The rocky road from research to operations for satellite ocean color data – what's fisheries got to do with it?

Cara Wilson

ABSTRACT

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 aim assumes that these data will be available in the future. However, for ocean color data, that assumption may not be true due to a possible gap in data continuity. Of the many types of satellite data, ocean color is the most important to fisheries, as it is the only biological measurement. The current ocean color sensors are all operating beyond their planned design life. While the US has thus far led the world in development of satellite ocean color science and technology, the continuation of this leadership role is in jeopardy. The next US ocean color sensor to be launched, VIIRS in 2012, may not perform well enough to continue the science-quality data provided by current satellites. While the research community is aware of the value of satellite ocean color data, advocacy from the operational community, fisheries management in particular, has been lacking. The absence of an easily identifiable operational need for ocean color data is largely responsible for the likely gap in the continuity of US ocean color.

Keywords: chlorophyll, fisheries, satellite ocean color, research-to-operations

Cara Wilson, NOAA Southwest Fisheries Science Center, Environmental Research Division, 1352 Lighthouse Ave., Pacific Grove, CA 93950; Phone: (831) 648-5337, Fax: (831) 648-8440, E-mail: cara.wilson@noaa.gov

Introduction

Environmental satellite data measurements such as sea-surface temperature, sea-surface height, ocean color, and surface vector winds, are valuable resources needed to understand, monitor, and predict changes in the earth's ecosystems, climate and weather. In the US the two agencies responsible for flying environmental satellites are NASA (National Aeronautics and Space Administration) and NOAA (National Oceanic and Atmospheric Administration). NASA is responsible for research and development of new satellite missions, while NOAA is responsible for launching and maintaining operational satellites to acquire data on the earth's atmosphere and oceans and for providing continuity for these data streams (National Research Council, 2003, U.S. Commission on Ocean Policy, 2004). However, little of the sensor technology developed by NASA has been utilized by NOAA (National Research Council, 2003, U.S. Commission on Ocean Policy, 2004). The difficulty of the transition from research to operations (R2O) has earned the process the nickname of the "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, National Research Council, 2000c). 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, S. Wilson, pers. comm.). However, there has been little discussion of R2O for ocean color data or for applications related to ecosystems and fisheries management. The absence of clearly-defined observational needs for ocean color data is a problem, since the justification for launching operational satellite missions requires defined operational usages, not meeting research desires.

Here a brief summary of past, current and scheduled ocean color sensors, both US and non-US, is given, as well an overview of the research that has developed out of the availability of ocean color data. After a discussion of what is meant by an "operational use", a range of current and potential operational usages of ocean color data are discussed. Some reasons for why ocean color data have been underutilized in fisheries management, and what can be done to mitigate them, are outlined. The US is not the only country flying ocean color satellites: Europe, Japan and India all have satellite ocean color programs, but this paper will focus on the R2O process of ocean color in the US. Hence this paper will discuss operational usages of ocean color data from a US perspective, which is an important caveat as there are international differences in what constitutes an "operational usage".

The history of satellite ocean color

The first ocean color 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 only last one year, which showed that satellite ocean color measurements could be reliably used to derive products such as chlorophyll *a* and sediment concentrations (Mitchell, 1994, Barale and Schlittenhardt, 1993). Most importantly, it provided justification for subsequent ocean color missions such as SeaWiFS (Sea-viewing Wide Field-of-view Sensor) and MODIS (Moderate Resolution

Imaging Spectroradiometer) in the US, although there was a ten-year gap between the 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, as a result of uncertainties and instabilities in the pre-launch and on-orbit characterization of MODIS-Terra this data has been largely unusable (Franz *et al*., 2008). In the rest of this paper "MODIS" will be referring to the sensor on the Aqua satellite. While SeaWiFS was still operating in 2010, there have been problems with its telemetry since January 2008, resulting in intermittent data gaps.

Other countries have also developed ocean color programs. Japan has launched two ocean color sensors, the OCTS (Ocean Color Temperature Scanner) in 1996 and the GLI (Global Imager) in 2002. Neither of them remained operational for more than a year (Figure 1).

