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The rocky road from research to operations for satellite ocean-colour data in fishery management

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The aim of the SAFARI project is to accelerate the assimilation of earth-observation data into fisheries research and management by facilitating the application of rapidly evolving satellite technology. This assumes that these data will be available in future. However, for ocean-colour data, that assumption may not hold because of possible gaps in data continuity. Of the many types of satellite data, ocean colour is the most important to fisheries, because it is the only biological measurement. However, current ocean-colour sensors are all operating beyond their planned design life, and there are potential problems with future launches. Although the research community is aware of the value of satellite ocean-colour data, advocacy from the operational community, fishery management in particular, has been lacking. In the United States, the absence of an easily identifiable operational need for ocean-colour data is largely responsible for the likely gap in data continuity. A range of current and potential operational uses of ocean-colour data, some reasons why these data have been underutilized in fishery management, and what can be done to mitigate them are discussed and outlined.

Keywords: chlorophyll, fisheries, research to operations, satellite ocean colour.

Introduction

Environmental satellite data measurements, such as sea surface temperature (SST), sea surface height, ocean colour, and surface vector winds, are valuable resources needed to understand, monitor, and predict changes in the earth's ecosystems, climate, and weather. In the United States, the two agencies responsible for flying environmental satellites are the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). NASA is responsible for research and development of new satellite missions, whereas NOAA is responsible for launching and maintaining operational satellites to acquire data on the earth's atmosphere and oceans and providing continuity for these datastreams. However, little of the sensor technology developed by NASA has been utilized by NOAA (National Research Council, 2003; US Commission on Ocean Policy, 2004). The transition process from research to operations (R2O) has earned the nickname "valley of death", a metaphor for the barriers separating research results from operational applications (National Research Council, 2000a). This "valley of death" has been bridged fairly successfully for weather forecasting (Serafin *et al.*, 2002) and discussion has started about the R2O process for climate issues (National Research Council, 2000b, c). The altimetry community has successfully lobbied for continued implementation, using the simple message that sea surface height measurements are imperative for monitoring global sea-level rise (Cazenave and Llovel, 2010). However, there has been little discussion of R2O for ocean-colour data or for applications related to ecosystems and fishery management. The absence of clearly defined operational needs for ocean-colour data is problematic, because the justification for launching operational satellite missions requires them.

Here, a brief summary of past, current, and scheduled ocean-colour sensors, from the United States and other countries, is given along with an overview of the research that has developed because of the availability of ocean-colour data. After describing the term operational, a range of current and potential "operational" uses of ocean-colour data is discussed. Some reasons why ocean-colour data have been underutilized in fishery management and what can be done to mitigate them are outlined. The United States is not the only country flying ocean-colour satellites: Europe, Japan, and India all have satellite ocean-colour programmes, but the focus here is on the R2O process of ocean colour in the United States. Hence, operational usages of ocean-colour data are discussed from a US perspective, an important caveat, because there are international differences in what constitutes operational usage.

The history of satellite ocean colour

The first ocean-colour satellite, the Coastal Zone Color Scanner (CZCS), was launched in 1978 by NASA, and was operational until late 1986 (Figure 1). CZCS was a "proof-of-concept" mission, intended to last just 1 year, which demonstrated that satellite ocean-colour measurements could be used reliably to derive products such as chlorophyll *a* and sediment concentrations (Barale and Schlittenhardt, 1993; Mitchell, 1994). Most importantly, it provided justification for subsequent ocean-colour missions, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging

Spectroradiometer (MODIS) in the United States, although there was a ten-year gap between CZCS and the launch of SeaWiFS in 1997 (Figure 1). SeaWiFS and MODIS were both launched by NASA as research missions. Two MODIS sensors were launched, one on the Terra satellite in 1999 and one on the Aqua satellite in 2002. However, because of uncertainties and instabilities in the pre-launch and in-orbit characterization of MODIS-Terra, these data have been largely unusable (Franz *et al.*, 2008). Hereafter, the term "MODIS" refers to the sensor on the Aqua satellite. Although SeaWiFS was still operating in 2010, there have been problems with its telemetry since January 2008, resulting in intermittent data gaps.

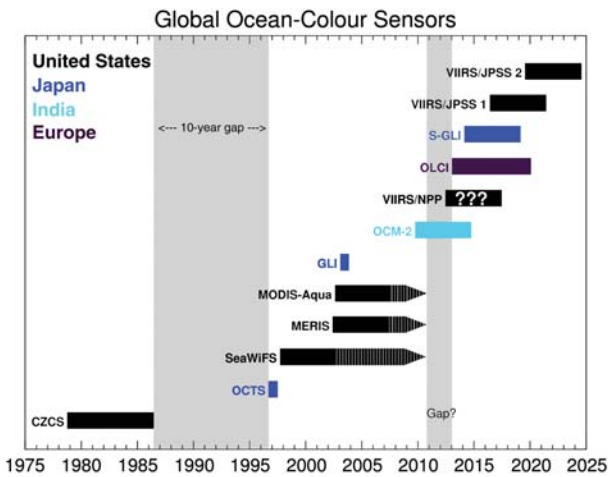

Figure 1. Time-line illustrating past, current, and future global ocean-colour satellite missions. Satellites still generating data are displayed as arrows, and hashed areas indicate the period when the current sensors have passed their 5-year design life. Grey-shaded areas indicate the past and potential future gap in ocean-colour data. CZCS, Coastal Zone Colour Scanner; OCTS, Ocean-Colour Temperature Scanner; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; OCM, Ocean Colour Monitor; MERIS, Medium Resolution Imaging Spectrometer; MODIS, Moderate Resolution Imaging Spectroradiometer; GLI, Global Imager; VIIRS, Visible Infrared Imager Radiometer Suite; NPP, NPOESS Preparatory Project (NPOESS: National Polar-orbiting Operational Environmental Satellite System, now restructured into JPSS); OLCI, Ocean Land Colour Instrument; S-GLI, Second-Generation Global Imager; JPSS, Joint Polar Satellite System.

Other countries have also developed ocean-colour programmes. Japan launched two ocean-colour sensors, the Ocean-Colour Temperature Scanner (OCTS) in 1996 and the Global Imager (GLI) in 2002. Neither remained operational for more than a year (Figure 1).

India launched the Ocean-Colour Monitor (OCM) in 1999. However, data from this sensor have generally not been available to the international community and there are also serious issues with its calibration (Lyon, 2009). The inaccessibility of these data is evident from the small number of papers citing OCM (65, see Table 1) relative to SeaWiFS (1175), despite their similar time in orbit (Figure 1). Most papers using OCM data have come from the Indian community (Figure 2), which underscores the inaccessibility of the data on an international level. The numbers in Figure 2 actually overestimate the international dissemination associated with a particular sensor. For example, of the 65 papers (Table 1) citing OCM data, only two have author lists without Indian affiliation. The follow-on to OCM, OCM-2, was launched in September 2009. A major impetus for OCM-2 was the need for ocean-colour data for forecasting potential fishing zones (PFZs; see Nayak *et al.*, 2003). It is anticipated that data from OCM-2 will be more accessible to the international community, but this remains to be seen.

Europe launched the Medium Resolution Imaging Spectro-meter (MERIS) in 2002. MERIS has a narrower swathe width than SeaWiFS and MODIS and, hence, less frequent coverage. Although MERIS data accessibility has improved since its launch, there are still issues. For example, level 1 data, which are needed to apply regional atmospheric corrections, are not openly distributed. The more restricted data availability, relative to US sensors, is reflected in the statistics on MERIS publications, which are predominantly European (Figure 2) and relatively few, given the time in orbit (Table 1).

