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Why Ocean Colour? The Societal Benefits of Ocean-Colour Technology

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Chapter 1

General Introduction

Trevor Platt and Paula Bontempi

The Earth system lies in a delicate balance set by a suite of forces operating in and between the land, ocean, atmosphere and cryosphere. Although the oceans play a critical role in our climate, they remain the least explored of the Earth's environments. Understanding the ecology, biogeochemistry and hazards of our oceans in a varying and changing climate is critical to sustaining Earth as a habitable planet.

The ecosystem of the ocean differs from that on the land in that the green plants in the ocean are predominantly microscopic. These are the community of single-celled algae collectively known as phytoplankton. The integrity of the marine ecosystem is maintained through the constant input of energy from the sun. Only the visible part of the solar spectrum can be captured by the ecosystem for photosynthesis, and the interface that couples it to the sun is provided by the pigment molecules (principally chlorophyll) contained in phytoplankton. As they absorb and scatter light from the sun, phytoplankton exert a profound influence on the submarine light field, including the flux upwards across the water surface. The intensity and wavelength of this flux can be measured by radiometers carried on space craft, thus providing the basis for visible spectral radiometry, also known as ocean-colour radiometry (OCR) or simply ocean colour.

An important property monitored through OCR is the concentration of chlorophyll in the ocean (or in fresh water), an index of phytoplankton biomass. In aquatic systems, phytoplankton biomass is a key ecological property: it quantifies the ecosystem component that is primarily responsible for the transformation of carbon dioxide into organic carbon, sustaining not only itself, but also all the other organisms in the ecosystem. In short, OCR quantifies the base of the marine food chain.

Ocean-colour radiometry by earth-orbiting spacecraft has already been conducted for some thirty years. The proof of concept that chlorophyll concentration could be observed all over the oceans on synoptic scales, with useful accuracy and precision, has been demonstrated beyond all doubt. The results of ocean colour have revolutionised the field of biological oceanography, and have made important contributions to biogeochemistry, to physical oceanography, to ocean-system

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modelling, to fisheries oceanography and to coastal management. It is a technology that has achieved much for a relatively modest investment. By the nature of the technology, OCR is global in scope, as are many of the outstanding issues of the day, such as those related to climate change. Moreover, ocean colour is our only window into the marine ecosystem on these scales. No other biological component of the marine ecosystem is accessible to remote sensing. To study the state of the marine ecosystem on synoptic scales, it is logical to start with chlorophyll derived from ocean-colour missions.

Having had its origins in the research community, ocean colour is already contributing effectively to the rapidly-growing discipline of operational oceanography. The research component will always be important: it must be protected and encouraged, for without it, the development of new and improved operational applications will stagnate.

In this monograph, we illustrate the many applications of data acquired by remote sensing of ocean colour, in both the research and operational arena. In other words, we seek to demonstrate the benefits to society of investment in ocean-colour technology. The benefits are many and varied, and taken together make a very impressive case for making ocean colour a key requirement in earth observation as a societal imperative.

The contents of this report are solely the opinions of the authors, and do not constitute a statement of policy, decision, or position on behalf of any of the space agencies or other organisations mentioned, or the governments of any country.

Ocean-Colour Radiometry and the Public

James Acker

When people think of 'ocean colour', they generally think of it in terms of what they can see. One of the most common questions asked about the ocean is "Why is the ocean blue?" However, in several important situations, a more important question might be asked, specifically, "Why ISN'T the ocean blue?" Although the reasons for

Figure 2.1   Foam created by an offshore bloom of *Phaeocystis* in the coastal waters of Wimereux, France. (Credit: Image provided by Luis Feline Artiad, University du Littoral, France).

an unusual colour on the surface of the ocean may not be immediately apparent, the result can be - and whether it is muddy brown water, a bright green sheen of algae, or sheets of brownish foam, people may become concerned when the ocean is not clear and blue, especially if that is what they expect it to be (Fig. 2.1).

Because the colour of ocean waters is related directly to the substances and the organisms within it, most people have an intuitive understanding of the importance of 'ocean colour', even if they do not know what causes it to vary. And they may be very familiar with ocean-colour imagery, and yet not realize how the images are produced. Images from ocean-colour sensors have been used in the media to

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illustrate unusual events, such as dust storms, hurricanes, fires, fog and haze. The images may also represent events more directly related to the oceans, such as red tides or sediment released into the oceans by floods. Even if they have never seen

Figure 2.2   Aerial photograph of an extensive bloom of the dinoflagellate *Gonyaulax polygramma* in False Bay, South Africa on 23 February 2007 (from Pitcher *et al.*, 2008).

an ocean-colour image, most people understand the term 'red tide' to imply that something is amiss with the colour of the ocean (see Fig. 2.2 which shows extreme discolouration of the water), although the condition isn't actually a tide and may not always be coloured red.

Because human lives and activities interact and intersect with the oceans in many different ways, ocean-colour data can be of interest for the general public. The coast has always been a popular place to live (either permanently or on holiday), and increasing numbers of people are drawn to reside near the ocean. In many countries, people live near the coast not by choice but by necessity, and their daily lives are strongly connected to the rhythms of the ocean, which supplies food, products that can be sold or exported, a means for shipping, and a mode of travel.

Through most of recorded history (and likely before), the health of the ocean has commonly been taken for granted. It is usually when the ocean is not healthy - when the ocean waters are not limpid and blue - that people become more concerned about the state of their particular patch of sand and water.

Ocean-colour radiometry data can be utilized by coastal resources management interests, both governmental and private, to monitor the condition of the coastal zone and report it to the general public. The NOAA Harmful Algal Bloom (HAB) prediction system for the Gulf of Mexico provides forecasts of possible red tide (*Karenia brevis*) blooms, and also addresses HAB occurrences in New England. Ocean-colour

data can also be utilized to analyze nearshore water conditions that affect water clarity, such as sediment runoff or upwelling events that trigger blooms. HABs can have a significant local economic impact: a devastating bloom of the dinoflagellate *Gymnodinium sanguineum* occurring in Paracas Bay, Peru in April 2004 resulted in massive fish deaths and port closure, with an estimated loss in revenue of $28.5 million for the anchovy, fish meal and aquaculture sectors (Kahru *et al.*, 2004; 2005). Analysis of this bloom utilized the 250 m and 500 m resolution bands of MODIS, indicating the desirability of increased spatial resolution for nearshore and estuarine processes and events. There is also significant interest in monitoring and predicting HABs which could affect the growing aquaculture industry.

Deep-sea fishing charter boat captains can enhance their business by subscribing to fish-finding analyses provided by commercial services. Fish-finding analyses utilize remotely-sensed chlorophyll, sea surface temperature (SST), and wind data, as well as interpretive skill to predict where the fish might be found. Captains of expedition dive boats may also wish to check ocean-colour data to see if the water is sufficiently clear for safe scuba diving or snorkelling. Commercial fishing operations also utilize fish-finding analyses to harvest seafood, and operators drilling for offshore oil and natural gas may refer to ocean-colour data and other ocean data types such as SST and sea surface height (SSH) to monitor the sea state, which could affect continued operations. On a larger scale, India has developed a system of scientific indicators to generate Potential Fishing Zone (PFZ) advisories for their fishing community (~6 million fishermen) using satellite-derived information on chlorophyll (IRS-P4 ocean-colour data) and SST (see Section 6.3.1). Ocean-colour data can also be used to monitor the response of the ocean ecosystem to an oil spill and the subsequent remediation and recovery from a spill, although other types of oceanographic data may be more suited to oil spill detection itself.

Ocean-colour radiometry data have been used extensively to monitor conditions related to many of the most charismatic and well-known animal species in the ocean. The distribution, movement, and migration of whales, dolphins, pinnipeds, penguins and sea turtles has been related, either directly or indirectly, to chlorophyll concentrations and other surface ocean conditions (see Chapter 6). In the Bering Sea, the location of whales was found to be related to the clarity of the water when the Bering Sea witnessed a massive bloom of coccolithophorids (Tynan, 1998). Radio-tagged loggerhead turtles followed a well-defined chlorophyll concentration level north of Hawaii as they cruised in search of floating organisms like jellyfish and organisms attached to other floating objects, such as barnacles and crabs (Polovina *et al.*, 2001), and elephant seals from Kerguelen Island were discovered to concentrate their diving efforts in search of food in areas with elevated chlorophyll concentrations (Guinet *et al.*, 2001).

Researchers at Cornell University and other institutions have created a Right Whale Prediction Center to study the endangered northern right whale; the system employs ocean-colour and other remotely-sensed data types to predict the

Figure 2.3   An extensive phytoplankton bloom, likely composed of coccol-ithophorids, in the Bay of Biscay (France). Image acquired by MODIS-Aqua on 16 May, 2004 (Credit: Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC).

distribution of the copepod, *Calanus finmarchus*, the primary food species of the whales (Clapham, 2004). In the northern Gulf of Mexico, sperm whale sightings have been correlated with Loop Current eddies detected using ocean-colour and altimetry data (Biggs *et al.*, 2003; 2005). A study in the northwest Pacific Ocean correlated blue whale call locations with ocean-colour data, determining that the calls were closely associated with high chlorophyll concentrations during the spring bloom period (Moore *et al.*, 2002). Another study combining altimetry and ocean-colour data was conducted around the Galapagos Islands to determine likely areas used by dolphins for foraging. This study discovered that one species of dolphin was found almost exclusively in an upwelling zone on the western side of the archipelago (Palacios, 2000).

Another area in which ocean-colour data are used, but which may be invisible to the public despite its importance to both daily life and the global economy, is commercial shipping and port operations. Oil and natural gas offshore drilling operations consult sea state analyses that combine several data types, notably SST, SSH, and ocean colour, to advise ships and drilling rigs about conditions that could impact operations and maintenance (Roffer *et al.*, 2006). Proper planning utilizing a variety of remotely-sensed data can save money by avoiding unnecessary delays and 'down time', as well as reduce risks to personnel and equipment. Commercial shipping interests may also access ocean-colour and SST data for navigation, to save fuel and to avoid potentially dangerous regions. Many shipping companies do this

routinely, but one of the most visible applications of this technology was during the Volvo Ocean Race in 2001-2002, when round-the-world yacht racing crews referred to ocean-colour and SST data to plot their fastest course (IOCCG, 2001). Since each yacht in the race required a substantial investment from several corporate sponsors, gaining even a small speed advantage from an accurate analysis of ocean currents was a requirement to attract news coverage and the prestige of leading a leg of the race, or eventually winning the globe-girdling challenge.

One of the advanced applications of ocean-colour data is for the detection and quantification of marine suspended sediments (Fig. 2.4, see also Section 7.4), and for the observation of changes in bottom topography caused by sediment transport. Sediments can either alter the course of, or reduce the depth of, shipping channels, and so the impact of sediment movement in the vicinity of shipping channels and ports is a significant concern. Data from SeaWiFS, MODIS and MERIS have been used to monitor the movement of sediments in several port areas and river estuaries (Hesselmans *et al.*, 2000; Ruddick *et al.*, 2003). Sediments mobilized either

Figure 2.4 A satellite view of the Bangladesh coastline showing the discharge of sediments from the mouths of the Ganges River. Image acquired by ESA's MERIS sensor on 8 November 2003. (Credit: European Space Agency).

by dredging or by natural processes such as winds and bottom currents can be deposited on vital benthic habitats such as seagrass beds, reducing or destroying the viability of the habitat. This impact can detrimentally affect marine life, as seagrass and similar aquatic vegetation habitats are frequently inhabited by larval fish and crustacean species that are commercially and recreationally desirable. In one study,

remote sensing data from several different sensors (Landsat, ASTER, MODIS) are being used to analyze the distribution of seagrasses in Florida Bay and the impact of harmful blooms of blue-green algae. This study is part of the United States Geological Survey's Priority Ecosystems Science program, focused on South Florida ecosystem restoration.

The capability of accurately observing the topography of the sea floor in shallow waters is also an important area of research for military applications. Water clarity is a significant concern for the detection of mines, for operations by divers intended to detect and neutralize mines, and to determine where such operations would be likely to succeed. Weidemann *et al.* (2004) describe the use of satellite ocean-colour data to deliver water clarity information in support of diving and de-mining operations during hostilities in the Middle East (see also Section 7.2). Advanced optical analysis of the water column and bottom characteristics is useful for port protection, detection of objects and/or changes in objects on the sea floor, and assessment of organic and inorganic particulate matter in the water column for water clarity prediction (Hou *et al.*, 2002; Carder *et al.*, 2003).

Predictive and forecast uses of ocean-colour data continue to be developed. The NOAA Red Tide Forecast System for the Gulf of Mexico mentioned above is an early example of this type of application. Many other uses have been envisioned for ocean-colour data in forecast and prediction modes. Because ocean-colour data is well-suited for detection of convergence zones and oceanic fronts, the data could be utilized for the prediction of the movement and potential coastal impact of stinging jellyfish and siphonophores, such as the Portuguese man-of-war and Australia's lethal box jellyfish. NOAA has implemented a sea nettle prediction system for the Chesapeake Bay based on the relationship between sea nettle distribution, salinity, and SST (Decker *et al.*, 2007). Similar systems could utilize ocean-colour data provided significant relationships between ocean-colour features and areas of potential occurrence of stinging and/or poisonous species can be reliably determined.

Beach and coastal areas are increasingly susceptible to hazardous conditions due to high bacterial levels in the water. Such conditions can be caused by excessive storm-water and sewage release, and can cause associated phytoplankton blooms (Fig. 2.5). High bacterial levels can cause various intestinal and diarrhoeal diseases. Ocean-colour data can be utilized in monitoring mode to observe water quality and water clarity conditions (see Chapter 7), and could also be used for short-term prediction of conditions requiring beach closure for public safety.

The association of cholera outbreaks with phytoplankton blooms is well-known (Colwell, 1996). Due to this association, ocean-colour data have been used in studies of the linkages between the terrestrial and aquatic ecosystems in areas where cholera outbreaks occur regularly (Lobitz *et al.*, 2000). This type of study seeks to determine the relationship between climate and infectious diseases such as cholera, and to predict the influence of climate change on disease progression and transmission in coming decades.

The uses described above for ocean-colour data mainly address the many ways in which the public utilizes ocean resources, both directly and indirectly. Another aspect of ocean-colour data that will become increasingly important is in oceanographic and geoscience education. Tools such as the SeaWiFS Data Analysis System (SeaDAS)

Figure 2.5 MODIS-Aqua image acquired on 12 August, 2003 showing a bright feature emanating from the city of Algiers on the Mediterranean coast of Africa a few days after torrential thunderstorms. This feature likely consists of phytoplankton utilizing nutrients in the runoff plume, as well as components of sewage and suspended sediments. (Credit: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC).

(Fu *et al.*, 1998) and the Goddard Earth Sciences Data and Information Services Center (GES DISC) Interactive Online Visualization and ANalysis Infrastructure ("Giovanni") (Berrick *et al.*, 2004; Acker *et al.*, 2005; Acker and Leptoukh, 2007) provide pathways for students to understand the oceanic environment - and perform research on it - using actual data. These tools, along with simpler methods to access and acquire data for specific topical research, allow a wider cross-section of the educational community to utilize the data for classroom instruction and 'hands-on' research project investigations. These tools open a previously-closed window on understanding basic oceanic processes, and also serve to instruct students on how scientists employ the data to gain insight on oceanic processes and physical-biological interrelationships. In addition to the tools, the creation of uniform, single format, multi-mission data sets covering several decades will allow even greater access to the data, and the discovery of relationships and trends that cannot be discerned in shorter-term data sets. Because undergraduate and high-school students will find and use the data in their classrooms, the general public (*i.e.*, parents) will also be exposed to, and develop increased awareness of, the usefulness and ubiquity of ocean-colour data in science and in the world community.

The world population is presently concerned with the issue of climate change, and the contribution of mankind's activities to the state of the current climate and future climate trends. Ocean-colour data is an important element in understanding how the oceans' biological systems respond to climate forcing and climate variability, and how they may change in the future in response to alteration of the global climate (see Chapter 10).

Although ocean-colour sensors usually acquire data at moderate spatial resolution, in general ranging between 1- and 10-km pixel size, the imagery provides excellent large-scale views of weather systems and the response of the ocean to significant weather events (see Chapter 9). Hurricanes and typhoons, in particular, are unmistakable features in ocean-colour imagery. Observations of hurricanes have revealed several different aspects of their interaction with the oceanic environment. The high surface winds of a hurricane stir the water column, bringing dissolved coloured organic matter and nutrients to the surface and creating detectable ocean-colour features (Hoge and Lyon, 2002; Shi and Wang, 2007). When hurricanes encounter the coast, the winds cause re-suspension of coastal sediments, which can be carried offshore (Acker *et al.*, 2002). Inland flooding caused by the heavy rains of a hurricane can lead to significant transport of terrigenous sediments offshore in days subsequent to the passage of the storm. These effects are not caused solely by hurricanes; elevated winds and rain from more conventional storms and "nor'easters" can also re-suspend sediments, and cause flooding and increased offshore sediment transport (Mertes and Warrick, 2001).

Other effects of weather are more subtle, and more seasonal. When the oceans warm up and sunlight increases in the spring, many oceanic regions witness the occurrence of the annual 'spring bloom', a marked increase in phytoplankton populations caused primarily by the increased availability of nutrients and increased sunlight. The timing and magnitude of this event is critical to many important species of fish, including commercial species (Platt *et al.*, 2003) (see Chapter 8). Other areas where the influence of seasonal weather patterns is clearly observable in ocean-colour imagery are the Arabian Sea, where the monsoon causes a dramatic increase in phytoplankton activity, and the Pacific Ocean coast of Central America, where powerful winds jetting through mountain passes, caused by winter weather systems in the Caribbean Sea, mix nutrients to the surface and foster the productivity necessary for commercial and sport fishing in that region.

Although the effects of weather on the ocean generally occur over short time periods ranging from days to weeks, the effects of climate variability and climate change on the oceans can be observed only over periods of months to years. One of the first observations of the interaction of climate processes and the oceans occurred when the Coastal Zone Colour Scanner (CZCS) documented the biological effects of the large El Niño event occurring in 1982-1983 (Feldman *et al.*, 1984). CZCS data indicated that phytoplankton pigment concentrations in the Equatorial Upwelling Zone, particularly near the Galapagos Islands, were markedly diminished during this

El Niño event. The observations confirmed that El Niño caused widespread changes in the biological dynamics of the Pacific Ocean. Under serendipitous circumstances, the launch of SeaWiFS in September 1997 coincided with the onset of another major El Niño event, which peaked in strength from November 1997 through May 1998. The nearly-continuous coverage of SeaWiFS allowed the observation of the strong cessation of biological activity in the Equatorial Upwelling Zone, and the remarkably rapid restoration of the upwelling and increased chlorophyll concentrations in June and July 1998 (Chavez *et al.*, 1998) (Fig. 2.6). The shift from El Niño to subsequent La Niña conditions caused a major shift in the uptake of carbon by the oceanic system (Behrenfeld *et al.*, 2001). El Niño and La Niña, also known as the El Niño Southern
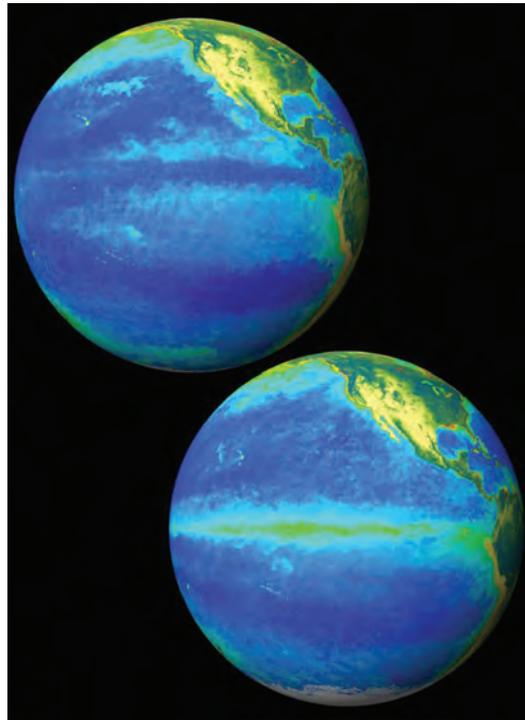
Figure 2.6 SeaWiFS images of the Pacific Ocean during the peak of the 1997-1998 El Niño (top), during which phytoplankton activity in the Equatorial Upwelling Zone was significantly reduced, and (bottom) during the subsequent La Niña when phytoplankton activity in the Equatorial Upwelling Zone was elevated (Credit: SeaWiFS Project, NASA/Goddard Space Flight Center and GeoEye).