India launched the OCM (Ocean Color Monitor) in 1999. However the data from this sensor has generally not been available to the international community, and there are also serious issues with its calibration (Lyon, 2009). The inaccessibility of this data is evident from the small number of papers citing OCM (65, see Table 1) relative to SeaWiFS (1175), despite their time in orbit being similar (Figure 1). The overwhelming majority of the papers using OCM data have come out of the Indian community (Figure 2), which again underscores the inaccessibility of this data on an international level. The numbers in Figure 2 actually over-estimate the international dissemination associated with a particular sensor. For example, of the 65 papers (Table 1) citing OCM data, only two of them have an author list without any Indian affiliations. The follow-on to OCM, OCM-2, was launched in September 2009. A major impetus for India to launch OCM-2 was the need for ocean color data for forecasts of potential fishing zones (PFZs). It is anticipated that data from OCM-2 will be more accessible to the international community, but that still remains to be seen.

Europe launched the Medium Resolution Imaging Spectrometer (MERIS) in 2002. MERIS has a narrower swath width than SeaWiFS and MODIS, and subsequently less frequent coverage. While MERIS data accessibility has improved since its launch, there are still issues. For example, level 1 data, which is needed to apply regional atmospheric corrections, is not openly distributed. The more restricted data availability, relative to the US sensors, is reflected in the statistics of the MERIS publications, which are predominately European (Figure 2), and relatively low in number, given the time in orbit (Table 1).

Future ocean color sensors

The first US ocean color sensor to be launched as an operational mission will be VIIRS (Visible/Infrared Imager Radiometer Suite) in 2012. VIIRS was developed as part of the National Polar-orbiting Operational Environmental Satellite (NPOESS) program, a program designed to meet the requirements of NASA, NOAA and the US Department of Defense. However in February 2010, due to huge cost overruns, NPOESS was restructured into the Joint Polar Satellite System (JPSS), a program to be run jointly by just 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 launch in 2012. The first two JPSS satellites, currently scheduled for launch in 2016 and 2019, will also have a VIIRS sensor on them (Figure 1).

If either MODIS or MERIS, both are past their design life, fail before the launch of NPP in 2012 there will be a gap in the continuity of the climate data record (CDR) for global ocean color 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)). A bigger problem than the lack of data inherent in a gap in continuity will be the inability to calibrate between different sensors, thereby prohibiting future ocean color data streams from being part of the current continuous stream of ocean color data that extends back to 1997.

Additionally there are technical issues with VIIRS such that it is not expected to deliver a CDR from NPP, though these issues should be resolved for the VIIRS sensors on JPSS-1 and JPSS-2. If the currently operating ocean color sensors fail before the launch of VIIRS, the availability of data from the OCM-2 will be critical (Figure 1). Europe is planning on launching the Ocean Land Colour Instrument (OLCI) in 2013, and Japan is planning on launching the Second-Generation Global Imager (SGLI) in 2014 (Figure 1). Both these sensors are planned for after the launch of VIIRS on NPP, so they will not mitigate any gap prior to VIIRS/NPP, but they could provide critical information to fill the gap if data from VIIRS/NPP is not of sufficient quality.

These ocean color sensors all have different number of spectral bands, different spatial resolutions, different repeat times and varying degrees of calibration, which makes comparisons and calibrations between them complicated (Maritorena and Siegel, 2005, Morel *et al*., 2007, D'Alimonte *et al*., 2008, Gregg and Casey, 2010). For example, SeaWiFS and MODIS, which are processed with consistent methods, have significant differences that need to be resolved before merging their data-streams into one record (Gregg and Casey, 2007, Gregg and Casey, 2010, Franz *et al*., 2005). An in-depth comparison of the different sensors is beyond the scope of this paper; these details can be found elsewhere (McClain, 2009, Djavidnia *et al*., 2010, Gower *et al*., 2008, Lee *et al*., 2007b, Gregg *et al*., 1998, Franz *et al*., 2005).

Importance of ocean color to research

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

- refining our understanding of the seasonal cycles of surface ocean chlorophyll (Yoder *et al*., 1993, Longhurst, 2007, Longhurst, 1995),
- defining ecological provinces in the ocean (Longhurst, 2007, Spalding *et al*., 2007, Longhurst, 1995, Devred *et al*., 2007, Platt and Sathyendranath, 1999),
- determining interannual variations in the seasonal cycle of chlorophyll (Vargas *et al*., 2009),