Future ocean-colour sensors and potential problems for the research community

The first US ocean-colour sensor to be launched as an operational mission will be the Visible/Infrared Imager Radiometer Suite (VIIRS) in 2012. VIIRS was developed as part of the National Polar-orbiting Operational Environmental Satellite (NPOESS) programme, designed to meet the requirements of NASA, NOAA, and the US Department of Defense. However, in February 2010, because of cost overruns, NPOESS was restructured into the Joint Polar Satellite System (JPSS), a programme to be run jointly by

Table 1. Number of publications citing the different ocean-colour sensors, the number of publications per year the satellite was in orbit, and the number of papers with a subject classification of "oceanography" or "fisheries", or with "fish" included in the search string.

			Oceanography		Fisheries		"Fish" in search	
Sensor[a]	Number of papers	Papers per orbit year	Number	%	Number	%	Number	%
CZCS	428	56	208	49	7	2	8	2
GLI	34	49	11	32	0	0	0	0
SeaWiFS	1 175	92	478	41	24	2	32	3
MERIS[a]	140	17	14	10	0	0	2	1
MODIS[a]	361	45	74	20	4	1	3	1
OCM[a]	65	6	19	29	0	0	8	12
OCTS[a]	64	80	17	27	0	0	1	2
Total	2 267	46	821	36	35	2	54	2

[a]Search string included the term "colour" ("color") or "chlorophyll".
As of 19 May 2010. *Source*: ISI Web of Science.

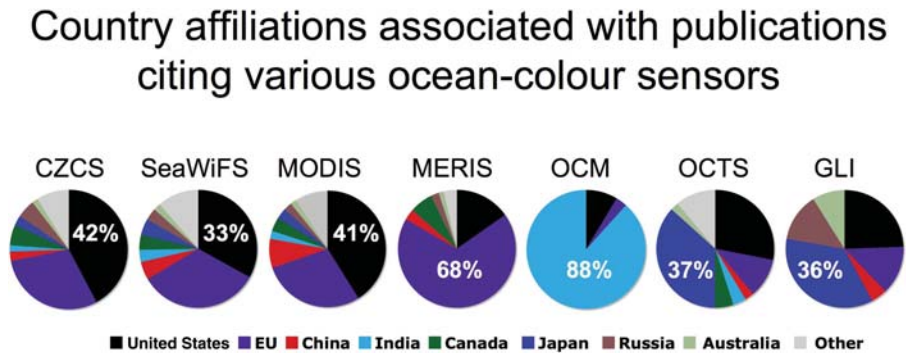

Figure 2. Distribution of the country affiliations associated with publications citing the CZCS, SeaWiFS, MODIS, MERIS, OCM, OCTS, and GLI ocean-colour sensors. The percentage of publications from the country that launched the satellite is displayed (as of 19 May 2010. *Source*: ISI Web of Science).

NOAA and NASA. The first satellite scheduled to be launched under NPOESS was a precursor satellite called the NPOESS Preparatory Project (NPP), whose name has not changed despite the program restructuring. Hence, the first VIIRS sensor will be launched on the NPP satellite, scheduled for 2012. The first two JPSS satellites, currently scheduled for launch in 2016 and 2019, will also carry a VIIRS sensor (Figure 1).

If either MODIS or MERIS, both past their design life, fails before the launch of NPP in 2012, there will be a gap in the continuity of the climate data record (CDR) for global ocean-colour data [a CDR has been defined as a time-series of measurements of sufficient length, consistency, and continuity to determine climate variability and change (National Research Council, 2004)]. Beyond the data-continuity problem is the inability to calibrate between different sensors, prohibiting incorporation of future ocean-colour datastreams into the current continuous stream extending back to 1997.

Additional technical issues with VIIRS preclude a CDR from NPP, although these should be resolved for the VIIRS sensors on JPSS-1 and JPSS-2. If the currently operating ocean-colour sensors fail before the launch of VIIRS, the availability of data from the OCM-2 will be critical (Figure 1). Europe is planning to launch the Ocean Land Colour Instrument (OLCI) in 2013 and Japan plans to launch the Second-Generation Global Imager (SGLI) in 2014 (Figure 1). Both launches are planned after VIIRS on NPP; therefore, they will not mitigate any gap before VIIRS/NPP, but they could provide critical information if data from VIIRS/NPP are not of sufficient quality.

The above ocean-colour sensors all have different numbers of spectral bands, spatial resolutions, repeat times, and degrees of calibration, which complicate data comparison between them (Maritorena and Siegel, 2005; Morel *et al.*, 2007; D'Alimonte *et al.*, 2008; Gregg and Casey, 2010). For example, SeaWiFS and MODIS, although processed with consistent methods, have significant differences that must be resolved before merging their datastreams into one record (Franz *et al.*, 2005; Gregg and Casey, 2007, 2010). An in-depth comparison of the different sensors is beyond the scope of this paper; detail can be found elsewhere (Gregg *et al.*, 1998; Franz *et al.*, 2005; Lee *et al.*, 2007a; Gower *et al.*, 2008; McClain, 2009; Djavidnia *et al.*, 2010).

Importance of ocean colour to research

The advent of satellite ocean-colour data transformed the field of biological oceanography. More than 2000 papers have been published using ocean-colour data (Table 1). In addition to a number of review articles summarizing the research impact of satellite ocean-colour data (McClain *et al.*, 2006; Yoder and Kennelly, 2006; McClain, 2009), there have been a number of special volumes devoted to ocean-colour results (Barale and Schlittenhardt, 1993; Mitchell, 1994; Siegel *et al.*, 2004a, b). Some specific contributions resulting from analysis of ocean-colour data include (in no particular order):

(i) refining our understanding of the seasonal cycles of surface-ocean chlorophyll (Yoder *et al.*, 1993; Longhurst, 1995, 2007);

(ii) defining ecological provinces in the ocean (Longhurst, 1995, 2007; Platt and Sathyendranath, 1999; Spalding *et al.*, 2007; Devred *et al.*, 2007);

(iii) determining interannual variations in the seasonal cycle of chlorophyll (Vargas *et al.*, 2009);

(iv) quantifying the phenological match between commercially important species and their planktonic food (Platt *et al.*, 2003; Koeller *et al.*, 2009a);

(v) identifying specific types of phytoplankton, such as coccolithophorids (Brown and Yoder, 1994; Gordon *et al.*, 2001), *Trichodesmium* (Borstad *et al.*, 1992; Subramaniam *et al.*, 2002; Westberry and Siegel, 2006), or different phytoplankton functional types (Sathyendranath *et al.*, 2004; Alvain *et al.*, 2008);

(vi) detecting and monitoring harmful algal blooms (HABs; Stumpf, 2001; Allen *et al.*, 2008; Hu *et al.*, 2008);

(vii) mapping river plumes (Hochman *et al.*, 1994; Hu *et al.*, 2004);

(viii) examining upwelling dynamics (Thomas *et al.*, 2001; Campillo-Campbell and Gordoa, 2004; Garcia *et al.*, 2008);

(ix) quantifying the basin-scale impact of *El Niño* events (Chavez *et al.*, 1999; Wilson and Adamec, 2001; McClain *et al.*, 2002; Sackmann *et al.*, 2004);

(x) depicting long-terms trends in global patterns of chlorophyll (Gregg and Conkright, 2002; Dandonneau *et al.*, 2004; Gregg *et al.*, 2005; Polovina *et al.*, 2008; Martinez *et al.*, 2009; Vantrepotte and Melin, 2009);

(xi) determining how variability of the penetration of solar radiation into the ocean surface affects circulation, mixing, and climate (Lewis *et al.*, 1990; Sweeney *et al.*, 2005; Wetzel *et al.*, 2006; Anderson *et al.*, 2007; Gnanadesikan and Anderson, 2009);

(xii) improving biological and ecological models through either data assimilation or validation (Fan and Lv, 2009; Fontana *et al.*, 2009; Jolliff *et al.*, 2009; Ourmieres *et al.*, 2009);

(xiii) determining ocean primary productivity (Behrenfeld and Falkowski, 1997; Campbell *et al.*, 2002; Carr *et al.*, 2006);

(xiv) mapping coloured dissolved organic matter (CDOM) distributions (Siegel *et al.*, 2005); and

(xv) identifying anomalous chlorophyll blooms (Uz, 2007; Wilson and Qiu, 2008).

