ICES Journal of Marine Science (2011), 68(4), 644–650. doi:10.1093/icesjms/fsq200

The future of fisheries science in management: a remote-sensing perspective

Venetia Stuart [1]*, Trevor Platt [2], and Shubha Sathyendranath [2]

[1] Bedford Institute of Oceanography, PO Box 1006, Dartmouth, NS, Canada B2Y 4A2
[2] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK

*Corresponding Author: tel: +1 902 426 3817; fax: +1 902 426 9388; e-mail: vstuart@ioccg.org.

Stuart, V., Platt, T., and Sathyendranath, S. 2011. The future of fisheries science in management: a remote-sensing perspective. – ICES Journal of Marine Science, 68: 644–650.

Received 15 November 2010; accepted 9 December 2010; advance access publication 17 January 2011.

Earth observation from satellites offers vast potential for fisheries applications, including management of marine resources, stock assessment, marine aquaculture, and fish harvesting. One of the most promising avenues for the use of satellite data for fisheries science in management lies in quantifying objectively the variables that result in large and small year classes of exploited stocks. The influence of fluctuations in the availability of food in the critical period of larval stages can be investigated through the application of ecological indicators describing the variability of the pelagic ecosystem at a given time and place. These indices can increase our understanding of the relationship between ecosystem factors and the recruitment of key species. Despite the many demonstration applications published to date, little use is being made of satellite data to support fisheries science in management. We discuss some of the obstacles that lie in the way of the operational use of satellite data and suggest actions that could facilitate its broader application.

Keywords: fisheries science, management, ocean-colour remote sensing, satellite data.

Background

Marine and freshwater fish stocks are an important high-protein food source for humankind, but world fisheries are coming under increasing pressure from a range of factors related to the growth in human population, including overfishing, global climate change, pollution, and habitat degradation. The result is that some 80% of the world fish stocks are either now fully exploited or overexploited (FAO, 2009). Sustainable use of aquatic ecosystems requires effective monitoring and management of the entire ecosystem, not just the exploited fish stocks. Over the past decade, there has been a global shift towards an ecosystem-based approach to fisheries management, recognizing the complexity of ecosystems and the interconnections among their component parts (Fisheries and Oceans Canada, 2002). Such an approach requires understanding of the characteristics of the ecosystem, including its geographic boundaries (which may vary in time and space), the dynamics of the ecosystem [e.g. top–down (predator/grazing pressure) or bottom–up (primary production) control], the natural variability of external forcing (including fluctuations in food supply and climate change), the use of reliable and informative indicators (e.g. ecosystem indicators), and understanding ecosystem structure (biotic and abiotic).

Conventional means of sampling and monitoring the ocean using oceanographic 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, particularly remote sensing of ocean colour, it has become possible to sample the global ocean on synoptic scales at a relatively high temporal resolution (1–3 d). Ocean-colour radiometry is the only means of quantifying the base of the marine food chain (i.e. phytoplankton biomass) on a global scale, providing a synoptic-scale window into the pelagic ecosystem (Platt *et al.*, 2007).

Fisheries-related applications of satellite data

Earth observation from satellites has revolutionized our view of the oceans and offers vast potential for fisheries applications, including marine resource management, stock assessment, marine aquaculture, and fish harvesting (IOCCG, 2009). As outlined in the International Ocean Colour Coordinating Group (IOCCG) report, there is a broad range of fisheries-related applications of remotely sensed data, including bycatch reduction, detection of harmful algal blooms, aquaculture site selection, identifying marine managed areas, and describing habitat changes. In other studies, satellite chlorophyll data, in conjunction with 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 they do vary seasonally and interannually, as demonstrated, for example, by Devred *et al.* (2007) for the Northwest Atlantic and by Moore *et al.* (2009) globally. The instantaneous boundaries of these ecological provinces can contribute to our understanding of ecosystem characteristics and can also be used to highlight the changes that happen because of both short- and long-term environmental variations (such as climate instability), which are often reflected in satellite-derived patterns of ocean temperature and primary productivity. These changes may affect the recruitment, survival, condition, distribution patterns, and migration of fish stocks, either directly or indirectly.

For example, warming events in the Bering Sea have been accompanied by unprecedented community shifts from large diatoms to smaller nanophytoplankton (Stockwell *et al.*, 2001; Hare *et al.*, 2007), creating a vastly different, less-productive ecosystem, which may support a lesser biomass of harvested fish species. Surely, such knowledge is of great value to those responsible for making decisions about management of resources in the Bering Sea.