- quantifing the phenological match between commercially-important species and their planktonic food (Platt *et al*., 2003, Koeller *et al*., 2009b),
- 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),
- detecting and monitoring Harmful Algal Blooms (HABs) (Allen *et al*., 2008, Stumpf, 2001, Hu *et al*., 2008)
- mapping river plumes (Hochman *et al*., 1994, Hu *et al*., 2004),
- examining upwelling dynamics (Thomas *et al*., 2001, Campillo-Campbell and Gordoa, 2004, Garcia *et al*., 2008),
- quantifying the basin-scale impact of El Niño events (Sackmann *et al*., 2004, Wilson and Adamec, 2001, Chavez *et al*., 1999, McClain *et al*., 2002),
- depicting long-terms trends in global patterns of chlorophyll (Polovina *et al*., 2008, Vantrepotte and Melin, 2009, Martinez *et al*., 2009, Gregg and Conkright, 2002, Gregg *et al*., 2005, Dandonneau *et al*., 2004),
- analyzing how variability in the penetration of solar radiation into the surface ocean impacts ocean circulation and mixing and climate (Anderson *et al*., 2007, Gnanadesikan and Anderson, 2009, Sweeney *et al*., 2005, Lewis *et al*., 1990, Wetzel *et al*., 2006),
- 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)

- determining ocean primary productivity (Carr *et al.*, 2006, Behrenfeld and Falkowski, 1997, Campbell *et al.*, 2002),
- mapping colored dissolved organic matter (CDOM) distributions (Siegel *et al.*, 2005), and
- identifying anomalous chlorophyll blooms (Wilson and Qiu, 2008, Uz, 2007).

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

Operational uses of ocean color

What it means to make something "operational" varies widely depending on the application or the community in question. One consistent aspect of the term "operational", however, is that it is seldom defined. The primary use of operational satellite data products has been weather forecasting, an application that requires access to near-real-time (NRT) data streams, 24 hours a day, 7 days a week. Hence, there is often a misconception that operational uses of satellite data must always depend on NRT, 24/7 data. However, for fisheries management applications, an interannual datastream, which requires climate quality datasets, is often more relevant that a NRT one. Another definition, used within the R2O context, interprets "operational" as encompassing "anything not research", which is extremely ambiguous. NOAA's policy on R2O

(NOAA, 2008) defined 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. Hence the integration of ocean color data into activities supporting those mission objectives should constitute an operational use by NOAA’s definiton. However, it is not clear how widely accepted this viewpoint is. While this issue of “what is operational?” might seem semantic, it is important because justification for lunching new operational satellite missions requires the identification of an operational need, particularly within the agency.

Operational Uses of Ocean Color: HABs

The monitoring of Harmful Algal Blooms (HABs) is one example of a clear R2O transition of ocean color data. HABs are blooms of toxin-producing algae that have negative impacts on humans, marine organisms, and/or coastal economies. HAB events 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. As a consequence, 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. Having an advanced warning of a HAB event, and an estimation of their spatial distribution, increases the options for managing these events and minimizing their harmful impact on society.

Because of the large spatial scale and high frequency of observations needed to assess bloom location and movements, ocean color satellite data is 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*., 2003b, Tomlinson *et al*., 2009). For some coastal waters with high amounts of organic matter, fluorescence data from the MODIS and MERIS sensors have the potential for providing better estimates of the bloom extent (Hu *et al*., 2005, Zhao *et al*., 2010). However, there are limitations to the applicability of satellite ocean color data to HAB detection. Since not all high chlorophyll features are HABs, definitive identification of a HAB from satellite data also requires in situ water sampling. There are many different types of HABs, and algorithms developed for one species in one region often are not transferable to other species or other regions. Additionally, not all HABs can be detected by satellite ocean color data (Anderson, 2009), and the spatial resolution of the current ocean color sensors can be too coarse to detect features in many of the coastal regions where HABs develop. Despite these limitations, satellite ocean color can be an effective tool to monitor HABs, which NOAA has done operationally in the US since 2006, producing HAB bulletins twice a week for the Gulf of Mexico (Stumpf *et al*., 2009). There are also efforts developing ocean-color based operational HAB forecasts in Europe (Johannessen *et al*., 2006) and in Australia (Roelfsema *et al*., 2006).