These research applications provide basic information about marine ecosystems. However, most of them do not have a direct operational component. Usages of ocean-colour data in the management of fisheries and aquaculture, and other societal benefits of ocean-colour data, were recently reviewed in two reports from the International Ocean Colour Coordination Group (IOCCG, 2008, 2009) and are summarized below.

Operational uses of ocean colour

The definition of "operational" varies widely depending on the application or the community in question. The primary use of operational satellite data products has been weather forecasting, an application that requires access to near-real-time (NRT) datastreams, 24 h a day, 7 d a week (24/7). Hence, there is a misconception that operational uses always require NRT, 24/7 data. However, for fishery management, an interannual climate quality datastream is often more relevant. Another definition used within the R2O context interprets the term operational as encompassing anything not research, which is very ambiguous. NOAA's policy on R2O (NOAA, 2008) defines operations as "sustained, systematic, reliable, and robust mission activities with an institutional commitment to deliver appropriate, cost-effective products and services". NOAA's mission includes mitigating coastal hazards, sustaining marine ecosystems, and monitoring climate variations. By this definition, the integration of ocean-colour data into activities supporting those mission objectives should constitute an operational use. However, it is not clear how widely this is accepted. Although the issue of what is operational might seem semantic, it is clearly important to the justification of new missions.

Harmful algal blooms

Monitoring HABs is one example of a clear R2O transition of ocean-colour data. Toxin-producing algae that have negative impacts on humans, marine organisms, and/or coastal economies, HABs can result in the closure of shellfish beds and beaches, massive fish kills, illness and death to marine mammals and seabirds, and alteration of marine habitats. Consequently, HAB events adversely affect commercial and recreational fishing, tourism, and valued habitats, creating a significant impact on local economies and the livelihood of coastal residents. Advanced warnings of HAB events and estimation of their spatial distributions increase the options for managing such events and minimizing their harmful impact.

The large spatial scale and high frequency of observations needed to assess bloom location and movements make ocean-colour satellite data a key component in HAB research and forecasting. New blooms can be identified by a chlorophyll-anomaly method that accounts for the complex optical properties in coastal waters that can confound the satellite chlorophyll algorithm (Stumpf *et al.*, 2003a; Tomlinson *et al.*, 2009). For some coastal waters with large quantities of organic matter, fluorescence data from the MODIS and MERIS sensors have the potential of providing better estimates of bloom extent (Hu *et al.*, 2005; Zhao *et al.*, 2010).

Limitations of satellite HAB research and forecasting include the need for *in situ* water sampling, because not all high-chlorophyll features are HABs. There are also many different types of HAB, and algorithms developed for one species and region often are not transferable. Additionally, not all HABs can be detected by satellite ocean-colour data (Anderson, 2009), and the spatial resolution of the current ocean-colour sensors can be too coarse to detect features in many of the coastal regions where HABs develop. Despite these limitations, satellite ocean colour can be an effective tool for monitoring HABs, which NOAA has done operationally in the United States since 2006, producing HAB bulletins twice a week for the Gulf of Mexico (Stumpf *et al.*, 2009). Ocean-colour-based operational HAB forecasts are also under development in Europe (Johannessen *et al.*, 2006) and Australia (Roelfsema *et al.*, 2006).

Fisheries

In the broadest sense, fisheries encompass not just commercially important fish stocks, but all living marine resources (LMRs), including threatened and endangered species of fish, as well as marine mammals and invertebrates. There are three distinct aspects of fisheries, harvesting, assessment, and management, all of which have different goals. Satellite ocean-colour data have been used extensively to help harvest fish more efficiently in India and Japan (Wilson *et al.*, 2008; Saitoh *et al.*, 2009). Although this is a clear operational use of the data by some definitions (Kendall and Duker, 1998), it is not applicable for NOAA, because improving harvesting efforts is not part of its mandate to manage and conserve LMRs. Consequently, the agency cannot provide services, such as the PFZ maps distributed by the Indian government (Nayak *et al.*, 2003; Choudhury *et al.*, 2007), or compete with those available commercially (Saitoh *et al.*, 2009, 2011). Hence, for NOAA, operational usages of ocean colour in a fisheries context refer to those that involve the assessment or management of LMRs.

Assessment and management of exploited species

The primary operation within NOAA Fisheries is stock assessment. NOAA is responsible for managing more than 900 commercially important stocks and ~210 protected or endangered species (National Marine Fisheries Service, 2001). Assessments provide the technical basis for setting annual fish quotas and other management measures to achieve optimum yield and concurrently avoiding overfishing and ecosystem harm. At a minimum, a quantitative stock assessment requires monitoring of catch, abundance, and biological characteristics of the stock. Achieving a balance between exploitation and conservation requires substantial information about the stock, its fishery, the ecosystem, and the habitat; however, data on the last two have seldom been incorporated into stock assessments. The environmental factors influencing populations are complex and poorly understood, so they have largely been excluded from traditional assessment models, which greatly limits their accuracy and effectiveness (Koeller *et al.*, 2009b). Bringing environmental and ecological data into the process requires radical changes to the overall management approach, including the adoption of conceptual and analytical frameworks that accommodate them—a daunting prospect counter to the conservative nature of fisheries assessment and management.

Recently, there has been a move towards ecosystem-based management of fisheries (Browman and Stergiou, 2005; Sherman *et al.*, 2005; Frid *et al.*, 2006), which has given new impetus to a better understanding of the environmental factors influencing fish stock dynamics and to include environmental variability as an integral part of the assessment process. Most of the spatial features that characterize ecosystems and ecosystem variability, i.e. ocean fronts, eddies, convergence zones, and river plumes, cannot be resolved adequately without satellite data. The measurements of primary productivity and chlorophyll obtained from satellite ocean-colour data greatly facilitate monitoring the base of the oceanic food chain, and these parameters form part of the assessment strategy for large marine ecosystems (LMEs; Sherman and Hempel, 2008; Chassot *et al.*, 2011; Sherman *et al.*, 2011).

Management of protected species

Satellite ocean-colour data provide key information about the oceanographic conditions associated with the distribution and migration patterns of protected species. For example, satellite ocean-colour data allow the tracking of seasonal and interannual variations of the transition zone chlorophyll front (TZCF), a boundary in the North Pacific separating cool, high-chlorophyll, vertically mixed water in the north, and warm, low-chlorophyll, vertically stratified subtropical water in the south (Polovina *et al.*, 2001). The TZCF is an important migration pathway for endangered loggerhead turtles (*Caretta caretta*) that forage in the high-chlorophyll, meandering eddies associated with the front (Polovina *et al.*, 2004; Kobayashi *et al.*, 2011). Other apex predators, such as albacore tuna (*Thunnus alalunga*), also use the front as a migratory corridor (Laurs and Lynn, 1977; Polovina *et al.*, 2001). The extent of meandering of the TZCF appears to influence trophic transfers and productivity, with more meandering resulting in higher catch per unit effort of albacore (Polovina *et al.*, 2001). Interannual variability of the southern extent of the TZCF also affects the survival of juvenile monk seals (*Monachus schauinslandi*) in the Hawaiian islands (Baker *et al.*, 2007).

The types of information described above provide the framework upon which to build ecosystem-based management strategies. For example, a NOAA programme called TurtleWatch uses satellite ocean-colour data, in part, to predict areas with a high probability of loggerheads and longline interactions, so that fishers can minimize turtle bycatch (Howell *et al.*, 2008). For monk seals, satellite ocean-colour data can be used to predict years when low survival is likely and, hence, when management intervention, such as a head-start programme, should be implemented (Wilson *et al.*, 2009). Ocean-colour data are also being used to predict the movement and congregation of highly endangered northern right whales (*Eubalaena glacialis*) in the Atlantic, with the management aim of mitigating their ship-strike mortality (Pershing *et al.*, 2009).