Another fisheries-related application of satellite-derived chlorophyll and SST data is that of habitat mapping to elucidate the basic relationships between marine species and their oceanic environment (Sanchez *et al.*, 2008; Kumari *et al.*, 2009). In this context, Druon (2010) proposed the use of satellite-derived habitat mapping as a potential tool for the sustainable management of the overfished Atlantic bluefin tuna (*Thunnus thynnus*) in the Mediterranean Sea. Habitat maps can be used either to restrict fishing grounds or to prompt fishers to move towards favourable areas. Satellite data have also been used to predict potential spawning habitat (using SST and chlorophyll) of northern anchovy (*Engraulis mordax*) and Pacific sardine (*Sardinops sagax*) in the California Current (Reiss *et al.*, 2008).

Rapid detection and operational monitoring of toxic dinoflagellate blooms, such as *Karenia brevis* in the Gulf of Mexico, is now possible using satellite data (Hu *et al.*, 2005; Cannizzaro *et al.*, 2008). Under certain conditions, blooms of these phytoplankton cells can kill fish, mammals, and other marine organisms, and adversely affect local tourism and commercial shellfish industries. As our ability to map the occurrence and fate of these blooms increases, remote sensing will become better equipped to serve the fisheries and aquaculture sectors.

Increasingly, satellite data are being used for operational fisheries applications. For example, in India, satellite data from the Indian IRS-P4 ocean-colour sensor, in combination with SST data, are used to generate potential fishing zone (PFZ) advisories. These advisories have helped artisanal fishers reduce search time by up to 70% and have increased significantly the catch per unit effort (Solanki *et al.*, 2003). A similar PFZ forecast is now being implemented in Sri Lanka (Figure 1), and it has resulted in significantly bigger catches of yellowfin tuna (*Thunnus albacares*) within the PFZ than outside it. On a larger scale, many purse-seiners employ SST and other satellite data to locate tuna schools, because the distribution of many species of tuna is directly

