since 1961

Baltica

http://www.geo.lt/geo/index.php?id=71C

BALTICA Volume 25 Number 2 December 2012 : 99–112

doi:10.5200/baltica.2012.25.10

Remote sensing of environmental indicators of potential fish aggregation: An overview

Victor Klemas

Klemas, V., 2012. Remote sensing of environmental indicators of potential fish aggregation: An overview. *Baltica, 25 (2), 99-112.* Vilnius. ISSN 0067-3064.

Manuscript submitted 31 July 2012 / Accepted 3 October 2012 / Published online 10 December 2012

Abstract Sustainable use of marine resources requires effective monitoring and management of the world's fish stocks. Acoustic and electromagnetic 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, aircraft and ships. 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.

Keywords *• Fisheries remote sensing • Fish environmental indicators • Fisheries management • Acoustic fish detection • Fisheries forecasts*

✉ *Victor Klemas [klemas@udel.edu], School of Marine Science and Policy, University of Delaware, Newark, DE 19716, U.S.A.*

INTRODUCTION AND BACKGROUND

Fish are an important high-protein food source for mankind, yet world fisheries are under increasing pressure from 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. Most of the world's fish stocks are now either fully exploited or overexploited (FAO, 2009). 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 entire ecosystems. Since the advent of satellite remote sensing, especially remote sensing of ocean color and temperature, it has become possible to sample the global ocean over large areas 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. 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. These changes can affect the recruitment, survival, condition, distribution patterns and migration of fish stocks (Chassott *et al.* 2011; Longhurst 2010, Oliver, Irwin 2008; Stuart, Platt, Sathyendranath 2011).

There are also many 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, 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 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 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, Barbieri, Gonzalez 1996; Dagorn, Petit, Stretta 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.

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, Sathyendrath 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, Lee, Tzeng 2005; Laurs, Fiedler, Montgomery 1984; Laevistu, Favorite 1988; Polovina, 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 (Holland, Brill, Chang 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 sea surface temperature (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, 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 are the environmental parameters used most often in investigations of relationships between the environment and fish behavior and abundance (Kellogg, Gift 1983; Ramos 1996). Many fish species can perceive water temperature changes as small as 0.1 deg 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, Maso, Voges 2000; Sund *et al.* 1981).

SST has often been used to relate the oceanic environment to tuna distribution. Laevistu and Rosa (1963) give thermal limits for yellowfin tuna from 18 deg to 31 deg C, with a fishery optimum between 21 and 24 deg C. For skipjack and for big eye tuna these authors give a thermal interval from 17 deg to 28 deg C and from 11 deg to 28 deg C, respectively, with fishery optima between 20 deg and 22 deg C and between 18 deg and 22 deg C, respectively. In the Tropical Atlantic Ocean, yellowfin and skipjack tuna are caught in waters where SST is between 22 deg and 29 deg C (Stretta, 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 deg 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 deg to 25 deg C, and off Ghana the main part of the catch during winter **is** made between 27 deg to 29 deg C (Stretta 1989). Hake, jack mackerel, anchovy, sardine and swordfish have also been found to respond to changes in water temperature (Gordoa, Maso, Voges 2000).

Another important environmental parameter for assessing marine fisheries resources is phytoplankton biomass, since this is the primary source of food within the sea (Zainudhin, Saitoh, Saitoh 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*. 2007; Ware, 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/ cu.m indicate the presence of sufficient planktonic activity to sustain a viable commercial fishery (FAO, 2003). 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, Fromentin, Gaspar 2004).

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 (Schofield *et al.* 2004). When light enters water, it is absorbed and scattered by pure water, dissolved organics and organic/inorganic particles (Martin 2004). Pure water scatters the blue portion of the sunlight spectrum, causing non-productive areas of the ocean to appear blue. Chlorophyll pigments have a distinctive spectral reflectance signature since they absorb blue (and red) light and strongly reflect the green, thus causing waters to turn from blue (unproductive) to green (productive). Multispectral observations from aircraft and satellites, therefore, allow the estimation of phytoplankton concentration.

Most open ocean regions have low primary productivity and appear blue in satellite images. In coastal upwelling regions and areas near river mouths the water appears greener, since the nutrients added from the sea bottom and river run-off produce waters having high plankton concentrations and high primary productivity (FAO, 2003; Montes-Hugo *et al.* 2005). Coastal and estuarine waters can also have high concentrations of suspended sediments and dissolved organics, making it difficult to remotely measure the concentrations of any of the dissolved or particulate substances (Cannizzaro, Carder 2006; Chang *et al.* 2004; Gitelson, Kondratyev 1991)**.**

The observed association of some fish species with ocean thermal structures cannot be explained by temperature alone, but also involve other behavioral aspects related to feeding activity (Laurs *et al.* 1984; Wright, Woodworth, O'Brien 1976). Thus the importance of sea surface temperature for operational fisheries oceanography is due mainly to the fact that it can be used as an indirect indicator of areas of fish forage concentration, that are also favorable zones for fish aggregation. Thermal fronts in particular seem to be associated with high concentrations of food for the fish (Andrade, Garcia 1999).

Frontal zones and eddy fields have been found as features attracting fish and larvae, and creating patchy zones of high phytoplankton concentrations (Kirobe *et al.* 1986; Lefevre 1986; Marshall *et al*. 1981; Sabates, Maso 1990). For instance, Laurs *et al*. (1984) found that albacore catch rates were highest in warm and blue oceanic waters, as measured from satellites, associated with the boundary (front) between oceanic and coastal waters. Shoreward intrusions of oceanic water coincided with sites of albacore aggregation. Tuna aggregation on the warm side of thermal fronts was explained by Laurs *et al.* (1984) as a behavioral mechanism related to the feeding activity, *i.e.* aggregation of the albacore in clear water on the oceanic side of fronts in near-shore areas reflects an inability to efficiently capture large, mobile prey in turbid coastal water and a dependence on food that has migrated across the coastal-oceanic boundary. The distribution and prevalence of anchovy, sardine and jack mackerel have also been associated with the occurrence of thermal and haline fronts (Castillo, Barbieri, Gonzalez 1996; Chassott *et al*. 2011; Fiedler, Bernard 1987; Kimura, Nakai, Sugimoto 1997; Logerwell, Smith 2001; Owen 1981).

A revealing study of the effect of thermal fronts on fish growth and aggregation via a bioenergetics evaluation of food and temperature was conducted by

Brandt (1993). He found that fish aggregations at fronts may be caused by either increased food availability or better thermal conditions at the front. Bioenergetic models were used to evaluate the growth rate potential of a cool-water fish, the Chinook salmon, and a warm-water fish, the striped bass, across thermal fronts of different temperatures and prey concentrations. When food was distributed uniformly across the front, the growth rates of both species were highest at their optimal temperatures, if sufficient prey was available. Lower temperatures were better for growth if prey availability was low. Increased food availability at the front enhanced the fish growth rate potential at the front. Actual growth rates depended on whether the fish behaviorally selected habitats by temperature, food, or growth rate potential. Results illustrate that prey patchiness and the nonlinearities in the relationship of fish growth to temperature and prey availability must be considered when evaluating the response of a fish population to a front (Brandt, 1993).

More recently, Zainuddin *et al*. (2006) used satellite SST and ocean color data to examine fishing grounds and showed that the areas of high probability (preferred biophysical environmental factors) correspond to the location of frontal zones and anti-cyclonic eddies where albacore prey were abundant. They also found that regions of tuna abundance occurred in relatively high eddy kinetic energy and geostrophic currents, showing that tuna aggregations were associated with anticyclonic eddies. These eddies may concentrate and trap albacore prey, producing productive fishing grounds (Zainuddin, Saitoh, Saitoh 2004). Sund *et al*. (1981) summarized the relationships between tuna distribution and abundance (larvae, juveniles and adults) and environmental properties of the Pacific Ocean, and tuna behavior in relation with their habitat (Santos 2000).

Another study investigated the relationship between yellowfin tuna caught in the tropical Atlantic by the northeast Brazilian longline fishing fleet and environmental variables obtained from remote sensors such as SST (AVHRR/NOAA), chlorophyll concentration (SeaWiFS/SeaStar), sea surface height anomaly (TOPEX/ Poseidon), and wind velocity (Scatterometer/ ERS-1 and -2). The relationships between catch data and satellite data were analyzed using statistical methods of generalized additive models (GAMs). The largest concentration of yellowfin tuna seemed to be associated with the Intertropical Convergence Zone (ITCZ) position and its temporal variability. Sea surface temperature, chlorophyll-a concentration and sea surface height anomaly were statistically significant, yet seemed to be of secondary importance in controlling yellowfin abundance in the region (Zagaglia, Lorenzzetti, Stech 2004).

Oceanographic features change with the seasons and inter-annually, influencing marine fish distributions. Prediction of these variations is essential for modeling of fish location, distribution and abundance. For instance, silver hake populations generally respond to environmental seasonal cycles, following similar water temperatures in winter and summer by changing their seasonal depth distribution.The influence of climate variations and environmental conditions on fish behavior has been reviewed by various investigators (Gordoa, Maso, Voges 2000; Laevastu, Favorite 1988).