Oscillation (ENSO) events, are probably the best-known recurring cyclic phenomena in the ocean, due to their widespread impact on Pacific Ocean regions, including the coasts of Central and South America, Indonesia, Polynesia, and Australia. Other cyclic phenomena that produce recurring patterns of interannual variability are the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO). Sea surface height data, SST data, ocean surface wind data, and ocean-colour data are all remotely-sensed data products that provide diagnostic

criteria allowing scientists to evaluate the dominant modes of these phenomena. As the data records become longer, it becomes possible to examine the recurrence frequency of these events and relate their frequency to the affects of climate change.

The accuracy of remotely-sensed data is, however, one of the primary concerns in the compilation of multi-decade climate data records (CDRs). Each satellite Earth-observing sensor is unique, even despite the best technological efforts to produce duplicate instruments, such as the Advanced Very High Resolution Radiometer (AVHRR). For ocean-colour data, the problem is more acute, as to date there has not been a 'series' of similar instruments primarily dedicated to ocean-colour observations. Merging the data from different sensors therefore presents a data processing and data analysis challenge. Initial efforts in this regard have indicated distinct trends in the chlorophyll concentration of the world's oceanic basins from the CZCS observational period in 1978-1986 to the present (Dutkiewicz *et al.*, 2001; Gregg and Conkright, 2002; Gregg *et al.*, 2003; 2005). NASA funded the Ocean Colour Time-Series Project to determine if CZCS and OCTS data could be reprocessed in a manner emulating, as closely as possible, the data processing methodology applied to SeaWiFS and MODIS-Aqua data by the Ocean Biology Processing Group (OBPG) at NASA GSFC. This effort indicates the difficulty of connecting disparate data sets into CDRs due to differences in sensor performance and operating conditions. Another merged data set is the ESA DUE GlobColour multi-parameter data set based on SeaWiFS, MERIS and MODIS data (see `http://www.globcolour.info`). The merging of data from individual sensors not only provides a long time-series, but also increases the temporal coverage and error characterisation of the final data set (see Section 10.3). The combination of the three sensors allows about 30% of the ocean to be covered on a daily basis (IOCCG, 1999).

In the 1960s, consultation of images from the first generation of weather satellites to improve forecasting was a pioneering endeavour, though we now consider such a practice commonplace and necessary. At the end of the first decade of routine ocean-colour observations, the increased use of ocean-colour data in applications that are directly related to the public interest is becoming more evident. It is certain that future ocean-colour radiometry missions will provide data addressing an increasing variety of topics where the interests of the scientific research community and the public would derive mutual benefit - a significant reason to invest in the continuation of accurate ocean-colour remote sensing from space.

Ocean-Colour Data - An Aid to Modelling

Ian Robinson

In many branches of oceanography numerical simulation is an important tool for research and operations. For example, research on climate change is strongly dependant on models, including models of the ocean carbon cycle. Simulating the role of the ocean on the Earth's carbon cycle needs an ecosystem model embedded in a general circulation model. For any model that purports to represent the large-scale features of the ocean, we require data from Earth observation to accomplish at least two information tasks: the provision of data fields for model initialization and for model validation. In this section the important role of ocean-colour data as an aid to modelling is discussed.

The use of satellite ocean-colour data in the context of numerical ocean models is a steadily developing field of study which is leading towards a variety of research and operational applications. It is not really a separate category of use, but rather should be viewed as the means by which a number of the applications of ocean-colour data discussed elsewhere in this document can be enhanced, or extended into operational situations. This section will first review the circumstances where ocean models can benefit from ocean-colour data and vice versa. It will then outline the different ways in which colour-derived ocean properties, normally the near surface concentration of chlorophyll-a, are assimilated or otherwise used to improve the predictions of ocean models. Finally, it will consider the implications for the co-ordinated planning of ocean-colour monitoring systems by different space agencies, if their data are required for operational models.

3.1 When Are Ocean-Colour Observations Used in Models?

In most applications of ocean colour, the satellite data provide the primary information about a particular ocean phenomenon or process. Ocean-colour data by itself, or in combination with observations of other ocean properties, is sufficient to present a clear story. But this is not always the case. What are the situations where the colour data need to be linked to the use of a numerical model? We can identify two types of use: the first is where a model is required to improve scientific

understanding, the second is where the model is needed in support of operational monitoring.

3.1.1 Model to Represent Scientific Complexity

In the first case, the subject typically requires the complex interactions between many parameters, including ocean colour, to be defined and a numerical model is used to do this. The parameters in the model need to be tuned to make it as realistic as possible in order to increase the confidence that can be placed on the results gained from running the model. An obvious example is that of ecosystem models capable of representing the growth and decay of a phytoplankton bloom in the ocean. Although the chlorophyll measurements obtained from ocean-colour data are able to show when and where blooms occur, this by itself is not sufficient to understand the processes. It needs a biochemical model of the balance between primary production, nutrient supply and grazing by zooplankton to be embedded in a physical/dynamical model describing circulation, mixing and upwelling, before we can begin to represent the complex interactions that constrain this most important of all oceanographic processes.

Ecosystem models of the open ocean that truly represent the distribution of primary producers in three spatial dimensions and time are needed to be able to answer a number of important scientific questions about, for example: the ratio of new to regenerated production; the proportion of carbon fixed by primary production that is exported from the surface layer; the impact of a phytoplankton bloom on the pCO$_2$ at the ocean surface and hence on the exchange of CO$_2$ between the ocean and atmosphere. These and similar questions need a reliable biogeochemical model embedded in a physical model to enable us to reach answers that account for the space-time variation of the real ocean. Satellite-derived observations of chlorophyll by themselves cannot answer these questions. Neither can a model do so by itself because without comparison against actual observations the model parameters cannot be tuned. Independent observations are also needed to evaluate the tuned or calibrated model with regard to its generality and reliability. Although *in situ* measurements are of some value, only satellite colour data can provide the high-resolution view of spatial structures, the wide area coverage and the repeated sampling over time to capture the detailed evolution of a phytoplankton population that is required to constrain the model parameters. Thus only a combination of satellite data and numerical models can answer some of today's key oceanographic questions.

In coastal seas the situation is even more complex than in the open ocean, and the use of models is even more essential. Here the additional factors of land-derived dissolved organic material, re-suspended bottom sediments or river borne particulates not only create the Case 2 optical conditions (IOCCG, 2000), but also add complexity to the biogeochemical processes. The potential of satellite ocean-

colour data to yield information about suspended sediments and CDOM as well as chlorophyll is very attractive, but can only be realised when the challenge of interpreting Case 2 data has been solved.

3.1.2 Model to Meet Operational Needs

In the second type of use, models are needed in conjunction with satellite ocean-colour data primarily because information about the ocean needs to be supplied for operational purposes. Take, for example, the operational responsibility of warning coastal holiday resorts about the occurrence of algal blooms which interfere with maritime leisure activities. Satellite data alone can be adequate for this task, but only if daily cloud-free cover is available. Since this can rarely be guaranteed, the authorities with operational responsibility are unable to rely exclusively on the satellite data. In these circumstances the use of a model capable of predicting the evolution and movement of algal blooms, regularly updated by satellite observations when skies are clear, offers an effective solution. Of course the model that is used might be very similar to one of the models discussed in the previous paragraph, but here it serves a different purpose. The combination of satellite data, *in situ* measurements and numerical model is conceived as an operational ocean or coastal 'observing system', in which the output of the model provides the best available estimate of the state of the ocean at a given time. The model effectively fills in the gaps, in space and time, between all the available observations. Typically it provides a 'nowcast', and if the system offers a modest capacity for forecasting, then that is a bonus.

It is not only tourism that needs such integrated observing systems but also the marine aquaculture industry and those with a statutory responsibility for water quality monitoring. As international legislation imposes greater demands on nations to monitor the quality of the water in their own exclusive economic zones (EEZ), ocean observing systems are increasingly seen as an essential tool. Although in most cases ocean colour is used to provide information about biogeochemical aspects of the sea, the use of ocean colour radiometry data as a tracer of water movement and water masses should not be overlooked. There are circumstances where knowledge of ocean surface currents is needed at fine spatial resolution, for example in order to supply information crucial for the planning of difficult offshore drilling operations. In these circumstances both ocean colour and temperature images can provide evidence of the smallest mesoscale features, but their assimilation in a dynamical model is essential to provide operational reliability in all weathers.

It is important to distinguish between what we may call the scientific and the operational model cases because they impose different requirements on the timeliness with which processed satellite data are provided to users, and on the continuity and sustainability of ocean-colour missions. These will be discussed in the final part of this section.

3.2   Confronting Models with Ocean-Colour Radiometry Data

3.2.1   The Basic Modelling Principles

The numerical models that have so far been adapted to assimilate satellite ocean-colour data are ecosystem models of varying complexity. For application in the open ocean, relatively simple pelagic ecosystem models are used, based largely on the approach pioneered by Fasham *et al.* (1990) and Fasham (1993). In Fasham *et al.* (1990) the ecosystem is separated into seven separate compartments. Using nitrogen as the basic currency of the model, each compartment is defined in terms of the amount of nitrogen per unit volume (mmol N m^{-3}). The seven compartments are; phytoplankton (P), zooplankton (Z), bacteria (B), nitrate, ammonium, dissolved organic nitrogen (DON), and detritus as non-living particulate organic nitrogen (PON). The model equations represent the applicable biological processes within a single model element for P, Z and B, such as primary production, respiration, grazing, excretion and mortality. There are many variants involving more or less than seven nitrogen pools. In some cases additional variables are introduced to represent the carbon partitioning and the alkalinity (Drange, 1996).

When the ecosystem model is embedded within a three-dimensional ocean circulation model, additional equations represent the transport of the different ecosystem components between the model grid cells by advection, diffusion, or sinking under gravity. A variety of different basin-scale models have been developed, using slightly different ecosystem and chemical models attached to different types of ocean circulation models, some with fine enough spatial resolution to resolve mesoscale eddies. They have been created for the North Atlantic (Drange, 1996; Gunson *et al.*, 1999; Oschlies and Garçon, 1998; 1999; Oschlies *et al.*, 2000), the tropical Pacific (Christian *et al.*, 2002) and the global ocean (Gregg, 2001; Palmer and Totterdell, 2001).

A critical challenge is to determine appropriate values for the parameters used in each model expression to represent a biological or chemical process. This requires a calibration procedure which optimises the model parameters to match an independent set of observations. Although local ecosystem models can be tuned for a particular place and season using a suite of *in situ* measurements of the main ecosystem components, parameter sets determined in this way can not be applied with confidence to a basin-scale model running throughout the year. In that case, chlorophyll data obtained from satellite ocean colour can provide the global geographical coverage, the spatial detail and most importantly the multiple annual cycles needed to represent the variety of conditions which such a model must be capable of simulating. Parameter estimation is the motivation behind most of the assimilation work reported so far.

In shelf seas where there is greater heterogeneity of the pelagic ecosystem over shorter length scales, and where benthic processes must also be taken into

account, modellers have used more complex designs, such as the European Regional Seas Ecosystem Model (ERSEM), which has been applied to the North Sea, the Mediterranean Sea, the Adriatic Sea and the Arabian Sea (Allen *et al.*, 2001). The marine ecosystem is represented by a network of physical, chemical and biological processes organised within pelagic and benthic components. In these more complex models the biota are necessarily segregated into functional groups that are intended to represent particular types of behaviour rather than species lists. Each functional group is defined by a number of explicitly-modelled components: carbon, nitrogen, and phosphorous and, in the case of diatoms, silicon. In ERSEM phytoplankton are represented by four functional types: picophytoplankton (0.2-2 μm), small autotrophic flagellates (2-20 μm), large autotrophic flagellates (20-200 μm) and diatoms (20-200 μm). When embedded into a three-dimensional physical model of a shelf sea, there are 36 pelagic state variables to be advected and diffused by the hydrodynamics. It is essential to establish valid parameterizations for each of the many processes if the model is to have a predictive capability. This is where modellers look to satellite ocean-colour data to provide time-evolving distributions of chlorophyll, and possibly also dissolved organic material and suspended particulate matter, against which to test and calibrate their parameterizations, and ultimately validate the model.

3.2.2 Experience with Assimilating Chlorophyll in Ecosystem Models

When using satellite-derived chlorophyll data for calibrating and validating models, there are three important factors to be noted because they are potentially limiting.

❖ Some ecosystem models do not use the concentration of chlorophyll-a (Chl-a) as an explicit model variable. In such cases the dependence of Chl-a (mg m^{-3}) on the magnitude P (mmol N m^{-3}) of the phytoplankton compartment of the model must be established, for example as characterised by the Michaelis-Menten relationships (Michaelis and Menten, 1913). The form proposed by Semovski and Woźniak (1995) is:

$$P = \frac{\rho_{max}\text{Chl}_a{}^2}{(\text{Chl}_a + K_{1/2})R},$$
(3.1)

where ρ_{max} is 90 mol C per g Chl and the half saturation constant, $K_{1/2}$, is 0.477 mg m^{-3}. R is the Redfield ratio to convert the expression from carbon to nitrogen units (taken to be 6.625 for the deep ocean). Before assimilation an expression such as this must be used to convert satellite-derived chlorophyll data into the model representation of phytoplankton, or *vice versa*.

❖ Satellite data provide observations of only one of the seven biogeochemical compartments used by the Fasham-type models.

❖ The typical accuracy of Chl-a retrieved from ocean colour is 35% in open seas and even poorer in Case 2 conditions. This compares unfavourably

with the accuracies of sea surface height anomaly and temperature, which are the satellite measurements used for assimilation into numerical models representing ocean physics and flow dynamics

However, when Natvik and Evensen (2003 a; b) developed techniques to assimilate SeaWiFS data into a full three dimensional ecosystem model embedded in a North Atlantic hydrodynamic model, they were able to demonstrate that the satellite data measurably improved the model response. This model uses an ensemble Kalman filter (EnKF) approach to assimilation. Using the satellite data reduced the variance fields for all the variables, including those partitions of the ecosystem that were not directly observed. They concluded that the use of a multivariate analysis scheme enabled the phytoplankton information supplied by the satellite data to improve the analyses for the other ecosystem partitions. This result confirms the relevance of satellite ocean-colour data for future biochemical ocean model developments.

Hemmings *et al.* (2003; 2004) used SeaWiFS-derived chlorophyll data from locations across the North Atlantic to calibrate a zero-dimensional plankton ecosystem model (that is, one that is not embedded within a circulation model but which attempts to describe the seasonal cycle separately at a number of different locations). The aim was to achieve this using a single set of parameters. They concluded that the derived parameter sets are improved by using the satellite data because the high volume of observed data can supply examples of a wide range of possible biogeochemical responses to different physical conditions. For the same reason they demonstrated that the model performance is improved if the north Atlantic is divided into two provinces for which the parameters are independently calibrated. However, they introduce a note of caution, observing that despite the advantage of using satellite chlorophyll for calibrating the model, the parameters remain poorly constrained without observations of the other ecosystem elements.

3.3 Operational Models Using Inputs of Satellite Ocean-Colour Data

The ecosystem models mentioned above are concerned with improving the scientific understanding of ecosystem processes. However, increasing operational use is being made of ecosystem modules embedded in physical circulation models to provide forecasts of the development of plankton blooms, in order to issue warnings of harmful algal blooms (HAB) or the risk of eutrophication in vulnerable sea areas. One example of how such a model makes use of satellite ocean-colour data is provided by Svendsen *et al.* (2004), in a case study describing the operational monitoring for a HAB of *Chattonella* spp. This species started to bloom in Scandinavian waters in 1998, returning in 2000 and 2001, killing thousands of tons of farmed salmon along the southern Norwegian coast. The study describes the real-time monitoring of the bloom in 2001, using SeaWiFS data.

At the heart of the monitoring process is an ecosystem model embedded in a hydrodynamic model of the Norwegian coastal seas, relying on observational data inputs to achieve a good representation of the real ocean, but still able to provide estimates of the ocean state at times and locations when no observations are available. Every cloud-free chlorophyll image is compared with the model phytoplankton prediction. When a bloom event is detected by the satellite but is not predicted by the model, the model phytoplankton field is manually re-initialised to the observed concentrations following the spatial distribution from the satellite image. The model then continues to predict the further development, advection and final decay of the bloom and warnings are issued if the bloom approaches the coast. Subsequent satellite observations are used just for validation, and further re-initialisation is performed only if the model output deviates badly from the satellite estimates.

The model includes as state variables the abundance of two functional groups, diatoms and flagellates, but does not specifically represent a particular harmful algae species. Therefore when a bloom is detected from space, *in situ* samples are urgently needed to determine whether it is a harmful species or not. Despite the obvious shortcomings that the HAB species are neither represented explicitly in the model nor directly distinguishable from non-harmful species in satellite ocean-colour data, this case study demonstrates how effective can be the combination of model, satellite data and *in situ* sampling for critical operational tasks. Although the assimilation technique is fairly crude, it is effective and adequate for the operational task.

3.4   Alternative Approaches

The assimilation of satellite data into ecosystem models is still at an early stage of development but shows promise, especially in the open ocean where the measurement of Chl-a from space is generally reliable. However, in coastal waters, where the requirement for observations is amplified by the complexity of the ecosystem model, the methodology of parameter retrieval from ocean colour is compromised by the ambiguity of Case 2 conditions. One of the difficulties with the interpretation of Case 2 ocean-colour images is not knowing the relative contribution of chlorophyll, CDOM and SPM which can, independently, affect the colour. However, when satellite data are being used for assimilation in support of a model, then the model may have some skill in predicting in advance what the balance is likely to be between the three possible colour-controlling constituents. This points towards the possibility of an interactive approach to Case 2 algorithms using the ecosystem model forecasts.

Taking this line of thinking further, a more radical approach would be to use the model to predict the colour of the sea (*i.e.* the reflectance in each spectral band) and to compare this directly with what the satellite observes, as discussed by Robinson and Sanjuan-Calzado (2006). This would eliminate the need for the relatively uncertain inversion of the colour data to retrieve chlorophyll or SPM or

CDOM. Although some progress has been made in this direction (Fujii *et al.*, 2007), it remains to be determined whether an assimilation technique can be developed which is able to adjust the model ecosystem state variables in order to shift the model's colour predictions closer to the satellite observations.

3.5   The Implications of Using Ocean-Colour Operationally

The emerging use of ocean-colour data for assimilation in ecosystem and/or ocean dynamical models, and the potential for supporting operational ocean monitoring systems by this means, implies a growing dependence of users on the agencies who provide ocean-colour sensors in space. As more routine use is made of satellite-derived chlorophyll data, users will look to the agencies to provide continuity of ocean-colour missions, with new sensors ready to replace old ones into the indefinite future. Operational users will also look for increased speed of processing and a reduction in the delivery time between data acquisition and the supply of a processed product. Despite the promise of benefits from using ocean-colour data in support of ecosystem models, many operational ocean forecasting agencies may hesitate to set up operational systems until they can be reasonably sure of the continuity of data provision and the timeliness of delivery.

Moreover, in the same way that data from different satellite altimeters are being supplied in a co-ordinated way (through the DUACS[1] programme) and standards for harmonising SST data from diverse satellite sensors have been set (by the GHRSST[2] project), so there is a growing demand from users for a harmonised set of ocean-colour products. Modellers and operational users simply want to obtain the most recently acquired observations of chlorophyll or other colour-related products from space. It is seen as an unnecessary complication if they have to interpret products from different agencies in different ways. For serious assimilation, an error estimate needs to be supplied with each measurement. Ideally all data should be supplied in a common and readily accessible format. Finally some users may prefer a single merged, averaged or blended global daily chlorophyll observation derived from all available ocean-colour sensors. This issue was the topic of a recent IOCCG report (IOCCG 2007) and is currently being addressed by the ESA GlobColour Project [3].

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[1]DUACS - Developing Use of Altimetry for Climate Studies system based at CLS which merges data from T/P and Jason-1, Envisat/ERS-2 and GFO altimeters to produce along-track data and Maps of Sea Level Anomalies (MSLA) on a near-real time basis. (See http://www.jason.oceanobs.com/html/donnees/duacs/welcome_uk.html

[2]GHOSTS - Global ocean data assimilation experiment High-Resolution Sea Surface Temperature pilot project. (See http://www.GHRSST-PP.org)

[3]For more information on GlobColour see: http://www.globcolour.info/index.html

Ocean-Colour Radiometry and Ocean Physics

Stephanie Dutkiewicz, Robert Frouin, Shubha Sathyendranath and B. Mete Uz

4.1   Introduction

Physical processes in the ocean dictate largely the chemical and light environment in which the phytoplankton find themselves. Growth of phytoplankton at sea requires light and nutrients. The average light experienced by the phytoplankton in the mixed layer of the ocean depends on the light reaching the sea surface, the rate of light attenuation with depth in the water column, and the depth of the mixed layer itself. In most areas of the world ocean, the supply of nutrients into the mixed layer depends on various physical processes: advection, diffusion and mixing. Thus, the distribution of phytoplankton in the surface mixed layer is intimately linked to the physical processes. Many of these processes are transient, and remote sensing has played a very useful role in providing evidence for the importance of transient processes in sustaining ocean productivity, which in turn has stimulated modelling studies designed to pinpoint the underlying physical mechanisms responsible for the observed biological features.