Why are satellite ocean-colour data underutilized in fisheries?

Despite these uses, it can be argued that the full potential of satellite ocean-colour data has not been realized within NOAA or in fisheries science generally. For example, <2% of the publications using ocean-colour data have involved any aspect of fisheries (Table 1). Perhaps the small number of fisheries-related publications is because of the exclusion of stock assessment papers to the grey literature, but this seems unlikely, given the paucity of environmental data in stock assessments generally (Koeller *et al.*, 2009b). The small number could also be an artefact of insufficient classification within the citation database. The numbers are based on citations with "fisheries" listed as the subject, so papers dealing with protected species are mostly excluded. Note also that just 35% of the ocean-colour papers are classified under "oceanography" (Table 1), yet one would expect the majority using ocean-colour data to have an oceanographic basis. Including "fish" in the search string resulted in a few more papers, but did not change the overall result. The relatively high percentage (12%) of OCM papers dealing with fish reflects the use of these data in the Indian PFZ programme (Nayak *et al.*, 2003; Choudhury *et al.*, 2007). Nonetheless, Table 1 supports the assertion that ocean-colour data are largely underutilized in fisheries science. There may be several reasons for this.

(i) *Dissemination*. Satellite data availability and their potential use in fisheries are not always effectively communicated outside the satellite community.

(ii) *Unfamiliarity*. Satellite data can be difficult to access, manipulate, and process, particularly when the skills and computational resources needed for manipulating large datasets are lacking.

(iii) *Unavailability of desired products*. For many fisheries applications, the parameter of interest may not be readily available or easily calculated. Examples of these include primary production, front locations, and climatologies.

(iv) *Data inadequacy*. The 12-year time-series of ocean-colour data is relatively short compared with fisheries datasets that often span many decades. Additionally, many fisheries operate in coastal (case II) waters, where interpretation of satellite ocean colour is complicated by the lack of site-specific algorithms—the standard algorithms are defined for open-ocean (case I) waters (Gordon and Morel, 1983).

(v) *Resistance to change*. Stock assessment/management tends to avoid the use of environmental data, because of the complexities involved, especially when simpler population models often suffice for short-term (~1 year) predictions. For assessment biologists, it can also be difficult or impossible to undertake new and innovative analyses in addition to preparing routine assessments built on traditional frameworks.

What can be done?

Some of the issues listed above are easier to address than others. The first three, involving data distribution and usage, are relatively straightforward, compared with ensuring data continuity, better characterization of coastal waters, or changing stock assessment methodologies.

Training

Satellite data literacy can be enhanced through training courses specifically designed for target audiences, such as marine resource managers. The IOCCG has a strong interest in capacity building and has, since 1997, been conducting and sponsoring courses on the usage and application of ocean-colour data in various developing countries. For example, the symposium covered by this issue included a training session attended by 55 trainees from 16 countries. NOAA has also held several satellite courses for its scientists since 2006. Such courses are particularly helpful when both data providers and data users are involved. In addition to educating participants about the availability, access, and use of satellite data, providers obtain a better understanding of user needs and requirements. Some examples of this are given below.

Better data accessibility

Courses conducted by NOAA were designed to help participants work with satellite data using ArcGIS, software familiar to many fishery scientists. Because importing satellite data into ArcGIS can be cumbersome, particularly for lengthy time-series, a new ArcGIS extension (Environmental Data Connector, EDC) now allows users to browse and subset large amounts of data online and convert them into raster or feature classes. The EDC also facilitates users animating and manipulating data for temporal analysis, including provision for non-uniform time-steps. A new version under development will allow access to sensor data served by protocols compliant with IOOS (Integrated Ocean Observing System). The EDC is available, at no cost, at http://www.pfeg.noaa.gov/products/EDC/ or http://www.asascience.com/.

NOAA courses also identified the need for a simple method of matching satellite data with moving datapoints, such as tagged animals or ships. Navigating global satellite datasets for the few values associated with a telemetry track can be daunting. To alleviate this problem, open-access routines were developed using either Matlab or R (freeware). These "xtractomatic" extraction routines take advantage of the effective data-delivery mechanisms provided by THREDDS (Thematic Real-time Environmental Distributed Data System) catalogues and perform extractions based on the input of longitude, latitude, time, and a chosen variable (SSH, SST, chlorophyll, etc.). These routines are freely available at http://coastwatch.pfel.noaa.gov/xtracto/.

In the past 5 years, web-based methods of accessing and visualizing different satellite data products have increased dramatically. It is no longer sufficient to simply post large datafiles on the web and expect them to be used. For example, NASA's Giovanni system allows online visualization and analysis of ocean-colour data, including views of climatologies or anomalies (http://reason.gsfc.nasa.gov/Giovanni/). Primary productivity products are now available online (at http://www.science.oregonstate.edu/ocean.productivity/ and http://coastwatch.pfel.noaa.gov/coastwatch/CWBrowserWW360.jsp). Ocean-colour data are often just one of many satellite products of interest, so sites that offer one-stop shopping are most useful. For example, a comprehensive collection of environmental satellite data products (including primary productivity and front locations) is available at NOAA's west coast Coastwatch site (http://coastwatch.pfel.noaa.gov/coastwatch/CWBrowserWW360.jsp).

Improving data coverage temporally and spatially

Coastal waters contain most of the world's fisheries, but they also contain CDOM and sediments that confound the chlorophyll algorithms designed for open waters without these constituents (IOCCG, 2000). Additionally, different atmospheric corrections are required for accurate characterization of case II waters (Land and Haigh, 1996; Stumpf *et al.*, 2003b; Schroeder *et al.*, 2007). Although improvements have been made in the chlorophyll algorithms for coastal waters from the current sensors (Gitelson *et al.*, 2009; Komick *et al.*, 2009; Kuchinke *et al.*, 2009; Moses *et al.*, 2009), these studies are all region-specific, as are the algorithms. To address this issue on a global scale, Europe recently established the CoastColour project, which will develop and validate different case II algorithms for the MERIS instrument over a global range of coastal water types.

Coastal zones are extremely dynamic relative to the open ocean, so greater spatial and temporal resolution is needed to resolve their features, e.g. 30–300 m, multiple looks per day (IOCCG, 2000). These spatial and temporal scales are unachievable simultaneously with polar-orbiting satellites. Airborne sensors deliver high spatial resolution, with fewer atmospheric correction issues, but provide only a single snapshot in time (Carder *et al.*, 1993; Davis *et al.*, 2002; Filippi *et al.*, 2006). Geostationary satellites are the best option for high temporal resolution, which has been demonstrated with SST data (Maturi *et al.*, 2008). The first ocean-colour sensor on a geostationary satellite was launched by South Korea in July 2010 (Neukermans *et al.*, 2009; Lee *et al.*, 2010). Additionally, there is increasing interest in satellite or airborne hyperspectral sensors to characterize coastal waters better (Malthus and Mumby, 2003; Brasseur *et al.*, 2009). For example, data from Hyperion, a NASA hyperspectral sensor originally designed for land applications, have been useful in complex coastal regions (Brando and Dekker, 2003; Lee *et al.*, 2007b).

It is crucial that CDRs of ocean-colour data be archived and maintained to provide a baseline for gauging marine ecosystem change and to track historical variations. Clearly, development and maintenance of global coverage requires an international effort, and considerable progress has been made. For example, the Committee on Earth Observation Satellites (CEOS) developed the concept of satellite constellations providing virtual global coverage. The implementation plan for the Ocean-Colour Radiometry Virtual Constellation (OCR–VC) is being developed by a working group of the IOCCG (Yoder *et al.*, 2009). The European GlobColour project currently generates a consistently calibrated global product with the best possible spatial coverage, by merging ocean-colour data from SeaWiFS, MODIS, and MERIS (Pinnock *et al.*, 2007).

