one, indicating that the use of satellite data improves the economics of fish catch.

Using the above approaches, INCOIS generates PFZ advisories three times a week, providing information such as latitudes and longitudes of the areas of potential fish abundance, and the distance and direction from different fishing harbours. This information is freely disseminated to local fishermen around the coast of India by fax, phone, internet, electronic display boards, newspaper and radio broadcasts in local languages. In order to maintain fish stocks at a sustainable level, PFZ advisories are not provided during the monsoon season (June-September), which coincides with the peak breeding season, and also with heavy cloud cover. These advisories have helped to reduce search time by up to 70%, and have significantly increased the catch per unit effort (Solanki *et al.*, 2003; Zainuddin *et al.*, 2004). This is a prime example of how satellite data can be put to effective use to ensure that the advantages of science and technology directly benefit society.

6.3.2 Pelagic and Migratory Fish: A Japanese Case Study

In the northwest Pacific, Skipjack tuna, a pelagic and highly migratory fish, are at the top of the pelagic food chain and support a valuable commercial fishery (Iizuka *et al.*, 1989; Shetty *et al.*, 1993). Skipjack tuna migrate between the subarctic (Oyashio) and the subtropical (Kuroshio) waters in the western Pacific (Kawasaki and Omori, 1995; Watanabe *et al.*, 1995), while planktivorous fish, such as Japanese sardine, Chub mackerel and Pacific saury also migrate between the two regions (Yasuda and Watanabe, 1994; Taniguchi, 1999). Satellite-borne sensors, such as the

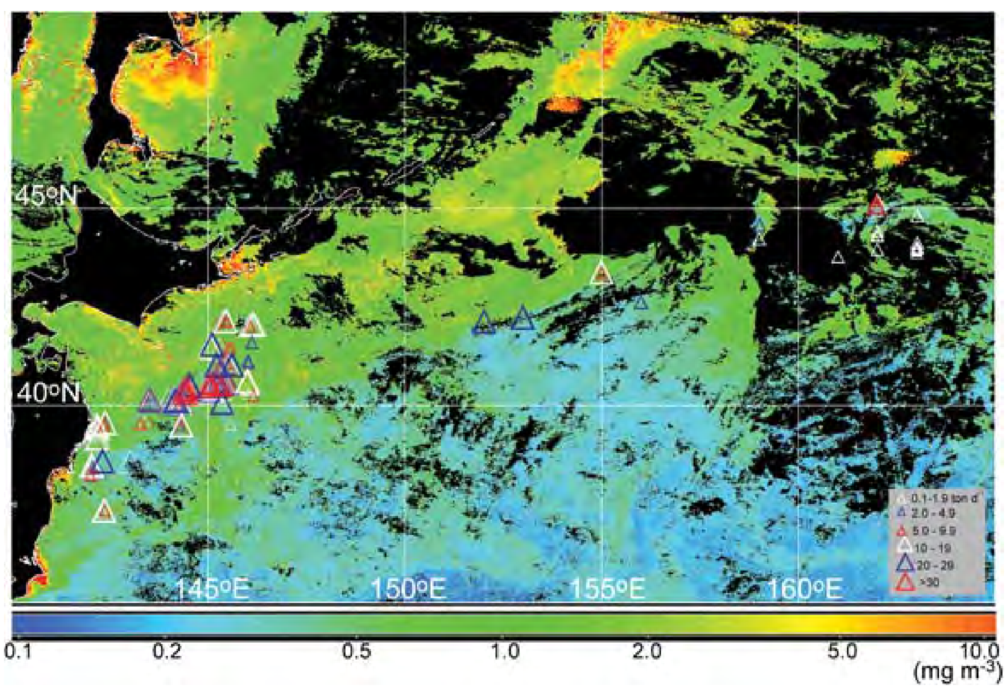

Figure 6.6 Distribution of Chl-a concentrations for 23-29 September, 2000, observed by SeaWiFS, and Skipjack tuna catches by fishing boats (in tonnes). The size of the triangles indicates the landings (tonnes per day). Image provided by Ichio Asanuma, Tokyo University, Japan.

Japanese Ocean Colour Temperature Scanner (OCTS), have been used to monitor the distribution of Chl-a with respect to the distribution of fish (Ishizaka, 1998; Asanuma *et al.*, 2003). In the northwest Pacific, complex mixing processes have been observed between the warm, nutrient-depleted water from the Kuroshio and the cold, nutrient-rich water from the Oyashio (Saitoh *et al.*, 1998). In general, the warmer Kuroshio water has a low Chl-a concentration while the colder Oyashio water has a high Chl-a concentration, with complex variability in regions of mixing (Yoshimori *et al.*, 1995; Ono *et al.*, 1998).