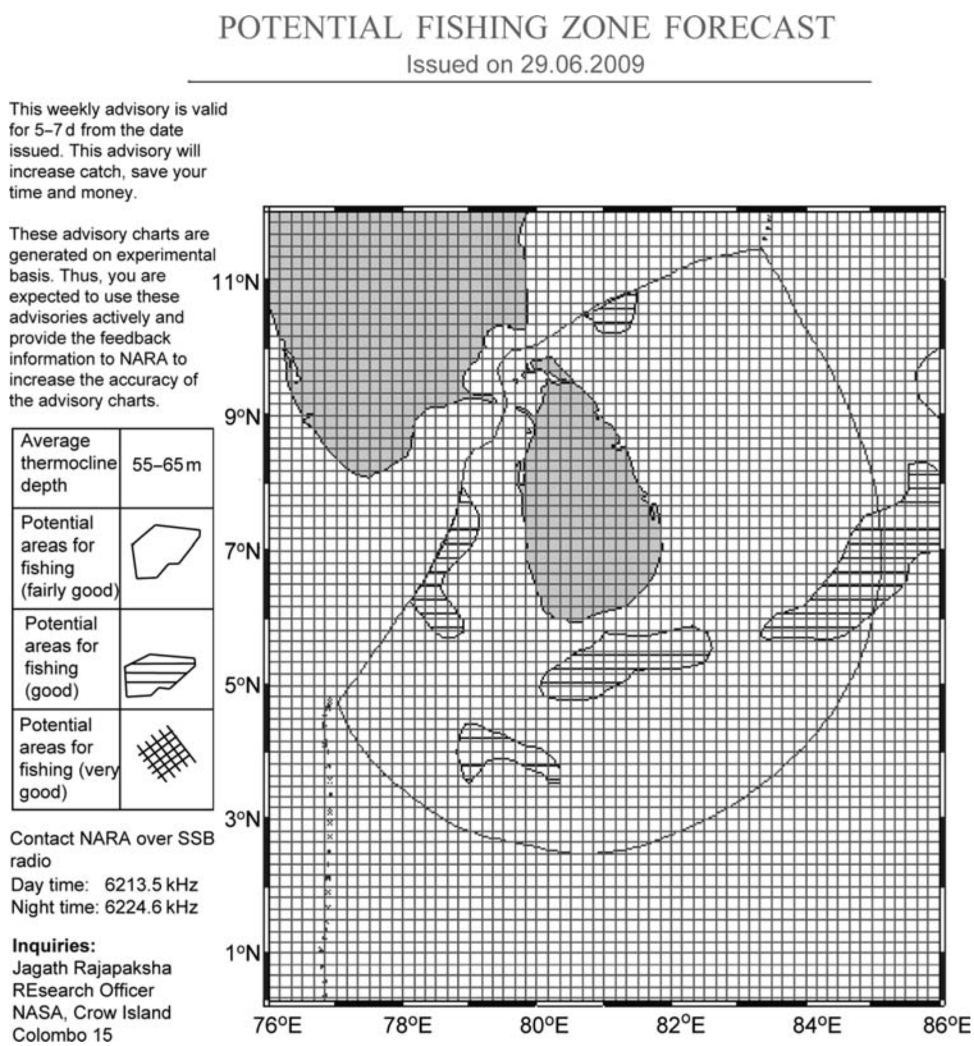

Figure 1. Example of a PFZ forecast issued by the National Aquatic Resources Research and Development Agency (NARA) in Sri Lanka. Image courtesy of Charitha Pattiaratchi, University of Western Australia (converted to greyscale).

related to such oceanic variables as SST, chlorophyll, and sea surface height anomalies (Laurs *et al.*, 1984; Zainuddin *et al.*, 2004). Obviously, the goal of the advisories is efficient harvesting and not overfishing. However, effective monitoring systems have to be put in place, to ensure that opportunities of systematic observations from remote sensing are not misused. In fact, commercial systems have been developed to facilitate the use of satellite data in conjunction with GIS (IOCCG, 2009) that could contribute to the development of stock-management methodology.

Example of a fisheries management approach using satellite data

Despite the increasing use of satellite data for research and commercial applications, and although remote-sensing techniques exhibit great potential for supporting fisheries management, the use of satellite data as a management tool remains in its infancy. In a recent symposium on the future of fisheries science in North America (Beamish and Rothschild, 2009), only a few passing references were made to the potential use of remotely sensed ocean-colour and SST data for fisheries applications, including management.

One of the most promising avenues for the use of satellite data in fisheries management lies in quantifying the variables that result in large and small year classes. For at least 100 years, it has been recognized that the key to understanding the variability of fish populations lies in understanding the variable forcing of the pelagic ecosystem when the fish are in their larval stage. As the larval stage is generally planktonic, it is mostly a prisoner of its environment, unable to travel far to seek optimal conditions for survival. In this sense, it may be considered a passive component of the pelagic ecosystem and its variable forcing. Planktonic stages of fish inhabit an ecosystem where the communities are mostly microscopic. The implication is that the intrinsic turnover times of the organisms are relatively rapid. In fact, the pelagic microflora (phytoplankton) is, on average, ~30-fold more active, metabolically, than the terrestrial flora, a consequence of the relative size of the organisms concerned.

To make sense of the ecological impact of the interannual variability of forcing of the pelagic ecosystem, we must study it on the appropriate scales of time and space. The long-standing hypothesis that the abundance of fish year classes is determined by food availability during the critical period of larval development (Hjort, 1914) has proven difficult to test at the relevant scales of time and space, with notable exceptions (Cushing, 1974, 1990). However, the advent of satellite visible spectral radiometry (ocean colour) has radically changed this situation. For the first time, we are suitably equipped to test hypotheses about the fisheries implications of ecosystem variability at the appropriate scales of time and space. Hence, we are equipped more adequately than ever before to manage exploited fish stocks (invertebrate as well as vertebrate) on a rational basis. In other words, rather than treating stocks as theoretical entities subject only to the equations of population dynamics, we can now consider, on the appropriate scales, the influence of environmental and ecosystem variability, in particular fluctuations in the availability of food at the critical period of larval stages (Platt *et al.*, 2003; Koeller *et al.*, 2009).

Moreover, remote sensing proves to be an ideal vehicle for retrieving a broad range of objective indices of ecosystem status (Platt and Sathyendranath, 2008). These so-called ecological indicators provide a compact description of the pelagic ecosystem at a given time and place. The comprehensive information they embody affords an invaluable background to biological oceanographic research, and constitutes important ecological intelligence for fisheries management and for ecosystem-based management of marine resources in the broadest sense.

It is clear that the information now at our disposal to elucidate fluctuations in the abundance of fish stocks is well enhanced over what was available only recently. Perhaps one can even say that fisheries science stands on the threshold of a renaissance. Research output holds great promise for management of the fishery, e.g. by improving the predictive capability for recruitment of key species. Therefore, it is necessary now to consider what actions are required to exploit this potential to the maximum and to integrate the information into the emerging discipline of fisheries management.