Shifting paradigms

Although traditional stock assessments do not usually incorporate environmental variability, there is growing interest in ecosystem-based management strategies (Sherman *et al.*, 2005; Frid *et al.*, 2006). Satellite chlorophyll measurements are a basic component in the definition and assessment of LMEs (Sherman *et al.*, 2011) and the development of an ecosystem approach to fisheries (EAF; Chassot *et al.*, 2011). Integrated ecosystem assessments (IEAs) with appropriate ecosystem indicators, including satellite observations, have been proposed as a framework for ecosystem-based management (Levin *et al.*, 2009). Although there is much uncertainty and controversy surrounding ecosystem indicators, there is general agreement that they should be directly observable, supported by historical time-series and understandable by the general public (Rice and Rochet, 2005; Levin *et al.*, 2009). These important criteria are all applicable to satellite ocean-colour data.

Concluding remarks

The research value of satellite ocean-colour data is substantial and they have become indispensible for many marine research applications. The value of satellite ocean-colour data for better understanding the oceans, which cover 71% of our planet, and monitoring interannual changes in marine ecosystems is compelling enough to require a sustained datastream of global ocean-colour data.

(i) Ocean-colour data are used operationally in the monitoring of HABs and in fish finding-type programmes (India, Japan).

(ii) The relevant time-scales for operational usages of ocean-colour data in fisheries assessment and management are seasonal and interannual, so they require a continuous time-series of science-quality, ocean-colour data.

(iii) Ocean-colour data are needed in the assessments of marine habitats and ecosystems and to monitor climate variability. Currently, many of the capabilities of ocean-colour data are still being researched actively and have not yet transitioned into management strategies.

(iv) It would be unfortunate if another gap in ocean-colour data developed, so prohibiting the merger of the current 12-year record with future ocean-colour data.

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References

Allen, J. I., Smyth, T. J., Siddorn, J. R., and Holt, M. 2008. How well can we forecast high biomass algal bloom events in a eutrophic coastal sea. Harmful Algae, 8: 70–76.

Alvain, S., Moulin, C., Dandonneau, Y., and Loisel, H. 2008. Seasonal distribution and succession of dominant phytoplankton groups in the global ocean: a satellite view. Global Biogeochemical Cycles, 22: BG3001, doi:3010.1029/2007GB003154.

Anderson, D. M. 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). Ocean and Coastal Management, 52: 342–347.

Anderson, W. G., Gnanadesikan, A., Hallberg, R. W., Dunne, J., and Samuels, B. L. 2007. Impact of ocean-color on the maintenance of the Pacific Cold Tongue. Geophysical Research Letters, 34: GB4006, doi:4010.1029/2006GB002907.

Baker, J. D., Polovina, J. J., and Howell, E. A. 2007. Effect of variable oceanic productivity on the survival of an upper trophic predator, the Hawaiian monk seal *Monachus schauinslandi*. Marine Ecology Progress Series, 346: 277–283.

Barale, V., and Schlittenhardt, P. M. (Eds). 1993. Ocean Colour: Theory and Applications in a Decade of CZCS Experience. Kluwer Academic, Dordrecht. 367 pp.

Behrenfeld, M. J., and Falkowski, P. G. 1997. A consumer's guide to phytoplankton primary productivity models. Limnology and Oceanography, 42: 1479–1491.

Borstad, G. A., Carpenter, E. J., and Gower, J. F. R. 1992. Development of algorithms for remote sensing of *Trichodesmium* blooms. *In* Marine Pelagic Cyanobacteria: *Trichodesmium* and Other Diazotrophs, pp. 193–210. Ed. by E. J. Carpenter, D. G. Capone, and J. G. Rueter. Kluwer Academic, Dordrecht. 376 pp.

Brando, V. E., and Dekker, A. G. 2003. Satellite hyperspectral remote sensing for estimating estuarine and coastal water quality. IEEE Transactions on Geoscience and Remote Sensing, 41: 1378–1387.

Brasseur, P., Gruber, N., Barciela, R., Brander, K., Doron, M., El Moussaoui, A., Hobday, A. J., *et al.* 2009. Integrating biogeochemistry and ecology into ocean data assimilation systems. Oceanography, 22: 206–215.

Browman, H. I., and Stergiou, K. I. 2005. Politics and socio-economics of ecosystem-based management of marine resources. Marine Ecology Progress Series, 300: 241–242.

Brown, C. W., and Yoder, J. A. 1994. Coccolithophorid blooms in the global ocean. Journal of Geophysical Research, 99: 7467–7482.

Campbell, J., Antoine, D., Armstrong, R., Arrigo, K., Balch, W., Barber, R. T., Behrenfeld, M. J., *et al.* 2002. Comparison of algorithm for estimating ocean primary production from surface chlorophyll, temperature and irradiance. Global Biogeochemical Cycles, 16, doi:10.1029/2001GB001444.

Campillo-Campbell, C., and Gordoa, A. 2004. Physical and biological variability in the Namibian upwelling system: October 1997–October 2001. Deep Sea Research Part II, 51: 147–158.

Carder, K. L., Reinersman, P., Chen, R. F., Muller-Karger, F. E., Davis, C. O., and Hamilton, M. 1993. AVIRIS calibration and application in coastal oceanic environments. Remote Sensing of Environment, 44: 205–216.

Carr, M-E., Friedrichs, M. A. M., Schmeltz, M., Aita, M. N., Antoine, D., Arrigo, K. R., Asanuma, I., *et al.* 2006. A comparison of global estimates of marine primary production from ocean-color. Deep Sea Research Part II, 53: 741–770.

Cazenave, A., and Llovel, W. 2010. Contemporary sea level rise. Annual Review of Marine Science, 2: 145–173.

Chassot, E., Bonhommeau, S., Reygondeau, G., Nieto, K., Polovina, J. J., Huret, M., Dulvy, N. K., *et al.* 2011. Satellite remote sensing for an ecosystem approach to fisheries management. ICES Journal of Marine Science, 68: 651–666.

Chavez, F. P., Strutton, P. G., Friederich, G. E., Feely, R. A., Feldman, G. C., Foley, D. G., and McPhaden, M. J. 1999. Biological and chemical response of the equatorial Pacific to the 1997–98 *El Niño*. Science, 286: 2126–2131.

Choudhury, S. B., Jena, B., Rao, M. V., Rao, K. H., Somvanshi, V. S., Gulati, D. K., and Sahu, S. K. 2007. Validation of integrated potential fishing zone (IPFZ) forecast using satellite based chlorophyll and sea surface temperature along the east coast of India. International Journal of Remote Sensing, 28: 2683–2693.

D'Alimonte, D., Zibordi, G., and Melin, F. 2008. A statistical method for generating cross-mission consistent normalized water-leaving radiances. IEEE Transactions on Geoscience and Remote Sensing, 46: 4075–4093.

Dandonneau, Y., Deschamps, P-Y., Nicolas, J-M., Loisel, H., Blanchot, J., Montel, Y., Thieuleux, F., *et al.* 2004. Seasonal and interannual variability of ocean-color and composition of phytoplankton communities in the North Atlantic, equatorial Pacific and South Pacific. Deep Sea Research Part II, 51: 303–318.

Davis, C., Bowles, J., Leathers, R., Korwan, D., Downes, T., Snyder, W., Rhea, W., *et al.* 2002. Ocean PHILLS hyperspectral imager: design, characterization, and calibration. Optics Express, 10: 210–221.

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

Djavidnia, S., Mélin, F., and Hoepffner, N. 2010. Comparison of global ocean colour data records. Ocean Science, 6: 61–76.

Fan, W., and Lv, X. 2009. Data assimilation in a simple marine ecosystem model based on spatial biological parameterizations. Ecological Modeling, 220: 1997–2008.

Filippi, A. M., Carder, K. L., and Davis, C. O. 2006. Vicarious calibration of the Ocean PHILLS hyperspectral sensor using a coastal tree-shadow method. Geophysical Research Letters, 33: L22605.