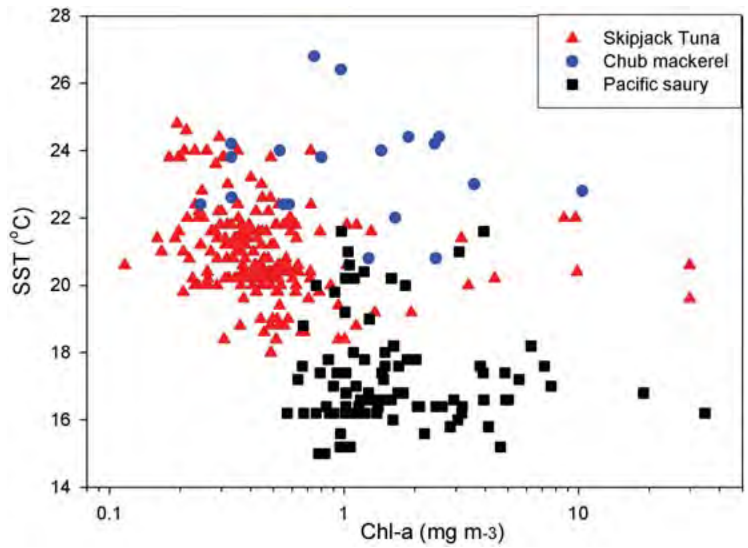

Figure 6.7 Distribution of Skipjack tuna, Chub mackerel and Pacific saury as a function of Chl-a and SST. Chl-a was obtained from SeaWiFS data, while SST was derived from NOAA-AVHRR data. Average SST and Chl-a concentrations were 21.0°C and 0.46 mg m^{-3} for Skipjack tuna, 23.0°C and 0.99 mg m^{-3} for Chub mackerel, and 17.2°C and 1.54 mg m^{-3} for Pacific saury. The study area encompassed 35°N to 45°N and 140°E to 150°E over the period 23-29 September, 2000. Image provided by Ichio Asanuma, Tokyo University, Japan.

In an experiment to assess the utility of providing Chl-a imagery to fishermen to determine fishing grounds, the highest catches (> 30 tonnes) were reported between two warm core rings around 41°N and 145°E (Fig. 6.6). Slightly lower catches (10 - 19 tonnes) were reported around 42°N and 153°E, along the boundary of the high Chl-a Oyashio and the low Chl-a Kuroshio. Very low catches of Skipjack tuna (2 to 4 tonnes) were evident further east (around 156°E) in the warmer, nutrient-depleted waters. Planktivorous Pacific saury and Chub mackerel were caught in water masses with high Chl-a concentrations (Fig. 6.7), although they tend to prefer different temperature ranges, with a mean temperature of 17.2°C and 23°C respectively. In contrast, Skipjack tuna catches occurred in a wide range of Chl-a concentrations (0.1 to 10 mg m^{-3}) and in temperatures ranging from 18°C to 25°C. Nonetheless, the majority of Skipjack tuna were caught in lower Chl-a waters (mean 0.46 mg m^{-3}), which corresponds to the warm core rings originating from the Kuroshio (mean temperature 21.0°C).

6.4 Species of Conservation Concern

6.4.1 Right Whales

One of the most endangered marine species is the Northern right whale (*Eubalaena glacialis*), with an estimated population of 350 individuals (International Whaling Commission, 1998; Kraus *et al.*, 2005). Although historically right whale populations were severely depleted by commercial whaling, at present the principal cause of mortality in the North Atlantic is from ship strikes (National Marine Fisheries Service, 2005). The primary habitat of the North Atlantic right whale is in coastal or shelf waters, which also experience heavy ship traffic. The recovery plan of NOAA (USA) for this species has focused on developing methods to identify the locations of right whale populations, and then to reduce ship traffic in these regions and lessen the number of whale-vessel collisions. This plan involves both limiting fishing in certain areas when whales are typically abundant, a procedure known as seasonal area management (SAM), and another strategy known as dynamic area management (DAM), with a synoptic level of control. Under DAM, if a group of whales is identified, NOAA Fisheries will limit activities in the area. Currently, research is underway to improve both management strategies by predicting the location of right whale congregations using satellite measurements of SST and ocean colour (Pershing *et al.*, 2008). The distribution of right whales is strongly correlated with the distribution of their prey, which appears to be primarily calanoid copepods (Kenney *et al.*, 2001). Satellite-derived chlorophyll data is a reasonable proxy for copepod egg production, and is analyzed in conjunction with SST data to estimate the development time of copepods, and model data to understand circulation patterns, to ultimately predict areas where whale aggregation is likely. This project is moving from proof of concept to operations, and daily *Calanus* distributions and right whale estimates should be available shortly. The science team is working with NOAA Fisheries to incorporate the products into right whale management.