Operational Use of Ocean Color: Fisheries

In the broadest sense fisheries encompass not just commercial 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 color data has been used extensively to help harvest fish more efficiently in India and Japan (Wilson *et al.*, 2008, Saitoh *et al.*, 2009). While this is a clear "operational" use of the data by some definitions (Kendall and Duker, 1998), it is not applicable for NOAA, as 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, Nayak, this volume) or compete with those available commercially (Saitoh *et al.*, 2009, Saitoh, this volume). Hence for NOAA, operational usages of ocean color 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 over 900 commercial stocks and ~210 protected or endangered species (National Marine Fisheries Service, 2001). Assessments provide the technical basis for setting annual fishery quotas and other fishery management measures to achieve optimum yield from the fishery while avoiding overfishing and ecosystem harm. At a minimum, a quantitative stock assessment requires monitoring of catch, abundance, and biological characteristics of the stock. While achieving a balance between exploitation and conservation requires substantial information about not just the fish stock, but also its fishery, its ecosystem and its habitat, traditionally environmental data have not been incorporated into stock assessments. The environmental factors influencing populations are complex and poorly understood, consequently they have largely been excluded from traditional assessment models, which greatly limits their accuracy and effectiveness (Koeller *et al.*, 2009a). However, bringing environmental and ecological data into the process requires radical changes to the overall management approach, including the adoption of conceptual and analytical frameworks which accommodate them – a daunting prospect counter to the conservative nature of fisheries assessment and management.

Recently there has been a move towards an ecosystem-based management of fisheries (Browman and Stergiou, 2005, Sherman *et al.*, 2005, Frid *et al.*, 2006), which has given new impetus to better understand 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 adequately resolved without satellite data. The measurements of primary productivity and chlorophyll obtained from satellite ocean color data greatly facilitate monitoring the base of the oceanic food chain, and these parameters are part of the assessment strategy for large marine ecosystems (LMEs) (Sherman and Hempel, 2008, Sherman *et al.*, this volume).

Management of protected species

Satellite ocean color data provide key information about oceanographic conditions needed to understand the distribution and migration patterns of protected species in order to manage them better. For example satellite ocean color data are necessary to track the seasonal and interannual migrations 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 that forage in the high chlorophyll eddies associated with meandering of the front (Polovina *et al.*, 2004, Kobayashi *et al.*, this volume). Other apex predators such as albacore tuna also use the front as a migratory corridor (Laurs and Lynn, 1977, Polovina *et al.*, 2001). The degree of meandering of the TZCF seems to impact trophic transfers and the level of productivity associated with the front. Periods with more meandering of the front have had significantly higher catch per unit effort (CPUE) of albacore, suggesting that the enhanced convergence creates more productive foraging grounds (Polovina *et al.*, 2001). Interannual variability in the southern extent of the TZCF also impacts the survival of juvenile monk seals in the Hawaiian islands (Baker *et al.*, 2007).

This information on turtle migration patterns and monk seal habitat quality provides the framework upon which to build management strategies for these populations. For example, a NOAA program called TurtleWatch uses satellite ocean color 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 color data can be used to predict years when low survival is likely and hence when management intervention, such as a head start program, should be implemented (Wilson *et al.*, 2009). Ocean color data are also being used to predict the movement and congregation of highly endangered right whales in the Atlantic, with the management aim of mitigating their ship-strike mortality (Pershing *et al.*, 2009).

Why are satellite ocean color data underutilized in fisheries?

Despite these uses, the full potential of satellite ocean color data has not been realized within either NOAA, or within fisheries science more generally. For example, less than 2% of the publications using ocean color data have involved any aspect of fisheries (Table 1). While it's possible that the low number of fisheries related ocean color publications is caused by stock assessment papers being published in the "gray" literature and thus not being represented in the citation database, it seems unlikely given the reluctance of the stock assessment community to incorporate environmental data (Koeller *et al.*, 2009a). The low number of papers could also be an artifact of insufficient classification within the database. The numbers are based on the number of citations with "fisheries" listed as a subject category, and papers dealing with protected species are probably not included in this category. Additionally only 35% of the ocean color papers are classified under "oceanography" (Table 1), yet one would expect the majority of papers using ocean color data to have an oceanographic basis. Using "fish" in the search string found a few more papers but did not change the overall result. However an interesting result of the last search is the relatively high percentage (12%) of OCM papers dealing with fish, which reflects the usage of this data in constructing PFZs which are used by the Indian fishing community (Nayak *et al.*, 2003, Choudhury *et al.*, 2007). Nonetheless, the numbers in Table 1 support the assertion that ocean color data is largely underutilized in fisheries science. There are several reasons for this:

1. Dissemination. The knowledge of what satellite data are available, and what they can be used for, is not always effectively communicated outside of the satellite community.