On the other hand, the growth of phytoplankton at sea modifies the light field underwater. In fact, in open-ocean waters, phytoplankton and associated material are recognised to be the most important factor responsible for modifying the underwater light field. The changes in the properties of light penetration in turn modifies the rate of solar heating at various depths in the ocean (Fig. 4.1), altering water-column stability and hence mixed-layer dynamics. Studies of such feedback mechanisms by which biological properties modulate the physical processes have also been given an impetus by the availability of ocean-colour data appropriate for such studies.

In this chapter, we summarise ocean-colour applications in studies of physical processes that influence phytoplankton dynamics at sea, and biological feedback mechanisms.
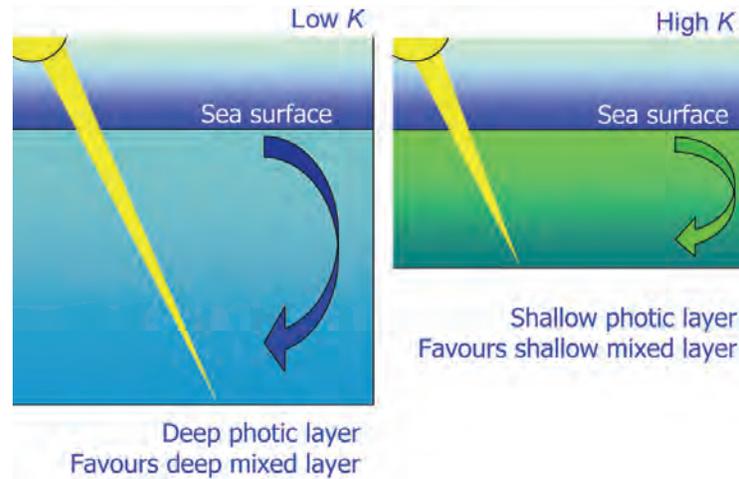
Figure 4.1 Schematic diagram showing links between diffuse attenuation coefficient *K* and mixed-layer depth. Small values of *K* would be associated with a weak vertical gradient in solar heating. Therefore, other things being equal, low values of *K* would favour deeper mixing, compared with waters where *K* is high.

4.2   Effect of Physical Processes on Fields of Phytoplankton and Primary Production

Ocean spectral reflectance in the visible domain is the only optical signal open to biological interpretation that is measured over the global ocean at resolutions comparable with the suite of physical properties observed by remote sensing, such as SST, SSH, wind vectors and precipitation. Consequently, it is often co-analyzed with one or more of these variables to elucidate mechanisms of physical-biological coupling in the ocean.

In the well-lit upper ocean, phytoplankton rapidly assimilate available nutrients into biomass. When particulate organic material falls out to deeper layers, nutrients incorporated into the material are also lost with it. For continued productivity in the upper ocean, this loss must be compensated by either atmospheric sources, or by the injection of nutrient-rich waters from below. Except for micronutrients such as iron, atmospheric deposition is generally not very important. And, as the water column is stably stratified over much of the ocean, the background level of nutrient supply through vertical mixing of denser nutrient-rich waters is very limited.

Much of the observed variability in phytoplankton biomass and productivity occurs as a result of processes such as winter mixing and coastal or equatorial upwelling which bring nutrients from deeper layers to the surface. However, at places such as the interior of subtropical gyres, as characterized by the Bermuda Atlantic Time Series site, primary productivity has been observed to be higher than can be accounted for by upwelling and vertical mixing, implying additional mechanisms

of nutrient replenishment. Numerical modelling and, most recently, shipboard observations have shown that processes associated with baroclinic disturbances can be a significant source of additional nutrients and thus support a significant increase in productivity.

4.2.1   Spring Bloom Dynamics

Phytoplankton blooms in the North Atlantic are some of the most pronounced of any open ocean region. Although this region and its immense seasonal blooms have been the subject of many investigations over the years, it was only with the advent of satellite ocean-colour data that we have been able to investigate the temporal and spatial variability of these blooms. One of the strongest controls on interannual variability in the blooms appears to be from meteorological modulation (Townsend *et al.*, 1992; Follows and Dutkiewicz, 2002; Lévy *et al.*, 2005; Ueyama and Monger, 2005).

Bloom dynamics involve a delicate balance between nutrient supply and light limitation. The latter is regulated by seasonal progression of the sun, but also significantly by the depth of the mixed layer (Sverdrup, 1953). If the mixed layer is too deep, phytoplankton will on average have too little light and growth will be impeded. Yet, a deeper mixed layer (stronger convective events) leads to entrainment of higher concentrations of nutrients from below. In fact, Dutkiewicz *et al.* (2001) showed, using model simulations, that vertical mixing can enhance productivity by supplying nutrients from below, but can also decrease productivity by mixing phytoplankton below the critical depth (here defined as the depth above which, in the absence of nutrient limitation, there is a net growth in phytoplankton).

It is only with detailed satellite ocean-colour studies that these patterns become more clearly and broadly visible. There is a difference in behaviour in bloom variability and indicators of mixing in the subtropical and subpolar regimes (Follows and Dutkiewicz, 2002). In the subtropics, enhanced mixing leads to increased chlorophyll amplitudes, while in the subpolar regions it leads to reduced amplitudes. Ueyama and Monger (2005) examined the interannual variability exhibited by the first EOF mode of SeaWiFS ocean-colour data together with SSM/I wind data between the year 1998 and 2004 in the North Atlantic. These modes exhibited strong spatial coherency and indicate regions where bloom timings and magnitudes are in phase and regions where they are out of phase with wind mixing. The southern subtropical regime showed strong positive correlation between bloom magnitude and wind mixing. Similarly, there is an out-of-phase relationship in the subpolar regime in both timing and magnitude of the bloom, supporting the idea of a negative impact of mixing in this region (Dutkiewicz *et al.*, 2001). Lévy *et al.* (2005) also find a striking pattern of an opposite interannual trend in bloom strength derived from SeaWiFS data and mixed layer depth (provided by a high resolution numerical model) in the two regimes in the North Eastern Atlantic.

Even in the subtropical and subpolar regimes the patterns are not always clear, and there are large tracts of the North Atlantic that do not fall into either of these two regimes (*e.g.*, Lévy *et al.*, 2005; Ueyama and Monger, 2005). Apart from other biogeochemical causes of variability, such as nitrogen fixation (Michaels *et al.*, 1994) and grazing (Popova *et al.*, 2002), there are also other physically-driven mechanisms that impact bloom variability. For instance mesoscale activity can significantly impact local supply of nutrients and enhance productivity (*e.g.*, McGillicuddy and Robinson, 1997; Oschlies and Garçon, 1999), and lateral supply of nutrients is crucial in some regions of the North Atlantic (Williams and Follows, 1998).

There are, however, striking broad patterns in interannual variability in the North Atlantic bloom that have emerged from ocean-colour studies, and these appear strongly linked to modulation in the synoptic atmospheric events between years (Follows and Dutkiewicz, 2002; Levy *et al.*, 2005; Ueyama and Monger, 2005). These connections lead to some interesting questions regarding the relation to larger scale patterns of meteorological variability (*e.g.* the major mode of wind variability is associated with the North Atlantic Oscillation, NAO) and to longer time-scale climate change. A characteristic of low NAO is enhanced mixing in subtropical regions; the discussion above then suggests that blooms may be enhanced in the subtropical regimes during this phase of the NAO. Uemaya and Monger (2005) also suggest that the major mode in the timing of the bloom might be linked to the NAO. Further ocean-colour studies of these and other phenomena will greatly enhance our understanding of the mechanism underlying the response of the oceans ecosystems to current and future variability in the climate.

4.2.2   Physical–Biological Interactions associated with Mesoscale Eddies

Baroclinic disturbances are ubiquitous distortions in the depth and slope of isopycnal lines, often caused by such processes as instabilities and wind stress variability over space or time. They generally propagate westward as eddies or planetary waves. They modulate the depth of isopycnal layers by hundreds of metres and the sea surface height by tens of centimetres.

Even though sea surface height anomalies are typically a few orders magnitude smaller than isopycnal displacements, they still form the basis of our observations of baroclinic features because they are detectable by satellite altimeters. The advent of altimetry allowed for global characterization of planetary waves and mid- to large-sized eddies in the ocean. Shortly after the launch of SeaWiFS, when continuous coverage of ocean spectral reflectance started, colour anomalies propagating westward at typical planetary-wave speeds were observed and shown to be phase-locked and coherent with sea surface height anomalies. It is still a matter of debate and active research whether this manifestation of planetary waves in ocean spectral reflectance is due to new production in response to nutrient renewal, or passive transport of existing biomass. With analysis of ocean spectral reflectance

imagery in comparison with other remotely-sensed properties and model results, a number of hypotheses have been put forward including horizontal advection of existing background gradients by the planetary wave, concentration of surface pigments due to the convergence associated with the waves, and the enhanced visibility of shoaled subsurface pigment maxima to the satellite sensor over the wave.

Assessing the mechanism for increased pigment concentrations often observed within eddies is even more complicated than those observed in association with planetary waves, because unlike waves, non-linear eddies transport water over considerable distance and time. It appears that the primary effect of eddies is to transport existing biomass, however this does not preclude biologically-active mechanisms, since these would be secondary in nature. To the first order, a geostrophically balanced eddy would simply move the water around. However, secondary effects, which are more pronounced under external forcing such as from wind stress, or when the eddy is actively spinning up or down, would result in significant vertical velocities, which should affect nutrient and pigment concentrations.

Present satellite instruments are capable of adequately resolving planetary waves and mesoscale eddies and significant progress should be expected in the near future with the available data. If a geostationary sensor were available, its capability to minimize the effect of cloud cover would be very useful for mesoscale process studies. The higher spatial and temporal resolution would also allow submesoscales to be resolved, which are particularly important for biological processes because of the significant vertical motions associated with these scales.

4.2.3 Effect of Storms

Whereas it is relatively straightforward to use *in situ* observations to monitor the supply of nutrients to the surface layer through winter mixing, it is much more difficult to rely on *in situ* techniques to monitor physical and biological responses to transient events such as the passage of storms. Remotely-sensed data provide unprecedented views into the biological consequences of such transient phenomena. Several authors (Babin *et al.*, 2004, Davis and Yan 2004; ; Fuentes-Yaco *et al.* 2005; Platt *et al.*, 2005, Son *et al.* 2006) have shown, using sequences of ocean-colour images, changes in chlorophyll concentrations in the surface layers of the sea following the passage of storms. Using a 3-D ocean circulation model of the Labrador Sea, Wu *et al.* (2007) identified two phases in the responses of the biological field to a steadily-moving storm. The first and immediate response is associated with deepening of the mixed-layer and redistribution of the chlorophyll biomass in the new mixed layer. This is followed by a period of inertial oscillation in the wake of the storm which may last a few days. An even longer-scale response would be associated with the new nitrogen that is brought into the well-lit mixed-layer as a result of the enhanced

storm-induced mixing, which would typically lead to enhanced production over a longer time scale.

Wu *et al.* (2008b) also studied a summer bloom in the Labrador Sea in 2006 that appeared as an anomaly compared with the multi-year climatology of the bloom dynamics in the area (Fig 4.2). Using models they showed that the bloom could be explained as the biological response to an intense storm in the area. The physical processes responsible for the phenomenon were entrainment due to mixing, and Ekman pumping in zones of divergence of wind stress. Both processes brought new nitrogen into the layer, which led to enhanced primary production in the layer.
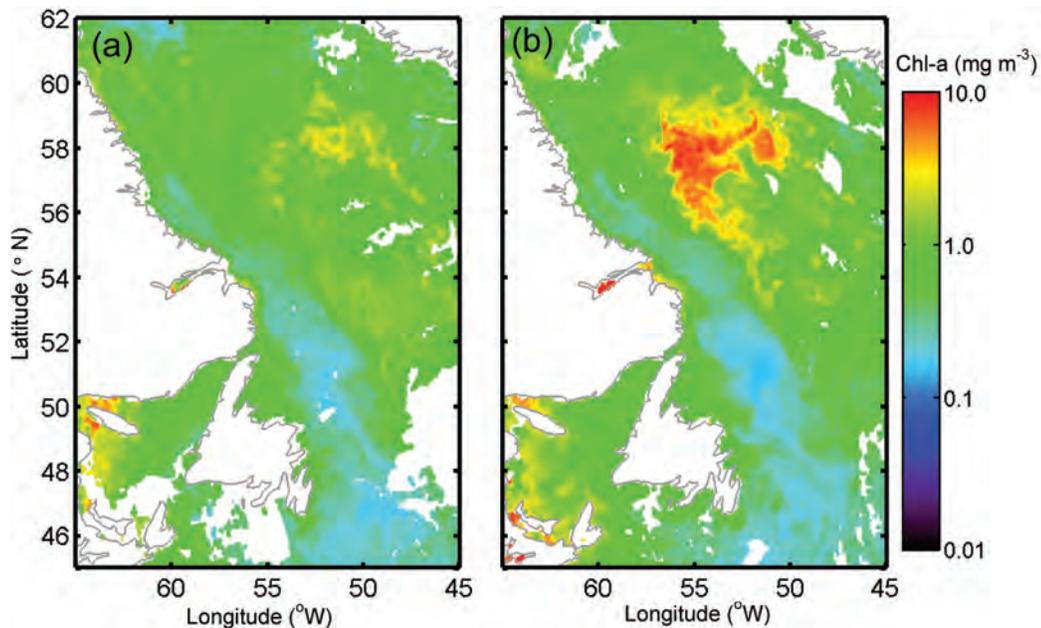
Figure 4.2 Composite MODIS images of the central Labrador Sea for (a) 8-15 July, 2006 and (b) 16-23 July 2006 (adapted from Wu *et al.* 2008b). Model results showed that the enrichment of nutrients in the euphotic layer and the subsequent bloom were related to two wind storms in the period 7-10 July 2006. (MODIS data provided by NASA/GSFC).

4.3   Biological Feedbacks on Physical Processes in the Sea

4.3.1   Attenuation of Solar Radiation and Mixed Layer Dynamics

Some sunlight is reflected at the ocean surface because electromagnetic waves travel slower in water than in air (due to the higher index of refraction of water). But most sunlight reaching the surface is transmitted into the ocean, where it is essentially absorbed. Only a small percentage of the transmitted light, typically 2%, is backscattered to the atmosphere. Unlike non-solar heat fluxes, which act in the

immediate vicinity of the surface, solar irradiance may reach, and therefore heat, waters below the mixed layer. Vertical attenuation of sunlight is due to absorption and scattering by molecules and particles (phytoplankton, sediments) and absorption by dissolved organic matter. About 95% of sunlight is absorbed in the upper 100 m of the clearest waters, but sunlight rarely penetrates deeper than a few metres in coastal turbid waters. Water composition thus affects the vertical distribution of solar heating, therefore stratification and mixing, and consequently heat exchange with the atmosphere and circulation patterns.

The importance of water clarity in determining the thermal structure of the ocean and mixed-layer dynamics was established by Denman (1973). Later Charlock (1982), employing a one-dimensional climate model with energy balance, noted that SST increased by 1-2°C when water was more turbid. Woods *et al.* (1984) emphasized the need for accurate calculation of the vertical profile of solar heating to meet the requirements of climate prediction. They showed that the rate of solar heating below the mixed layer depends more on water turbidity than on cloud cover. Sathyendranath *et al.* (1991), using the Kraus-Turner mixed-layer model, calculated a biological heating of up to 4°C per month in the Arabian Sea.
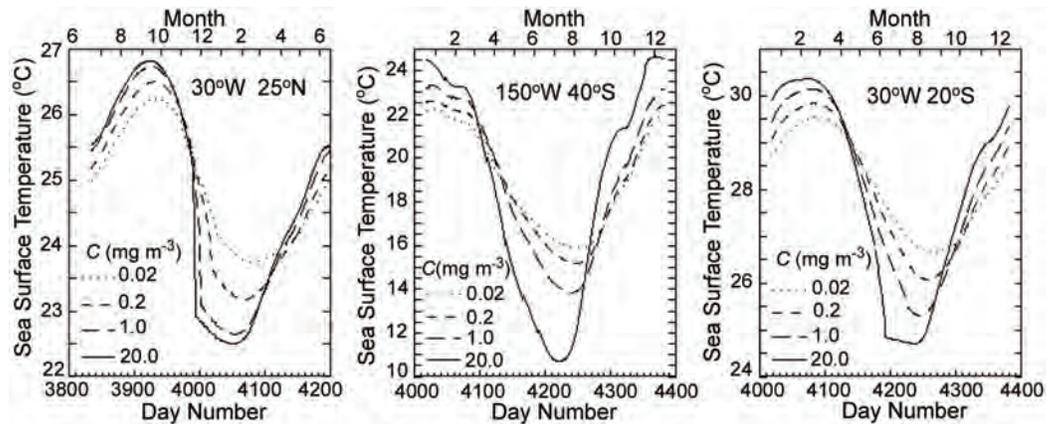
Figure 4.3 Sea surface temperature response to increasing phytoplankton pigment concentration, *C*. The one-dimensional mixed-layer model of Price *et al.* (1986) was used in the simulations. The atmospheric forcing, specified from the Comprehensive Ocean-Atmosphere Data Set (COADS), corresponds to the location, and *C* was constant during the entire year. Solar absorption by phytoplankton was parameterized according to Morel and Antoine (1994). The amplitude of the SST annual cycle increases as *C* increases.

Figure 4.3 illustrates the importance of water turbidity in mixed-layer dynamics. The one-dimensional model of Price *et al.* (1986) was used to simulate seasonal changes in the mixed layer at selected locations. Depending on phytoplankton pigment concentration, SST may change by several degrees C. As pigment concentration increases, SST becomes warmer in summer and colder in winter, *i.e.*, the seasonal cycle of SST is amplified. More radiation is absorbed in the mixed layer when pigment

concentration is higher, and less radiation penetrates below the mixed layer. In winter, the ocean surface is able to transfer heat to the atmosphere more efficiently. When the mixed layer deepens in winter, it brings up water from below that is cooler than the water corresponding to lower pigment concentrations, resulting in a cooler mixed layer.
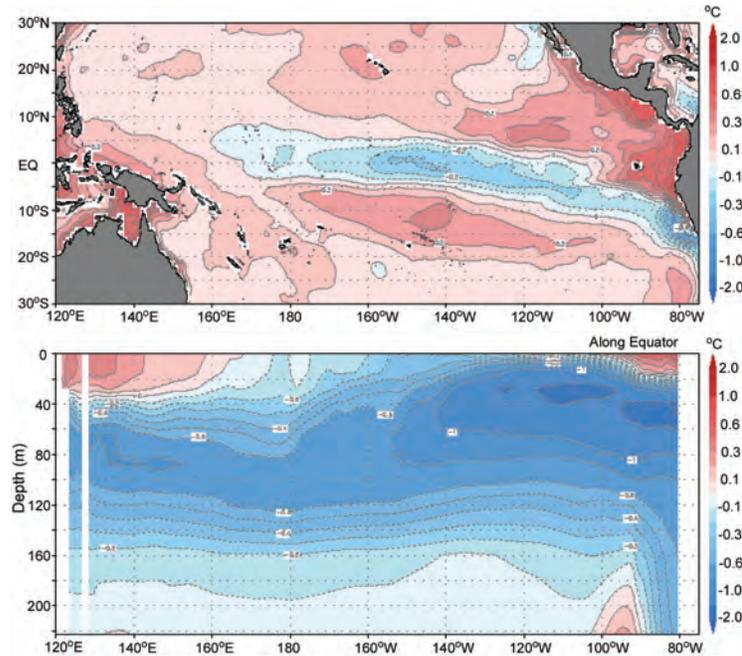
Figure 4.4 Top: Surface temperature difference between OGCM runs with and without phytoplankton-radiation forcing in the Pacific, between 30°S and 30°N. Bottom: Vertical profile of temperature along the equator, between the surface and 220 m. Surface temperature is generally increased in the entire horizontal domain, by 0.1 to 0.5°C, except in a relatively narrow latitude band along the equator between 180 and 100°W, where temperature is decreased by up to 0.4°C. This cooling, due to remote processes, is even more pronounced at depth along the equator, with differences reaching -1.5°C at 40 m at 110°W (adapted from Ueyoshi *et al.*, 2005).

Recently, using satellite ocean-colour imagery, absorption of solar radiation by phytoplankton was incorporated in Ocean General Circulation Models (OGCMs). This treatment is appropriate since changes in phytoplankton biomass are primarily responsible for solar attenuation variability in 98% of the ocean. Nakamoto *et al.* (2000; 2001), Frouin *et al.* (2001), and Ueyoshi *et al.* (2005) found a large-scale amplification of the SST seasonal cycle due to phytoplankton, by typically 20%. The amplification reached 1.5°C in some regions where the mixed layer was shallow. The simulations also revealed a systematically lower SST in the eastern Equatorial Pacific, which was explained by remote processes in which advection played a role (Nakamoto *et al.*, 2000). Similar results were also obtained by Manizza *et al.* (2005) in model runs that considered not only the impact of phytoplankton on ocean physics,

but also the response of phytoplankton to the modified nutrient supply and light availability.