6.4.2 Loggerhead Turtles

Satellite ocean-colour data, in conjunction with telemetry data from tagged sea turtles have shown that in the North Pacific, the Transitional Zone Chlorophyll Front (TZCF) is an important foraging ground and migration pathway for endangered loggerhead turtles (Polovina *et al.*, 2004). These turtles follow the TZCF, and spend time foraging in the high chlorophyll eddies that are associated with meandering of the front (Fig. 6.8). Other apex predators such as albacore tuna also use the front as a migratory corridor (Laurs and Lynn, 1991; Polovina *et al.*, 2001). The degree of meandering of the TZCF seems to impact trophic transfers and the level of productivity associated with the front. Periods with more meandering of the front have had significantly higher catch per unit effort (CPUE) of albacore, suggesting that the enhanced convergence creates more productive foraging grounds (Polovina

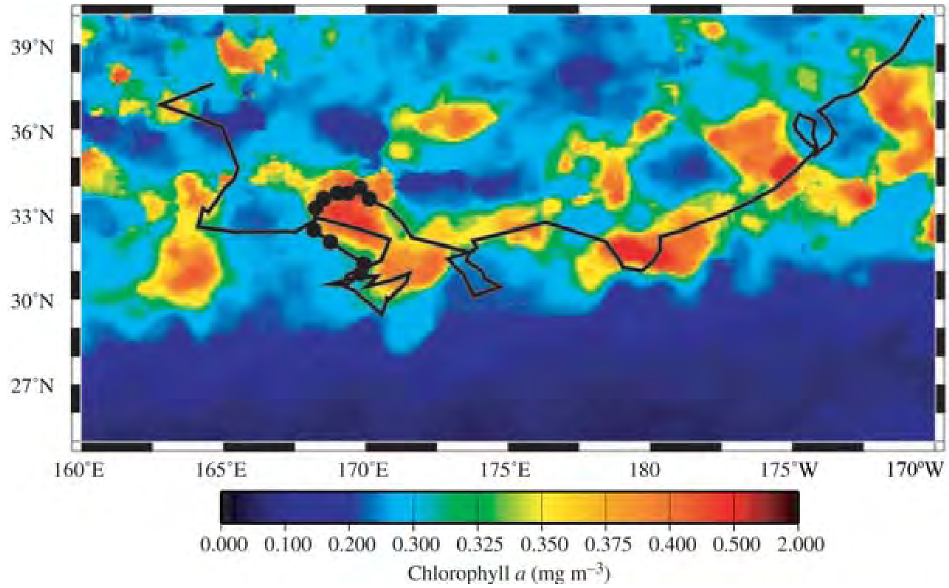

Figure 6.8 Track of a tagged Loggerhead turtle (black line) overlain on SeaWiFS chlorophyll data along the Transitional Zone Chlorophyll Front in the North Pacific Ocean. Figure adapted from Polovina *et al.* (2004), reproduced with permission of Blackwell Publishing Ltd.

et al., 2001). Interannual variability in the southern extent of the TZCF impacts the survival of juvenile monk seals in the Hawaiian islands (Baker *et al.*, 2007).

Extracting information about animal habitat by using satellite telemetry location in conjunction with environmental satellite data has been used on a variety of species. For example the Census of Marine Life program, Tagging of Pacific Predators (TOPP), is involved with tagging a suite of more than 20 marine predators and integrating the tagging information with satellite data to better understand the animal's habitat usage (Block *et al.*, 2003). Relating the movements and activities of these animals to satellite-derived features is an important advancement toward understanding environment-population linkages in marine ecosystems.

6.5 Summary and Conclusions

Satellite data characterize oceanic properties of habitat and ecosystems that influence living marine resources at spatial and temporal resolutions that are impossible to achieve any other way. The high spatial resolution provides an important geographical context for interpreting other data and results. The daily-to-weekly temporal resolution allows for effective monitoring of many oceanic features and permits the extraction of value-added products such as the timing of seasonal events. Time series of science-quality satellite data are needed to understand linkages between climate and ecosystems, and to characterize and monitor ecosystems as part of an ecosystem-based approach to fisheries management. For example, satellite chlorophyll can be used to observe changes in the timing of the spring bloom that can affect recruitment (Platt *et al.*, 2003), to classify the productivity of the oceans (Sherman *et al.*, 2005), to detect interannual differences in the frontal structures that are important to fisheries (Bograd *et al.*, 2004; Polovina *et al.*, 2001) and to map the spatial extent of the ocean experiencing lower productivity during an El Niño event (Wilson and Adamec, 2001). Near-real-time satellite data are needed to optimize sampling for fisheries survey cruises for management and stock assessment and also to increase the efficiency of fishing effort.