Closer to shore, coral reef fisheries are important as a source of food and income in developing and developed countries. Understanding spatial variations in coral reef fish diversity, as well as community structures, is also critical for science and conservation of coral reef ecosystems. The diversity, abundance and distribution of reef fish are related to the heterogeneity and physical complexity of their benthic habitat (Walker, Jordan, Spieler 2009). With moderate ground truthing, both substratum type and seabed topography can be monitored using airborne lidar and imagery, as well as high resolution satellite data (Hamel, Andrefouet 2010; Mellin 2009). Wedding *et al*. (2008) examined the relationship between habitat complexity and Hawaiian reef fish assembly characteristics, showing that airborne lidar could provide information about the seascape structure that can be used to prioritize areas for conservation and management. Purkis, Graham and Riegl (2008) used high resolution (Ikonos) satellite imagery to resolve the bathymetry and benthic character of a reef system in Diego Garcia. Monte Carlo simulation revealed that species richness and abundance of several guilds and size groupings of reef fish appraised in situ were correlated with the satellite-derived seabed parameters over areas of seafloor as large as 5,000 sq m.

ACOUSTIC SENSING OF FISH SCHOOLS

Acoustic techniques are widely used for detecting fish schools in coastal and deep ocean waters. The advantages of sonar methods include their ability to provide better high-resolution data on fish abundance and distribution than can be obtained with typical trawl surveys. For instance, abundance (density estimates) for herring, pollock, and whiting can be estimated with nearly 75% accuracy (Jaffe, Roberts 2011). Also acoustic techniques can sense much farther in the marine environment than those that use visible light. Acoustic sensors help reduce the search and sampling effort, enabling fishermen to save on fuel and ship time.

There are several different sonar systems available The most common acoustic systems used in fisheries research, monitoring and harvesting are echo-sounders and side-scan sonars. Echo-sounding profilers, which can also measure water depth and changes in bottom topography, send out pulses of acoustic energy beneath a boat or other platform through a transducer. The transmitted energy is concentrated within a beam whose width depends on the size of the transducer. Any fish or other target within the beam scatters the transmitted energy, producing echoes which are detected by a receiver. The depth to target calculation is based on how long it takes the reflected pulse to return to the surface and the speed of sound in water under prevailing environmental conditions. An inverse scattering approach is used to extract as much information as possible by “deciphering” the signal. Ideally, one would like to detect what species and sizes of animals are present, and to measure quantities such as the biomass or number of fish within the acoustic beam .

The fish bones, liver and fatty tissues reflect sound, but the strongest signal is returned from gas-filled organs, such as the swimbladder, because the echo strength depends mainly on the difference in density between the reflecting organ and the surrounding water. The gas in the swimbladder has a very low density compared to the water or body tissues. Therefore, the backscattered signal from fish having no gas-filled organs is much smaller than that of species which have a swimbladder, comparing size for size (Foote 1985, Simmonds, MacLennan 2005).

The single-beam echosounder is the simplest acoustic instrument and indicates only the presence of an object. Yet this traditional single (and split) beam technique is used to provide better information on fish abundance and distribution than typical trawl surveys. Furthermore, one can learn more if one views the signals received over a period of time or a number of transmissions. The earliest sounders used single beams, but the newer systems use multiple beams, with a large array of beams measuring submerged targets and bottom depths across a wide swath (Bergeron, Worley, O’Brien 2007; Wiebe *et al*. 1990).

When the fish are in the near-surface zone, good results can be obtained with side-scan sonar. Although it is commonly used to image wrecks and oil pipelines on the seabed, it has also proved useful in fisheries applications. Side-scan imaging sonars emit acoustic pulses in the form of a very wide fan-shaped beam to both sides and at right angles to the track, to produce an image of the submerged objects and the seabottom from the backscattered acoustic energy. The received signals are displayed on an echogram which represents an image of a rectangular area to one side of the survey track. A more complete picture of fish school shapes can be obtained using instruments which are sensitive to the direction as well as range of targets, such as multi-beam sonars (Simmonds, MacLennan 2005).

Sonar echo-sounders and side-scan sonars are sometimes housed in a torpedo-shaped “towfish”, which is towed by cable behind the survey ship at a predetermined height off the bottom (Avery, Berlin 1992; Pittenger 1989; Thompson, Schroeder 2010). More recently various acoustic sensors have been housed in Remotely Controlled Vehicles (ROVs) or Autonomous Underwater Vehicles (AUV’s) (Chadwick 2010).

For water depths of less than 5 m, horizontally applied sonar surveys have recently been made possible due to transducer and post-processing technology, especially through the development of narrow acoustic beams (Boswell, Wilson, Wilson 2007; Knudsen, Saegrov 2002; Simmonds, MacLennan 2005). With proper alignment, horizontally deployed transducers are capable of fish detection at ranges many times that of the water depth. For instance, Knudsen and Saegrov (2002) were able to obtain ranges of up to 100 meters when beaming horizontally in lakes. They showed that, in comparison, vertical beaming underestimated the presence of fish by 20-100 %, supporting the conclusion that horizontal beaming is a critical factor in compiling accurate fish stock assessments.

Until recently, the continental shelves have been surveyed with localized line-transects using acoustic devices from slow-moving research vessels, which typically survey along widely spaced line transects to cover the vast areas that fish inhabit. Also, traditional sonar methods cannot provide an accurate distribution of fish schools, i.e. school patterns and fish density. These methods miss some fish schools and provide an incomplete record of fish abundance and behavior.

Fish populations on continental shelves can now be imaged directly over thousands of square kilometers and continuously monitored by a remote sensing technique in which the continental shelf acts as an acoustic waveguide (Jagannathan *et al*. 2009; Makris *et al*. 2006). This range improvement is possible because traditional down-looking fish-finding sonars face a spherical spreading loss (signal power decreases with the square of the range), whereas in the Ocean Acoustic Waveguide Remote Sensing (OAWRS) method the continental shelf acts as a waveguide within which sound propagates over long distances via trapped modes, facing only cylindrical spreading loss (signal power decreases linearly with range). As shown in Figure 1, the OAWRS technique makes it possible to continuously monitor fish population dynamics, behavior, and abundance, with minute-to-minute updates of large fish schools containing tens of millions of fish stretching over many kilometers (Makris 2006).

Figure 1 shows two instantaneous areal density images of fish shoals near the continental shelf edge obtained by ocean acoustic waveguide remote sensing

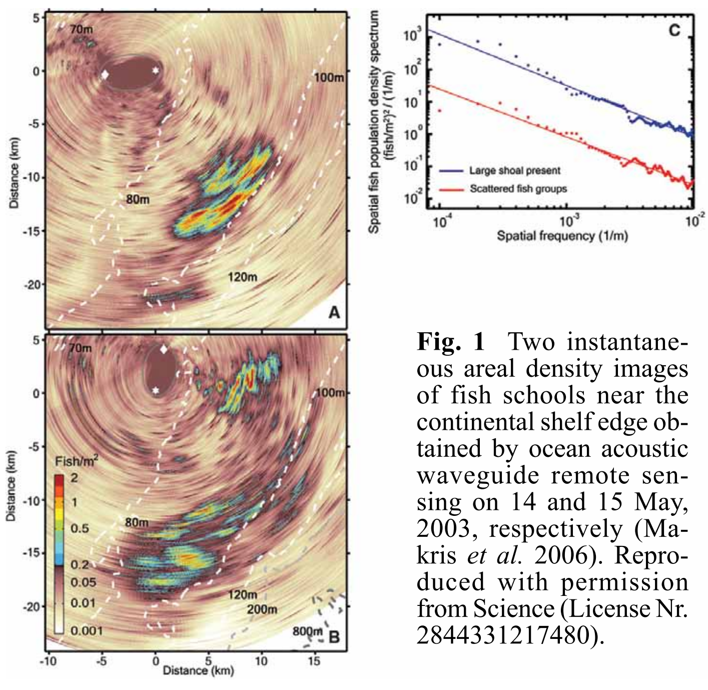

Fig. 1 Two instantaneous areal density images of fish schools near the continental shelf edge obtained by ocean acoustic waveguide remote sensing on 14 and 15 May, 2003, respectively (Makris *et al.* 2006). Reproduced with permission from Science (License Nr. 2844331217480).

(OAWRS) at (**A**) 09:32 EDT, 14 May 2003, and (**B**) 08:38 EDT, 15 May 2003, each acquired within 40 s. Spatial fish population density is shown in color. The moored source (the white star) is the coordinate origin in all figures at 39.0563°N, 73.0365°W. The towed horizontal receiving array (the white diamond) has 2.6° azimuthal resolution at array broadside. The range resolution is 30 m after averaging. The forward propagation of sound masks imaging inside the gray ellipse surrounding the source and receiver. The positive vertical axis points north. Depth contours are indicated by dashed lines. In (A) and (B), the continental shelf edge begins at roughly the 100-m contour. (**C**) Spatial frequency spectra, based on scores of instantaneous OAWRS images of fish density, for cases where a large shoal is present and only small scattered fish groups are present. A consistent spectral power law of spatial frequency to the –1.5 is observed (Makris *et al*. 2006).

Recently Makris *et al*. (2009), performed a study using OAWRS to investigate the conditions leading to rapid formation of large fish shoals (schools) by Atlantic herring. Aggregating into large schools of fish offers survival advantages such as enhanced spawning, predator avoidance, and feeding improvements. The investigators found that shoal formation depends on initial conditions and happens rapidly when those conditions are satisfied. The preexisting population density of scattered individuals had to reach a critical threshold of 0.2 fish per square meter. Then shoal formation commenced in a highly organized fashion near sunset, triggered by reduction in light level. The vast shoals then migrated at speeds consistent with synchronous swimming of hundreds of millions of individual fish, in accord with predictions of general behavioral models. The migrations had definite directions, such as toward southern spawning grounds on Georges Bank (Makris *et al*. 2009).