Changes in the thermal structure of the Equatorial Pacific Ocean due to phytoplankton-radiation forcing are displayed in Figure 4.4. Murtugudde *et al.* (2002) argued that the problem of a colder than observed cold tongue in model results for the eastern Equatorial Pacific is remedied by using an accurate solar heating parameterisation derived from ocean-colour data. Subrahmanyam *et al.* (2008) reported large seasonal variability in the meridional overturning circulation and heat transport of the Indian Ocean. In all these studies, the heating changes due to phytoplankton resulted in dynamical changes, such as anomalous currents and upwelling.

The heating changes resulting from absorption of solar radiation by phytoplankton can in turn influence the atmosphere, which responds to the SST. The atmospheric response has been investigated with the NCAR Community Climate Model, version 3 by Shell *et al.* (2001; 2003), who used SST anomalies generated as part of Nakamoto *et al.* (2000; 2001). The main effect of incorporating the perturbed SST due to phytoplankton is an amplification of the seasonal cycle in the lowest layer atmospheric temperature by about 0.3°C, similar to the amplification found in the SST itself. The warming in summer is marginally larger than the cooling in winter, so that air temperature in the phytoplankton run is about 0.05°C warmer overall than in the control run. The air temperature anomalies over the ocean closely follow the SST anomalies, but there are also significant temperature changes over land (remote effects).

The impact of phytoplankton-radiation forcing is felt throughout the entire troposphere (Fig. 4.5). In response to the amplification of the seasonal cycle in the phytoplankton run, precipitation in the inter-tropical convergence zone is enhanced in the summer hemisphere. Timmerman and Jin (2002) and Marzeion *et al.* (2005), using coupled ocean-atmosphere models, found that effects of phytoplankton-radiation forcing in the Tropical Pacific might be enhanced via interactions with the atmosphere. Potential feedbacks in inter-decadal climate variation, due to altered oceanic ecosystems, are discussed in Miller *et al.* (2003). Further investigation is needed, however, to understand the mechanisms at work and quantify effects that can be compared with observations.

4.3.2   Use of Phytoplankton for Carbon Sequestration

In the context of global warming and its mitigation by stimulating phytoplankton growth, the numerical experiments discussed above are pointing to unintended negative feedbacks. The increased phytoplankton biomass resulting from fertilization by iron or nitrogen, or by using long open-ended tubes to enhance mixing (some of several ideas put forward) would trap sunlight in the upper ocean, warm the mixed layer, and increase stratification. Consequently, more heat would be transferred from
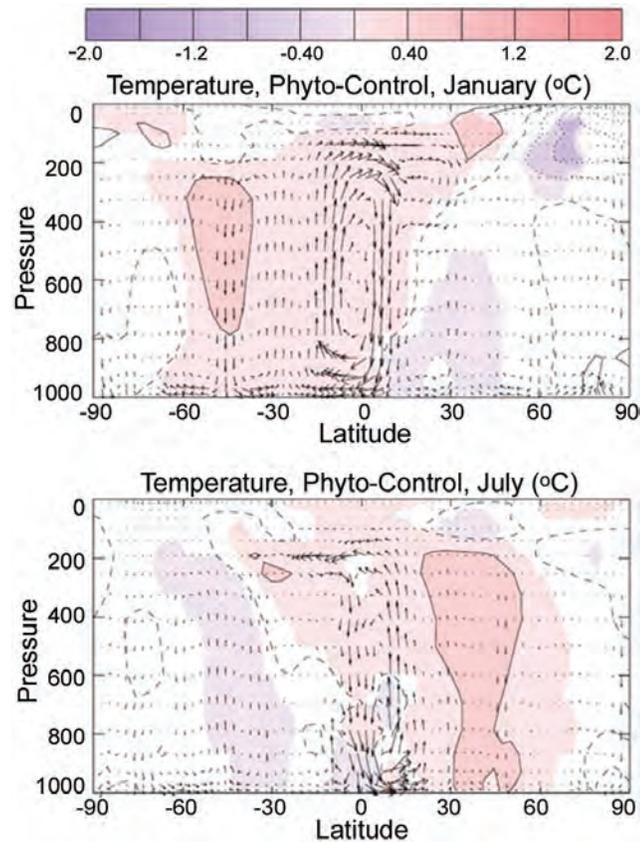
Figure 4.5 Difference between phytoplankton and control runs for January (top) and July (bottom) longitudinally averaged temperature (coloured contours) and circulation (arrows). Solid contours indicate positive temperature differences, while dotted contours indicate negative temperature differences. The dashed line follows the zero contour line. Temperature differences with a significance of at least 95% are shaded. The seasonal cycle of air temperature is amplified. The increased subsidence in the middle latitudes during summer traps heat (adapted from Shell *et al.*, 2003.)

the ocean to the atmosphere, resulting in a warmer air temperature. This opposite effect would contribute to negate the cooling associated with the sequestration of carbon dioxide. Furthermore, the partial pressure of carbon dioxide would increase, reducing the dissolution of atmospheric carbon dioxide. The enhanced stratification would also make nutrients less available in the sunlit layers, reducing phytoplankton growth. These adverse effects, as well as uncertainty in ecological consequences, make this carbon mitigation strategy highly questionable. To alleviate the impact on climate of rising atmospheric CO_2, one could alternatively investigate ways to trap transmitted sunlight below the mixed layer.

Biogeochemical Cycles

Nicolas Hoepffner, Frédéric Mélin, Mark Dowell, John Marra, Toshiro Saino and Cara Wilson

The ocean contains the largest active pool of carbon near the surface of the Earth. Important carbon-related processes include exchange of CO_2 with the atmosphere through the sea surface; conversion of CO_2 into organic carbon by phytoplankton photosynthesis in the sunlit upper layers; and sequestration of carbon into the deeper aphotic zone, either by settling of particulate matter or by diffusive or advective transport of carbon in organic or inorganic form. An inorganic long-term cycle driven by water alkalinity and the formation of calcium carbonate is also a component of the overall oceanic carbon cycle.

Knowledge of the magnitude of the carbon pools and fluxes in the ocean is a prerequisite to gaining a better understanding of the biogeochemical cycles, and is also a requirement for the construction of models to improve prediction of atmospheric $p CO_2$ concentrations, a major contributor of global warming (Fasham, 2003; Le Quéré *et al.* 2005; Behrenfeld *et al.*, 2006; Doney *et al.*, 2006). In this domain, satellite ocean-colour radiometry (OCR) has emerged as an essential tool to understanding and quantifying several aspects of the biogeochemical cycles of carbon as well as other elements.

The radiance reflected from the upper layer of the ocean (*i.e.* the water-leaving radiance) in the visible domain determines ocean colour and it varies with the concentration and composition of optically-active components in the water. These constituents span a broad size range from water molecules and dissolved matter to large zooplankton particles, and include a variety of material such as bacteria, viruses, phytoplankton, organic detritus, minerals, and more. The water-leaving radiances result from the additive contribution of these constituents to absorption and scattering of light. Remote observations of ocean colour from space are therefore directly related to various components of biogeochemical cycles and associated processes, and complement traditional ship observations in the global assessment of the flux of material through the water column.

5.1 Assessment of Carbon Reservoirs

5.1.1 Particulate Organic Carbon (POC)

Particulate organic carbon (POC) in the ocean represents an assemblage of living particles (bacteria, phyto- and zooplankton) and non-living material (detritus, fecal pellets, aggregates) that contribute to the biological pump (transfer of carbon from the upper layers to the deeper ocean by biological processes). POC sinks from surface waters to deeper layers, removing carbon from the surface layer and supplying food to mesopelagic and benthic organisms. Despite its importance, POC concentrations and its variability over basin or global scales have been poorly assessed. All components of POC are optically active and thus modify the light path through their absorption and scattering properties. Several attempts have been made to characterize POC in the ocean using optical measurements such as the beam attenuation coefficient at 660 nm (Bishop, 1999; Claustre *et al.*, 1999; Mishonov *et al.*, 2003), and the scattering or backscattering coefficient (Balch *et al.*, 1999; Twardowski *et al.*, 2001; Boss *et al.*, 2004; Loisel *et al.*, 2007; Stramski *et al.*, 2007). Relationships linking POC and chlorophyll have also been proposed (Legendre and Michaud 1999; Sathyendranath *et al.*, 2008) for application in remote sensing. Interestingly, these bio-optical variables are potentially retrievable from satellite OCR (Stramski *et al.*, 1999; Loisel and Stramski, 2000; Lee *et al.*, 2002; Roesler and Boss, 2003; IOCCG, 2006; Doron *et al.*, 2007).

POC concentrations and its seasonal variations have been estimated at regional (Stramski *et al.*, 1999; Loisel *et al.*, 2001) and global (Loisel *et al.*, 2002) scales using ocean-colour sensors (Fig. 5.1), based on the relationships linking particle concentrations to backscattering, on the one hand, and remote sensing reflectance (R_{rs}) and backscattering, on the other hand. In all cases, sensor wavebands around 555 nm (*e.g.* SeaWiFS) appear to be most suitable in retrieving the particle backscattering coefficient, where the effect of phytoplankton absorption on the remote-sensing reflectance is often small. Recently, algorithms based on ratios of $R_{rs}(443)/R_{rs}(555)$ and $R_{rs}(490)/R_{rs}(555)$ have been proposed for a standard processing of ocean-colour satellite data to map POC distribution at the ocean surface (Stramski *et al.*, 2007).

So far, remote sensing of POC relies very much on a few contemporary studies, but it is gaining interest and momentum from these promising results. Theoretically, backscattering is related to the total suspended particulate matter (SPM) of which POC is just a component. Global and basin-scale mapping of POC (Fig. 5.1) from satellite-derived optical properties requires the assumption that POC is dominant within SPM, or that the POC contribution to SPM is known over different conditions. Field measurements tend, however, to demonstrate substantial variability of the POC: SPM ratio even in the open ocean (Stramski *et al.*, 2007), which would impact the relationships between POC and bulk optical properties. More field investigations

with concurrent measurements of POC and optical variables in different marine environments and improvements in our understanding of the relationships between SPM and POC will certainly improve the performance of the algorithms for retrieval of POC using satellite data.
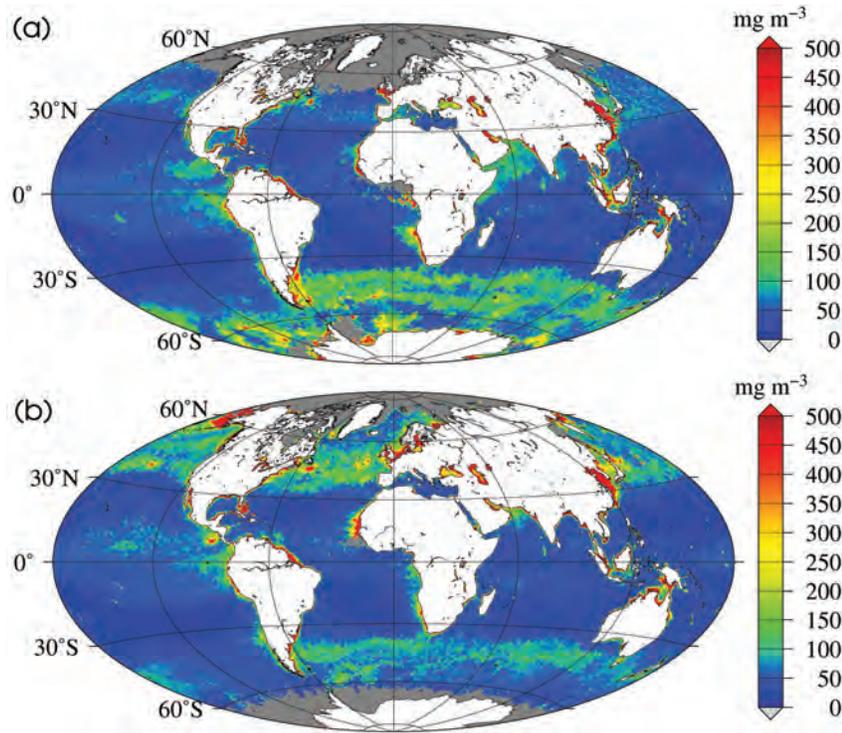
Figure 5.1 Maps of global POC in (a) January 2001 and (b) April 2001. (Image provided by David Dessailly, Université du Littoral Côte d'Opale, France).

5.1.2 Phytoplankton Carbon

Since the advent of OCR three decades ago, the global distribution of phytoplankton biomass, expressed as the surface concentration of chlorophyll-a, has been analysed extensively at time scales of a few days to weeks, to multi-annual time series (Yoder, 2000; Gregg *et al.*, 2005). In marine biogeochemistry studies, the biomass of any population is often required in carbon units. Facing difficulties in directly measuring phytoplankton carbon in the field, biogeochemical studies rely on a carbon:chlorophyll ratio to transform chlorophyll concentration to phytoplankton carbon biomass. Although known to vary over a wide range (10 to >200 g C:g Chl; Taylor *et al.*, 1997; Lefèvre *et al.*, 2003; Marañón, 2005), the C:Chl ratio is often treated as a constant, with typical values ranging from 30 to 60 (Eppley, 1972; Fasham *et al.*, 1990). This can result in unrealistic estimates of primary production rates and the carbon stock of plant biomass in the marine environment and its contribution to the

global carbon budget (Faugeras *et al.*, 2004). A more accurate assessment of this factor could also lead to improved parameterisation of photosynthetic rates and insights into physiological processes (*e.g.* growth rate).

The variability of the C:Chl ratio has been investigated primarily in laboratory settings (Banse, 1977; Laws and Bannister, 1980; Geider, 1987; Geider *et al.*, 1997). It has been shown, experimentally, to be regulated by light level, temperature, and nutrient availability (Geider, 1987; Cloern *et al.*, 1995). The C:Chl ratio is also tightly linked to phytoplankton growth (Landry and Hassett, 1982; Geider, 1987), and has been used in the calculation of the light-saturated photosynthetic rate (Geider *et al.*, 1998) and in the interpretation of widely used temperature-growth relationships (Eppley, 1972). Under nutrient-replete conditions and at balanced growth, C:Chl increases linearly with increasing irradiance levels (at constant temperature), and decreases exponentially with increasing temperature (Geider, 1987). Nutrient limitation also impacts growth rate which translates into changes in cellular C:Chl (Sakshaug *et al.*, 1989).

Accordingly, empirical relationships have been established for C:Chl ratio as a function of temperature, daily irradiance, and nutrient-limited growth rate (Cloern *et al.*, 1995). Their model includes both light-limited and nutrient-limited conditions. Using this model and input variables from ocean-colour radiometry and other satellite-derived data sets or atlases, it is possible to generate global fields of C:Chl (Moore and Dowell, 2004). From another angle, Behrenfeld *et al.* (2005) provided an initial attempt to map phytoplankton biomass in carbon units, and the C:Chl ratio of phytoplankton on the global scale using the particulate backscattering coefficient at 440 nm retrieved from OCR. The assumptions associated with this study are more speculative than in the algorithms for retrieval of POC from space, and must be carefully considered for any application of this method. More recently, Sathyendranath *et al.*, (2008) have used a large number of observations on POC and chlorophyll, along with simple ecological considerations, to propose a method of retrieving phytoplankton carbon from ocean colour. These recent investigations are encouraging, and the knowledge of the phytoplankton C:Chl ratio from satellite data may lead to improved calculations of the flow of carbon and energy through the marine system and may also provide additional insight into the physiological status of phytoplankton.

5.1.3 Particulate Inorganic Carbon (Calcium Carbonate)

Calcification is an integral component of the ocean carbon cycle and calcium carbonate, whether in the form of calcite or aragonite, represents an important constituent of the total marine particulate inorganic carbon (PIC). Calcification, as described by the reaction:

$$Ca^{2+} + 2HCO_3^- \Leftrightarrow CaCO_3 + H_2O + CO_2, \tag{5.1}$$
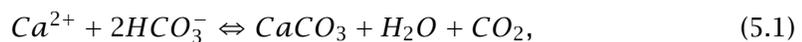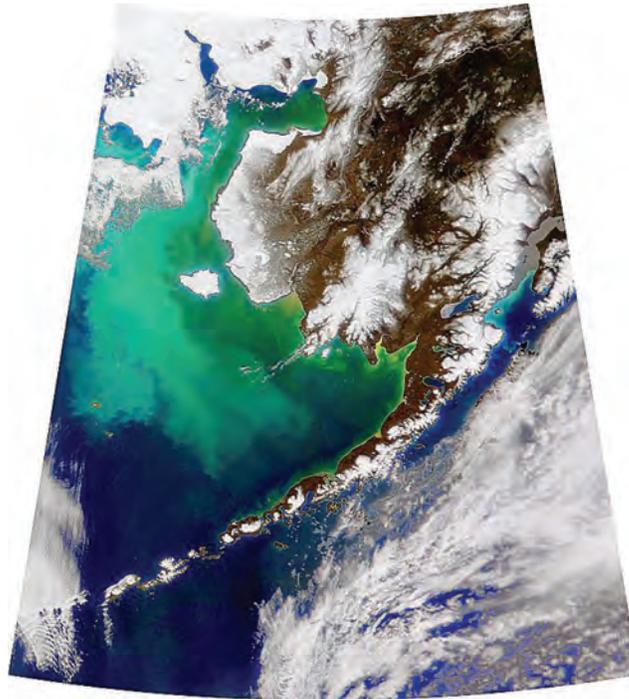
Figure 5.2 Turquoise shades indicate the spatial extent of a coccolithophore bloom in the Bering Sea captured by the SeaWiFS sensor on 25 April 1998 (Credit: NASA/GSFC SeaWiFS Project and GeoEye).

leads to a disequilibrium in the ocean carbonate system that can drive an outgassing of CO_2 to the atmosphere. Specifically, calcification depletes surface CO_3^{2-}, reduces alkalinity, and tends to increase pCO$_2$. The effect of $CaCO_3$ formation on fluxes of pCO$_2$ (surface water and air-sea) is therefore counter to the effect of organic carbon production through photosynthesis. On the other hand, the biogenic production and subsequent sedimentation of calcite promotes a long-term carbon export into the deep ocean, acting as 'ballast' for more efficient sinking of associated organic matter as well as increasing overall particle density (Armstrong, 2002).

The annual calcite production in the global ocean varies from 0.8 to 1.4 Gt C yr^{-1} (Feely *et al*., 2004), most of it being derived from calcification by planktonic organisms. Coccolithophorids are small phytoplankton that synthesize small plates or 'liths' (coccoliths) of pure calcium carbonate covering the external surface of the cell. The shape and style of the liths identify particular species. These organisms create massive blooms in the ocean, and during the later stages of the blooms, the cells shed their liths. Calcium carbonate, being white, strongly reflects light, lending a turquoise-blue-white colour to the ocean. The blooms are easily observed in the pseudo-true-colour images from satellites (Fig. 5.2), meaning that their distribution, both temporally and spatially, can be monitored using ocean-colour radiometry (Brown and Yoder, 1994; Brown, 1995). It has been determined that *Emiliania huxleyi*,

a well-known and abundant coccolithophore, has increased its geographic range, blooming with greater frequency in northern waters, such as the Bering Sea (Iida *et al.*, 2002) and the Barents Sea (Smyth *et al.*, 2004a).