Actions for exploiting satellite data for fisheries science applications

One of the first steps in analysing the effects of ecosystem fluctuation on the variability in recruitment of exploited stocks is the establishment of a long-term history of the pelagic ecosystem on a synoptic scale. This can be achieved through construction of a suitable time-series of satellite data, e.g. weekly (or biweekly) composite images of phytoplankton biomass (chlorophyll concentration) using data from a number of global ocean-colour sensors (e.g. SeaWiFS, MODIS, or MERIS). A similar time-series can be constructed for other satellite-derived measurements, such as SST, sea surface height, winds (Polovina and Howell, 2005), and, soon, sea surface salinity as measured by ESA's recently launched SMOS mission and the future NASA Aquarius mission.

Because the success of recruitment in exploited stocks is linked so closely to the phase and other properties of the spring phytoplankton bloom at intermediate latitudes in the northern hemisphere (Cushing, 1974, 1990; Platt *et al.*, 2003), it is useful to characterize the spring bloom using a number of ecological indicators, e.g. the timing of initiation, the amplitude of the peak, the duration of the bloom, and the timing of the peak (Figure 2; Platt and Sathyendranath, 2008). Other ecosystem metrics that can be derived from satellite data include parameters of the photosynthesis light curve and phytoplankton production (Platt *et al.*, 2008), phytoplankton community structure (e.g. the presence of diatoms; Sathyendranath *et al.*, 2004), size structure (Devred *et al.*, 2006, in press; Loisel *et al.*, 2006; Uitz *et al.*, 2006), and ecological partition of the region of interest into provinces (Devred *et al.*, 2007; Moore *et al.*, 2009). These properties can be calculated for all pixels in the region of interest, such that all spatial structure is preserved. Interannual variation in bloom properties can be evaluated by comparison with climatological means, and the anomalies in these properties can be calculated for particular years. For example, Fuentes-Yaco *et al.* (2007) found that the timing of the spring bloom could vary by as much as 6 weeks between years in a given region.

Primary production is a first-order index of local carrying capacity, and various studies (Ware and Thomson, 2005; Chassot *et al.*, 2007) have demonstrated the connection between phytoplankton production and fish landings. Phytoplankton community structure may have profound effects on the trophic links in the rest of the food chain. For example, van der Lingen