The accuracy and performance of acoustic sensing techniques are constantly improving, yet still need more work. Marine surveys often suffer from interpretational ambiguities, since the acoustic reflectors can be fish, air bubbles or suspended particles (Jaffe, Roberts 2011). Abundance estimates and fish species identification are also complicated by the fact that many small fish that are extremely close together can appear as a single, big one. As some of the new techniques become operational, they will further enhance fisheries activities, including research, management and fishing (Simmonds, MacLennan 2006).

AIRBORNE REMOTE SENSING

Every class of aerial platform, including balloons, helicopters, small single engine aircraft to large multi-engine aircraft, have been used to study fish habitat and detect fish schools for at least four decades. The major advantage of airborne remote sensing is that users can define the deployment and characteristics of the remote sensing system. By choosing the appropriate flight altitude and focal length, they can control the spatial resolution and coverage. Furthermore, the users can choose suitable atmospheric (i.e., cloud-free), sun angle and tidal (i.e., low water) conditions (Myers, Miller 2005). Small single-engine planes are particularly cost-effective for near-shore studies of coastal fish habitat.

Trained aerial spotters have been able to detect schools of herring, menhaden and sardines, from low altitudes. Skilled spotter pilots are used by fishing fleets to locate schools and direct the boats by radio transmission. Furthermore, having arrived at the fish school, the pilots can guide the fishing vessels to surround a school of fish, such as menhaden, with a purse seine and catch a sizeable fraction of the school. Commercial aerial fish-spotter data, environmental information (SST and mixed layer depth), and delta-lognormal models have been used to develop a cost effective index of relative abundance and have been used to improve biomass estimates of pelagic fish species, like northern anchovy (Lo *et al*. 1992; Santos 2011).

Some aerial spotters are even able to identify species and estimate school sizes. However, their years of experience and intuition are not readily transferable to others (Hunter, Churnside 1995; Lo, Jacobson, Squire 1992). Fish schools can be detected by naked eye at night whenever plankton are stimulated to bioluminesce by fish movements (Cram 1977).

Even though the human eye has a wide dynamic range, wide field of view and excellent resolution, visual observations still face a depth limit for detection, which depends on illumination, sea state and skill of the spotter pilot (Cram 1977; Hunter, Churnside 1995). To remedy this situation, a large number of airborne sensors have been added, including low-light-level television, digital cameras, thermal infrared radiometers, lidar and radar systems (Borstad *et al*. 1992; Santos 2000). For instance, O'Brien *et al*. (1974) used systematic airborne measurements of the sea surface temperature (SST) successfully to forecast areas of potential availability of coho salmon off the Oregon coast. It is interesting to note that Coast Guard surveillance aircraft are equipped with similar types of sensors.

Low-light-level television contains an image intensifier tube that amplifies light thousands of times producing a brighter image that can be displayed on a television screen. These systems can detect fish schools invisible to the naked eye at night. This is especially effective, whenever plankton are stimulated into bioluminescense by fish school movements at night (Roithmayr 1970).

Lidar systems designed for fisheries applications are being used to overcome the limitations of passive observation systems. Lidars emit powerful pulses of light which can penetrate up to three times the Secchi depth of a water column. The return pulse indicates the presence of a school and the elapsed time indicates its depth below the surface. The strength of the return also provides information on the size and reflectivity of the target, permitting discrimination of a fish school from the reflectance of suspended particles. The low cost, small size and low power requirements make it possible to fly lidar systems on small aircraft (Churnside, Hunter 1996).

Airborne Lidar has also been used to study coral reef habitats of fish and other marine life. An important application of airborne lidar and high resolution imagers is in coral reef fisheries, which are a significant source of food and income in developing and developed countries. Coral reef ecosystems are topographically complex environments and this structural heterogeneity influences the distribution, abundance and behavior of local marine organisms. Lidar and high resolution airborne and satellite imagers are being used to study and map these complex habitats of coral reef fish and other marine life (Hamel, Andrefouet 2010; Purkis, Graham, Riegl 2008). Since there is a relationship between the coral reef habitat and potential diversity and abundance of fish, these maps are used by reef managers to guide sampling strategies, identify conservation areas, and facilitate Ecosystem Based Fishery Management (EBFM) approaches.

Pittman, Costa and Battista (2009) demonstrated the value of lidar bathymetry for the development of benthic habitat maps and faunal distribution maps to support ecosystem-based management. They applied seven different morphometrics to a 4 m resolution bathymetry grid and then quantified at multiple spatial scales using a circular moving window analysis. The slope change at relatively local spatial scales (15–100 m radii) emerged as the single best predictor. Herbivorous fish responded to topographic complexity at spatial scales of 15 and 25 m radii, while broader spatial scales of between 25 and 300 m radii were relevant for piscivorous fish (Pittman, Costa, Battista 2009). Lidar topography and orthophotography has also been used to map side channel and fish habitat suitability in upstream waters (Jones 2006).

Another useful airborne sensor is Side-Looking Airborne Radar (SLAR). It emits radar pulses and receives signals that represent the backscattering intensities from the ocean surface. Fish swimming close to the surface produce small-scale waves (2–20 cm) that can be detected by the radar. The intensity and size of these wavelets depends on fish behavior at the surface, school size, fish size and swimming activities. The SLAR can pick up the small changes in the backscatter pattern caused by the fish school (Santos 2000). An aircraft with SLAR can search much larger areas than visual spotters, especially at higher wind speeds, when visual spotting distances tend to decrease. Schools of jack mackerel, skipjack tuna, southern bluefin tuna, and dolphins have been detected with such radar techniques (Griffiths *et al*. 1989).

The importance of modern airborne remote sensing methods in fisheries management and research of small epipelagic fish species (sardine, menhaden, anchovy, mackerel, herring) and improvements needed to obtain accurate stock biomass estimates are discussed in more detail by other authors (Hunter, Churnside 1995; Santos 2000).

SATELLITE REMOTE SENSING

Satellite remote sensing has been an important technique in fishery research, management and harvesting, because it provides synoptic ocean measurements for evaluating environmental influences on the abundance and distribution of fish populations and allows ecological analyses at community and ecosystem scales (Chassot *et al*. 2011; Santos 2011; Stuart, Platt, Sathyendranath 2011). Satellite images combined with other data can be analyzed to find ocean environmental conditions suitable for fish aggregation. Therefore, forecast models depend heavily on inputs from satellite sensors, in addition to in-situ measurements and observations. Fisheries-related satellite data include SST, ocean color (productivity), turbidity, sea surface salinity, ocean fronts and gyres, sea surface currents, winds and waves (Martin 2004; McLain *et al*. 2006; Purkis, Klemas 2011; Santos 2000). Table 1 summarizes the satellite ocean sensing techniques which will be discussed in subsequent sections.

Data in the form of analyzed sea surface temperature and chlorophyll charts are provided daily to the fisheries and shipping industries, whereas information on the location of the north wall of the Gulf Stream and the center of each eddy is broadcast daily over the Marine Radio Network. Because certain species of commercial and game fish are indigenous to waters of a specific temperature, fishermen can save fuel and ship time by being able to locate areas of higher potential more rapidly (Carr, Broad 2000; Chassot *et al*. 2011; Gordoa, Maso, Voges 2000).

Another reason that satellites are at the forefront in fisheries research and management is that the ma-

Table 1 Space-borne ocean sensing techniques.

Color Scanner	Ocean color (chlorophyll conc., susp. sediment, atten. coeff.)
Infrared Radiometer	Sea surface temperature (surface temperature, current patterns)
Synthetic Aperture Radar	Short surface waves (swell, internal waves, oil slicks, etc.)
Altimeter	Topography and roughness of sea surface (sea level, currents, wave height)
Scatterometer	Amplitude of short surface waves (surface wind velocity, roughness)
Microwave Radiometer	Microwave brightness temperature (salinity, surface temp., water vapor, soil moisture)

gnitude and variability of oceanic primary production are poorly known on a global scale, largely because of the high spatial and temporal variability of marine phytoplankton concentrations. For instance, wind-induced upwelling in coastal regions brings nutrients to the surface, creating patchy zones of high biological productivity, accompanied by high concentrations of chlorophyll and phytoplankton, which can be detected and monitored by color and temperature sensors on satellites (Balch *et al.* 1992; Chassot *et al*. 2011; Longhurst *et al*. 1995, Montgomery, Wittenberg-Frey, Austin 1986). The waters off Peru and California are good examples, where long term upwelling events influence the abundance of fish over periods of months.

Remote sensing of ocean color and productivity

The open ocean is biologically quite unproductive when compared to the shallow waters of the continental shelves and coastal upwelling areas. On the continental shelves, nutrients are supplied by rivers and by wave mixing of surface and bottom water. There are also upwelling regions which owe their high productivity to the persistent upward flow of deep water, which continually charges the photic zone with nutrients. For instance, the estimated mean productivities of the open ocean, coastal areas and upwelling areas are 50, 100 and 300 grams/c/sq.m/yr, respectively. Therefore, some of the world's largest fisheries are located in upwelling areas, such as the main ones located on the west coasts of North and South America, the west coast of Africa and off the coast of Somalia (Behrenfeld *et al.* 2005; Pinet 2009).