More importantly, specific algorithms have been elaborated to retrieve quantitatively calcite concentration and PIC standing stocks at regional and global scales (Fig. 5.3) from ocean-colour data (Gordon *et al.*, 2001; Balch *et al.*, 2005). An averaged, global total of euphotic PIC, derived from MODIS data, has been estimated at 18.8 Mt, with systematically higher concentrations at latitudes greater than 30° (Balch *et al.*, 2005). It is possible that these values may be contaminated by other suspended mineral compounds, *e.g.* opal from diatom populations (Broerse *et al.*, 2003). More verification with field measurements of PIC concentrations, PIC turnover time, and the opal:PIC ratio are therefore necessary to optimize the use of ocean-colour radiometry in models of the marine carbonate cycle.
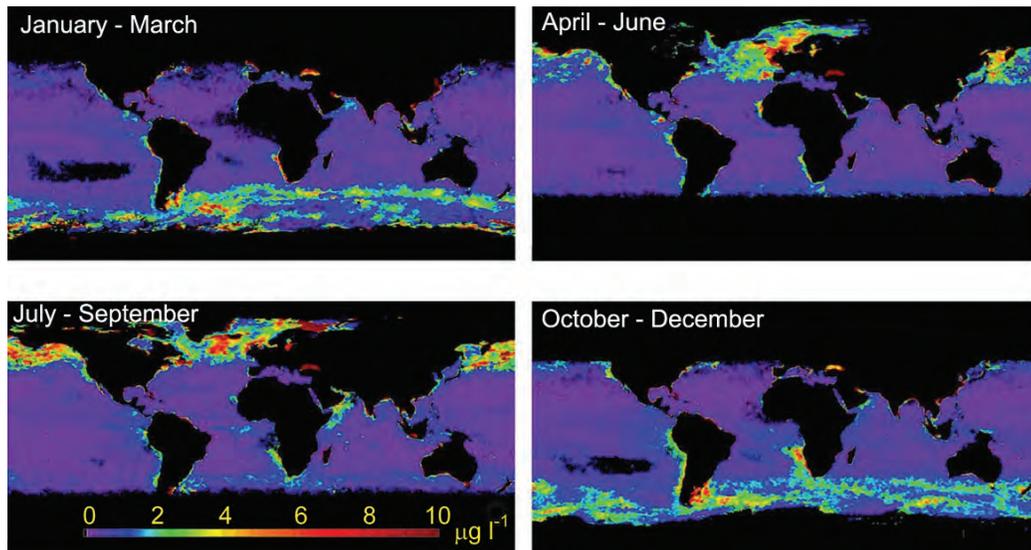
Figure 5.3 Global composite images of seasonal suspended particulate inorganic carbon (PIC) concentration in 2002, as derived from MODIS/Terra data using a two-band calcite algorithm (adapted from Balch *et al.*, 2005).

With increasing concern about marine acidification, it is not clear if coccolithophores and other carbonate-dependant organisms can survive or adapt to a high CO_2 world. Substitution by other species will modify the overall ecosystem, as well as the carbon budget in unknown ways. Long time-series of coccolithophore blooms and PIC concentrations will be essential in studies on the impact of ocean acidification on the marine ecosystem.

5.1.4 Coloured Dissolved Organic Matter

One of the largest reservoirs of carbon on Earth is the organic matter dissolved in the ocean (see review by Hansell and Carlson, 2002). The distribution, sources and sinks of dissolved organic matter (DOM) in the ocean remains insufficiently known. Obstacles to progress include the fact that DOM comprises a complex array of molecules that are difficult to analyze and identify chemically. In practice, DOM is defined operationally as the fraction of suspended material that goes through a sub-micrometre filter (usually 0.2 μm). A fraction of DOM strongly absorbs light in the UV-blue region of the spectrum, such that its presence turns the water yellow. This is why it was originally called 'gelbstoff' or 'yellow substance' by oceanographers. The term in common usage today for this component of DOM is chromophoric (or coloured) dissolved organic matter, or CDOM. Its abundance in sea water can be assessed through its optical properties, particularly the absorption coefficient at blue wavelengths (Bricaud *et al.*, 1981; Blough and Del Vecchio, 2002, and references therein; Twardowski *et al.*, 2004) which can be retrieved from space by ocean-colour radiometry (Carder *et al.*, 1999; Lee *et al.*, 2002; Maritorena *et al.*, 2002; Fichot *et al.*, 2008). However, the similarity between the absorption spectra of CDOM and detrital matter, which decrease exponentially with wavelength, makes it impossible to distinguish between the two using remote sensing. The retrieved absorption coefficient is thus representative of some 'coloured detrital material' (CDM) combining CDOM and detritus (IOCCG, 2006). Assuming a negligible contribution of detritus in the open ocean, the global distribution of CDOM has been derived from ocean-colour radiometry (Siegel *et al.*, 2002; 2005). Obviously, the interpretation of these data becomes more difficult in coastal waters where the contribution of organic detrital matter could be significant. Most remote sensing algorithms treat the absorption coefficient of CDM as a measure of its concentration. To convert absorption into carbon units remains problematic. It is also not easy to establish the relationship between the total detrital material and the coloured component.

In general, CDOM concentrations are higher in coastal areas compared with the open ocean, pointing towards river and coastal runoff as being a major source of CDOM in these areas. The source of CDOM in open ocean waters needs an improved characterization (Nelson and Siegel, 2002), although its occurrence following bloom peaks suggests a local origin from decaying phytoplankton cells, zooplankton grazing, and microbial activity (Hu *et al.*, 2006). In any case, CDM is an important element in determining the light field in marine waters, which is required in the analysis of photobiological and photochemical processes. CDOM has an important role in the production of dissolved inorganic carbon (see section 5.2.2). Moreover, the variability in CDM concentration affects the penetration of harmful UV radiation within the surface layer with consequences for the surrounding ecosystem and biogeochemical cycles. Finally, CDM can also be used as a tracer of water masses, particularly freshwater inputs. CDM and salinity have often been found to vary inversely as river

water mixes with ocean water; thus, CDM can help to understand the interactions between rivers and the coastal ocean (Ferrari and Dowell, 1998; Chen *et al.*, 2007a). Systematic observations of CDM over regional and basin scales using ocean-colour radiometry are essential to gain a better understanding of the biogeochemical cycles and to reduce uncertainties in the marine carbon cycle.

5.2 Carbon Fluxes

5.2.1 Calculating Phytoplankton Productivity from Ocean Colour

Ocean colour from satellite sensors offers the possibility of providing global estimates of the most important transformation occurring in the ocean carbon cycle: the conversion of inorganic carbon to organic carbon through photosynthesis, termed primary production. This marine component of carbon fixation represents approximately half the global total, making it a critical element of the Earth's carbon budget and biogeochemical cycles (Longhurst *et al.* 1995; Antoine *et al.*, 1996; Falkowski *et al.*, 1998). Moreover, synoptic estimates of algal biomass and primary production, as descriptors of the first trophic level, provide insights into the dynamics of marine ecosystems. Access to estimates of primary productivity at spatial scales of about one kilometre, and at time scales of about one week (average time required to obtain clear skies for satellite observations) has thus become a considerable asset in ocean sciences (*e.g.*, Platt and Sathyendranath, 1988).

Primary productivity, P, at any particular location, depth (z), and time (t) in the ocean is determined by chlorophyll-a concentration $B(z,t)$ and a function ($f(E)$) which describes the photosynthetic response of phytoplankton to the available irradiance $E(z,t)$, as follows:

$$P(z,t) = B(z,t) \times f(E;z,t). \tag{5.2}$$

In Equation 5.2, chlorophyll-a concentration is used as an index of phytoplankton biomass, since it is the main data product derived from ocean-colour remote sensing, and is also at the heart of the photosynthetic process. Another possibility is to use phytoplankton carbon, but these methods require further research and validation as mentioned previously. The irradiance, E, refers to that part of the electro-magnetic spectrum between 400 and 700 nm, *i.e.*, the photosynthetically available radiation (PAR), expressed as a spectrally-resolved or integrated quantity. Surface PAR can be derived directly from satellite ocean-colour radiometry (Frouin *et al.*, 2003), or using various spectral approaches based on remote sensing (Frouin and Pinker, 1995; Bouvet *et al.*, 2002). Other relevant environmental variables such as SST (which appear in some implementations of the function f) are also available from remote sensing. Thus, in principle, we can retrieve the major elements required to calculate primary productivity from satellite data.

In reality, satellite ocean-colour radiometry is only sensitive to constituents in the ocean upper layer, whereas biological and chemical processes such as photosynthesis extend to deeper zones (*e.g.* 1% or 0.1% surface light level). The application of Equation 5.2 therefore requires additional knowledge on the vertical structure of the phytoplankton biomass (Platt *et al.*, 1988; Morel and Berthon, 1989), and the attenuation of irradiance with depth (Sathyendranath and Platt, 1989). Integration of Equation 5.2 over depth and day-length provides an aerial daily rate of primary production. Primary-production models may vary from each other depending on how E is expressed (spectral or non-spectral), on how vertical structure of phytoplankton is specified and on how the function $f(E; z, t)$ in Equation 5.2 is specified (Platt *et al.*, 1977; Platt and Sathyendranath, 1993; Sathyendranath and Platt 1993; Behrenfeld and Falkowski, 1997a; Sathyendranath and Platt 2007). Spectral models account for the wavelength-dependent characteristics of the propagation and absorption of light, whereas non-spectral models use total PAR. Time-integrated models express the daily integrated productivity from daily averaged inputs. Depth-integrated versions of models are also in use. Figure 5.4 shows an example of global primary production calculated using a wavelength and depth-resolved primary production model.
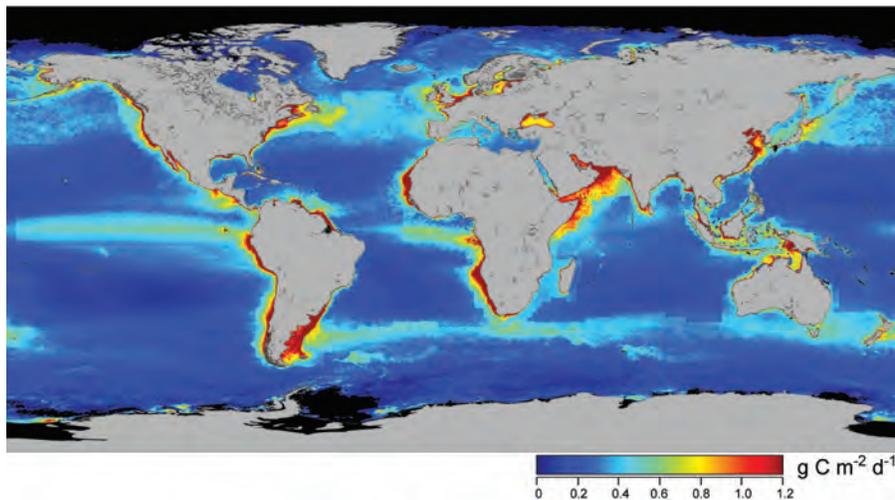
Figure 5.4 Global primary production computed using MODIS-Aqua data from July 2002 to June 2005 with a wavelength, depth-resolved, primary production model down to the 0.1% light-level. (Credit: Frédéric Mélin, Joint Research Centre, EC, unpublished data. MODIS data provided by NASA/GSFC).

Regardless of the complexity of the model formulation, a critical aspect of estimating productivity is specifying the photosynthetic parameters that are contained in the term f in Equation 5.2. In particular, we need to know the rate of photosynthesis per unit B, a property sometimes known as the photosynthetic index, P^B. The relationship between P^B and E, the photosynthesis-irradiance ($P - E$) curve, is well known empirically and can be described using two parameters: the

slope of the curve at the origin, and the maximum photosynthetic rate at saturating light levels. As for the shape of the vertical biomass profile, this information is not accessible directly from space, although P^B at saturating light levels has been shown to vary with temperature (Eppley 1972; Bouman *et al.* 2005), a relationship at the heart of some models of productivity based on satellite data (*e.g.*, Antoine *et al.*, 1996; Behrenfeld and Falkowski, 1997b). Another approach has been to identify biogeochemical provinces for which a comprehensive data set of field measurements enables the definition of representative photosynthetic parameters (Longhurst *et al.*, 1995; Sathyendranath *et al.*, 1995). This method acknowledges the existence of oceanographic regions characterized by distinct physical forcing and variability, as well as the primary importance of the physical forcing in regulating algal processes (Longhurst, 2006). Both implementation methods can be combined in various ways. In any case, satisfactory representation of algal physiology at the global scale by simple relationships applicable to remote sensing has so far proved elusive, though regional approaches are promising (Bouman *et al.*, 2005).

Several years ago, NASA established the Primary Productivity Working Group (PPWG) to investigate the various issues surrounding the calculation of productivity from ocean-colour radiometry. Campbell *et al.* (2002) reported the first results of a comparison between different models using a database of *in situ* primary production. The model results were generally within a factor of two of the observations. A similar exercise conducted more recently by the PPWG (Carr *et al.*, 2006) showed that most models yielded an annual global primary production estimate in the range 35-60 Gt C y^{-1}. Breaking down the results by season or region can lead to larger differences between the models. In the description of the approaches adopted for deriving primary productivity from ocean-colour data, some of the assumptions, limitations and difficulties have already been highlighted (Platt *et al.*, 1988; Platt *et al.*, 1995). The discrepancies between satellite-derived products and field observations may be grouped into the following sources of uncertainties: (1) the input fields from ocean colour, mainly the surface concentration of Chl-a or the phytoplankton absorption coefficient, and the optical properties of the other constituents, (2) the explicit or implicit definition of a vertical structure for the algal biomass and the inherent optical properties, (3) the propagation of the light field, and (4) the rate at which the photons absorbed by the phytoplankton are used for photosynthesis.

The immense value of primary production estimates based on ocean-colour radiometry and other remote-sensing data products is unquestionable. The limitations noted above call our attention to the fundamental aspects of the functioning of marine ecosystems and the challenges in their faithful representation in models. Primary production models are continuously improving, owing to advanced characteristics of on-going ocean-colour sensors, and significant progress in bio-optical algorithms. A third exercise of the PPWG (Friedrichs *et al.*, 2008) demonstrated a reduction by 58% of the differences between ocean-colour derived primary production and *in situ* data when compared with the first series of round-

robin experiments by the PPWG to evaluate and compare primary productivity algorithms. Another conclusion from this exercise is that algorithm performance is not always related to model complexity (Campbell *et al.*, 2002; Friedrichs *et al.*, 2008). This is not surprising considering the comprehensive knowledge on physiology and optics required by all algorithms. However, the continuing development of more elaborate, wavelength-resolved and depth-resolved models have the potential to create new parameterizations and to provide better quality estimates as new insights of the various processes involved are ascertained. At present, the greatest uncertainty in production estimates arises from uncertainty in the estimate of Chl-a from satellite data (Platt *et al.* 1995). As improved ocean-colour sensors lead to better estimates of Chl-a and other bio-optical properties, one anticipates immediate improvements in primary production estimates as well.

5.2.2   Photochemistry in the Upper Ocean

Both biogeochemistry of marine dissolved organic matter (DOM) and photochemistry have shown impressive developments in recent years (Hansell and Carlson, 2002). Deciphering the complex interactions of DOM with microorganisms and the radiation regime is important in understanding the oceanic system and its relation with climate, and the fate of terrestrial input of DOM into the oceans. As stated previously, the absorption of coloured dissolved organic matter (CDOM) increases exponentially towards the blue and ultraviolet wavelengths, a spectral domain that is very energetic for photochemical reactions. The CDOM absorption of blue and UV light modifies chemical species to more reactive forms (free radicals, other reactive species), that will then take part in biochemical processes. The availability of CDOM absorption maps from ocean colour (see section 5.1.4) thus opens new perspectives for quantifying a complex array of biogeochemical rates. Some parallels can be made between the framework of primary production modelling and photochemistry through the definition of absorbed photochemically usable radiation, and quantum yield or action spectra of photochemically-driven rates.

The direct production (through photo-oxidation) of carbon monoxide (CO) and dissolved inorganic carbon (DIC) from terrestrial organic matter may be a major term in the cycle of organic carbon (Miller and Zepp, 1995). The photochemical degradation of DOM may also lead to eventual remineralisation of nitrogen-rich, biologically available compounds (Bushaw *et al.*, 1996). A major decomposition process of the terrestrial inputs of DOM is the transformation into lower-molecular-weight, more biologically-labile, organic substances. Various studies have shown how this pathway modifies the availability of substrates for the microbial loop (Mopper and Kieber, 2002). Photobleaching, the loss of colour and fluorescence properties due to the degradation of chromophores induced by radiation, is a 'visible' manifestation of these phenomena. This process has been well documented, particularly for coastal waters. Far from land, the dynamics of CDOM is heavily conditioned by bleaching,

especially in the top layer of the water column (Nelson *et al.*, 1998). Quantum yields have been documented for photochemical production of DIC (Johannessen and Miller, 2001), CO (Zafiriou *et al.*, 2003), hydrogen peroxide (H_2O_2, Yocis *et al.*, 2000), biologically labile photoproducts (Miller *et al.*, 2002) and CDOM photobleaching (Del Vecchio and Blough, 2002). Global estimates of CO photoproduction using SeaWiFS data have been presented by Miller and Fichot (2004). Organic compounds and photochemical reactions are also part of the marine cycle of trace metals (*e.g.*, Barbeau *et al.* 2001), important for phytoplankton populations.

Photochemical processes are also important drivers of the oceanic sulfur cycle and DOM is an element of many of the related transformations. For instance in the upper ocean, DOM is involved in the production (by photolysis) of carbonyl sulfide, an important gas for stratospheric processes (Weiss *et al.*, 1995). A similar involvement of DOM also appears for the photolysis of dimethyl sulfide (DMS, *e.g.*, Toole *et al.*, 2003), a cycle that has received particular attention since the description of possible climate feedbacks (Charlson *et al.*, 1987). Also relevant to ocean-colour radiometry is the use of Chl-a maps in association with physical variables to derive surface concentrations of DMS at the global scale through empirical relationships (Simó and Dachs, 2002).

That short-wavelength radiation is efficient for photosensitizing dissolved organic compounds, and thus enhancing the overall reactivity of the medium, opens the door to all sorts of processes and it is clear that many of those mentioned above interact. For instance, photodegradation of DOM and microbial activity are intertwined. Photobleaching of CDOM deepens the euphotic zone, and results in increased PAR in the water, as well as increased potentially damaging, UV radiation. From the point of view of carbon fluxes, photosynthesis is enhanced by a greater availability of light and of macro- and micro-nutrients, whereas photochemical production of DIC reinforces the source terms of CO_2. Therefore, these various processes should be analyzed in an integrated way. The extrapolation of local measurements to regional and global scales will certainly require a better understanding of the complex photochemical pathways. Ocean colour has an emerging role to play, by providing information on the distribution of optically significant constituents, thus contributing to a better definition of the light field in the ocean, but also more specifically to an assessment of the CDOM dynamics.

5.3   Ocean Colour and Nitrogen Cycling

Total primary production in the ocean is partitioned into recycled production, which is dependent on recycled nutrients in the upper layer, usually ammonia, and new production, which is fuelled by allochtonous nitrogen supply (Dugdale and Goering, 1967). The paradigm in biological oceanography is that the vertical upwelling of nitrate from the deep drives new production in the nutrient-limited regions of the

surface ocean (Lewis *et al.*, 1986). This process is well documented, particularly in the equatorial ocean where surface chlorophyll increases with shoaling of the thermocline, bringing more nutrients to the surface (Chavez *et al.*, 1998; Siegel *et al.*, 1999; Ryan *et al.*, 2002; Wilson, 2003). Nitrate is assumed to be the limiting nutrient on short time scales (Lewis *et al.*, 1986), outside of high-nutrient, low-chlorophyll (HNLC) regions, where iron becomes a factor. Since transport of nitrogen from the deep, cool waters to the surface is typically accompanied by a decrease in surface temperature, it has been possible to use sea-surface temperature data to track the supply of new nitrogen into the surface waters, and to use a combination of ocean-colour and thermal infra-red remote sensing to measure new production in the ocean (Dugdale *et al.*, 1989; Sathyendranath *et al.*, 1991; Goes *et al.*, 2000). Campbell and Aarup (1992) used information on the nitrate concentrations in oceanic waters prior to the spring bloom, and mixed-layer depths at the time of the collapse of the bloom, to derive consumption of nitrate by new production. In this study, CZCS data were used to estimate the time of collapse of the blooms. Since only new nitrogen can be responsible for phytoplankton growth in nitrogen- limited areas, primary production integrated over the spring bloom can be used to infer a lower limit on new production over that time interval (Platt and Sathyendranath, 2008).
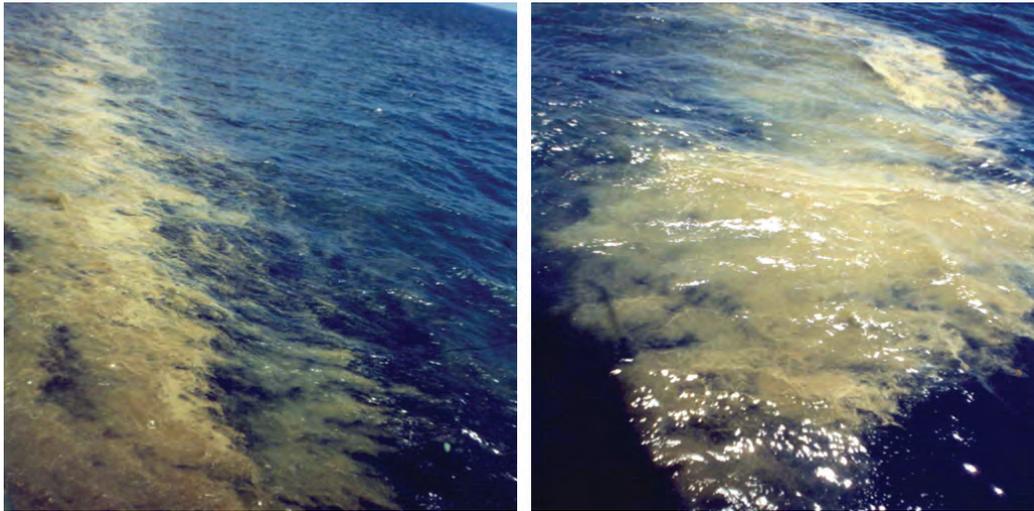
Figure 5.5 Photograph of a *Trichodesmium erythraeum* bloom in the North East Arabian Sea (off the Gulf of Khambhat), taken from the research vessel "ORV Sagar Kanya", April 2000. (Credit: Image provided by Shailesh Nayak, Space Applications Centre, ISRO, India).