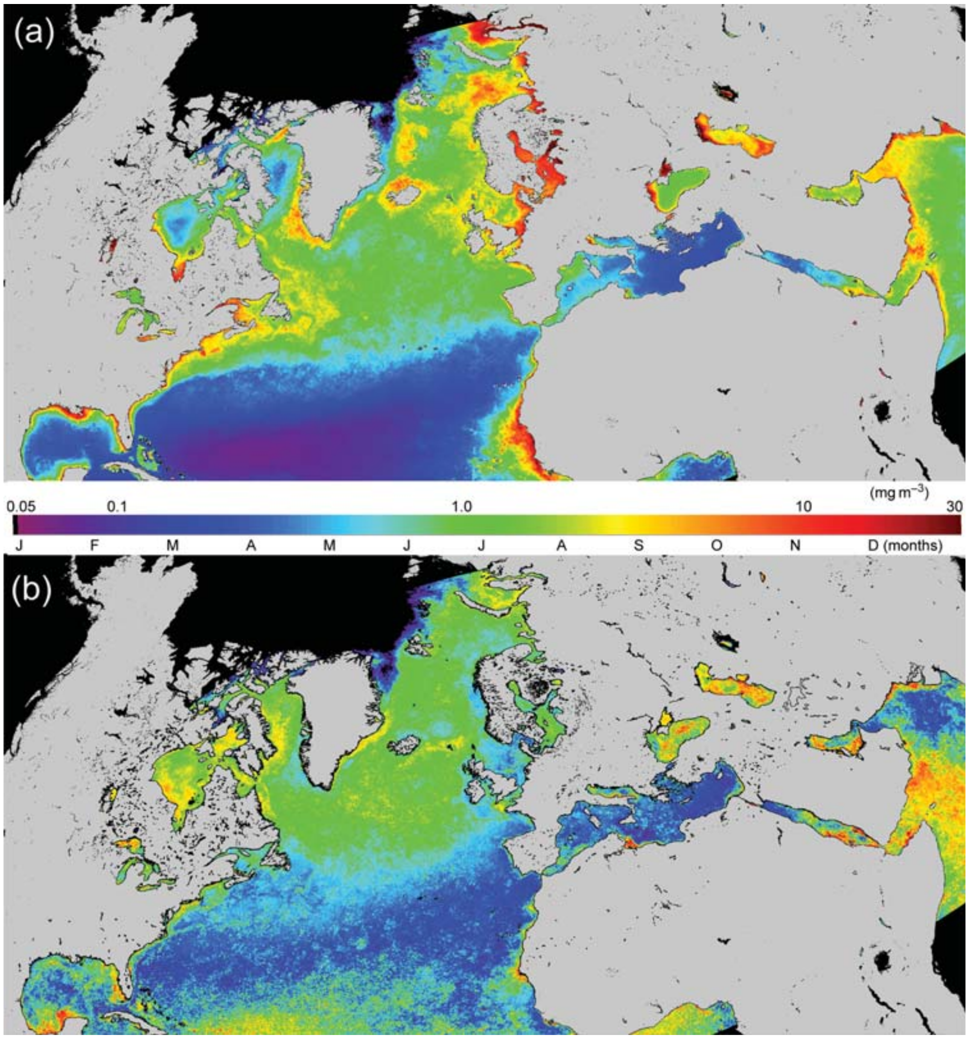

Figure 2. Climatology (1998–2005) of the (a) amplitude of the maximum chlorophyll concentration (mg m^{-3}), and (b) timing of the maximum chlorophyll concentration (months), in the North Atlantic derived from SeaWiFS data. Image provided by César Fuentes-Yaco, Bedford Institute of Oceanography, Canada.

et al. (2006) and Cury *et al.* (2008) established that, in the Benguela Current system, food environments dominated by small cells (e.g. flagellates) favour a sardine (*S. sagax*) fishery, whereas food environments comprising large particles (e.g. diatoms) favour an anchovy (*Engraulis encrasicolus*) fishery. Such changes are probably related to the size of the phytoplankton cells, as well as their taxonomic status, so that the retrieval of phytoplankton size structure from remote sensing would be an important step forward (Figure 3). Furthermore, the size-resolved data should find an immediate application in models of the pelagic ecosystem based on size-dependent metabolism (Cury *et al.*, 2008).

The next step is to ensure that the information is readily available in a timely manner for use by fisheries researchers and managers. Oceanographic organizations should be encouraged to develop a comprehensive operational, ecosystem information tool, based on the ecosystem indicators discussed (at optimal scales of time and space). The products so derived could be disseminated to the user community via the Internet on a regular (e.g. 8 d) basis. Moreover, retrospective information products could be constructed for the region of interest over the lifespan of the sensor (more than 13 years for SeaWiFS).

A current limitation is the relatively short length of the time-series that can be derived directly from remote sensing. For example, for research on the connection between phytoplankton phenology and fisheries, a time-series of the timing of onset of the spring bloom is needed. These are rather easy to construct from remotely sensed data, but the record is short compared with the data record for fisheries. One possible remedy using the existing information on the phase of the bloom, as developed from remote sensing, is to construct models of the relationship between bloom timing and local physics. When the available time-series of physical properties is longer than that of ocean colour (as is usually the case), the physical proxy for the bloom timing could be used to extend the time-series of bloom timing farther into the past.

Analysis of the effect of ecosystem fluctuation on variability of recruitment of exploited stocks should now be possible, assuming easy access to relevant fisheries data (e.g. survey, catch, and ancillary data in user-friendly format). Fishery scientists and industry need to share data with remote-sensing scientists to advance fisheries research and to help develop suitable management strategies. It would be most helpful if fisheries data were to be made available