As shown in Figure 2, ocean color sensors and thermal infrared imagers have been used successfully to monitor coastal upwelling areas (Abbott, Zion 1987). In the upwelling zones in Figure 2, the water, which rises from the bottom and brings nutrients to the surface, is shown as being cold (blue) in the thermal infrared image (right), while the ocean color sensor (left) indicates that the upwelling area is highly productive (red). Satellite ocean color data has been used to observe fisheries-related processes and measure the primary production of the four Eastern Boundary Currents (EBC), *i.e.* the California, Humboldt, Canary and Benguela currents, during the first 24 months of SeaWiFS operation. Within each EBC, production was estimated for active areas of high chlorophyll concentration (>1 mg/ cubic m), which displayed productivity levels likely to be utilized by higher trophic levels. Primary production decreased with latitude within each EBC, while the extent of the active area was related to the magnitude of off-shore transport. Differences in observed fish catch were also related to differing trophic structure and spatial accessibility (Carr 2001; Chassot *et al*. 2011; Santos 2011).

Another fisheries-related application of satellite-derived chlorophyll and SST data is that of habitat mapping to better understand the basic relationships between marine species and their oceanic environment (Kumari *et al*. 2009; Sanchez *et al*. 2008). Habitat maps can also be used to restrict fishing grounds or to prompt fishermen to move to more favorable areas. For instance, monitoring chlorophyll concentrations is important for detecting toxic dinoflagellate blooms, such as *Karenia brevis* in the Gulf of Mexico. Under some conditions blooms of these phytoplankton cells can kill fish, mammals and other marine organisms and adversely affect commercial shellfish industries (Cannizzaro *et al*. 2008).

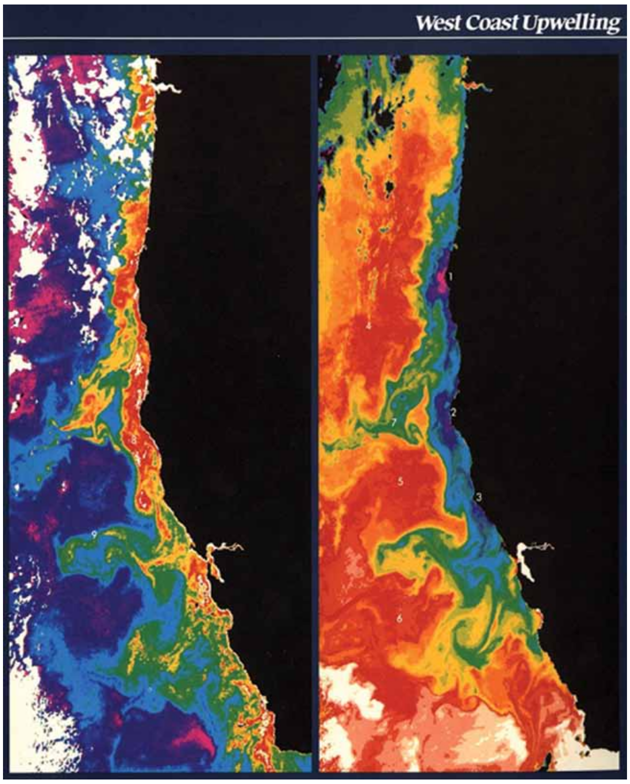

Fig. 2 Satellite ocean color (left) and temperature (right) maps showing the upwelling areas and chlorophyll distribution along the California coast. In the left image biological productivity ranges from high (red) to low (blue). In the right image ocean temperature is cold (blue) near the coast and warmer (red) away from the coast (Credit: P. Zion and M. Abbott, Jet Propulsion Laboratory, NASA).

Table 2 presents the characteristics of some of the important satellite systems used to measure ocean color, such as the NIMBUS-7 Coastal Zone Color Scanner (CZCS), Sea-Viewing Wide Field of View Sensor (SeaWiFS), and MODerate Resolution Imaging Spectroradiometer (MODIS). Several points are noteworthy: 1) Due to their limited spatial resolution, the sensors in Table 2 are more suitable for imaging the open ocean than near-shore coastal waters. 2) The polar orbits of the satellites and their inability to penetrate frequent cloud cover prevents them from tracking some rapidly varying coastal processes. 3) The ability of MODIS to measure both, ocean color and sea surface temperature, makes it very attractive for mapping productive coastal upwelling areas. 4)

MODIS has the hyperspectral capability required for discriminating complex coastal waters.

Satellite remote sensors measure the spectral radiances at the top of the atmosphere from which (after atmospheric and other corrections) the spectral radiances emerging from the ocean surface are extracted. The surface radiances are converted to reflectances, providing the spectral signatures required for identifying chlorophyll and other water constituents. To produce valid products, such as global ocean chlorophyll concentrations for estimating primary productivity, a meticulous calibration and validation approach must be used. Instrumented ships, buoys, and ocean gliders are used to calibrate and validate chlorophyll-a and total suspended sediment maps obtained with ocean color sensors (Bailey, Werdell 2006; Schofield *et al.* 2004).

Table 2 Some satellite remote sensing systems used to measure ocean color. Note that the MODIS instrument is carried aboard two platforms (Terra and Aqua). Modified from Jensen (2007). Printed and electronically reproduced by permission of Pearson Education, Inc.

Sensor	Agency	Satellite	Operating dates	Spatial resolution (m)	Number of bands	Spectral coverage (nm)
CZCS	NASA	Nimbus-7	1978–1986	825	6	433 – 12,500
SeaWiFS	NASA	Orb View-2	1997–2010	1,100	8	402 – 885
MODIS-Terra	NASA	Terra	Launch 1997	250 / 500 / 1,000	36	405 – 14,385
MODIS-Aqua	NASA	Aqua	Launch 2002	250 / 500 / 1,000	36	405 – 14,385
MERIS	ESA	Envisat-1	Launch 2002	300 / 1,200	15	412 – 1,050
VIIRS	NASA	Suomi NPP	Launch 2011	370 / 740	22	412 – 12,013

As one approaches the coast and enters the bays and estuaries, the water becomes quite turbid and contains suspended sediment, dissolved organics and other substances, in addition to chlorophyll. To identify each substance in this complex mixture of Case 2 waters requires higher spatial resolution, hyperspectral sensors and more sophisticated algorithms than the empirical regression models used in Case 1 waters for the open ocean (Cannizzaro, Carder 2006; Oliver *et al.* 2004; Schofield *et al.* 2004; Sydor 2006).

A new generation of ocean color sensors onboard US and other satellites has allowed the measurement of phytoplankton pigment concentrations with significantly increased resolution and accuracy (Arnone, Parsons 2005; Martin 2004; Santos 2011; Schofield *et al.* 2004). For instance, the Hyperspectral Imager for the Coastal Ocean (HICO) is the first space-borne imaging spectrometer designed to study the coastal ocean. HICO will sample selected coastal regions with a 90 m spatial resolution, full spectral coverage (380 to 960 nm, sampled at 5.7 nm) and a very high signal-to-noise ratio to resolve the complexity of coastal waters. HICO was launched and transferred to the International Space Station in September of 2009, and has been providing hyperspectral imagery of coasts around the world during its demonstration phase, which ended in October 2010. These data are available to users for scientific research (Lewis 2009; Lucke 2011).

Mapping sea surface temperature

In the past, satellite remote sensing applications in fisheries have focused mainly on thermal infrared images to produce sea surface temperature maps (Power, May 1991). Thermal infrared (TIR) sensors have been deployed for over 40 years on operational meteorological satellites to provide images of cloud top temperatures, and when there are no clouds, they observe sea surface temperature (SST) patterns. Thermal infrared instruments that have been used for deriving SST include the Advanced Very High Resolution Radiometer (AVHRR) on NOAA Polar-orbiting Operational Environmental Satellites (POES), Along-Track Scanning Radiometer (ATSR) aboard the European Remote Sensing Satellite (ERS-2), the Geostationary Operational Environmental Satellite (GOES) imagers, and Moderate Resolution Imaging Spectro-radiometer (MODIS) aboard NASA Earth Observing System (EOS) Terra and Aqua satellites (Miller *et al.* 2006; Robinson 2004; Santos 2011).

Thermal infrared was the first method of remote sensing to gain widespread acceptance by the oceanographic and meteorological communities. One reason for the early success of measuring SST is that the TIR radiance depends on the temperature and emissivity of the target, yet over water the emissivity is known and nearly constant, 98 %, approaching the behavior of a perfect blackbody radiator (Ikeda, Dobson 1995). Thus the TIR radiance measured over the oceans will vary primarily with the sea surface temperature (see Table 1). This makes it possible to determine the SST accurately (±0.5 ºC), with certain atmospheric corrections (Barton 1995; Martin 2004).

An important application of sea surface temperature sensing is in studies of coastal upwelling, where rising cold water brings nutrients to the surface inducing phytoplankton and zooplankton to grow and attract large concentrations of fish. Such upwelling areas and their condition can be observed by satellites with thermal infrared imagers, such as AVHRR, or ocean color sensors, such as SeaWiFS (Martin 2004; Schofield *et al.* 2004). When wind patterns over the Pacific Ocean change, warm waters from the Western Pacific shift to the Eastern Pacific and the upwelling of nutrient-rich cold water off the Peruvian coast is suppressed, resulting in well-recognized “El Niño” conditions.