Nitrogen fixation is another mechanism responsible for new production in the ocean. Diazotrophs, organisms that fix nitrogen gas, can thrive in nitrate-depleted waters, and might even shift the ocean from nitrogen to phosphorus limitation (Karl *et al.*, 1997; Cullen, 1999; Tyrrell, 1999). The most well-known oceanic diazotroph is *Trichodesmium* (Fig. 5.5) but nitrogen fixation occurs in a number of organisms,

including unicellular cyanobacteria (Zehr *et al.*, 2001; Montoya *et al.*, 2004), and the endosymbiotic *Richelia* that is found within several species of diatoms (Venrick, 1974; Villareal, 1992).

Recent studies have shown that nitrogen gas assimilated by nitrogen fixation could form a significant proportion of the total oceanic new production (the fraction of total primary production fuelled by nitrate) (Michaels *et al.*, 1996; Karl *et al.*, 1997; Zehr *et al.*, 2001). This source of new production could have an important impact on the overall global carbon cycle since, unlike nitrate brought to the surface from upwelling, N_2-fixation is not coupled to fluxes of dissolved carbon from the deep ocean, and can potentially drive a net uptake of atmospheric CO_2 and export of carbon (Hood *et al.*, 2000). Another biologically mediated process that increases surface nitrate is the vertical migration of *Rhizosolenia* diatom mats. These mats use carbohydrate ballasting to migrate vertically between the nutricline, where they uptake nitrate, and the surface, where they photosynthesize (Villareal and Carpenter, 1989; Villareal *et al.*, 1999). Similar to nitrogen fixation, this process results in new production without a flux of deep carbon to the surface, and so can result in more efficient removal of carbon from surface waters (Richardson *et al.*, 1998).

However, it remains difficult to quantify these processes because ship-based observations can provide only limited coverage over large spatial scales. The high spatial and temporal coverage of satellite chlorophyll data supports improved assessments of these processes at regional and global scales. Two different methodologies have been used to identify nitrogen fixation from ocean-colour data. Genera-specific optical properties have been used to develop an algorithm to identify *Trichodesmium* from analysis of satellite measured water-leaving radiances. Initial algorithms only worked on significantly dense blooms, with chlorophyll values >1 mg m^{-3} (Subramaniam *et al.*, 1999, Subramaniam *et al.*, 2002), and therefore could not be applied globally, as chlorophyll levels do not approach this threshold in the oligotrophic ocean, where nitrate-deplete waters will favour nitrogen fixation. Recently, a new algorithm has been developed that appears promising for detecting *Trichodesmium* globally (Westberry *et al.*, 2005). Such algorithms, however, are genera specific, and will not identify production stimulated by other forms of nitrogen fixation, or by migrating mats.

An alternative approach to identifying nitrogen fixation from satellite data takes into account the oceanic conditions conducive to nitrogen fixation (and mat migration) that are very different from conditions leading to upwelling-derived production. Populations of *Trichodesmium* and *Rhizosolenia* mats are generally found in stable, stratified waters, with low winds (Capone *et al.*, 1997; Villareal and Carpenter, 1989; Subramaniam *et al.*, 2002). *Trichodesmium* is usually not present in waters colder than 20°C, and rarely blooms below 25°C (Carpenter and Capone, 1992; Capone *et al.*, 1997; Subramaniam *et al.*, 2002). Culture studies indicate an ideal temperature range of 24 to 30°C for *Trichodesmium* (Breitbarth *et al.*, 2007).

Chlorophyll blooms in the southwest Pacific, observed by both CZCS and SeaWiFS,
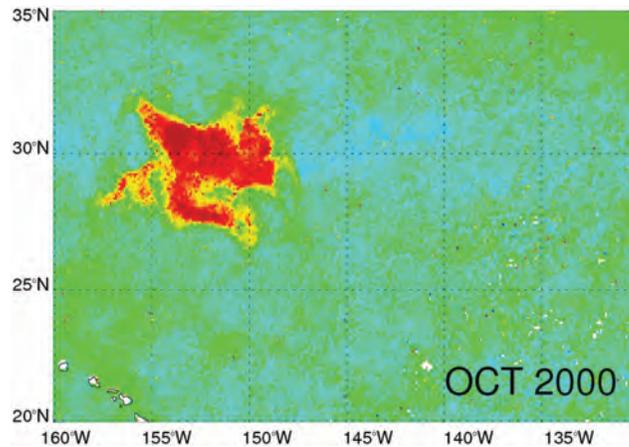
Figure 5.6 Monthly SeaWiFS composite of chlorophyll for October 2000, showing a large chlorophyll bloom northeast of Hawaii in the oligotrophic Pacific. The bloom developed at the end of August and lasted into December. It has been speculated that the bloom was driven by nitrogen fixation or vertically migrating diatom mats (adapted from Wilson, 2003).

have been identified as *Trichodesmium*, based on previous reports of *Trichodesmium* in the area, especially in summer when the surface water is warm and stratified (Dupouy*et al.*, 1988; Dupouy *et al.*, 2000). Chlorophyll blooms which develop in late summer in the oligotrophic Pacific, northeast of Hawaii, have been observed by CZCS, OCTS and SeaWiFS, as seen in Figure 5.6 (Wilson, 2003; Wilson *et al.* 2008). The cause of these blooms has been attributed to either nitrogen fixation (although not necessarily *Trichodesmium*) or vertically migrating *Rhizosolenia* diatom mats, based on concurrent SSH and SST data, and previous biological observations in the area (Wilson, 2003; Wilson *et al.*, 2008). Since diatom blooms are important mechanisms for sequestering carbon into the deep ocean (Goldman, 1988), the carbon export from these blooms could be significant given their size and duration: they can become as large as the state of California and can last up to 5 months. A similar analysis of satellite data (Coles *et al.*, 2004) has identified an annual summer chlorophyll bloom in the western tropical Atlantic as attributable to nitrogen fixation. Coles *et al.* (2004) showed further that the seasonal cycle of satellite chlorophyll for this area could only be reproduced in a biological model that explicitly simulated nitrogen fixation.

The approach of using multiple satellite measurements to identify production under conditions favouring diazotrophy (stratified, low nutrient, high light, sufficient iron) can provide a means for estimating patterns of nitrogen fixation on global scales. If diazotrophs have the potential to shift the ocean from nitrogen to phosphorus limitation (Karl *et al.* , 1997) and alter global climate through changes in the biological pump (Michaels *et al.*, 2001; Sañudo-Wilhelmy *et al.*, 2001), then improving our understanding of their spatial and temporal patterns and production is essential.

5.4   Future Directions

Optical remote sensing aims at quantifying optical properties in the surface layer of the oceans. Algorithms have been steadily increasing and diversifying in the remote-sensing era. Nevertheless, there is a demand for even better descriptions of marine absorption and scattering properties, especially those associated with phytoplankton stocks or CDOM absorption. This is particularly true in coastal waters, which are also areas of intense biogeochemical cycling. In turn, better optical descriptions may lead to more accurate derived information on dissolved and particulate organic carbon or particle size spectra that can be used in studies of biogeochemistry. Also, the detection of phytoplankton functional groups has been proposed by Sathyendranath *et al.* (2004), Alvain *et al.* (2005) and Aiken *et al.* (2008) among others, and such techniques would favour a better representation of algal physiology in satellite-based models of primary production.

Moreover, an improved retrieval of optical properties will improve the modelling of radiative transfer in the water column. The importance of an accurate, spectral, three-dimensional depiction of the light field in the ocean cannot be understated for studies of biogeochemical cycles, because of its effects on physics, biology and chemistry. Clearly, the potential of ocean colour in the field of biogeochemistry will be enhanced if links between other remote-sensing products and dynamic models are improved. Besides accurate bio-optical measurements, applications of ocean colour to biogeochemical cycles will benefit from data sets gathered by field measurements. For example, the progress of Fast Repetition Rate Fluorometer (FRRF)-based techniques to determine *in situ* primary productivity or photosynthetic parameters (*e.g.* Smyth *et al.*, 2004b) will help primary production modelling, while autonomous sensors (Bishop *et al.*, 2002) will complement studies of particles and carbon dynamics in the ocean. Finally, understanding biogeochemical cycles relies on long-term data series, and the existence of an ocean-colour record that now exceeds 10 years will give more weight to studies addressing time scales beyond the seasonal cycle.

Ocean-Colour Radiometry and Fisheries

Cara Wilson, Jesus Morales, Shailesh Nayak, Ichio Asanuma and Gene Feldman

The food requirements of an expanding human population have increased the pressure on fisheries resources. In the last half century the world fish harvest has increased more than four-fold from 20 million tonnes in 1950 to 95 million tons in 2004 (FAO Fisheries Department, 2007). However, the number of overexploited or depleted stocks has increased, and the capture fishery production has, in fact, declined or remained static since 2000, reflecting over-harvest in many regions (Hilborn *et al.*, 2003). Better fisheries management, through a deeper understanding of marine ecology, is needed to maximize the utility of living marine resources now and into the future. A major challenge for fisheries scientists is distinguishing fluctuations caused by human activities (such as overexploitation, habitat alteration and pollution) from natural environmental variability. Over 100 years ago with the formation of the International Council for the Exploration of the Seas (ICES), the fundamental question of what drives the interannual variability of fish stocks was first posed, and still has not been adequately resolved (Kendall and Duker, 1998; Bakun and Broad, 2003; Anderson *et al.*, 2008).

In the broadest sense, fisheries science encompasses not just commercial fish stocks, but all living marine resources, including efforts to help recover threatened and endangered species. Satellite data can be used to characterize the habitat and ecosystem properties that influence marine resources at large temporal and spatial scales, and high temporal and spatial resolution. There are two primary ways that ocean-colour data are used for fisheries management. One is to monitor the environment, with a view to better understand ecosystem processes or stock biology. The other is to locate populations of fish, with a view to increase fishing efficiency or enhance conservation by mitigating human interactions. Additionally, ocean-colour data are used to monitor a number of issues that impact fisheries, such as harmful algal blooms and coastal pollution, which are discussed in further detail elsewhere in this volume.

6.1 The Oceanic Food Web

Satellite chlorophyll provides an index of phytoplankton biomass, which is the base of the oceanic food web, as depicted in simplified form in Figure 6.1. The relationship between satellite chlorophyll data and a specific fish stock depends upon the number of linkages between phytoplankton and the higher trophic level. For some species, such as anchovies and sardines, which eat phytoplankton at some points in their life cycle, the linkage can be direct (Ware and Thomson, 2005), whereas for other species there are many trophic levels in between, and the relationship can be quite non-linear. There can also be spatial disconnects between satellite measurements of the ocean surface and demersal and deep-water species. Nonetheless, chlorophyll is the only
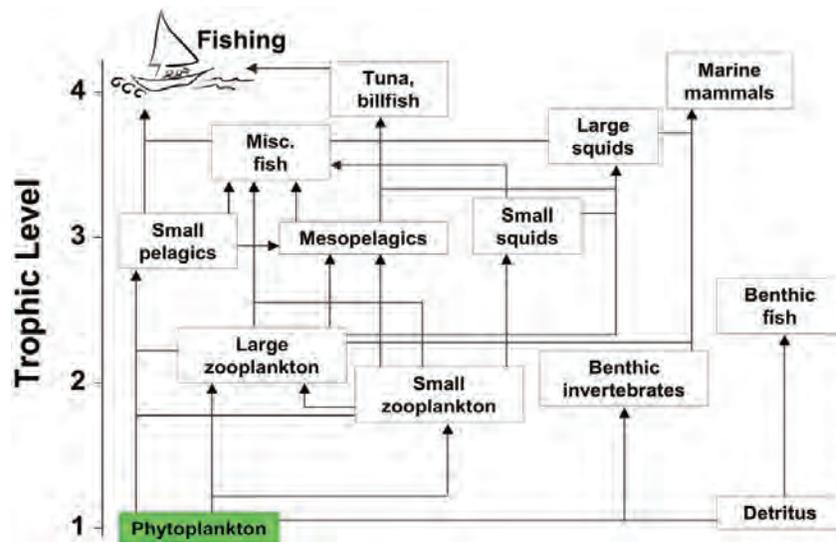
Figure 6.1 Simplified oceanic food web, showing the varying complexities in the linkages between phytoplankton, measured by satellite ocean-colour data, and higher trophic levels. Modified from Pauly and Christensen (1995).

biological component of the marine ecosystem accessible to remote sensing, and as such it provides a key metric to measuring ecosystems on a global scale. Satellite chlorophyll measurements are the primary component in algorithms to calculate the primary productivity (PP) of the ocean. Global PP measurements, in conjunction with fish catch statistics and food web models, such as shown in Figure 6.1 can be used to estimate the carrying capacity of the world's fisheries. In the open ocean 2% of the PP is needed to support the fishery catch, but in coastal regions the requirement ranges from 24-35%, suggesting that these systems are at or beyond their carrying capacity (Pauly and Christensen, 1995), which is cause for concern as the bulk of the world's fish catch comes from coastal areas. In a similar manner, discrepancies between the values of satellite derived PP and reported fish catches have been used to demonstrate spurious trends in global fish catches as reported by the Food and

Agriculture Organization (FAO) of the United Nations (Watson and Pauly, 2001). In this instance satellite ocean-colour data provide an important objective baseline against which to gauge data that can have socio-economic biases.

There is growing awareness that the long-standing approach to fisheries management which focuses on a specific species is inadequate (Browman and Stergiou, 2005; Sherman *et al.*, 2005). Interactions with other species, complex predator-prey dynamics, and temporal and spatial variability in physical aspects of the ecosystem all need to be incorporated into an ecosystem-based approach to management. Although not all of these aspects can be addressed by satellite data, the high spatial and temporal resolution of satellite ocean-colour data make it an efficient tool to characterize and monitor marine ecosystems to better manage them. For example, satellite-derived primary productivity is one of the indicators used in the assessment of Large Marine Ecosystems (LME) (Sherman *et al.*, 2005).

6.2   Recruitment

A fundamental issue in fisheries oceanography is understanding how environmental variability affects annual recruitment, the number of new individuals entering a stock. Most fish have planktonic larval stages that are strongly influenced by ocean circulation and can have narrow ranges of optimal thermal conditions. Availability of a suitable food source is important for successful recruitment and hence many fish reproduce near the seasonal peak in phytoplankton abundance. A long-standing hypothesis in fisheries has been that recruitment success is related to the degree of timing between spawning and the seasonal phytoplankton bloom, the Cushing-Hjort or match-mismatch hypothesis (Cushing, 1990). This hypothesis has been difficult to address with traditional shipboard measurements that have limited spatial and temporal resolution, but with satellite ocean-colour data, interannual fluctuations in the timing and extent of the seasonal bloom can be clearly seen. In an application on the Nova Scotia Shelf, the timing of the spring bloom determined from satellite ocean colour was compared with available *in situ* data on larval survival of haddock, an important commercial fish species. Comparison of these two independent data sets indicated that highly successful year classes of haddock are associated with exceptionally early spring blooms of phytoplankton (Fig. 6.2), confirming the match-mismatch hypothesis (Platt *et al.*, 2003). A comparable study has also documented a relationship between the timing of the spring bloom and the growth rate of shrimp (Fuentes-Yaco, 2007). These studies demonstrate that it is possible to separate ecosystem-associated variability in fish stocks from other components, such as human exploitation or predation effects. The satellite-derived time series permits the extraction of value-added products, in this case the timing of the seasonal biological cycle.
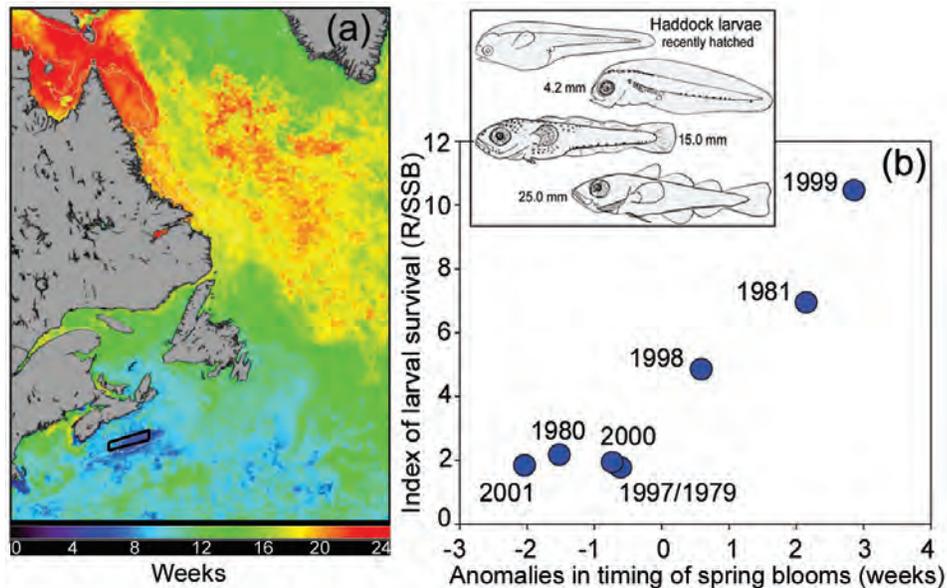
Figure 6.2 (a) Timing of the maximum phytoplankton biomass in the NW Atlantic from February to July, derived from SeaWiFS climatology (1998-2001). Units in weeks; blue indicates early spring bloom (March), red indicates late spring bloom (July). Image provided by César Fuentes-Yaco, Dalhousie University, Canada. (b) Relationship between larval haddock survival index (normalized to recruitment) and local anomalies in bloom timing. Data from the continental shelf off Nova Scotia (see black rectangle on map) for the periods 1979-1981 and 1997-2001, adapted from Platt *et al.* (2003).

6.3   Harvesting

Locating and catching fish is becoming more challenging as easily accessible fish stocks dwindle. As search time increases, so does cost. Satellite data can help to increase the efficiency of fishing efforts by identifying oceanographic features that are sites of fish aggregation and migration such as temperature fronts, meanders, eddies, rings and upwelling areas (Laurs *et al.*, 1984; Fiedler and Bernard, 1987; Chen *et al.*, 2005). Fishermen have been using SST from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar orbiting satellite for the past 20 years. Fishermen also use remotely-sensed ocean-colour maps at sea to guide fishing effort. Thermal or colour gradients often indicate sites of high biological productivity. Temperature is also an important factor determining the distribution of fish, as different species have different preferred temperature ranges.

To be of practical use to the fishing industry, satellite ocean-colour data must be available in a near-real time basis. There are differences between countries in how satellite data is disseminated to users. While in some countries, notably Japan and India, the national fisheries agencies are actively involved with helping to increase the efficiency of their fishing fleets. NOAA Fisheries in the USA is not allowed to

provide services such as distributing 'fish finding maps' that would compete with commercial interests. For example, the SeaWiFS satellite is privately owned, and its chlorophyll data is only available on a real-time basis to commercial subscribers. Clients of the service company can receive custom-tailored maps of ocean colour, as well as other oceanic properties derived from satellite data, directly onboard their fishing vessel. In contrast, data from the Indian IRS-P4 ocean-colour sensor (in conjunction with satellite SST from AVHRR) is used operationally to produce maps of potential fishing zones (PFZs).