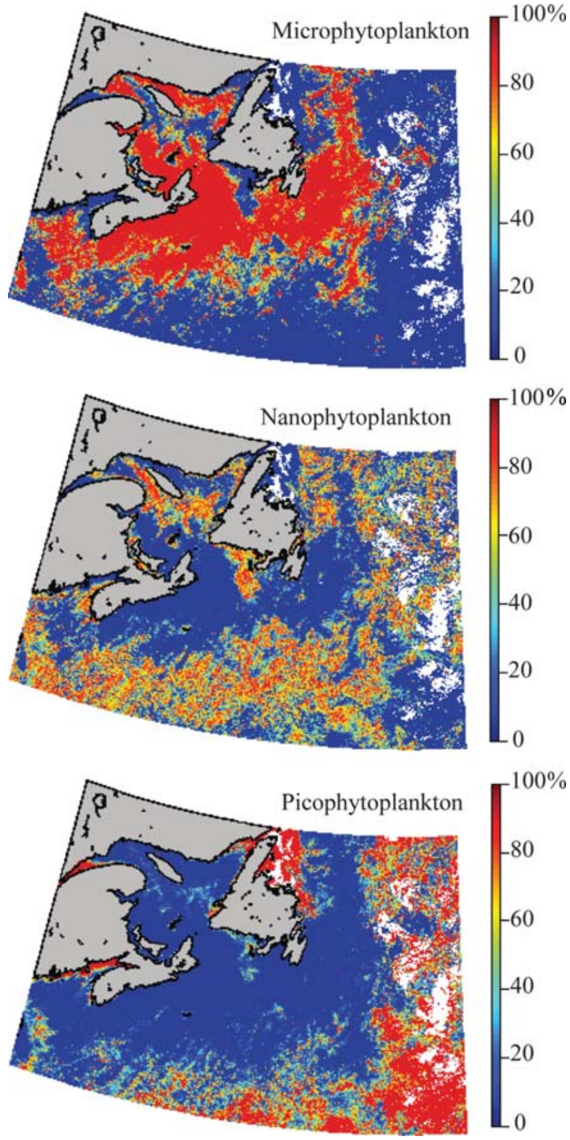

Figure 3. Fractions of micro-, nano-, and picophytoplankton in the Northwest Atlantic for April 2007, derived using SeaWiFS data. Image provided by Emmanuel Devred, Bedford Institute of Oceanography, Canada.

in a form suitable for direct exploitation. For example, the work of Platt *et al.* (2003) on the survival of larval haddock (*Melanogrammus aeglefinus*) was facilitated by access to data where the survival (normalized to spawning biomass) had already been calculated. The investment of effort implied by those holding fisheries data is small compared with the potential gain, so a decision to proceed should not be difficult to take.

Most importantly, it is essential that the continuity of the ocean-colour data stream is maintained to ensure a high-quality, uninterrupted time-series of satellite data (including the derived ecological indicators). Currently, this issue is being addressed by the IOCCG via the "Virtual Constellation" for Ocean Colour Radiometry (OCR). The Virtual Constellation concept was developed by CEOS (Committee on Earth Observation Satellites) and involves multiple satellites working in harmony to augment coverage, enhance system compatibility, and increase data availability via international cooperation among space agencies, simultaneously stimulating the agencies to develop a coordinated response to space-based observation needs. The OCR constellation will ensure a long-term record of calibrated ocean-colour radiances from which various products are derived (including phytoplankton chlorophyll *a*). There is also a concerted inter-agency effort regarding activities relating to sensor intercomparison, and uncertainty assessment of the datasets required for generation of essential climate variables, such as ocean colour.

It is evident that earth observation via remote sensing would facilitate and improve the implementation of an ecosystem-based approach to fisheries management. Using the operational tools described above, it should be possible now to understand plankton dynamics better and to demonstrate, on a routine basis, the influence of ecosystem fluctuations on recruitment of exploited species. Ultimately, such information could be integrated into operational bases for fisheries management. For this to become a reality, policy-makers need to be receptive to the idea of using satellite data as an essential management tool in support of sustainable fisheries. In fact, the application of satellite technology to fisheries research and management questions is already being promoted on an international scale through the intergovernmental Group on Earth Observations (GEO). That group is leading a worldwide effort to build a Global Earth Observation System of Systems (GEOSS) to address a broad range of societal benefits, such as the improvement of management and protection of terrestrial, coastal, and marine ecosystems and the support of sustainable agriculture and aquaculture programmes. To achieve such goals, GEO has set up a workplan structured around specific socio-economic benefit areas. GEO task AG-06-02 falls under agriculture (including fisheries and aquaculture) and calls for consultation at the international level to identify opportunities for the enhanced utilization of earth observation data in fisheries and aquaculture. In response, the SAFARI Programme (Societal Applications in Fisheries and Aquaculture using Remotely-sensed Imagery), funded by the Canadian Space Agency, was developed to address these issues and was quickly accepted by GEO as a way forward. It is foreseen that satellite technology will rapidly become more valuable as an aid to management of the marine ecosystem in general, as well as to the global fishing industry. The growing suite of publications using remotely sensed data to demonstrate the link between variability of year-class strength and matches or mismatches in the timing of the phytoplankton spring bloom, as well as the demonstrable economies of fuel and effort that follow from the use of remotely sensed imagery in captive fisheries, underscore the rapidly expanding requirement for satellite data.