Microwave radiometry and sea surface salinity

As shown in Table 1, sea surface salinity can be measured with microwave radiometers. In microwave radiometry, the power received by the radiometer antennae is proportional to the microwave emissivity and temperature of the ocean surface. Salt dissolves in water creating charged ions and anions. These charged particles increase the reflectivity and decrease the emissivity of the water. Thus, if the water temperature can be obtained by other means, such as thermal infrared radiometers, the salinity can be deduced from the received power. Salinity is measured in units of parts per thousand (ppt). Average seawater has a salinity of about 35 ppt. Another set of units used to measure salinity, which are related to the conductivity of the water, are Practical Salinity Units (PSU). Their numerical values are identical to ppt units (Klemas, 2011a**;** Miller, Goodberlet 2004).

Airborne microwave radiometers have been used to determine the structure and influence of river plumes, since the input of freshwater plumes from rivers is a critical consideration in the study and management of coral and seagrass ecosystems (Burrage *et al*. 2003; Burrage *et al*. 2008; Wang, Heron, Hacker 2007). Low salinity water can transport natural and man- made river-borne contaminants into the sea, and can directly stress marine ecosystems that are adapted to higher salinity level.

Since 2009, sea surface salinity has been measured from satellite orbit by the European Soil Moisture and Ocean Salinity satellite (SMOS), which is designed to provide synthesized sea surface salinity maps with a high accuracy. SMOS retrieves salinity with an accuracy of about 0.5 psu and a resolution of about 50 km (Barre, Duismann, Kerr 2008; ESA 2009; Font *et al*. 2010). Other salinity-related satellites are being developed, such as Aquarius, which will provide a global view of salinity variability (NASA 2011).

Remote sensing of ocean fronts and gyres

Estuarine and ocean fronts are similar to atmospheric fronts in that the denser fluid tends to under-ride the lighter fluid giving rise to an inclined interface. A common feature of both large- and small-scale fronts is the persistence of this large density difference across the front for long periods of time. Since fronts are formed by a combination of mechanisms, there are many different types of fronts, such as estuarine fronts, shelf fronts, shelf break fronts, coastal upwelling fronts, *etc*. (Belkin 2005; Belkin, Cornillon 2003; Largier 1993). There are many practical reasons for tracking and studying oceanic fronts. For instance, fish abundance seems to be higher near fronts due to an increased prevalence of prey (Polovina *et al*. 2001).

To detect and map ocean fronts and gyres, remote sensors exploit their differences in turbidity, color, temperature, salinity or sea state from ambient background waters. Thermal infrared and color sensors on satellites have been very effective for observing coastal plumes and fronts on the shelf and in the open ocean. Open ocean fronts, such as the Iceland-Faroes front in Figure 3, often have strong temperature gradients while coastal upwelling fronts can be detected by their colder temperatures and colors due to high chlorophyll concentrations (Belkin, Cornillon 2007; Johnson *et al*. 2001). Coastal fronts and plumes have also been detected with microwave radiometers due to their salinity gradients (Burrage *et al*. 2008; Klemas 2011b).

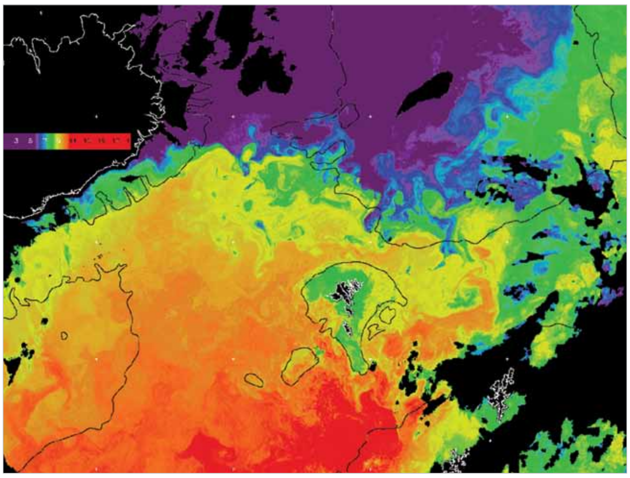

Fig. 3 Satellite thermal infrared images of Iceland-Faroes front and associated eddies. Iceland and the Faroes Islands are outlined by the white dots. North is upward. The scale in the upper left is in degrees Centigrade.The purple and blue colors represent cold arctic water. The red and yellow colors indicate warmer water of the Gulf Stream (Millar, Rossby 2004).

Radar measurements of physical ocean features

Three active microwave devices, radar altimeters, scatterometers and synthetic aperture radar (SAR) imagers, are of particular importance to physical oceanography, because they provide accurate global and regional information on ocean elevation, currents, winds and waves (see Table 1). Furthermore, SAR has been used to image sea surface life and fishing activities (Petit *et al.* 1992). The application of these radars depends on the character of the pulse emitted, which may be long or short, of uniform frequency or of swept frequency. It also depends on what properties of the reflected pulse are measured. For a nadir-pointing radar the timing of the returned pulse after reflection from the ocean surface, knowing the speed of light (EM waves), allows one to measure the distance between the radar and the sea surface. This is the basic principle of radar altimeters. Oblique-viewing instruments which measure the backscatter from the sea surface can be divided into two types. Those that measure average backscatter from a wide field of view are called scatterometers, and are used primarily to measure characteristics of winds, which create the surface roughness. Radars that have a much finer spatial resolution, called imaging radars, provide maps of sea surface roughness and are capable of defining a variety of small and meso-scale ocean characteristics, such as wave fields (Martin 2004).

CONCLUSIONS

The fisheries productivity of the world has been declining over the past four decades due to pressures from overfishing, habitat change, pollution, and climate change. Most of the world fish stocks are now either fully exploited or overexploited. Sustainable use of marine resources requires effective monitoring and management fish stocks and fish habitat. Conventional approaches of sampling the ocean using research vessels are limited in both time and space scales of coverage, making it difficult to study entire ecosystems. 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. During the past few decades new satellites have been able to provide accurate information on sea surface temperature, ocean color (productivity), salinity, fronts, winds, currents, waves and some other key parameters.

This satellite-derived information is being used not only to manage marine resources for more sustainable use, but also in models to forecast the probable location of fish aggregations and monitor environmental conditions preferred by different species of fish. Satellite images and a wide range of fishing-aid products are being provided to the fishing fleets in near-real time. The combined use of these modern techniques may facilitate the implementation of an ecosystem-based approach to fisheries management and, at the same time, decrease the costs of fishing. Furthermore, ocean observation by satellite-borne remote sensors is already improving oceanographic and meteorological forecasting, leading to enhanced scientific knowledge and safer operations at sea.

Traditionally acoustic techniques have been widely used for detecting fish schools in coastal and deep ocean waters. The advantages of sonar methods include their ability to provide high-resolution data on fish schools and related features. Acoustic sensors help reduce the search and sampling effort, enabling fishermen to save on fuel and ship time. However, traditional sonar methods cannot provide an accurate distribution of fish schools, i.e. school patterns and fish density. Recently, fish populations on continental shelves have been imaged directly over thousands of square kilometers and continuously monitored by a new technique in which the continental shelf acts as an acoustic waveguide within which sound propagates over long distances via trapped modes.

Aerial spotters on low-flying aircraft have been employed to help find fish schools for at least four decades. Skilled aerial spotters have been able to detect schools of herring, menhaden and sardines and direct the fishing fleets by radio transmission. To help aircraft crews detect and track fish, a variety of airborne sensors have been developed, including low-light-level television, digital cameras, thermal infrared radiometers, lidar and radar systems.

One of the important aspects of predicting and finding the locations of fish aggregations is to know how the ocean environment influences the behavior of various fish species. Each species has its own preferred temperature range, water clarity (turbidity), prey availability (near fronts), ocean productivity (color), and other requirements. For instance, albacore tuna aggregate near fronts and eddies, which concentrate and trap prey consumed by the tuna. Yellowfin and skipjack tuna prefer waters within relatively narrow, specific temperature ranges. The distribution and prevalence of anchovy, sardine and jack mackerel have also been associated with thermal fronts. The results of a wide range of ongoing studies relating oceanic environmental conditions and fish behavior/distribution will facilitate forecast modeling and improve the management and harvesting of fisheries resources.

Some of the problems that need further improvement include insuring that the relevant information is readily available in a timely manner for use by fisheries managers, modelers and fishing fleets. Longer time series of remotely sensed satellite images are required. For instance, for research on the connection between phytoplankton phenology and fisheries, a time-series from the onset of the spring bloom is needed. Due to frequent cloud cover, which blocks visible and infrared radiation, obtaining such time series is difficult. Fishery scientists and industry need to share data with remote sensing scientists to advance fisheries research, improve forecasting models, and help develop suitable management strategies. Above all, it is important that the continuity of the ocean-color data stream is maintained to insure a high quality, uninterrupted time-series of satellite data, including the derived ecological indicators (Stuart, Platt, Sathyendranath 2011).

References

Abbott, M. R., Zion, P. M., 1987. Spatial and tempopral variability of phytoplankton pigment off Northern California during Coastal Ocean Dynamics Experiment 1. *Journal of Geophysical Research*, 92, 1745–1755. http://dx.doi.org/10.1029/JC092iC02p01745

Andrade, H.A., Garcia, A.E., 1999. Skipjack tuna in relation to sea surface temperature off the southern Brazilian coast. *Fisheries Oceanography*, 8, 245–254. http://dx.doi.org/10.1046/j.1365-2419.1999.00107.x

A.P.T., 2006. Depletion of ocean fisheries. Aquaculture Production Technology, Ltd. http://www. aquaculture.co.il/markets/deterioration.html (accessed October 4, 2011).