6.3.1   Potential Fishing Zones: The Indian Experience

Methods for locating potential fishing zones (PFZ) in India from satellite data were developed initially through detection of SST gradients revealed by oceanic features such as fronts, eddies and upwelling (Lasker *et al.* 1981, Laurs *et al.* 1984, Narain *et al.* 1990) known to be conducive to fish aggregation. This approach has the
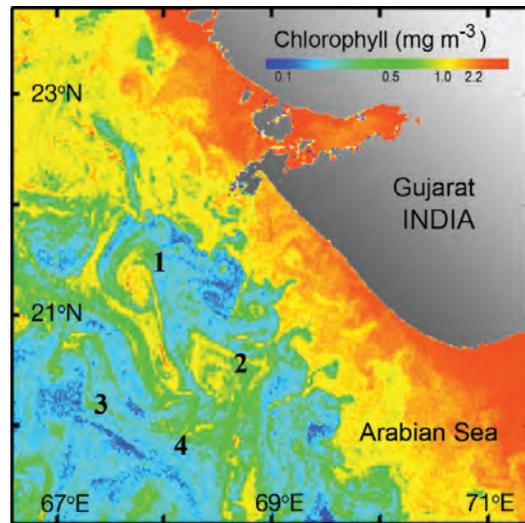
Figure 6.3 Chlorophyll image of northwest India on 29 February 2006 generated from the Indian OCM sensor. Oceanic features such as cyclonic eddies (1 and 2 on the image) and fronts (3 and 4) are known to be productive sites and are hence relevant for fishery exploration (Credit: R.M. Dwivedi, Indian Space Research Organisation, India).

basic limitation that SST images provide data on the temperature of the surface skin only (upper ten microns). Heating of sea surface, particularly in equatorial and tropical waters during summer, gives rise to strong stratification of the water column, preventing arrival of cool nutrient rich waters from deeper layers to the surface. This, in turn, inhibits appearance of SST gradients in the satellite imagery. For this reason, SST images are not always adequate for identification of potential fishing zones. Another problem with detection of thermal features is that surface

frontal structures may be perturbed by prevailing surface winds or currents of even moderate magnitude (Dwivedi *et al.*, 2005). Unlike thermal sensors, ocean-colour
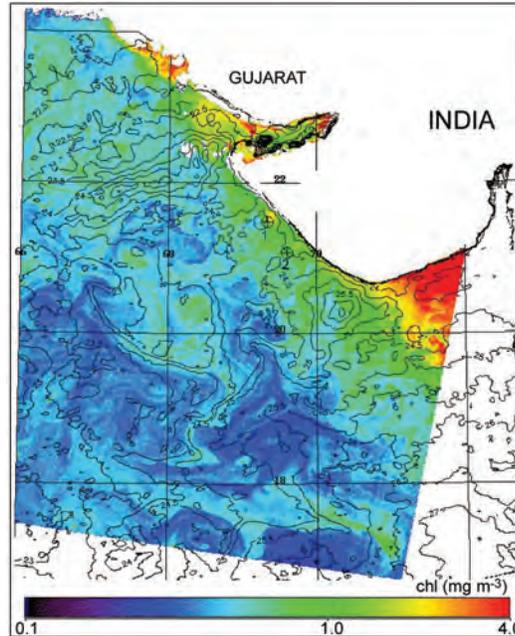
Figure 6.4   An example of a chlorophyll map overlaid with SST contours, for detection of Potential Fishing Zones (PFZ). The chlorophyll image was captured by India's IRS-P4 OCM sensor on 29 February 2000 off the west coast of India (Credit: Space Applications Centre, Indian Space Research Organisation, India.)

sensors can detect signals from below the surface due to penetration of visible radiation down to one attenuation depth (typically metres to tens of metres), and thus have advantages over the SST-based approach for fishery applications. One of the benefits of water penetration capability of visible radiation is that it provides the ability to predict occurrence of oceanic features such as diverging fronts and eddies (Fig. 6.3). These features are known to be the most reliable indicators of potential fishing zone (Laurs *et al.* 1984). It also enables detection of variations in biomass in a column at different stages of feature development in serial chlorophyll images. This advantage was exploited to develop the ability to anticipate formation of oceanic features such as eddies, at least two days before their actual occurrence. Verification of the experimental forecasts with inclusion of ocean colour proved superior to those using SST alone in terms of rate of success and magnitude of fish catch. Secondly, chlorophyll images, unlike those of SST, reveal many more frontal structures, given the penetration capability of visible radiation. Moreover, unlike SST, the ocean-colour front detected from chlorophyll image is a true biological front and hence, relevant to exploration for fish.

Two approaches are routinely used by the Indian National Centre for Ocean Information Services (INCOIS) to identify potential fishing zones. In the first approach,
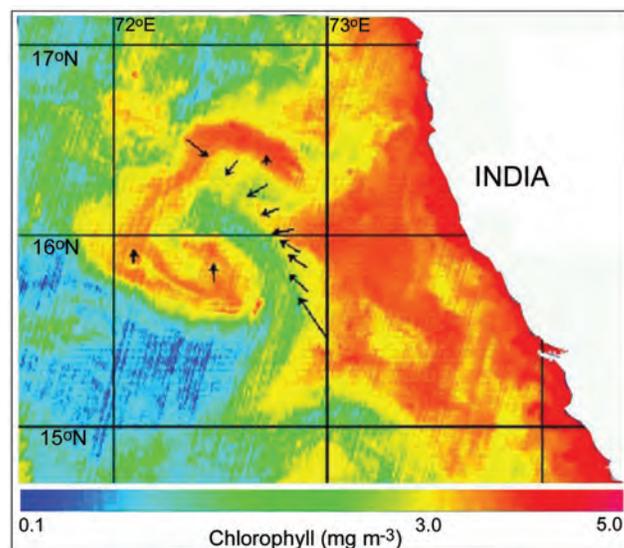
Figure 6.5 This image shows chlorophyll concentrations off the west coast of India, captured by India's OCM sensor onboard the Oceansat-1 satellite on 17 November 1999 . Arrows indicate areas where fishing was conducted (Credit: Space Applications Centre, Indian Space Research Organisation, India).

SST contours derived from NOAA-AVHRR data are overlaid on chlorophyll images generated from the Indian OCM sensor, to enable identification of matching features revealed by corresponding gradients (Solanki *et al.* 2000) (Fig. 6.4). This method has provided consistent positive feedback, although frontal structures common in both SST and chlorophyll images are generally few in number. There are many more features detectable from a chlorophyll image for which there is no matching counterpart in SST images, so the second approach uses satellite chlorophyll data alone, especially when relatively sparse thermal gradients are detected in SST imagery (Fig. 6.5). Selective use of these additional features from ocean-colour imagery has successfully enabled identification of potential fishing zones, and is a major contribution to the improved fishery forecast in Indian waters. Nayak *et al.* (2003) carried out a cost benefit analysis to assess the impact of using satellite PFZ forecasts on fish catch. The benefit-to-cost ratio (*i.e.* value of the fish catch vs. cost of fishing and generating PFZ charts) was found to be greater than one, indicating that the use of satellite data improves the economics of fish catch.

Using the above approaches, INCOIS generates PFZ advisories three times a week, providing information such as latitudes and longitudes of the areas of potential fish abundance, and the distance and direction from different fishing harbours. This information is freely disseminated to local fishermen around the coast of India by fax, phone, internet, electronic display boards, newspaper and radio broadcasts in local languages. In order to maintain fish stocks at a sustainable level, PFZ advisories are not provided during the monsoon season (June-September), which coincides with

the peak breeding season, and also with heavy cloud cover. These advisories have helped to reduce search time by up to 70%, and have significantly increased the catch per unit effort (Solanki *et al.*, 2003; Zainuddin *et al.*, 2004). This is a prime example of how satellite data can be put to effective use to ensure that the advantages of science and technology directly benefit society.

6.3.2   Pelagic and Migratory Fish: A Japanese Case Study

In the northwest Pacific, Skipjack tuna, a pelagic and highly migratory fish, are at the top of the pelagic food chain and support a valuable commercial fishery (Iizuka *et al.*, 1989; Shetty *et al.*, 1993). Skipjack tuna migrate between the subarctic (Oyashio) and the subtropical (Kuroshio) waters in the western Pacific (Kawasaki and Omori, 1995; Watanabe *et al.*, 1995), while planktivorous fish, such as Japanese sardine, Chub mackerel and Pacific saury also migrate between the two regions (Yasuda and Watanabe, 1994; Taniguchi, 1999). Satellite-borne sensors, such as the
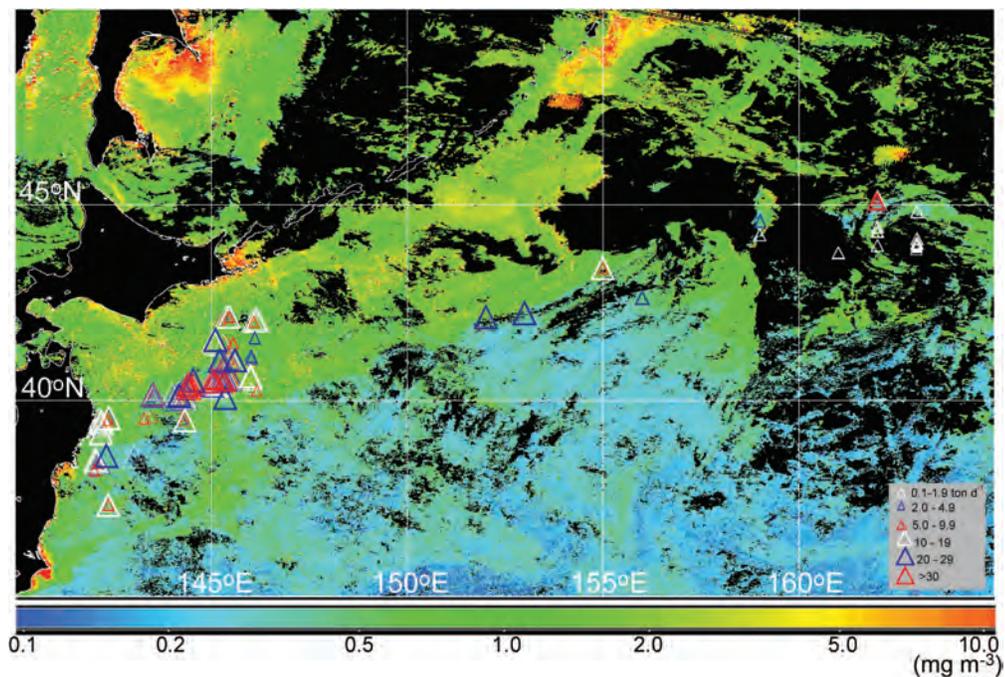
Figure 6.6   Distribution of Chl-a concentrations for 23-29 September, 2000, observed by SeaWiFS, and Skipjack tuna catches by fishing boats (in tonnes). The size of the triangles indicates the landings (tonnes per day). Image provided by Ichio Asanuma, Tokyo University, Japan.

Japanese Ocean Colour Temperature Scanner (OCTS), have been used to monitor the distribution of Chl-a with respect to the distribution of fish (Ishizaka, 1998; Asanuma *et al.*, 2003). In the northwest Pacific, complex mixing processes have been observed between the warm, nutrient-depleted water from the Kuroshio and the cold,

nutrient-rich water from the Oyashio (Saitoh *et al.*, 1998). In general, the warmer Kuroshio water has a low Chl-a concentration while the colder Oyashio water has a high Chl-a concentration, with complex variability in regions of mixing (Yoshimori *et al.*, 1995; Ono *et al.*, 1998).
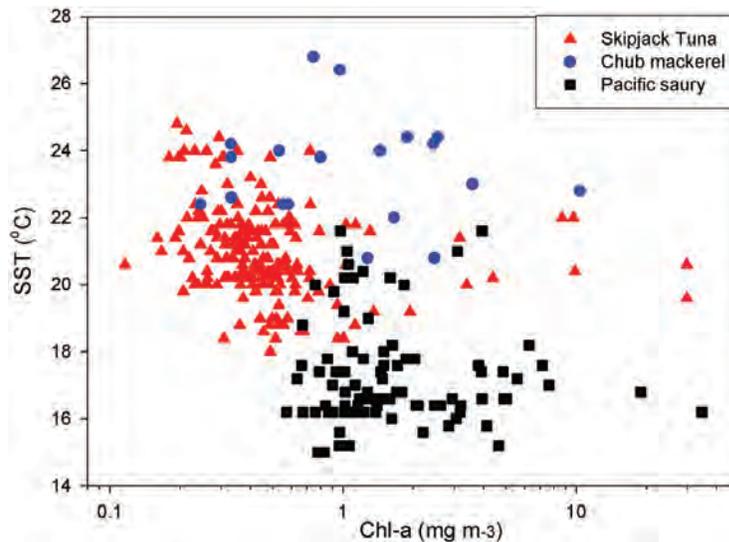
Figure 6.7 Distribution of Skipjack tuna, Chub mackerel and Pacific saury as a function of Chl-a and SST. Chl-a was obtained from SeaWiFS data, while SST was derived from NOAA-AVHRR data. Average SST and Chl-a concentrations were 21.0°C and 0.46 mg m^{-3} for Skipjack tuna, 23.0°C and 0.99 mg m^{-3} for Chub mackerel, and 17.2°C and 1.54 mg m^{-3} for Pacific saury. The study area encompassed 35°N to 45°N and 140°E to 150°E over the period 23-29 September, 2000. Image provided by Ichio Asanuma, Tokyo University, Japan.

In an experiment to assess the utility of providing Chl-a imagery to fishermen to determine fishing grounds, the highest catches (> 30 tonnes) were reported between two warm core rings around 41°N and 145°E (Fig. 6.6). Slightly lower catches (10 - 19 tonnes) were reported around 42°N and 153°E, along the boundary of the high Chl-a Oyashio and the low Chl-a Kuroshio. Very low catches of Skipjack tuna (2 to 4 tonnes) were evident further east (around 156°E) in the warmer, nutrient-depleted waters. Planktivorous Pacific saury and Chub mackerel were caught in water masses with high Chl-a concentrations (Fig. 6.7), although they tend to prefer different temperature ranges, with a mean temperature of 17.2°C and 23°C respectively. In contrast, Skipjack tuna catches occurred in a wide range of Chl-a concentrations (0.1 to 10 mg m^{-3}) and in temperatures ranging from 18°C to 25°C. Nonetheless, the majority of Skipjack tuna were caught in lower Chl-a waters (mean 0.46 mg m^{-3}), which corresponds to the warm core rings originating from the Kuroshio (mean temperature 21.0°C).

6.4   Species of Conservation Concern

6.4.1   Right Whales

One of the most endangered marine species is the Northern right whale (*Eubalaena glacialis*), with an estimated population of 350 individuals (International Whaling Commission, 1998; Kraus *et al.*, 2005). Although historically right whale populations were severely depleted by commercial whaling, at present the principal cause of mortality in the North Atlantic is from ship strikes (National Marine Fisheries Service, 2005). The primary habitat of the North Atlantic right whale is in coastal or shelf waters, which also experience heavy ship traffic. The recovery plan of NOAA (USA) for this species has focused on developing methods to identify the locations of right whale populations, and then to reduce ship traffic in these regions and lessen the number of whale-vessel collisions. This plan involves both limiting fishing in certain areas when whales are typically abundant, a procedure known as seasonal area management (SAM), and another strategy known as dynamic area management (DAM), with a synoptic level of control. Under DAM, if a group of whales is identified, NOAA Fisheries will limit activities in the area. Currently, research is underway to improve both management strategies by predicting the location of right whale congregations using satellite measurements of SST and ocean colour (Pershing *et al.*, 2008). The distribution of right whales is strongly correlated with the distribution of their prey, which appears to be primarily calanoid copepods (Kenney *et al.*, 2001). Satellite-derived chlorophyll data is a reasonable proxy for copepod egg production, and is analyzed in conjunction with SST data to estimate the development time of copepods, and model data to understand circulation patterns, to ultimately predict areas where whale aggregation is likely. This project is moving from proof of concept to operations, and daily *Calanus* distributions and right whale estimates should be available shortly. The science team is working with NOAA Fisheries to incorporate the products into right whale management.

6.4.2   Loggerhead Turtles

Satellite ocean-colour data, in conjunction with telemetry data from tagged sea turtles have shown that in the North Pacific, the Transitional Zone Chlorophyll Front (TZCF) is an important foraging ground and migration pathway for endangered loggerhead turtles (Polovina *et al.*, 2004). These turtles follow the TZCF, and spend time foraging in the high chlorophyll eddies that are associated with meandering of the front (Fig. 6.8). Other apex predators such as albacore tuna also use the front as a migratory corridor (Laurs and Lynn, 1991; 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
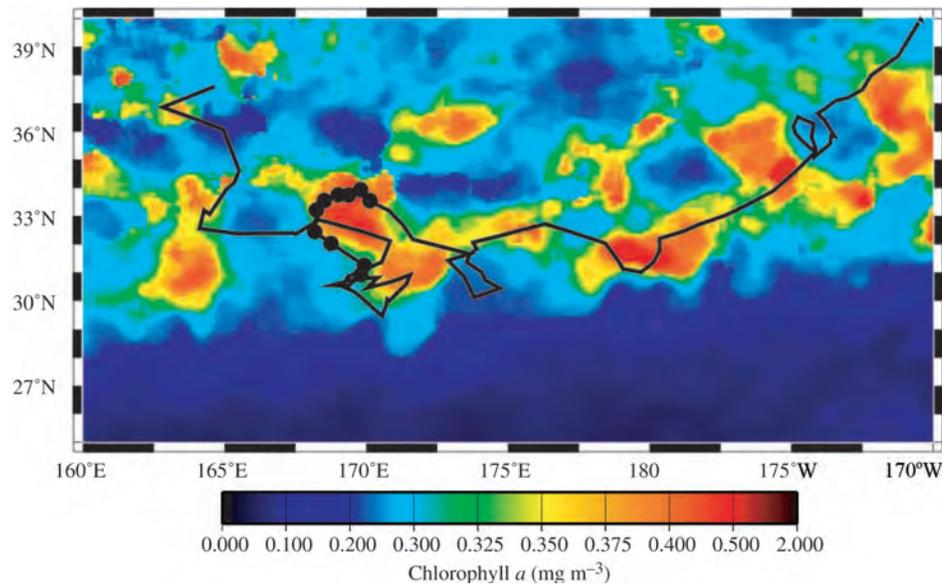
Figure 6.8 Track of a tagged Loggerhead turtle (black line) overlain on SeaWiFS chlorophyll data along the Transitional Zone Chlorophyll Front in the North Pacific Ocean. Figure adapted from Polovina *et al.* (2004).

et al., 2001). Interannual variability in the southern extent of the TZCF impacts the survival of juvenile monk seals in the Hawaiian islands (Baker *et al.*, 2007).

Extracting information about animal habitat by using satellite telemetry location in conjunction with environmental satellite data has been used on a variety of species. For example the Census of Marine Life program, Tagging of Pacific Predators (TOPP), is involved with tagging a suite of more than 20 marine predators and integrating the tagging information with satellite data to better understand the animal's habitat usage (Block *et al.*, 2003). Relating the movements and activities of these animals to satellite-derived features is an important advancement toward understanding environment-population linkages in marine ecosystems.

6.5 Summary and Conclusions

Satellite data characterize oceanic properties of habitat and ecosystems that influence living marine resources at spatial and temporal resolutions that are impossible to achieve any other way. The high spatial resolution provides an important geographical context for interpreting other data and results. The daily-to-weekly temporal resolution allows for effective monitoring of many oceanic features and permits the extraction of value-added products such as the timing of seasonal events. Time series of science-quality satellite data are needed to understand linkages between climate and ecosystems, and to characterize and monitor ecosystems as part of an ecosystem-based approach to fisheries management. For example, satellite

chlorophyll can be used to observe changes in the timing of the spring bloom that can affect recruitment (Platt *et al.*, 2003), to classify the productivity of the oceans (Sherman *et al.*, 2005), to detect interannual differences in the frontal structures that are important to fisheries (Bograd *et al.*, 2004; Polovina *et al.*, 2001) and to map the spatial extent of the ocean experiencing lower productivity during an El Niño event (Wilson and Adamec, 2001). Near-real-time satellite data are needed to optimize sampling for fisheries survey cruises for management and stock assessment and also to increase the efficiency of fishing effort.

Ocean-Colour Radiometry and Water Quality

Nicolas Hoepffner, Christopher Brown, Roland Doerffer, Joji Ishizaka, Jim Gower and Mervyn Lynch

All water systems, such as inland surface waters, estuaries, coastal waters and ground-waters, are exposed to increasing external pressures, resulting from climate change and direct human activities. Pressures that are expected to have the largest impact on water systems are temperature changes, sea-level rise, increasing greenhouse gases in the atmosphere, and increasing precipitation and river runoff. In addition, water bodies receive agricultural, domestic and industrial pollutants, and are subject to recreational pressures from the leisure industry, as well as intensive fishing and farming of marine organisms. These pressures are interconnected and may be acting concurrently to reduce water quality and contribute to the deterioration of the ecosystem, including habitat loss and reduced biodiversity.

To lessen or reverse negative trends, national plans and international programmes have recently emerged to assess and monitor the present quality status of water bodies. The Water Framework Directive in the EU (EC, 2000) sets the goal of achieving a 'good status' for all of Europe's surface waters by 2015. Similarly, Goal 2 of the National 2006-2011 Strategic Plan in the US (US Environmental Protection Agency, 2006) targets a full recovery of water quality standards in more than 2,250 'polluted' water bodies by 2012.

These plans establish reference conditions and reference sites for an inter-calibration network, to specify indicators and criteria for an ecological status classification system, and to implement appropriate measures that would sustain an improvement of the aquatic environment.

7.1 Conceptual Framework for Satellite Water Quality Monitoring

Many chemical and biological characteristics are used, either individually or in combination, as indices to assess water quality. Appropriate measurements and thresholds are prescribed according to the targeted application of the water systems, *e.g.*, drinking water, bathing water, or water used in industry and aquaculture.