Remote sensing by itself is not a predictive tool. It requires a combination of tools to translate improved understanding of the variability of year classes that may be achieved through remote sensing to a strategy for setting fisheries targets for sustainable management. The longer the interval between the time when the success or otherwise of a particular year class of fish is determined (according to data available by remote sensing) and when that year class enters the fishery, the more difficult it becomes to make predictions based on remote sensing alone. Typically, ocean-colour data are useful for understanding recruitment in the early life cycle of fish, when they depend on plankton as a major component of their diet. For multiyear fisheries, sound predictions would require that we understand the contributions to fluctuations in the intervening year classes too, which may or may not be amenable to remote sensing. It is of note that better prediction is linked to fisheries for which we understand the entire life cycle of the fish, their dietary requirements, and the environmental fluctuations that are likely to affect them. For example, the Northwest Fisheries Science Center of the US National Oceanic and Atmospheric Administration (NOAA) has developed ecological indicators to predict the survival of juvenile salmon in the Columbia River, 1–2 years ahead (www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm). These predictions depend on large-scale features derived from satellite observations, as well as local measurements of additional variables not amenable to remote sensing. Therefore, what is required is a judicious combination of remote sensing, *in situ* observations, and appropriate modelling.

Despite such positive and encouraging signs from the research community, the biggest impediment to operational usage of remote-sensing technology in fisheries management seems to be a lack of willingness in the fisheries community to support it. Although conventional fisheries management undoubtedly has limitations (Longhurst, 2010), and notwithstanding the almost universally accepted wish to manage ecosystems holistically, the possibility to assimilate into fisheries management an objective new datastream on the pelagic ecosystem (its fluctuation in space, time, and structure) is being ignored. Management might not be improved by such assimilation, but we will not know that unless we first make the attempt. The potential benefits are massive; the waste by not using the data is equally great. Only seeming inertia stands in the way.

References

Beamish, R. J., and Rothschild, B. J. (eds). 2009. The Future of Fisheries Science in North America. Fish and Fisheries Series, 31. Springer Science + Business Media BV. 736 pp.

Cannizzaro, J. P., Carder, K. L., Chen, F. R., Heil, C. A., and Vargo, G. A. 2008. A novel technique for detection of the toxic dinoflagellate, *Karenia brevis*, in the Gulf of Mexico from remotely sensed ocean color data. Continental Shelf Research, 28: 137–158.

Chassot, E., Mélin, F., Le Pape, O., and Gascuel, D. 2007. Bottom–up control regulates fisheries production at the scale of eco-regions in European seas. Marine Ecology Progress Series, 343: 45–55.

Cury, P. M., Shin, Y-J., Planque, B., Durant, J. M., Fromentin, J-M., Kramer-Schadt, S., Stenseth, N. Ch., *et al.* 2008. Ecosystem oceanography for global change in fisheries. Trends in Ecology and Evolution, 23: 338–346.

Cushing, D. H. 1974. The natural regulation of fish populations. *In* Sea Fisheries Research, pp. 399–412. Ed. by F. R. Harden Jones. Elek Science, London. 510 pp.

Cushing, D. H. 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Advances in Marine Biology, 26: 249–294.

Devred, E., Sathyendranath, S., and Platt, T. 2007. Delineation of ecological provinces using ocean colour radiometry. Marine Ecology Progress Series, 346: 1–13.

Devred, E., Sathyendranath, S., Stuart, V., Maass, H., Ulloa, O., and Platt, T. 2006. A two-component model of phytoplankton absorption in the open ocean: theory and applications. Journal of Geophysical Research, 111: C03011. doi:10.1029/2005JC002880.

Devred, E., Sathyendranath, S., Stuart, V., and Platt, T. A three component classification of phytoplankton absorption spectra: application to ocean-colour data. Remote Sensing of Environment, in press.

Druon, J-N. 2010. Habitat mapping of the Atlantic bluefin tuna derived from satellite data: its potential as a tool for the sustainable management of pelagic fisheries. Marine Policy, 34: 293–297.

FAO. 2009. The State of the World's Fisheries and Aquaculture 2008. FAO, Rome. 176 pp.

Fisheries and Oceans Canada. 2002. Canada's ocean strategy. Policy and operational framework for integrated management of estuarine, coastal and marine environments in Canada. Fisheries and Oceans Canada. 36 pp.

Fuentes-Yaco, C., Koeller, P. A., Sathyendranath, S., and Platt, T. 2007. Shrimp (*Pandalus borealis*) growth and timing of the spring phytoplankton bloom on the Newfoundland–Labrador shelf. Fisheries Oceanography, 16: 116–129.

Hare, C. E., Leblanc, K., DiTullio, G. R., Kudela, R. M., Zhang, Y., Lee, P. A., Riseman, S., *et al.* 2007. Consequences of increased temperature and CO_2 for phytoplankton community structure in the Bering Sea. Marine Ecology Progress Series, 352: 9–16.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe, viewed in the light of biological research. Rapports et Procès-Verbaux des Réunions du Conseil Permanent International pour l'Exploration de la Mer, 20: 1–228.