2. Unfamiliarity. Satellite data can be difficult to access, manipulate and process, particularly for people who do not have the skills and computational resources needed for the quantitative manipulation of terabytes of data. It can be also difficult to find time to undertake new and different types of analyses.
3. Desired products not available. For many fisheries applications the relevant parameter of interest is a product derived from ocean color data, which might not be readily available, nor is simple enough to be calculated by the users. Examples of this include calculating primary productivity from chlorophyll, front locations from chlorophyll, and building climatologies in order to examine anomalies.
4. Data inadequacy. The time series of ocean color data, while currently 12 years long, is relatively short compared to fisheries datasets that often span many decades. Additionally, most fisheries operate in coastal (case II) waters, where interpretation of satellite ocean color is complicated, as the algorithms are defined for open-ocean (case I) waters (Gordon and Morel, 1983).
5. Resistance to change. Traditional stock assessment/management shies away from involvement of environmental data due to the complexities involved, especially when simpler population models often suffice for the required short term (~1 yr) predictions.

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 to ensuring a continuous record of ocean color data, having a better characterization of coastal waters, or changing the way stock assessments are performed.

Training

One way to improve satellite data “literacy” is to conduct training courses specifically designed for marine resource managers or other target audiences. The IOCCG has a strong interest in capacity building, and since 1997 has been conducting and sponsoring courses on the usages and applications of ocean-color data in various developing countries. As part of the 2010 SAFARI Symposium in Kochi a training session was held, which was attended by 55 trainees from 16 countries. NOAA has also held several satellite courses for its scientists since 2006. These types of courses are particularly helpful when both data providers and data users are involved, as then, in addition to the primary goal of educating participants about the availability of satellite data, and showing them how to access and use the data, the data providers obtain a better understanding of users’ needs and requirements, which allows them to address those needs better. Some examples of this are given below.

Better data accessibility

The courses conducted by NOAA have been designed to help participants work with satellite data using the software that they are accustomed to, consequentially these course have focused on ArcGIS use, as it is used by many fisheries scientists. However importing satellite data into ArcGIS can be a cumbersome process, particularly for lengthy timeseries. To alleviate this difficulty, NOAA contracted ASA (Applied Science Associates) to build a new extension for ArcGIS that allows users to connect to online data servers and browse and subset large amounts of data in space and time and convert them into raster or feature classes in ArcGIS. This extension, called the Environmental Data Connector (EDC), allows users to easily animate and manipulate data for temporal analysis including provisions for non-uniform time-steps. A new version under development will also 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/

Another need that became apparent through the NOAA satellite courses was an easy method for matching up satellite data with a datapoint moving in x-y-t space, such as a tagged animal or a ship. Mining global satellite datasets for the few synoptic values associated with a telemetry track is a daunting task for most marine biologists unaccustomed to working with large satellite datasets. To alleviate this problem open-access routines have been developed to allow client-side access of satellite data using either Matlab or R (freeware). These "xtractomatic" routines take advantage of the effective data delivery mechanisms provided by THREDDS (Thematic Real-time Environmental Distributed Data System) catalogs 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 last five years web-based methods of accessing and visualizing different satellite data products have increased dramatically. It is not sufficient anymore to simply post large data files on the web and expect the data to be used. For example, NASA's Giovanni system allows online visualization and analysis of ocean color data, and the data can also be viewed as climatologies or as 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). However, ocean color data is often just one of many satellite data parameters of interest, and for these applications 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 & spatially

Coastal waters, where the majority of the world's fisheries are, contain CDOM and sediments which confound the chlorophyll algorithms designed for waters without these constituents (IOCCG, 2000). Additionally different atmospheric corrections are required for accurate characterization of case II waters (Land and Haigh, 1996, Schroeder *et al*., 2007, Stumpf *et al*., 2003a). Improvements have been made in the past few years in the chlorophyll algorithms for coastal waters from the current sensors (Moses *et al*., 2009, Gitelson *et al*., 2009, Komick *et al*., 2009, Kuchinke *et al*., 2009). However, 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, and higher spatial and temporal resolutions are needed to resolve their dynamics, relative to open-ocean features, on the order of 30-