Fontana, C., Grenz, C., Pinazo, C., Marsaleix, P., and Diaz, F. 2009. Assimilation of SeaWiFS chlorophyll data into a 3D-coupled physical–biogeochemical model applied to a freshwater-influenced coastal zone. Continental Shelf Research, 29: 1397–1409.

Franz, B. A., Kwiatkowska, E. J., Meister, G., and McClain, C. R. 2008. Moderate resolution imaging spectroradiometer on Terra: limitations for ocean-color applications. Journal of Applied Remote Sensing, 2: 023525.

Franz, B. A., Werdell, P. J., Meister, G., Bailey, S. W., Eplee, R. E., Feldman, G. C., Kwiatkowska, E., *et al.* 2005. The continuity of ocean-color measurements from SeaWiFS to MODIS. *In* Earth Observing Systems X. Ed. by J. J. Butler. SPIE Proceedings, 5882.

Frid, C. L. J., Paramor, O. A. L., and Scott, C. L. 2006. Ecosystem-based management of fisheries: is science limiting? ICES Journal of Marine Science, 63: 1567–1572.

Garcia, V. M. T., Garcia, C. A. E., Mata, M. M., Pollery, R. C., Piola, A. R., Signorini, S. R., McClain, C. R., *et al.* 2008. Environmental factors controlling the phytoplankton blooms at the Patagonia shelf-break in spring. Deep Sea Research Part I, 55: 1150–1166.

Gitelson, A. A., Gurlin, D., Moses, W. J., and Barrow, T. 2009. A bio-optical algorithm for the remote estimation of the chlorophyll-*a* concentration in case 2 waters. Environmental Research Letters, 4: 045003.

Gnanadesikan, A., and Anderson, W. G. 2009. Ocean water clarity and the ocean general circulation in a coupled climate model. Journal of Physical Oceanography, 39: 314–332.

Gordon, H. R., Boynton, G. C., Balch, W. M., Groom, S. B., Harbour, D. S., and Smyth, T. J. 2001. Retrieval of coccolithophore calcite concentration from SeaWiFS imagery. Geophysical Research Letters, 28: 1587–1590.

Gordon, H. R., and Morel, A. 1983. Remote assessment of ocean-color for interpretation of satellite visible imagery: a review. Lecture Notes on Coastal and Estuarine Studies, 4. Springer, New York. 114 pp.

Gower, J., King, S., Borstad, G., and Brown, L. 2008. The importance of a band at 709 nm for interpreting water-leaving spectral radiance. Canadian Journal of Remote Sensing, 34: 287–295.

Gregg, W. W., and Casey, N. W. 2007. Sampling biases in MODIS and SeaWiFS ocean chlorophyll data. Remote Sensing of Environment, 111: 25–35.

Gregg, W. W., and Casey, N. W. 2010. Improving the consistency of ocean-color data: a step toward climate data records. Geophysical Research Letters, 37, doi: 10.1029/2009GL041893.

Gregg, W. W., Casey, N. W., and McClain, C. R. 2005. Recent trends in global ocean chlorophyll. Geophysical Research Letters, 32: L03606, doi:03610.01029/02004GL021808.

Gregg, W. W., and Conkright, M. E. 2002. Decadal changes in global ocean chlorophyll. Geophysical Research Letters, 29, 10.1029/2002GL014689.

Gregg, W. W., Esaias, W. E., Feldman, G. C., Frouin, R., Hooker, S. B., McClain, C. R., and Woodward, R. H. 1998. Coverage opportunities for global ocean-color in a multimission era. IEEE Transactions on Geoscience and Remote Sensing, 36: 1620–1627.

Hochman, H. T., Müller-Karger, F. E., and Walsh, J. J. 1994. Interpretation of the coastal zone color scanner signature of the Orinoco River plume. Journal of Geophysical Research, 99: 7443–7455.

Howell, E. A., Kobayashi, D. R., Parker, D. M., Balazs, G. H., and Polovina, J. J. 2008. TurtleWatch: a data product to aid in the bycatch reduction of loggerhead turtle (*Caretta caretta*) in the Hawaii-based pelagic longline fishery. Endangered Species Research, 5: 267–278.

Hu, C., Luerssen, R., Muller-Karger, F. E., Carder, K. L., and Heil, C. A. 2008. On the remote monitoring of *Karenia brevis* blooms of the west Florida shelf. Continental Shelf Research, 28: 159–176.

Hu, C., Montgomery, E. T., Schmitt, R. W., and Muller-Karger, F. E. 2004. The dispersal of the Amazon and Orinoco River water in the tropical Atlantic and Caribbean Sea: observation from space and S-PALACE floats. Deep Sea Research Part II, 51: 1151–1171.

Hu, C., Muller-Karger, F. E., Taylor, C., 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 the Environment, 97: 311–321.

IOCCG. 2000. Remote sensing of ocean colour in coastal, and other optically-complex, waters. *In* Reports of the International Ocean Colour Coordinating Group, 3. Ed. by S. Sathyendranath. IOCCG, Dartmouth, Canada. 140 pp.

IOCCG. 2008. Why ocean colour? The societal benefits of ocean-colour technology. *In* Reports of the International Ocean Colour Coordinating Group, 7. Ed. by T. Platt, N. Hoepffner, V. Stuart, and C. W. Brown. IOCCG, Dartmouth, Canada. 141 pp.

IOCCG. 2009. Remote sensing in fisheries and aquaculture. *In* Reports of the International Ocean Colour Coordinating Group, 8. Ed. by M-H. Forget, V. Stuart, and T. Platt. IOCCG, Dartmouth, Canada. 120 pp.

Johannessen, J. A., Le Traon, P-Y., Robinson, I. S., Nittis, K., Bell, M. J., Pinardi, N., and Bahurel, P. 2006. Marine environment and security for the European area—toward operational oceanography. Bulletin of the American Meteorological Society, 87: 1081–1090.

Jolliff, J. K., Kindle, J. C., Shulman, I., Penta, B., Friedrichs, M. A. M., Helber, R., and Arnone, R. A. 2009. Summary diagrams for coupled hydrodynamic-ecosystem model skill assessment. Journal of Marine Systems, 76, doi:10.1016/j.marsys.2008.05.014.

Kendall, A. W., and Duker, G. J. 1998. The development of recruitment fisheries oceanography in the United States. Fisheries Oceanography, 7: 69–88.

Kobayashi, D. R., Cheng, I-J., Parker, D. M., Polovina, J. J., Kamezaki, N., and Balazs, G. H. 2011. Loggerhead turtle (Caretta caretta) movement off the coast of Taiwan: characterization of a hotspot in the East China Sea and investigation of mesoscale eddies. ICES Journal of Marine Science, 68: 707–718.

Koeller, P., Friedland, K., Fuentes-Yaco, C., Han, G., Kulka, D., O'Reilly, J., Platt, T., *et al.* 2009a. Remote sensing applications in stock assessments. *In* Remote Sensing in Fisheries and Aquaculture, pp. 29–42. Ed. by M-H. Forget, V. Stuart, and T. Platt. IOCCG Report 8, Dartmouth, Canada. 120 pp.

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

Komick, N. M., Costa, M. P. F., and Gower, J. 2009. Bio-optical algorithm evaluation for MODIS for western Canada coastal waters: an exploratory approach using *in situ* reflectance. Remote Sensing of Environment, 113: 794–804.

Kuchinke, C. P., Gordon, H. R., and Franz, B. A. 2009. Spectral optimization for constituent retrieval in Case 2 waters I: implementation and performance. Remote Sensing of Environment, 113: 571–587.

Land, P. E., and Haigh, J. D. 1996. Atmospheric correction over case 2 waters with an iterative fitting algorithm. Applied Optics, 35: 5443–5451.

Laurs, R. M., and Lynn, R. J. 1977. Seasonal migration of North Pacific albacore, *Thunnus alalunga*, into North American coastal waters:

distribution, relative abundance, and association with transition zone waters. Fishery Bulletin US, 75: 795–822.