Hu, C. M., Muller-Karger, F. E., Taylor, C. J., Carder, K. L., Kelble, C., Johns, E., and Heil, C. A. 2005. Red tide detection and tracing using MODIS fluorescence data: a regional example in SW Florida coastal waters. Remote Sensing of Environment, 97: 311–321.

IOCCG. 2009. Remote Sensing in Fisheries and Aquaculture. Ed. by M-H. Forget, V. Stuart, and T. Platt. Reports of the International Ocean-Colour Coordinating Group, 8. IOCCG, Dartmouth, Canada. 120 pp.

Koeller, P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, A., Ouellet, P., Orr, D., *et al.* 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science, 324: 791–793.

Kumari, B., Raman, M., and Mali, K. 2009. Locating tuna forage ground through satellite remote sensing. International Journal of Remote Sensing, 30: 5977–5988.

Laurs, R. M., Fiedler, P. C., and Montgomery, D. R. 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. Deep Sea Research, 31: 1085–1099.

Loisel, H., Nicolas, J. M., Sciandra, A., Stramski, D., and Poteau, A. 2006. Spectral dependency of optical backscattering by marine particles from satellite remote sensing of the global ocean. Journal of Geophysical Research, 111: C09024. doi:10.1029/2005JC003367

Longhurst, A. 2010. Mismanagement of Marine Fisheries. Cambridge University Press, Cambridge, UK. 334 pp.

Moore, T. S., Campbell, J. W., and Dowell, M. D. 2009. A class-based approach to characterizing and mapping the uncertainty of the MODIS ocean chlorophyll product. Remote Sensing of Environment, 113: 2424–2430.

Platt, T., Fuentes-Yaco, C., and Frank, K. T. 2003. Marine ecology: spring algal bloom and larval fish survival. Nature, 423: 398–399.

Platt, T., and Sathyendranath, S. 2008. Ecological indicators for the pelagic zone of the ocean from remote sensing. Remote Sensing of Environment, 112: 3426–3436.

Platt, T., Sathyendranath, S., Forget, M-H., White, G. N., Caverhill, C., Bouman, H., Devred, E., *et al.* 2008. Operational mode estimation of primary production at large geographical scales. Remote Sensing of Environment, 112: 3437–3448.

Platt, T., Sathyendranath, S., and Fuentes-Yaco, C. 2007. Biological oceanography and fisheries management: perspective after 10 years. ICES Journal of Marine Science, 64: 863–869.

Polovina, J. J., and Howell, E. A. 2005. Ecosystem indicators derived from satellite remotely sensed oceanographic data for the North Pacific. ICES Journal of Marine Science, 62: 319–327.

Reiss, C. S., Checkley, D. M., and Bograd, S. J. 2008. Remotely sensed spawning habitat of Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) within the California Current. Fisheries Oceanography, 17: 126–136.

Sanchez, P., Demestre, M., Recasens, L., Maynou, F., and Martin, P. 2008. Combining GIS and GAMs to identify potential habitats of squid *Loligo vulgaris* in the northwestern Mediterranean. Hydrobiologia, 612: 91–98.

Sathyendranath, S., Watts, L., Devred, E., Platt, T., Caverhill, C., and Maass, H. 2004. Discrimination of diatoms from other phytoplankton using ocean-colour data. Marine Ecology Progress Series, 272: 59–68.

Solanki, H. U., Dwivedi, R. M., Nayak, S. R., Somvanshi, V. S., Gulati, D. K., and Pattnayak, S. K. 2003. Fishery forecast using OCM chlorophyll concentration and AVHRR SST: validation results off Gujarat coast, India. International Journal of Remote Sensing, 24: 3691–3699.

Stockwell, D. A., Whitledge, T. E., Zeeman, S. I., Coyle, K. O., Napp, J. M., Brodeur, R. D., Pinchuk, A. I., *et al.* 2001. Anomalous conditions in the south-eastern Bering Sea, 1997: nutrients, phytoplankton and zooplankton. Fisheries Oceanography, 10: 99–116.

Uitz, J., Claustre, H., Morel, A., and Hooker, S. B. 2006. Vertical distribution of phytoplankton communities in open ocean: an assessment based on surface chlorophyll. Journal of Geophysical Research, 111: C08005. doi:10.1029/2005JC003207

van der Lingen, C. D., Hutchings, L., and Field, J. G. 2006. Comparative trophodynamics of anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax* in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated? African Journal of Marine Science, 28: 465–477.

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

Zainuddin, M., Saitoh, S-I., and Saitoh, K. 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, 31: L20311, doi:10.1029/2004GL021000