300 m spatial resolution, and with multiple looks a day (IOCCG, 2000). Achieving these spatial and temporal scales simultaneously is not feasible with sensors on polar orbiting satellites. Airborne sensors deliver high spatial resolution datasets, with less atmospheric correction issues, but provide only a single snapshot in time (Davis *et al*., 2002, Filippi *et al*., 2006, Carder *et al*., 1993). Geostationary satellites are the best option for obtaining data with high temporal resolution, which has been demonstrated with sea surface temperature data (Maturi *et al*., 2008). The first ocean color sensor on a geostationary satellite will be launched by Korea in November 2010 (Lee *et al*., 2010, Neukermans *et al*., 2009). Additionally, there is increasing interest in flying hyperspectral sensors, either on satellites or airborne, in order to better characterize coastal waters (Brasseur *et al*., 2009, Malthus and Mumby, 2003). For example, data from Hyperion, a NASA hyperspectral sensor originally designed for land applications, has been useful for making observations in complex coastal regions (Lee *et al*., 2007a, Brando and Dekker, 2003).

It is crucial that CDRs of ocean color data be archived and maintained so that existing satellite records will be able to serve as a benchmark against which to gauge secular changes in our marine ecosystems and to track historical variations. It has become clear that maintaining the global coverage of ocean color observations will require an international effort. The international community has taken strides to increase data accessibility and ensure continuity of ocean color data. For example, the Committee on Earth Observation Satellites (CEOS) developed the concept of virtual, space-based Constellations operating together in a coordinated manner to provide global coverage. The implementation plan for this Ocean Color Radiometry Virtual Constellation (OCR-VC) is being developed by a working group of the IOCCG (Yoder *et al*., 2009). The

European GlobColour project generates a consistently calibrated global product with the best possible spatial coverage by merging ocean color data from SeaWiFS, MODIS, and MERIS (Pinnock *et al.*, 2007).

Shifting paradigms

While traditional stock assessments have not yet embraced incorporating environmental variability, there is growing interest in ecosystem-based management strategies for marine ecosystems (Frid *et al*., 2006, Sherman *et al*., 2005) and satellite chlorophyll measurements are being used as fundamental component in the assessment strategy for LMEs (Sherman *et al.*, this volume). The biggest challenges associated with ecosystem-based management are implementation, and developing specific management measures (Levin *et al*., 2009). Integrated Ecosystem Assessments (IEAs) have been proposed as a framework from which to implement ecosystem-based management. A key component of IEAs is the identification of appropriate indicators to monitor and assess ecosystems (Levin *et al*., 2009). While there is still much uncertainty about what parameters are appropriate ecosystem indicators, the criteria that as been put forth to describe indicators, that they be directly observable, supported by historical time series, and easily understandable to the general public (Levin *et al*., 2009, Rice and Rochet, 2005), all are applicable to satellite ocean color data.

Concluding Remarks

- The research value of satellite ocean color data is substantial and it has become indispensible for many marine research applications. The value of satellite ocean color 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 data stream of global ocean color data.

- Ocean color data are used operationally in the monitoring of HABs and in fish finding-type programs (India, Japan).
- The relevant timescales for operational usages of ocean color data in fisheries assessment and management are seasonal and interannual and thus require a continuous time series of science-quality ocean color data.
- Ocean color data are needed in the assessments of marine habitat and ecosystems and to monitor climate variability. Currently many of the capabilities of ocean color data are still being actively researched and have not yet transitioned into management strategies.
- It would be unfortunate if another gap in ocean color data developed, thereby prohibiting the merger of the current 12 year record with future ocean color data.