Lee, J., Kim, J., Song, C. H., Ryu, J-H., Ahn, Y-H., and Song, C. K. 2010. Algorithm for retrieval of aerosol optical properties over the ocean from the Geostationary Ocean-color Imager. Remote Sensing of Environment, 114: 1077–1088.

Lee, Z., Casey, B., Arnone, R., Weidemann, A., Parsons, R., Montes, M. J., Gao, B-C., *et al.* 2007b. Water and bottom properties of a coastal environment derived from Hyperion data measured from the EO-1 spacecraft platform. Journal of Applied Remote Sensing, 1: 011502.

Lee, Z. P., Carder, K., Arnone, R., and He, M. X. 2007a. Determination of primary spectral bands for remote sensing of aquatic environments. Sensors, 7: 3428–3441.

Levin, P. S., Fogarty, M. J., Murawski, S. A., and Fluharty, D. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology, 7: 23–28.

Lewis, M. R., Carr, M-E., Feldman, G. C., Esaias, W., and McClain, C. 1990. Influence of penetrating solar radiation on the heat budget of the equatorial Pacific Ocean. Nature, 347: 543–545.

Longhurst, A. 1995. Seasonal cycles of pelagic production and consumption. Progress in Oceanography, 36: 77–167.

Longhurst, A. R. 2007. Ecological Geography of the Sea, 2nd edn. Academic Press, San Diego. 560 pp.

Lyon, P. E. 2009. An automated de-striping algorithm for Ocean Colour Monitor imagery. International Journal of Remote Sensing, 30: 1493–1502.

Malthus, T. J., and Mumby, P. J. 2003. Remote sensing of the coastal zone: an overview and priorities for future research. International Journal of Remote Sensing, 24: 2805–2815.

Maritorena, S., and Siegel, D. A. 2005. Consistent merging of satellite ocean colour data sets using a bio-optical model. Remote Sensing of Environment, 94: 429–440.

Martinez, E., Antoine, D., D'Ortenzio, F., and Gentili, B. 2009. Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. Science, 326: 1253–1256.

Maturi, E., Harris, A., Merchant, C., Mittaz, J., Potash, B., Meng, W., and Sapper, J. 2008. NOAA's sea surface temperature products from operational geostationary satellites. Bulletin of the American Meteorological Society, 89: 1877–1888.

McClain, C. R. 2009. A decade of satellite ocean-color observations. Annual Review of Marine Science, 1: 19–42.

McClain, C. R., Christian, J. R., Signorini, S. R., Lewis, M. R., Asanuma, I., Turk, D., and Dupouy-Douchement, C. 2002. Satellite ocean-color observations of the tropical Pacific Ocean. Deep Sea Research Part II, 49: 2533–2560.

McClain, C. R., Hooker, S., Feldman, G., and Bontempi, P. 2006. Satellite data for ocean biology, biogeochemistry, and climate research. EOS, Transactions of the American Geophysical Union, 87: 337–343.

Mitchell, B. G. 1994. Coastal zone color scanner retrospective. Journal of Geophysical Research, 99: 7291–7292.

Morel, A., Huot, Y., Gentili, B., Werdell, P. J., Hooker, S. B., and Franz, B. A. 2007. Examining the consistency of products derived from various ocean-color sensors in open ocean (Case 1) waters in the perspective of a multi-sensor approach. Remote Sensing of Environment, 111: 69–88.

Moses, W. J., Gitelson, A. A., Berdnikov, S., and Povazhnyy, V. 2009. Estimation of chlorophyll-*a* concentration in case II waters using MODIS and MERIS data-successes and challenges. Environmental Research Letters, 4: 045005.

National Marine Fisheries Service. 2001. Report to Congress on the Status of Fisheries of the United States 2000. 122 pp.

National Research Council. 2000a. From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death. National Academy Press, Washington, DC. 96 pp.

National Research Council. 2000b. Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design. National Academy Press, Washington, DC. 152 pp.

National Research Council. 2000c. Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part II. Implementation. National Academy Press, Washington, DC. 98 pp.

National Research Council. 2003. Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations. National Academy Press, Washington, DC. 182 pp.

National Research Council. 2004. Climate Data Records from Environmental Satellites. National Academy Press, Washington, DC. 116 pp.

Nayak, S. R., Solanki, H. U., and Dwivedi, R. M. 2003. Utilization of IRS P4 ocean colour data for potential fishing zone—a cost benefit analysis. Indian Journal of Marine Sciences, 32: 244–248.

Neukermans, G., Ruddick, K., Bernard, E., Ramon, D., Nechad, B., and Deschamps, P-Y. 2009. Mapping total suspended matter from geostationary satellites: a feasibility study with SEVIRI in the southern North Sea. Optics Express, 17: 14029–14052.

NOAA. 2008. NOAA Administrative Order 216-105. http://www.corporateservices.noaa.gov/%7Eames/NAOs/Chap_216/naos_216_105.html.

Ourmieres, Y., Brasseur, P., Levy, M., Brankart, J-M., and Verron, J. 2009. On the key role of nutrient data to constrain a coupled physical–biogeochemical assimilative model of the North Atlantic Ocean. Journal of Marine Systems, 75: 100–115.

Pershing, A. J., Record, N. R., Monger, B. C., Mayo, C. A., Brown, M. W., Cole, T. V. N., Kenney, R. D., *et al.* 2009. Model-based estimates of right whale habitat use in the Gulf of Maine. Marine Ecology Progress Series, 378: 245–257.

Pinnock, S., D'Andon, O. F., and Lavender, S. 2007. GlobColour—a precursor to the GMES marine core service ocean colour Thematic Assembly Centre. ESA Bulletin, 132: 42–49.

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

Platt, T., and Sathyendranath, S. 1999. Spatial structure of pelagic ecosystem processes in the global ocean. Ecosystems, 2: 384–394.

Polovina, J. J., Balazs, G. H., Howell, E. A., Parker, D. M., Seki, M. P., and Dutton, P. H. 2004. Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific Ocean. Fisheries Oceanography, 13: 36–51.

Polovina, J. J., Howell, E., Kobayashi, D. R., and Seki, M. P. 2001. The transition zone chlorophyll front, a dynamic global feature defined migration and forage habitat for marine resources. Progress in Oceanography, 49: 469–483.

Polovina, J. J., Howell, E. A., and Abecassis, M. 2008. The ocean's least productive waters are expanding. Geophysical Research Letters, L03618, doi:03610.01029/02007GL031745.

Rice, J. C., and Rochet, M-J. 2005. A framework for selecting a suite of indicators for fisheries management. ICES Journal of Marine Science, 62: 516–527.

Roelfsema, C. M., Phinn, S. R., Dennison, W. C., Dekker, A. G., and Brando, V. E. 2006. Monitoring toxic cyanobacteria *Lyngbya majuscula* (Gomont) in Moreton Bay, Australia by integrating satellite image data and field mapping. Harmful Algae, 5: 45–56.

Sackmann, B., Mack, L., Logsdon, M., and Perry, M. J. 2004. Seasonal and inter-annual variability of SeaWiFS-derived chlorophyll *a* concentrations in waters off the Washington and Vancouver Island coasts, 1998–2002. Deep Sea Research Part II, 51: 945–965.

Saitoh, S., Chassot, E., Dwivedi, R., Fonteneau, A., Kiyofuji, H., Kumari, B., Kuno, M., *et al.* 2009. Remote sensing applications to fish harvesting. *In* Remote Sensing in Fisheries and

Aquaculture, pp. 57–76. Ed. by M-H. Forget, V. Stuart, and T. Platt. IOCCG Report 8. Dartmouth, Canada. 120 pp.

Saitoh, S-I., Mugo, R., Radiarta, I. N., Asaga, S., Takahashi, F., Hirawake, T., Ishikawa, Y., *et al.* 2011. Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. ICES Journal of Marine Science, 68: 687–695.

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.