Arnone, R.A., Parsons, A.R., 2005. Real-time use of ocean color remote sensing for coastal monitoring. *In*Miller, DelCastillo and McKee (Eds*), Remote Sensing of Coastal Aquatic Environments.*Dordrecht, The Netherlands, Springer.

Avery, T.E., Berlin, G.L., 1992. *Fundamentals of Remote Sensing and Airphoto Interpretation*. Macmillan Publishing Company, New York.

Bailey, S.W., Werdell, P.J., 2006. A multi-sensor approach for the on-orbit of ocean color satellite data products. *Remote Sensing of Environment*, 102, 12–23. http://dx.doi.org/10.1016/j.rse.2006.01.015

Balch, W., Evans, R., Brown, J., Feldman, G., McLain, C., Esaias, W., 1992. The remote sensing of ocean primary productivity. Use of a new data compilation to test satellite algorithms. *Journal of Geophysical Research*, 97, 2279–2293. http://dx.doi.org/10.1029/91JC02843

Barre, H.M.J., Duismann, B., Kerr, Y.H., 2008. SMOS: The mission and the system. *IEEE Transactions on Geoscience and Remote Sensing*, 46, 587–593. http://dx.doi.org/10.1109/TGRS.2008.916264

Barton, I.J., 1995. Satellite-derived sea surface temperatures: current status. *Journal of Geophysical Research*, , 8777. http://dx.doi.org/10.1029/95JC00365

Behrenfeld, M.J., Boss, E., Siegel, D.A., Shea, D.M., 2005. Carbon-based ocean productivity and phytoplankton phy-

siology from space. *Global Biogeochemical Cycles*, 19, GB1006, 14 pp.
Belkin, I.M., 2005. Oceanic fronts in large marine ecosystems. *Final Report to the United Nations Environment Programme*, 49 pp., 64 maps.
Belkin, I.M., Cornillon, P.C., 2007. Fronts in the world ocean's large marine ecosystems. *International Council for the Exploration of the Sea*. ICES CM 2007/D:21.
Bergeron, E., Worley, C.R., O'Brien, T., 2007. Progress in the development of shallow water mapping systems. *Sea Technology*, June, 2007.
Borstad, G.A., Hill, D.A., Kerr, R.C., Nakashima, B.S., 1992. Direct digital remote sensing of herring schools. *International Journal of Remote Sensing*, 13, 2191–2198. http://dx.doi.org/10.1080/01431169208904262
Boswell, K.M., Wilson, M.P., Wilson, C.A., 2007. Hydroacoustics as a tool for assessing fish biomass and size distribution associated with discrete shallow water estuarine habitats in Louisiana. *Estuaries and Coasts*, 30, 607–617.
Brandt, S.B., 1993. The effect of thermal fronts on fish growth: A bioenergetics evaluation of food and temperature. *Estuaries*, 16, 142–159. http://dx.doi.org/10.2307/1352771
Breaker, L.C., 1981. The applications of satellite remote sensing to West Coast fisheries. *Marine Technology Society Journal*, 15, 32–40.
Burrage, D.M., Heron, M.L., Hacker, J.M., Miller, J.L., Steiglitz, T.C., Steinberg, C.R., Prytz, A., 2003. Structure and influence of tropical river plumes in the Great Barrier Reef: application and performance of an airborne sea surface salinity mapping system. *Remote Sensing of Environment*, 85, 204–220. http://dx.doi.org/10.1016/S0034-4257(02)00206-7
Burrage, D., Wesson, J., Martinez, C., Perez, T., Moller Jr., O., Piola, A., 2008. Patos lagoon overflow within the Rio de la Plata plume using an airborne salinity mapper: observing an embedded plume. *Continental Shelf Research*, , 1625–1638. http://dx.doi.org/10.1016/j.csr.2007.02.014
Cannizzaro, J.P., Carder, K.L., 2006. Estimating chlorophyll-a concentrations from remote-sensing reflectance in optically shallow waters. *Remote Sensing of Environment*, 101, 13–24. http://dx.doi.org/10.1016/j.rse.2005.12.002
Cannizzaro, J.P., Carder, K.L., Chen, F.R., Heil, C.A., Vargo, G.A., 2008. A novel technique for detection of the toxic dinogfagellate, *Karenia brevis*, in the Gulf of Mexico from remotely sensed ocean color data. *Continental Shelf Research,*28, 137–158. http://dx.doi.org/10.1016/j.csr.2004.04.007
Carr, M-L., 2001. Estimation of potential productivity in Eastern Boundary Currents using remote sensing. *Deep Sea Research Part II:Topical Studies in Oceanography,* 49, 59–80. http://dx.doi.org/10.1016/S0967-0645(01)00094-7
Carr, M-E., Broad, K., 2000. Satellites, society, and the Peruvian fisheries during the 1997–1998 El Nino. *In* D. Halpern (Ed.), *Satellites, Oceanography and Society. Elsevier Oceanography S*eries. Amsterdam,The Netherlands, Elsevier Science B.V., 171–191.
Castillo, J., Barbieri, M.A., Gonzalez, A., 1996. Relationships between sea surface temperature, salinity and pelagic fish distribution off northern Chile. *ICES Journal of Marine Science*, 53, 139–146. http://dx.doi.org/10.1006/jmsc.1996.0014
Chadwick,W., 2010. Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). *NOAA Ocean Explorer*: *Submarine Ring of Fire 2002: Background.* http://oceanexplorer.noaa.gov/explorations/02fire/background/rovsauvs/rov_auv.html
Chang, C., Mahoney, K., Briggs-Whitmire, A., Kohler, D.D.R., Mobley, C.D., Lewis, M., Moline, M.A., Boss, E., Kim, M., Philpot, D., Dickey, T.D., 2004. The new age of hyperspectral oceanography. *Oceanography*, 17, 16–23. http://dx.doi.org/10.5670/oceanog.2004.43
Chassot, E., Bonhommeau, S., Reygondeau, G., Nieto, K., Polovina, J.J., Huret, M., Dulvy, N.K., Demarcq, H., 2011. Satellite remote sensing for an ecosystem approach to fisheries management. *ICES Journal of Marine Science*, 68, 651–666. http://dx.doi.org/10.1093/icesjms/fsq195
Chen, I.C., Lee, P.F., Tzeng, W.N., 2005. Distribution of albacore (Thunnus alalunga) in the Indian Ocean and its relation to environmental factors. *Fisheries Oceanography*, 14, 71–80. http://dx.doi.org/10.1111/j.1365-2419.2004.00322.x
Churnside, J.H., Hunter, J.R., 1996. Laser remote sensing of epipelagic fishes. *Society of Photo-Optical Instrumentation Engineers*, 2964, 38–53.
Cram, D.L., 1977. Fishery surveillance and advisory systems in southern Africa. *In* Tomczak, G.H. (Ed.), *Environmental Analyses in Marine Fisheries Research.* Fisheries Environmental Services, FAO Fisheries Technical Paper No. 170, 84–87.
Dagorn, L., Petit, M., Stretta, J-M., 1997. Simulation of large-scale tropical tuna movements in relation with daily remote sensing data: the artificial life approach. *Biosystems,* 44, 167–180. http://dx.doi.org/10.1016/S0303-2647(97)00051-8
FAO, 2003. The application of remote sensing technology to marine fisheries: an introductory manual (Section 7). *Food and Agriculture Organization Corporate Document Repository.*
FAO, 2009. The state of world fisheries and aquaculture 2008. *FAO Documentation Group*, Rome, Italy, 176 pp.
Fiedler, P.C., Bernard, H.J., 1987. Tuna aggregation and feeding near fronts observed in satellite imagery. *Continental Shelf Research*, 7, 871–881. http://dx.doi.org/10.1016/0278-4343(87)90003-3
Font, J., Camps, A., Borges, A., Martin-Neira, N., Boutin, J., Reul, N., Kerr, Y.H., Hahne, A., Mecklenburg, S., 2010. SMOS: The challenging sea surface salinity measurement from space. *Proceedings of the IEEE*, 98, 649–665. http://dx.doi.org/10.1109/JPROC.2009.2033096
Foote, K.G., 1985. Rather-high-frequency sound scattering by swimbladdered fish. *Journal of the Acoustic Society of America*, 78, 688. http://dx.doi.org/10.1121/1.392438
Gitelson, A.A., Kondratyev, K.Y., 1991. Remote chlorophyll-a retrieval in turbid, productive estuaries: Chesapeake Bay case study. *Remote Sensing of Environment*, 109, 464–472. http://dx.doi.org/10.1016/j.rse.2007.01.016
Gordoa, A., Maso, M., Voges, L., 2000. Satellites and fisheries: The Namibian hake, a case study. *In* D. Halpern (Ed.), *Satellites, Oceanography and Society. Elsevier Oceanography S*eries. Amsterdam,The Netherlands, Elsevier Science B.V., 193–206.
Griffiths, F.B., Lyne, V.D., Harris, G.P., Parslow, J.S., 1989. Tracking fish by airborne radar-fishermen could be the winners. *Australian Fisheries*, 48, 19–21.
Hamel, M.A., Andréfouët, S., 2010. Using very high resolution remote sensing for the management of coral reef fisheries: review and perspectives. *Marine Pollution Bulletin*, 60, 1397–1405. http://dx.doi.org/10.1016/j.marpolbul.2010.07.002
Holland, K.N., Brill, R.W., Chang, R.K.C., 1990. Horizontal and vertical movements of yellowfin and big eye tuna associated with fish aggregation devices. *Fisheries Bulletin*, 88, 397–402.
Hunter, J.R., Churnside, J.H. (eds), 1995. *Airborne Fishery Assessment Technology*. NOAA Workshop report. SWFSC Administrative Report, La Jolla, LJ-95-02, 71 pp.
Jaffe, J.S., Robertson, P.L.D., 2011. Acoustic reflections on marine populations. *Physics Today*, September 2011, 76–77. http://dx.doi.org/10.1063/PT.3.1260
Jagannathan, S., Bertsatos, I., Symonds, D., Chen, T.,Nia, H.T., Jain, A.D., Andrews, M., Gong, Z., Nero, R., Ngor, L., Jech, M., Godo, O.R., Lee, S., Ratilal, P., Makris, N., 2009. Ocean acoustic waveguide remote sensing (OAWRS) of marine ecosystems. *Marine Ecology Progress Series*, 395, 137–160. http://dx.doi.org/10.3354/meps08266
Kellogg, R.L., Gift, J.J., 1983. Relationship between optimum temperature for growth and preferred temperatures for the young of four fish species. *Transactions of the American Fisheries Soc*iety, 112, 424–430. http://dx.doi.org/10.1577/1548-8659(1983)112<424:RBOTFG>2.0.CO;2