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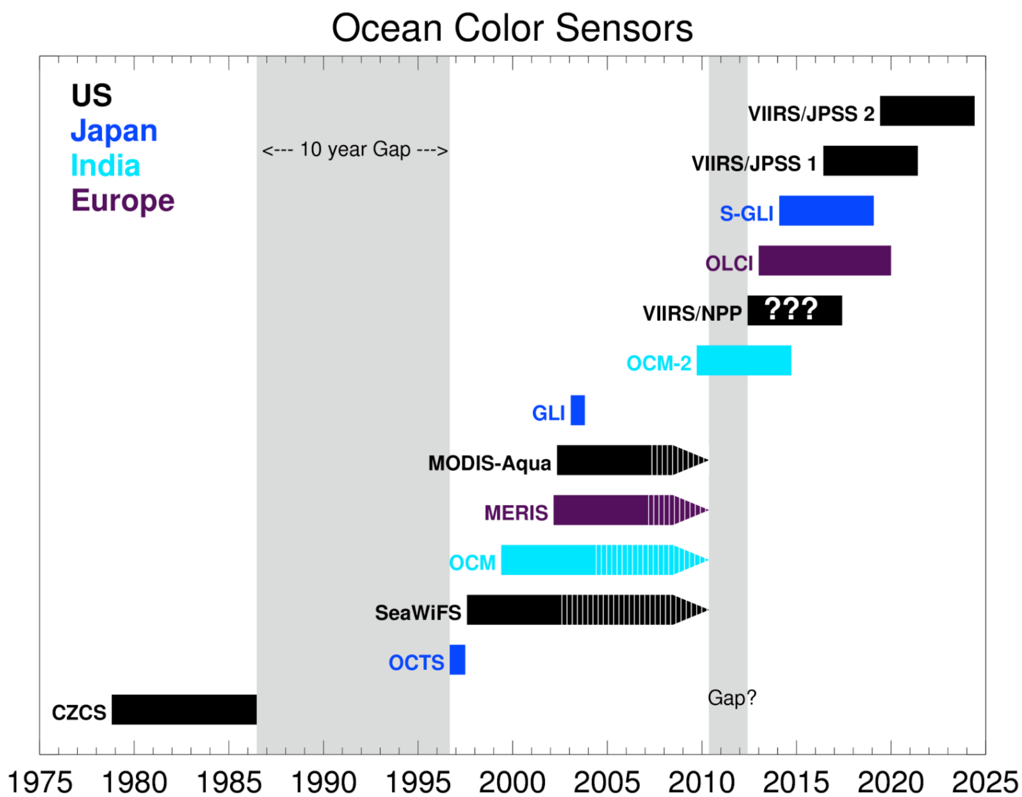

Figure 1. Time line showing past, current and future global ocean color satellite missions. Satellites still generating data are shown as arrows, hashed areas indicate the period when the current sensors have passed their 5-year design life. Gray shaded areas indicate the past and potential future gap in ocean color data. CZCS: Coastal Zone Color Scanner; OCTS: Ocean Color 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.

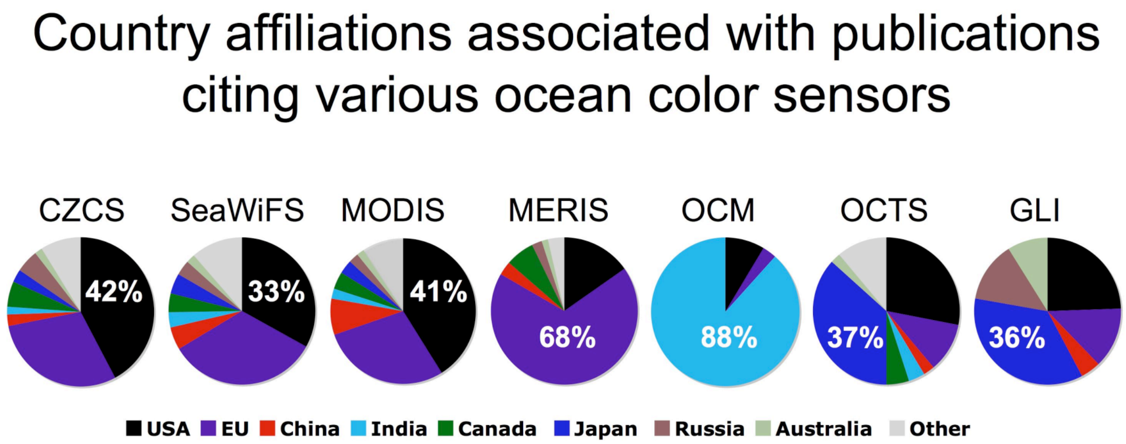

Figure 2. Distribution of the country affiliations associated with publications citing the CZCS, SeaWiFS, MODIS, MERIS, OCM, OCTS and GLI ocean color sensors. The percentage of publications from the country that launched the satellite is shown. As of May 19, 2010. Source: ISI Web of Science

