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Fisheries applications of remote sensing: An overview

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ABSTRACT

During the past 40 years the fisheries productivity of the world has been declining due to pressures from overfishing, habitat change, pollution, and climate change. Sustainable use of marine resources requires effective monitoring and management of the world's fish stocks. Remote sensing techniques are being used to help manage fisheries at sustainable levels, while also guiding fishing fleets to locate fish schools more efficiently. Fish tend to aggregate in ocean areas that exhibit conditions favored by specific fish species. Some of the relevant oceanographic conditions, such as sea surface temperature, ocean color (productivity) and oceanic fronts, which strongly influence natural fluctuations of fish stocks, can be observed and measured by remote sensors on satellites and aircraft. The remotely sensed data are provided in near-real time to help fishermen save fuel and ship time during their search for fish; to modelers who produce fisheries forecasts; and to scientists who help develop strategies for sustainable fisheries management. This article describes how acoustic, optical and radar sensors on ships, satellites and aircraft are used with forecast models to improve the management and harvesting of fisheries resources.

1. Introduction and background

Fish stocks are an important high-protein food source for mankind, yet world fisheries are under increasing pressure factors related to the growth of the human population, including overfishing, global climate change, pollution, and habitat degradation. About 40 years ago, ocean productivity began declining, having reached Maximum Sustainable Yield. Nearly 80% of the world fish stocks are now either fully exploited or overexploited (FAO, 2009). Moreover, world demand for seafood has been rising everywhere, both in developed countries due to increasing standards of living, as well as less-developed countries, whose population keeps growing rapidly (A.P.T., 2006).

Sustainable use of marine resources requires effective monitoring and management of entire ecosystems, not just exploited fish stocks. Conventional approaches of sampling the ocean using research vessels are limited in both time and space scales of coverage, making it difficult to study the entire ecosystem. Since the advent of satellite remote sensing, especially remote sensing of ocean color and temperature, it has become possible to sample the global ocean on synoptic scales and with acceptable temporal resolutions. For example, satellite data on chlorophyll concentrations and sea surface temperature (SST) have been used to delineate regions, or ecological provinces, in the ocean with similar physical and biological forcing. These ecological provinces are not fixed in time or space, but vary seasonally and inter-annually. The instantaneous boundaries of these ecological provinces can contribute to our understanding of ecosystem characteristics and can highlight the changes that happen due to short- and long-term environmental variations which can frequently be observed in satellite-derived patterns of ocean temperature and productivity. These changes can affect the recruitment, survival, condition, distribution patterns and migration of fish stocks (Chassot et al., 2011; Moore et al., 2009; Longhurst, 2010; Oliver and Irwin, 2008; Stuart et al., 2011a,b).

There is also a wide range of practical fisheries-related applications of remotely sensed data, including by-catch reduction, detection of harmful algal blooms, aquaculture site selection, identifying marine managed areas, and describing habitat changes. Newly developed satellite remote sensing techniques, combined with in situ measurements, constitute the most effective ways for efficient management and controlled exploitation of marine resources. The satellite data are also used successfully in oceanographic and meteorological forecasting, which improves scientific knowledge and safety of operations at sea (Santos, 2000; Tyler and Rose, 1994).

Many species of oceanic fish tend to band together in large schools (shoals) that can span tens of kilometers and involve many millions of individuals. Aggregating into large schools of fish offers survival advantages such as enhanced spawning, predator avoidance, and feeding improvements (Makris et al., 2009). Finding fish schools and productive fishing areas is the main cause of fuel consumption and ship time expense in many commercial fisheries. In

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order to lower the cost of fishing operations, there is a need to accurately predict and detect economically fishable aggregations of fish in space and time. Remote sensing, like a two-edged sword, can be used not only to help manage fisheries at sustainable levels, but also guide fishing fleets to increase their catch. Early studies showed that satellite-derived fishery-aid charts can reduce 25–50% of some US commercial fisheries search time (Laurs et al., 1984). Wright et al. (1976) found that the average catches of coho salmon off the Oregon coast were double in forecast areas detected by airborne remote sensors, as compared to non-forecast areas. There are many similar examples of improved fishing efficiency when remotely sensed data are provided to fishing fleets and included in predictive models (Carr, 2001; Castillo et al., 1996; Dagorn et al., 1997; Santos, 2000; Stretta, 1991; Zainuddin et al., 2006). Therefore, it becomes obvious that remote sensing can play an important role in guiding fleets to optimal fishing grounds, resulting in a more efficient fishing effort with greater economic returns.

Fish and fish schools can be seen directly from spotter planes, but not from satellite altitudes. However, satellites can be used to locate and predict potentially favorable areas of fish aggregation based on remotely detectable environmental indicators. These indicators may include ocean fronts, separating waters of different temperature or color; upwelling areas, which are cooler and more productive (greener) than background waters; specific temperature ranges preferred by certain fish, *etc*.

Santos (2000) summarizes the advantages of using remote sensing to aid fishing activities as follows: (1) saving fuel while searching for fish schools; (2) lower crew expenses as a consequence of spending fewer days at sea; (3) lower costs of ship maintenance and improved safety at sea.