Kimura, S., Nakai, M., Sugimoto, T., 1997. Migration of albacore, Thunnus alallunga, in the North Pacific Ocea, in relation to large oceanic phenomena. *Fisheries Oceanography*, 6, 51–57. http://dx.doi.org/10.1046/j.1365-2419.1997.00029.x

Kirobe, T., Munk, D., Richardson, K., Christiansen, V., Paulsen, H., 1986. Plankton dynamics and larval herring growth, drift and survival in a frontal area. *Marine Ecology Progress Series*, 44, 205–219. http://dx.doi.org/10.3354/meps044205

Klemas, V., 2011a. Remote sensing of sea surface salinity: An overview with case studies. *Journal of Coastal Research,* , 830–838. http://dx.doi.org/10.2112/JCOASTRES-D-11-00060.1

Klemas, V., 2011b. Remote sensing of coastal plumes and ocean fronts: Overview and case study. *Journal of Coastal Research*, 28, 1–7.

Knudsen, F.R., Saegrov, H., 2002. Benefits from horizontal beaming during acoustic survey: application to three Norwegian lakes. *Fisheries Research*, 56, 205–211. http://dx.doi.org/10.1016/S0165-7836(01)00318-6

Kumari, B., Raman, M., Mali, K., 2009. Locating tuna forage grounds through satellite remote sensing. *International Journal of Remote Sensing*, 30, 5977–5988. http://dx.doi.org/10.1080/01431160902798387

Laevastu, T., Favorite, F., 1988. *Fishing and Stock Fluctuations.* Fishing News (Books), Farnham, 239 pp.

Laevastu, T., Rosa, H., 1963. Distribution and relative abundance of tunas in relation to their environment. *FAO Fisheries Report*, 6, 1835–1851.

Largier, J.L., 1993. Estuarine fronts: How important are they. *Estuaries*, 16, 1–11. http://dx.doi.org/10.2307/1352760

Laurs, R.M., Fiedler, P.C., Montgomery, D.R., 1984. Albacore tuna catch distributions relative to environmental features observed from satellite. *Deep-Sea Research*, 31, 1085–1099. http://dx.doi.org/10.1016/0198-0149(84)90014-1

Le Fevre, J., 1986. Aspects of the biology of frontal systems. *Advances in Marine Biology*, 23, 163–299. http://dx.doi.org/10.1016/S0065-2881(08)60109-1

Leming, T.D., 1990. Satellite imagery analysis/PC data link for directed butterfish fishing. Final Report-Phase I. *Mississippi Department of Economic Development,* 63 pp.

Lewis, D., 2009. The Hyperspectral Imager for the Coastal Ocean (HICO): Sensor and data processing overview. *Oceans*, October, 2009.

Lo, N.C.H., Jacobsen, L.D., Squire, J.L., 1992. Indices of relative abundance from fish spotter databased on delta-lognormal models. *Canadian Journal of Fisheries and Aquatic Sciences*, 49, 2551–2526. http://dx.doi.org/10.1139/f92-278

Logerwell, E.A., Smith, P.E., 2001. Mesoscale eddies and survival of late stage Pacific sardine *(Sardinops sagax)* larvae. *Fisheries Oceanography*, 10, 13–25. http://dx.doi.org/10.1046/j.1365-2419.2001.00152.x

Longhurst, A., 2010. *Mismanagement of Marine Fisheries*. Cambridge University Press, Cambridge, UK, 334 pp. http://dx.doi.org/10.1093/plankt/17.6.1245

Longhurst, A., Sathyendranath, S., Platt, T., Caverhill, C., 1995. An estimate of global primary production in the ocean from satellite radiometer data. *Journal of Plankton Research*, 17, 1245–1271.

Lucke, R.L., 2011. Hyperspectral Imager for the Coastal Ocean (HICO) : Instrument description and first images. *Applied Optics*, 50, 1501–1516. http://dx.doi.org/10.1364/AO.50.001501

MacLennan, D.N., Simmonds, F.J., 1992. *Fisheries Acoustics*. London, Chapman and Hall, 325 pp.

Makris, N.C., Ratilal, P., Jagannathan, S., Gong, Z., Andrews, M., Bertsatos, I., Godo, O.R., Nero, R.W., Jech, J.M., 2009. Critical population density triggers rapid formation of vast oceanic fish shoals. *Science*, 323, 1734–1737. http://dx.doi.org/10.1126/science.1169441

Makris, N.C., Ratilal, P., Symonds, D., Jagannathan, S., Lee, S., Nero, R.W., 2006. Fish population and behavior revealed by instantaneous shelf-scale imaging. *Science*, 311, 661–663. http://dx.doi.org/10.1126/science.1121756

Marshall, H.G., McKinley, K.R., Biggley, W.H., Rivkin, R.B., and Aspden, K.R.H., 1981. Phytoplankton patchiness and frontal regions. *Marine Biology*, 61, 119-131. http://dx.doi.org/10.1007/BF00386651

Martin, S., 2004. *An Introduction to Remote Sensing*. Cambridge University Press, Cambridge, UK.

McLain, C., Hooker, S., Feldman, G., Bontempi, P., 2006. Satellite data for ocean biology, biogeochemistry and climate research. *EOS, Transactions, American Geophysical Union,* 87, 337–343. http://dx.doi.org/10.1029/2006EO340002

Mellin, C., Andrefouet, S., Kulbicki, M., Dalleau, M., Vigliola, L., 2009. Remote sensing and fish-habitat relationships in coral reef ecosystems: Review and pathways for systematic multiscale hierarchical research. *Marine Pollution Bulletin,* 58, 11–19. http://dx.doi.org/10.1016/j.marpolbul.2008.10.010

Millar, P., Rossby,T., 2004. Satellite imaging techniques are shedding new light on an ancient map of the northeast Atlantic. *Siemens Innovations Report,* 29/04/2004. http://dx.doi.org/10.1080/01431160310001592571

Miller, J.L., Goodberlet, M., 2004. Development and applications of STARRS: a next generation airborne salinity imager. *International Journal of Remote Sensing*, , 1319–1324. http://dx.doi.org/10.1175/BAMS-87-4-433

Miller, S.D., Hawkins, J.D., Kent, J., Turk, F.J., Lee, T.F., Kuciauskas, A.P., Richardson, K., Wade, R., Hoffman, C., 2006. NexSat: Previewing NPOESS/VIIRS imagery capabilities. *Bulletin of the American Meteorological Society*, April, 2006, 433–446.

Montes-Hugo, M.A., Carder, K., Foy, R.J., Cannizzaro, J., Brown, E., Pegau, S., 2005. Estimating phytoplankton biomass in coastal waters of Alaska using airborne remote sensing. *Remote Sensing of Environment*, 98, 481–493. http://dx.doi.org/10.1016/j.rse.2005.08.013

Montgomery, D.R., Wittenberg-Frey, R.E., Austin, R.W., 1986. The applications of satellite-derived ocean color products to commercial fishing operations. *Marine Technology Society Journal*, 20, 72–86.

Myers, J.S., Miller, R.L., 2005. Optical Airborne Remote Sensing. *In* Miller, R.L., DelCastillo, C.E. and McKee, B.A. (eds), *Remote Sensing of Coastal Aquatic Environments: Technologies, Techniques and Applications.* Dordrecht, The Netherlands, Springer, 51–68. http://dx.doi.org/10.1007/978-1-4020-3100-7_3

NASA, 2011. *Aquarius. NASA Science: Missions.* http://science.nasa.gov/missions/aquarius/ (accessed April 6, 2011).

O'Brien, J.J., Woodworth, B.M., Wright, D.J., 1974. *The Coho Project Reports. Living resources prediction feasibility study, Vols. I-III.* School of Oceanography, Oregon State University, Corvallis, OR.

Oliver, M.J., Irwin, A.J., 2008. Objective global ocean biogeographic provinces. *Geophysical Research Letters*, Vol. 35, L15601, http://dx.doi.org/10.1029/2008GL034238

Oliver, M.J., Schofield, O., Bergman, T., Glenn, S., Orrico, C., Moline, M., 2004. Deriving in situ phytoplankton absorption for bio-optical productivity models in turbid waters. *Journal of Geophysical Research*, 109, C07S11.