Sensor	Number of Papers	Papers per orbit year	Oceanography		Fisheries		“Fish” in search	
			#	Percent	#	Percent	#	Percent
CZCS	428	56	208	49%	7	2%	8	2%
GLI	34	49	11	32%	0	0%	0	0%
SeaWiFS	1175	92	478	41%	24	2%	32	3%
MERIS*	140	17	14	10%	0	0%	2	1%
MODIS*	361	45	74	20%	4	1%	3	1%
OCM*	65	6	19	29%	0	0%	8	12%
OCTS*	64	80	17	27%	0	0%	1	2%
Total:	2267	46	821	36%	35	2%	54	2%

*search string included the term “color” or “chlorophyll”

Table 1. Number of publications citing the different ocean color sensors, the number of publications per years 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. As of May 19, 2010. Source: ISI Web of Science

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 (SI): 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. 1993. Ocean colour: theory and applications in a decade of CZCS experience. p. 367. Kluwer Academic, Dordrecht ; Boston.

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, Dordrechtpp.

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, 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, II, 53: 741-770.

Cazenave, A., and Llovel, W. 2010. Contemporary Sea Level Rise. Annual Review of Marine Science, 2: 145-173.

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, 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., Robert E. Eplee, J., Feldman, G. C., Kwiatkowska, E. J., 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. Vol. 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, 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. *In* Lecture Notes on Coastal and Estuarine Studies, p. 114. Springer Verlag, New York.

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, II.

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, No. 3, p. 140. Ed. by S. Sathyendranath. IOCCG, Dartmouth, Canada.

IOCCG 2008. Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology. *In* Reports of the International Ocean Colour Coordinating Group, No. 7, p. 141. Ed. by T. Platt, N. Hoepffner, V. Stuart, and C. W. Brown. IOCCG, Dartmouth, Canada.

IOCCG 2009. Remote Sensing in Fisheries and Aquaculture. *In* Reports of the International Ocean Colour Coordinating Group, No. 8, p. 120. Ed. by M.-H. Forget, V. Stuart, and T. Platt. IOCCG, Dartmouth, Canada.

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.

Kendall, A. W., Jr., 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., Chelton, D., and Balazs, G. H. this volume. Eddy field randomization: A simple statistic to quantify spatio-temporal associations between remotely-sensed oceanographic features and satellite-tagged loggerhead turtles (*Caretta caretta*) off the coast of Taiwan. . ICES Journal of Marine Science.

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 No. 8, Dartmouth, Canada.

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. Fisheries Bulletin, 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. 2007a. 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. 2007b. 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, Academic Press, San Diego.

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 tempaerture 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, 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 Trans. AGU, 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.

National Research Council. 2000a. From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death. 182 pp.

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

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

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

National Research Council. 2004. Climate Data Records from Environmental Satellites. 116 pp.

Nayak, S. this volume. ICES Journal of Marine Science.

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, II.

Saitoh, S. this volume. ICES Journal of Marine Science.

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: The Societal Benefits. Ed. by T. Platt, M.-H. Forget, and V. Stuart. IOCCG Dartmouth, Canada.

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 Ecosystem Report: A perspective on changing conditions in LMEs of the world's regional seas. ICES Document 182 872 pp.

Sherman, K., O'Reilly, J., Belkin, I., and Melrose, C. this volume. The application of satellite remote sensing for assessing productivity and fisheries yields of the world's Large Marine Ecosystems. ICES Journal of Marine Science.

Sherman, K., Sissenwine, M., Christensen, V., Duda, A., Hempel, G., Ibe, C., Levin, S., et al. 2005. A global movement toward an ecosystem aproach 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, 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, 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.

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., R.W. Gould, J., Martinolich, P. M., and Ransibrahmanakul, V. 2003a. 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. Ed. by S. B. H. a. E. R. Firestone. NASA Goddard Space Flight Center, Greenbelt, Maryland.

Stumpf, R. P., Culver, M. E., Tester, P. A., Tomlinson, M., Kirkpatrick, G. J., Pederson, B. A., Truby, E., et al. 2003b. 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, 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.

U.S. Commission on Ocean Policy 2004. An Ocean Blueprint for the 21st Century, Washington, DC.

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 Fisheries Management. *In* Remote Sensing in Fisheries and Aquaculture: The Societal Benefits. Ed. by T. Platt, M.-H. Forget, and V. Stuart. IOCCG Dartmouth, Canada.

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 No. 7, Dartmouth, Canada.

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). http://www.ioccg.org/groups/OCR-VC.html 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.