2. Environmental indicators of fish distribution

Variations in environmental conditions affect the recruitment, distribution, abundance and availability of fish. Therefore, any use of environmental data for the preparation of oceanographic analyses and forecasts in support of fishery operations will depend on an adequate understanding of the complex linkage between marine environmental and biological processes (Makris et al., 2009). Specific conditions and processes affecting fish populations may often be deduced from measurements made by remote sensors. Remote sensors can provide a broad range of indices of ecosystem status, including a compact description of the pelagic ecosystem at a given time and place (Platt and Sathyhendranath, 2008; Platt et al., 2008).

The specific environmental parameters most commonly measured from airborne and satellite remote sensors include: surface temperature; surface optical or bio-optical properties (ocean color, diffuse attenuation coefficient, total suspended matter, yellow substance, chlorophyll pigments); salinity; vertical and horizontal circulation, including fronts and gyres; oil pollution; wind and sea state. Information about these environmental/ecological “indicators” helps to forecast fish location, distribution and behavior (Chen et al., 2005; Laurs et al., 1984; Laevastu and Favorite, 1988; Polovina and Howell, 2004; Simpson, 1992).

Since the complex interactions between the marine environment and its organisms are still poorly understood and difficult to investigate, information is being gathered from various sources and research is conducted to try to relate environmental ocean properties to the distribution and abundance of fish (FAO, 1999; Holland et al., 1990). Fishermen are well aware of how to take advantage of their empirical knowledge about the generally observed correlation of fish distribution with ocean features, especially those related to water temperature. For instance, with the observational support by fishermen, scientists have studied the relationship between the distribution of swordfish, tuna and sardine off the mainland of Portugal and oceanographic parameters, mainly SST and its horizontal gradients. Some typical results of these early investigations were: (1) sardines tend to concentrate in moderately cool upwelled waters on the inner shelf off Portugal (Santos and Fiuza, 1992); (2) swordfish fishing success was higher near frontal structures associated with events of intensification/relaxation of coastal upwelling (Santos, 2000); (3) larger catches of tuna occurred mainly in association with persistent and strong upwelling events, and were particularly concentrated within shoreward intrusions of warm oceanic waters into the cool upwelling ones, and also along the edge of mushroom-like structures associated with offshore filaments of upwelled waters (Santos, 2000).

Water temperature and its fluctuations is the environmental parameter used most often in investigations of relationships between the environment and fish behavior and abundance (Kellogg and Gift, 1983; Ramos et al., 1996). Many fish species can perceive water temperature changes as small as 0.1 °C and temperature can impact fish in many different ways. Temperature affects the rates of metabolic processes and thus modifies their activity level. Growth, feeding rates, swimming speed, and spawning time are directly influenced by the water temperature. Temperature influences fish species at different stages of their life cycles, for instance, during spawning, and at the development and survival of the eggs and larvae, as well as influencing distribution, aggregation, migration and schooling behavior of juveniles and adults (Gordoa et al., 2000; Laevastu and Hayes, 1981; Sund et al., 1981).

SST has often been used to relate the oceanic environment to tuna distribution. Laevastu and Rosa (1963) give thermal limits for yellowfin tuna from 18 to 31 °C, with a fishery optimum between 21 and 24 °C. For skipjack and for big eye tuna these authors give a thermal interval from 17 to 28 °C and from 11 to 28 °C, respectively, with fishery optima between 20 and 22 °C and between 18 and 22 °C, respectively. In the Tropical Atlantic Ocean, yellowfin and skipjack tuna are caught in waters where SST is between 22 and 29 °C (Stretta and Slepoukha, 1983). Furthermore, 69% of the set containing yellowfin and 62% of the set containing skipjack take place in waters with a temperature higher than 25 °C.

The distribution of tuna catches in relation to SST also depends on the seasons and geographical areas. For instance, off Cape Lopez, Gabon, in the summer tuna are caught between 23 and 25 °C, and off Ghana the main part of the catch during winter is made between 27 and 29 °C (Stretta, 1989). Hake, jack mackerel, anchovy, sardine and swordfish have also been found to respond to changes in water temperature (Gordoa et al., 2000).

Another important environmental parameter for assessing marine fisheries resources is phytoplankton biomass, since this is the primary source of food within the sea (Zainuddin et al., 2004). Primary production is a key index of local carrying capacity, and phytoplankton production has been shown to be related to fish landings (Chassot et al., 2011; Ware and Thomson, 2005).

The concentration of chlorophyll (chl) pigments, which are the photosynthetic pigments of phytoplankton, is often considered an index of biological productivity. Chlorophyll concentrations above 0.2 mg/m^3 indicate the presence of sufficient planktonic activity to sustain a viable commercial fishery (FAO, 2003; Gower, 1986). For instance, bluefin tuna schools spotted during aerial surveys in the Gulf of Lions seemed to aggregate along fronts separating productive (greenish) waters from less productive (blue) waters, which also displayed a difference in temperature. Dynamical ecological processes, such as foraging, seem to have contributed to this tuna aggregation near temperature/productivity fronts (Royer et al., 2004; Ryan et al., 1999).

Satellite or airborne measurement of spectral reflectance (ocean color) is an effective method for monitoring phytoplankton by its proxy, concentration of chlorophyll-*a*, the green pigment (Morel and Gordon, 1980; Schalles et al., 1998; Schofield et al., 2004;