Schroeder, T., Behnert, I., Schaale, M., Fischer, J., and Doerffer, R. 2007. Atmospheric correction algorithm for MERIS above case-2 waters. International Journal of Remote Sensing, 28: 1469–1486.

Serafin, R. J., MacDonald, A. E., and Gall, R. L. 2002. Transition of weather research to operations: opportunities and challenges. Bulletin of the American Meteorological Society, 83: 377–392.

Sherman, K., and Hempel, G. 2008. The UNEP Large Marine Ecosystems Report: a Perspective on Changing Conditions in LMEs of the World's Regional Seas. UNEP Regional Seas Report and Studies, 182. United Nations Environment Programme. Nairobi, Kenya. 872 pp.

Sherman, K., O'Reilly, J., Belkin, I. M., Melrose, C., and Friedland, K. D. 2011. The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. ICES Journal of Marine Science, 68: 667–676.

Sherman, K., Sissenwine, M., Christensen, V., Duda, A., Hempel, G., Ibe, C., Levin, S., *et al.* 2005. A global movement toward an ecosystem approach to management of marine resources. Marine Ecology Progress Series, 300: 275–279.

Siegel, D. A., Maritorena, S., Nelson, N. B., Behrenfeld, M. J., and McClain, C. R. 2005. Colored dissolved organic matter and its influence on the satellite-based characterization of the ocean biosphere. Geophysical Research Letters, 32: L20605, doi:20610.21029/22005GL024310.

Siegel, D. A., Thomas, A. C., and Marra, J. 2004a. Views of ocean processes from the Sea-viewing Wide Field-of-view Sensor mission: introduction to the first special issue. Deep Sea Research Part II, 51: 1–3.

Siegel, D. A., Thomas, A. C., and Marra, J. 2004b. Views of ocean processes from the Sea-viewing Wide Field-of-view Sensor mission: introduction to the second special issue. Deep Sea Research Part II, 51: 911–912.

Spalding, M. D., Fox, H. E., Halpern, B. S., McManus, M. A., Molnar, J., Allen, G. R., Davidson, N., *et al.* 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. BioScience, 57: 573–582.

Stumpf, R. P. 2001. Applications of satellite ocean-color sensors for monitoring and predicting harmful algal blooms. Human and Ecological Risk Assessment, 7: 1363–1368.

Stumpf, R. P., Arnone, R. A., Gould, R. W., Martinolich, P. M., and Ransibrahmanakul, V. 2003b. A partially-coupled ocean- atmosphere model for retrieval of water-leaving radiance from SeaWiFS in coastal waters. *In* Algorithm Updates for the Fourth SeaWiFS Data Reprocessing, pp. 51–59. Ed. by S. F. Patt, R. A. Barnes, R. E. Eplee, B. A. Franz, W. D. Robinson, G. C. Feldman, S. W. Bailey, *et al.* NASA Technical Memorandum 2003-206892, 22. NASA Goddard Space Flight Center, Greenbelt, MD. 74 pp.

Stumpf, R. P., Culver, M. E., Tester, P. A., Tomlinson, M., Kirkpatrick, G. J., Pederson, B. A., Truby, E., *et al.* 2003a. Monitoring *Karenia brevis* blooms in the Gulf of Mexico using satellite ocean-color imagery and other data. Harmful Algae, 2: 147–160.

Stumpf, R. P., Tomlinson, M. C., Calkins, J. A., Kirkpatrick, B., Fisher, K., Nierenberg, K., Currier, R., *et al.* 2009. Skill assessment for an operational algal bloom forecast system. Journal of Marine Systems, 76: 151–161.

Subramaniam, A., Brown, C. W., Hood, R. R., Carpenter, E. J., and Capone, D. G. 2002. Detecting *Trichodesmium* blooms in SeaWiFS imagery. Deep Sea Research Part II, 49: 107–121.

Sweeney, C. O., Gnanadesikan, A., Griffies, S. M., Harrison, M. J., Rosati, A., and Samuels, B. L. 2005. Impacts of shortwave penetration depth on the large-scale circulation and heat transport. Journal of Physical Oceanography, 35: 1103–1119.

Thomas, A. C., Carr, M-E., and Strub, P. T. 2001. Chlorophyll variability in eastern boundary currents. Geophysical Research Letters, 28: 3421–3424.

Tomlinson, M. C., Wynne, T. T., and Stumpf, R. P. 2009. Evaluation of the use of remote sensing techniques for enhanced detection of the toxic dinoflagellate, *Karenia brevis*. Remote Sensing of the Environment, 113: 598–609.

US Commission on Ocean Policy. 2004. An Ocean Blueprint for the 21st Century. Final Report. Washington, DC. 672 pp.

Uz, B. M. 2007. What causes the sporadic phytoplankton bloom southeast of Madagascar? Journal of Geophysical Research, 112: C09010, doi:09010.01029/02006JC003685.

Vantrepotte, V., and Melin, F. 2009. Temporal variability of 10-year global SeaWiFS time-series of phytoplankton chlorophyll *a* concentration. ICES Journal of Marine Science, 66: 1547–1556.

Vargas, M., Brown, C. W., and Sapiano, M. R. P. 2009. Phenology of marine phytoplankton from satellite ocean-color measurements. Geophysical Research Letters, 36: L01608, doi:01610.01029/02008GL036006.

Westberry, T. K., and Siegel, D. A. 2006. Spatial and temporal distribution of *Trichodesmium* blooms in the world's oceans. Global Biogeochemical Cycles, 20: GB4016, doi:4010.1029/2005GB002673.

Wetzel, P., Maier-Reimer, E., Botzet, M., Jungclaus, J., Keenlyside, N., and Latif, M. 2006. Effects of ocean biology on the penetrative radiation in a coupled climate model. Journal of Climate, 19: 3973–3987.

Wilson, C., and Adamec, D. 2001. Correlations between surface chlorophyll and sea surface height in the tropical Pacific during the 1997–1999 *El Niño*–Southern Oscillation event. Journal of Geophysical Research, 106: 31175–31188.

Wilson, C., Chen, C., Clark, C., Fanning, P., Forget, M-H., Friedland, K., Howell, E. A., *et al.* 2009. Remote sensing applications to natural resource management. *In* Remote Sensing in Fisheries and Aquaculture, pp. 43–56. Ed. by M-H. Forget, V. Stuart, and T. Platt. IOCCG Report 8. Dartmouth, Canada. 120 pp.

Wilson, C., Morales, J., Nayak, S., Asanuma, I., and Feldman, G. 2008. Ocean colour radiometry and fisheries. *In* Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology, pp. 47–58. Ed. by T. Platt, N. Hoepffner, V. Stuart, and C. W. Brown. IOCCG Report 7. Dartmouth, Canada. 141 pp.

Wilson, C., and Qiu, X. 2008. Global distribution of summer chlorophyll blooms in the oligotrophic gyres. Progress in Oceanography, 78: 107–134.

Yoder, J. A., Dowell, M., Hoepffner, N., Murakami, H., and Stuart, V. 2009. The Ocean Colour Radiance Virtual Constellation (OCR-VC). OceanObs'09 Conference, 21–25 September 2009, Venice Convention Centre, Venice-Lido, Italy. http://www.ioccg.org/groups/OCR-VC.html. 8 pp.

Yoder, J. A., and Kennelly, M. A. 2006. What have we learned about ocean variability from satellite ocean-color imagers? Oceanography, 19: 152–171.

Yoder, J. A., McClain, C. R., Feldman, G. C., and Esaias, W. E. 1993. Annual cycles of phytoplankton chlorophyll concentrations in the global ocean: a satellite view. Global Biogeochemical Cycles, 7: 181–193.

Zhao, D., Xing, X., Liu, Y., Yang, J., and Wang, L. 2010. The relation of chlorophyll-*a* concentration with the reflectance peak near 700 nm in algae-dominated waters and sensitivity of fluorescence algorithms for detecting algal blooms. International Journal of Remote Sensing, 31: 39–48.