Otero, M.P., Siegel, D.A. 2004. Spatial and temporal characteristics of sediment plumes and phytoplankton blooms in the Santa Barbara Channel. *Deep-Sea Research Part II: Topical Studies in Oceanography,* 51, 1129–1149.

Owen, R.W., 1981. Fronts and eddies in the sea: mechanism, interaction and biological effects. *In* A.R. Longhurst (Ed.), *Analysis of Marine Ecosystems*. New York, Academic Press, 197–234.

Petit, M., Stretta, J.M., Farrugio, H., Wadsworth, A., 1992. Synthetic aperture radar imaging of sea surface life and fishing activities. *IEEE Transactions on Geoscience and Remote Sensing,* 30, 1085–1089. http://dx.doi.org/10.1109/36.175346

Pinet, P.R., 2009. *Invitation to Oceanography*, 5th Edn. Sudbury, MA, Jones and Bartlett.

Pittman, S.J., Costa, B.M., Battista, T.A., 2009. Using lidar bathymetry and boosted regression trees to predict the diversity and abundance of fish and corals. *Journal of Coastal Research*, 25, 27–38. http://dx.doi.org/10.2112/SI53-004.1

Platt, T., Sathyhendranath, S., 2008. Ecological indicators for the pelagic zone of the ocean from remote sensing. *Remote Sensing of Environment*, 112, 3426–3436. http://dx.doi.org/10.1016/j.rse.2007.10.016

Polovina, J.J., Howell, E.A., 2004. Ecosystem indicators derived from satellite remotely sensed oceanographic data for the North Pacific. *ICES Journal of Marine Science,* 62, 319–327. http://dx.doi.org/10.1016/j.icesjms.2004.07.031

Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P., 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography*, 49, 469–483. http://dx.doi.org/10.1016/S0079-6611(01)00036-2

Power, J.H., May, L.N.Jr., 1991. Satellite observed sea-surface temperatures and yellowfin tuna catch effort in the Gulf of Mexico. *Fisheries Bulletin*, 89, 429–439.

Purkis, S.J., Graham, N.A.J., Riegl, B.M., 2008. Predictability of reef fish diversity and abundance using remote sensing data in Diego Garcia (Chagos Archipelago). *Coral Reefs,* 27, 167–178. http://dx.doi.org/10.1007/s00338-007-0306-y

Purkis, S., Klemas, V., 2011. *Remote Sensing and Global Environmental Change*. Oxford, Wiley-Blackwell.

Ramos, A.G., Santiago, J., Sangra, P., Canton, P., 1996. An application of satellite-derived sea surface temperature data to the skipjack and albacore tuna fisheries in the north-east Atlantic. *International Journal of Remote Sensing*, 17, 749–759. http://dx.doi.org/10.1080/01431169608949042

Roithmayr, C.M., 1970. Airborne low-light sensor detects luminescing fish schools at night. *Commun. Fisheries Revue*, 32, 42–51.

Royer, F., Fromentin, J-M., Gaspar, P., 2004. Association between bluefin tuna schools and oceanic features in the western Mediterranian. *Marine Ecology Progress Series,* 269, 249–263. http://dx.doi.org/10.3354/meps269249

Sabates, A., Maso, M., 1990. Effect of a shelf-slope front on the spatial distribution on mesopelagic fish larvae in the western Mediterranean. *Deep-Sea Research,* 37, 1085–1098. http://dx.doi.org/10.1016/0198-0149(90)90052-W

Sanchez, P., Demestre, M., Recasens, L., Maynou, F., Martin, P., 2008. Combining GIS and GAMS to identify potential habitats of squid *Loligo vulgaris* in the northwestern Mediterranean. *Hydrobiologia*, 612, 91–98. http://dx.doi.org/10.1007/s10750-008-9487-9

Santos, A.M.P., 2000. Fisheries oceanography using satellite and airborne remote sensing methods: a review. *Fisheries Research*, 49, 1–20. http://dx.doi.org/10.1016/S0165-7836(00)00201-0

Schofield, O., Arnone, R.A., Bissett, W.P., Dickey, T.D., Davis, C.O., Finkel, Z., Oliver, M., Moline, M.A., 2004. Watercolors in the coastal zone: What can we see? *Oceanography*, 17, 24–31. http://dx.doi.org/10.5670/oceanog.2004.44

Simmonds, J., MacLennan, D., 2006 (2nd edn). *Fisheries Acoustics: Theory and Practice*. Chichester, U.K., Wiley-Blackwell.

Simpson, J.J., 1992. Remote sensing and geographical information systems: their present and future use in global marine fisheries. *Fisheries Oceanography*, 1, 238–280. http://dx.doi.org/10.1111/j.1365-2419.1992.tb00042.x

Stretta, J-M., 1989. Forecasting tuna fishery area. What parameters and what models: the praxeological response. *La Mer*, 27, 133–134. http://dx.doi.org/10.1080/01431169108929693

Stretta, J-M., 1991. Forecasting models for tuna fishery with aerospatial remote sensing. *International Journal of Remote Sensing*, 12, 771-779.

Stretta, J-M., Slepoukha, M., 1983. A forecasting model for tuna fisheries in the intertropical Atlantic. *Proceedings of the 34th Annual Tuna Conference,* Lake Arrowhead on 15–18 May, 1983.

Stuart, V., Platt, T., Sathyendranath, S., 2011. The future of fisheries science in management: a remote-sensing perspective. *ICES Journal of Marine Science,* 68, 644–650. http://dx.doi.org/10.1093/icesjms/fsq200

Stuart, V., Platt, T., Sathyendranath, S., Pravin, P., 2011. Remote sensing and fisheries: an introduction. *ICES Journal of Marine Science,* 68, 639–641. http://dx.doi.org/10.1093/icesjms/fsq193

Sund, P.N., Blackburn, M., Williams, F., 1981. Tuna and their environment in the Pacific Ocean: a review. *Oceanography and Marine Biology Annual Review*, 19, 443–512.

Thomas, A.C., Weatherbee, R.A., 2006. Satellite-measured temporal variability of the Columbia River plume. *Remote Sensing of Environment,* 100, 167–178. http://dx.doi.org/10.1016/j.rse.2005.10.018

Thompson, R.L., Schroeder, A.J. Jr., 2010. High-definition 3-D tools for underwater surveying and inspection. *Sea Technology*, April, 2010.

Trautwein, G., 2011. Sockeye hydroacoustics: Quinaults river system is first of its kind sockeye salmon counter. *Marine Technology Reporter*, October, 2011, 29–33.

Tyler, J.A., Rose, K.A., 1994. Individual variability and individual heterogeneity in fish population models. *Revue of Fish Biology in Fisheries*, 4, 91–123. http://dx.doi.org/10.1007/BF00043262

Walker, B.K., Jordan, L.K.B., Spieler, R.E., 2009. Relationship of reef fish assemblages and topographic complexity on Southern Florida coral reef habitats. *Journal of Coastal Research:*Special Issue 53, 1–5.

Wang,Y., Heron, M.M., Hacker, J.M., 2007. Evaluation of a new airborne microwave remote sensing radiometer by measuring the salinity gradients across the shelf of the Great Barrier Reef Lagoon. *IEEE Transactions on Geoscience and Remote Sensing*, 45, 3701–3709. http://dx.doi.org/10.1109/TGRS.2007.903400

Ware, D.M., Thomson, R.E., 2005. Bottom-up ecosystem trophic dynamics determine fish production in the northeast Pacific. *Science*, 308, 1280–1284.

Wedding, L.M., Friedlander, A.M., McGranaghan, M., Yost, R.S., Monaco, M.E., 2008. Using bathymetric lidar to define nearshore benthic habitat complexity: Implications for management of reef fish assemblages in Hawaii. *Remote Sens. Environ.* 112, 4159–4165. http://dx.doi.org/10.1016/j.rse.2008.01.025

Wiebe, P.H., Greene, C.H., Stanton, T.K., Burczynski, J., 1990. Sound scattering by live zooplankton and micronekton: Empirical studies with a dual-beam acoustical system. *Journal of the Acoustical Society of America*, 88, 2346–2360. http://dx.doi.org/10.1121/1.400077

Wright, D.J., Woodworth, B.M., O'Brien, J.J., 1976. A system for monitoring the location of harvestable coho salmon stocks. *Marine Fisheries Review*, 38, 1–7.

Zagaglia, C.R., Lorenzzetti, J., Stech, J.L., 2004. Remote sensing data and longline catches of yellowfin tuna *(Thunnus albacores)*in the equatorial Atlantic. *Remote Sensing of Environment*, 93, 267–281. http://dx.doi.org/10.1016/j.rse.2004.07.015

Zainuddin, M., Kiyofuji, H., Saitoh, K., Saitoh, S., 2006. Using multi-sensor satellite remote sensing and catch data to detect ocean hot spots for albacore *(Thunnus alalalunga)* in the northwestern North Pacific. *Deep-Sea Research*, 53, 419–431. http://dx.doi.org/10.1016/j.dsr2.2006.01.007

Zainuddin, M., Saitoh, K., Saitoh, S., 2004. Detection of potential fishing ground for albacore tuna using synoptic measurements of ocean color and thermal remote sensing in the northwestern North Pacific. *Geophysical Research Letters,* , L20311, http://dx.doi.org/10.1029/2004GL021000