However, a common set of key water-quality indicators that include physical, chemical, and biological endpoints such as conductivity, dissolved oxygen, pH, turbidity, biomass concentration, total suspended matter, pathogens and primary production, can be identified from various legislation texts and directives.

In coastal and marine waters, the variables associated with a defined 'quality status' can change over a wide range of spatial and temporal scales, leading to substantial logistic and economic difficulties to monitor them on a regular basis. Realistically, the approach to coastal water management is to undertake ongoing assessments of the population and condition of marine flora and fauna, as well as what might be termed 'water quality'. This approach usually employs *in situ* techniques, which correspond essentially to a statistical/spatial sampling of the system, and has been designed to capture the key attributes and system spatial variability. It is important to recognize that these *in situ* efforts are extremely valuable, though costly, and need to be implemented at regular intervals if they are to become a meaningful management tool. However, an *in situ* approach can rarely sustain the repeat frequency and spatial coverage that is required to support effective management practices in vulnerable areas, where more intensive monitoring needs to be in place. Processes such as coastal currents, sediment transport from flooding river systems, wind driven vertical mixing, coastal upwelling, nutrient fluxes and algal blooms can rapidly modify coastal water properties. It is likely that these changes will not be captured by *in situ* sampling on an adequate spatial and temporal scale. In contrast, satellite remote sensing is particularly good at depicting changes in the water properties at appropriate scales. Over the past decade, several studies have demonstrated the utility of satellite measurements of 'water colour' to assess water quality (Prasad *et al.*, 1998). Several of the indicators are directly or indirectly related to the colour or reflectance of the water and, therefore, potentially accessible from remote sensing.

The colour of a water body, as recorded by a satellite, depends on the capacity of the water constituents to absorb and scatter solar radiation at specific wavelengths. As the concentration and variety of the constituents increase in the water column, the interpretation of ocean-colour data becomes more difficult. Often, turbid or 'Case 2' waters (Morel and Prieur *et al.*, 1977; Sathyendranath *et al.*, 1989), occur in areas requiring specific attention with respect to water quality assessment. The new generation of optical sensors, and new algorithms that have been developed to specifically address the problem of differentiation between optically-active components in Case 2 waters (IOCCG, 2000), provide a basis for an operational cost-benefit analysis of water quality in sensitive and economically important areas.

A brief review of operational ocean-colour products that are currently available or under development is presented in a previous IOCCG Report (IOCCG, 2000). Several of these products can be used directly as water quality indicators. For example, satellite estimates of the light attenuation at different wavelengths provide information on the depth of penetration of the solar radiation and, therefore, can be

related to water transparency and Secchi depth (see below), which is commonly used to assess and classify lakes and coastal waters (EC, 2000). In addition, operational colour products, in combination with data from different platforms, can support the rapid and flexible implementation of statistical and modelling schemes to transform these data into operational water quality maps (Fig. 7.1).
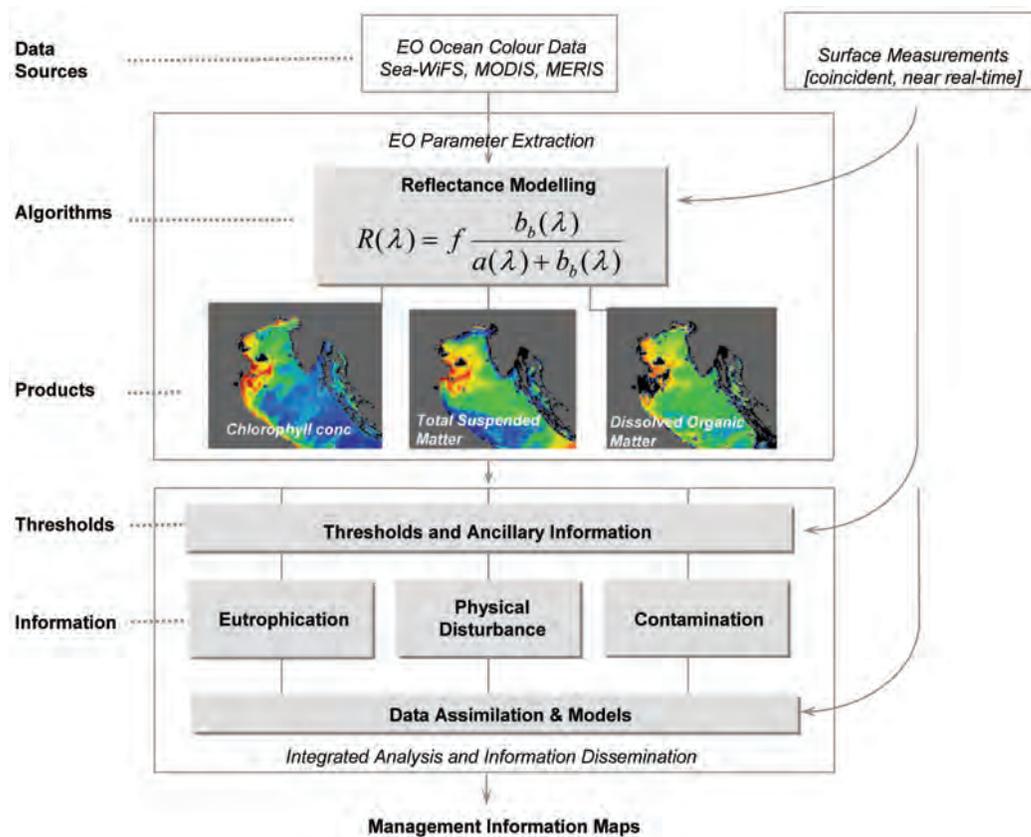
Figure 7.1 Example of a sequential process for the use of ocean-colour radiance data and field measurements into an integrated water quality analysis and monitoring system.

The depth-integrated rate of photosynthesis or water column primary production also represents an important water quality indicator associated with marine ecosystem health and its capacity to provide ecosystem services such as supporting commercial fish stocks. The calculation of the daily rate of depth-integrated photosynthesis using ocean-colour data relies on the additional knowledge of the irradiance field and/or SST, and some physiological parameters collected from ships. Other integrated products use multi-source data for water quality classification, and can be supported by remotely-sensed ocean-colour data (see Table 7.1 for some examples).

Table 7.1   Products or state indicators and their applications.

Product Name	Standard and Advanced Product Requirement	Application
Transparency / Secchi disk depth	Pigments, total suspended matter (TSM), light attenuation coefficient, dissolved organic matter (DOM),	Water quality monitoring
Primary production	Pigments, TSM, DOM, inherent optical properties of water constituents, SST, surface irradiance	Water quality monitoring, ecosystem and habitat assessment
Differential biomass/ phytoplankton community structure	Pigments, chemotaxonomic equations	Water quality monitoring, ecosystem assessment, hazards
Eutrophication index	Chlorophyll, primary production , nutrients, SST	Water quality monitoring, hazards
Turbidity index	Transparency, phytoplankton biomass	Water quality monitoring
Submerged benthic vegetation index	Pigments, sediment, dissolved organic matter, bathymetry, albedo data base	Aquaculture, water quality monitoring, impact assessment
Bloom/ plume dynamics	Chlorophyll, TSM , DOM	Hazards, ecosystem and habitat assessment

Note that all products/indices in the first column of Table 7.1 meet the definition of 'state indicators' as given by the Organization for Economic Cooperation and Development (OECD, 1993), which further stipulates that an indicator could be the expression of a parameter or a pool of environmental parameters. From a management perspective, these indicators need to be integrated into a more complex information and assessment system tool, such as the 'pressure-state-response' framework (OECD, 1993) or the 'Driver-Pressure-State-Impact-Response' (DPSIR) framework introduced within the IGBP-LOICZ project (Turner *et al.*, 1998) and adopted in the European Water Framework Directive (EC, 2000).

7.2   Water Clarity / Transparency

The transparency or clarity of a water body reflects the degree that light can penetrate vertically into the water column. It is commonly measured in the field using one of the oldest 'optical' instruments in oceanography, the Secchi disk: a white (or black and white) disk lowered in the water until it reaches the Secchi Depth (*SD*) where the disk pattern becomes no longer visible. A large number of these measurements were compiled to establish global climatological mean fields of water transparency in the ocean (Lewis *et al.*, 1988). More sophisticated submersible radiometers enable precise measurements of the light field in the water at multiple wavelengths. The

light attenuation coefficient (K_d , in m) as derived from these instruments, and *SD* (in m^{-1}) are both interrelated (Holmes, 1970; Preisendorfer, 1986) and depend on the structure of the light field, as well as the nature and concentration of the material in suspension. Another approach to measuring water transparency is through turbidity. As apposed to water clarity measurements by the Secchi disk, turbidity meters or nephelometers provide a quantitative indication (in nephelometric turbidity units, NTU) of the light scattered by particles in suspension.

Satellite ocean-colour radiometry offers an excellent opportunity to supplement this database by providing water attenuation coefficients from remotely-sensed surface water-leaving radiances (Austin and Petzold, 1981; Mueller, 2000). Empirical band-ratio algorithms have been implemented by space agencies to provide global maps of diffuse attenuation coefficients, $K_d(\lambda)$, a descriptor of the penetration of sunlight in water. The complexity of coastal waters requires, however, significant tuning of these algorithms (Kratzer *et al.*, 2003; Mélin *et al.*, 2003), or the inversion of analytical bio-optical models allowing the properties of the various constituents in the water to vary independently in time and space (see IOCCG, 2000 and references therein; Lee *et al.*, 2005a). The retrieval of the absorption and backscattering properties of the water from satellite ocean-colour radiometry using advanced algorithms (IOCCG, 2006) reduces considerably the uncertainties in the determination of the diffuse attenuation coefficient over a wide range of values including coastal waters (Lee *et al.*, 2005b). Doron *et al.* (2007) have developed a method to assess the horizontal and vertical visibility in the water by means of analytical expressions that determine both the diffuse and the beam attenuation coefficients at 490 nm from satellite-derived IOPs, and reflectance at two different wavelengths. In a recent study, Chen *et al.* (2007b) have successfully used high resolution MODIS imagery to map the temporal variations of turbidity in Tampa Bay where field values varied from 0.8 to 8.0 NTU. Even though the formulation is empirical, the temporal stability of the regression observed between the remote sensing reflectance at 645 nm and the field measurements of turbidity would support the possibility to apply this method to other turbid waters.

Note that the advantage of using longer wavebands, *i.e.*, 600-700 nm, has been emphasized on several occasions in these studies as a way to improve the algorithm performance in coastal waters (Chen *et al.*, 2007b; Doron *et al.*, 2007). At these wavelengths, the contribution of absorption by dissolved organic matter to the water-leaving radiance can be assumed to be negligible, thus limiting the algorithm inversion to only a few parameters. Longer wavelengths in the red and near-infrared part of the spectrum also facilitate the differentiation between optically-active components in near-shore turbid waters (Ferrari *et al.*, 1996; Doxaran *et al.*, 2002) and lakes (Bukata, 2005). The MERIS Maximum Chlorophyll Index (MCI) (Gower and King 2008) can also be used to provide a signature for intense plankton blooms, especially in the presence of high sediment concentrations (Fig. 7.2). MCI is computed from the above-atmosphere spectral radiances for each pixel to show excess radiance at

709 nm, above a baseline defined by linear interpolation between the two adjacent spectral bands at 681 and 754 nm (Equation 7.1):

$$MCI = L_{790} - L_{681} - (709 - 681) \times (L_{754} - L_{681})/(754 - 681), \qquad (7.1)$$

where L_{790} represents radiance at 790 nm *etc.* MERIS is uniquely suited for computation of the MCI index because it has a band at 709 nm which is lacking on other current ocean-colour sensors.
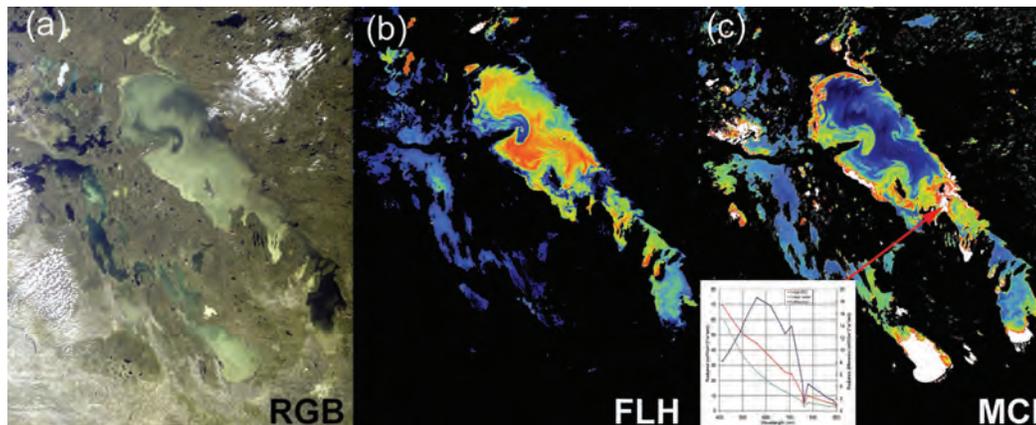
Figure 7.2 Patterns of high sediment and chlorophyll in the Manitoba Lakes, Canada, imaged by MERIS on 27 May 2007. (a)'true colour' (RGB) image, (b) chlorophyll fluorescence (FLH), and (c) excess radiance at 709 nm (MCI). Values of FLH are increased in areas of high sediment load (*i.e.* only partly due to fluorescence). The inset shows how absorption by chlorophyll at wavelengths 665 and 681 nm lead to a reduction in radiance at these two wavelengths. The resulting high MCI indicates presence of chlorophyll in water with high concentrations of suspended sediment. (Image provided by Jim Gower, Institute of Ocean Sciences, Canada. MERIS data provided by the European Space Agency).

Ocean-colour data can also be used to provide information on underwater visibility for maritime defence and security operations. For example, the underwater visibility in the Eastern Canadian Arctic was required for the month of August for the planning of Canadian Navy surface vessel and submarine exercises: all options had to be considered for avoidance of ice. The underwater visibility for this area was calculated by averaging SeaWiFS chlorophyll concentrations for the month of August over several years (1998-2005) and computing the total attenuation coefficient of light at 532 nm, based on optical models developed at the Bedford Institute of Oceanography (Platt and Sathyendranath, unpublished data). Optical absorption was calculated as a non-linear function of chlorophyll, including contributions from water, phytoplankton and coloured dissolved organic matter, while scattering was estimated from contributions by water and phytoplankton, expressed as a non-linear function of chlorophyll. Total attenuation of light was estimated from the sum of absorption plus scattering, with a ten-percent safety margin added, such that the

estimates of visibility were conservative by the same amount. Horizontal visibility is generally taken to be a linear multiple of the reciprocal of total attenuation. The multiplication factor given in the literature is somewhat variable, around 4.8, but a more conservative figure of 4.0 was used in this study. In the map produced (Fig. 7.3), there are striking variations in horizontal visibility, in particular an abrupt reduction in visibility at the mouth of the Hudson Strait (south of Baffin Island). On a Canadian Navy submarine voyage to the area, this figure provided an indication of turbidity/visibility, and the ranges were found to be remarkably accurate.
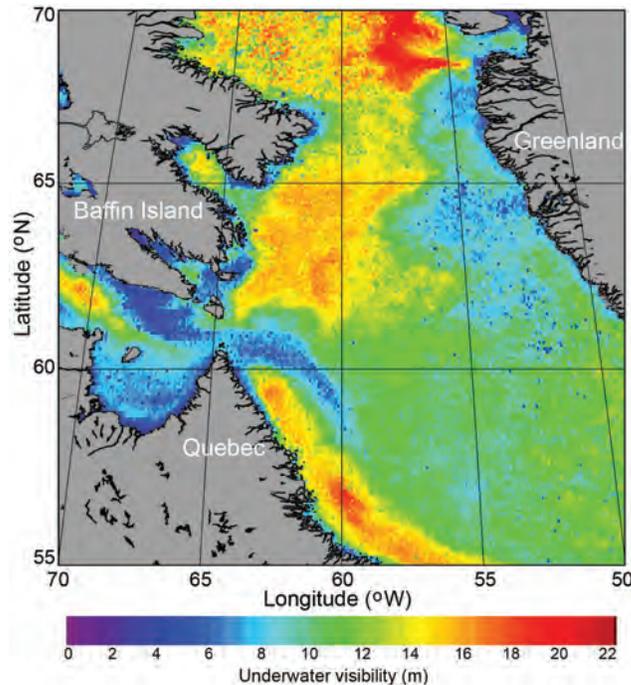
Figure 7.3 Estimated underwater visibility (m) in the Eastern Canadian Arctic for the month of August, based on SeaWiFS climatological records (Platt and Sathyendranath, unpublished data).

7.3 Coastal Eutrophication

The process of eutrophication is the ecosystem's response to an excess of nutrients commonly issued from human activities through river runoff, direct inputs from urban and industrial waste treatment, and atmospheric pollution. According to Andersen *et al.* (2006), eutrophication is defined as 'the enrichment of water by nutrients, especially nitrogen and/or phosphorus and organic matter, causing an increased growth of algae and higher forms of plant life to produce an unacceptable deviation in structure, function and stability of organisms present in the water, and to the quality of water concerned, compared to reference conditions'. The increase

in nutrients results in an escalation in photosynthesis and production of organic carbon, which in turn can reduce the water transparency and oxygen availability at depth, causing irreversible loss of habitats and mortality.

Nutrient pollution is one of the most severe and widespread environmental threats to enclosed and semi-enclosed seas, estuaries and bays. For example, the Black Sea ecosystem has been severely damaged by eutrophication over the past 30 to 40 years, with massive loads of anthropogenic nutrients entering the sea from the major river systems, especially the Danube. Subsequent phytoplankton growth and changes in the water transparency over the entire basin have negatively impacted the rest of the ecosystem, with a loss of biodiversity due to oxygen depletion at depth. This process is reflected in the optical signature of the Black Sea. Figure 7.4 shows the contrasting features of the Black Sea when compared with the rest of the Mediterranean basin.

Figure 7.4 True-colour image captured by SeaWiFS on 14 June 2000, showing large amounts of reflecting material (phytoplankton biomass) in the Black Sea, contrasting with the clearer eastern Mediterranean waters (Credit: Ocean Biology Processing Group, NASA/GSFC and GeoEye).

7.3.1 Eutrophication Index in the Mediterranean Sea

Although Mediterranean waters are classified as oligotrophic, several alarming cases of eutrophication have been recorded in coastal regions and enclosed bays, such as in the Northern Adriatic Sea where the United Nations Environment Programme established an 'Eutrophication Monitoring Strategy' in its Mediterranean Action Plan (UNEP, 2003). This strategy proposed that each Mediterranean country establish a monitoring program to sample a minimal set of parameters (Table 7.2). The plan

mentions explicitly the use of optical remote sensing as a complementary technique to support the measurements of some of these parameters including chlorophyll, suspended material distributions, and turbidity. In addition, it is recommended that remotely-sensed data be incorporated with *in situ* observations to provide eutrophication-indicator maps on a routine basis.

The set of parameters highlighted in Table 7.2 in bold are used to calculate a trophic index (TRIX) as defined by Vollenweider *et al.* (1998) and Giovanardi and Vollenweider (2004), on the basis of 10 years of data collected along the northwestern Adriatic coast. The trophic index combines factors that describe phytoplankton biomass and nutrient availability as follows:

$$TRIX = [\log_{10}(\text{Chl}.dO.DIN.TP) - (k)]/m, \tag{7.2}$$

where Chl is the chlorophyll-a concentration (*i.e.* phytoplankton biomass) in μg l^{-1}, dO is oxygen, as absolute % deviation from saturation, DIN is the sum of all dissolved inorganic nitrogen compounds in μg l^{-1}, TP is total phosphorus in μg l^{-1}, and the coefficients k and m are scale coefficients of the trophic index based on the upper and lower limits of the parameters. Since 1999, TRIX has been incorporated into the Italian water legislation (Casazza *et al.*, 2003) with values distributed in 4 classes, ranging from 'high' environmental state (TRIX values from 2 to 4), *i.e.*, good water transparency, well distributed dissolved oxygen in the entire water column, to 'poor' environmental state (TRIX values from 6 to 8), *i.e.*, highly turbid waters, persistence of hypoxic/anoxic bottom layers. The Mediterranean Action Plan proposes to extend the use of TRIX in all Mediterranean coastal waters (UNEP, 2003).

Table 7.2 Mandatory parameters to be monitored by each country following the guidelines of the UNEP/MED POL monitoring strategy for assessing Mediterranean eutrophication (adapted from UNEP, 2003). Parameters highlighted in bold (right hand column) are used to calculate a trophic index (TRIX, see text).

Temperature (°C)	**Dissolved Oxygen (mg l^{-1})**
pH	**Chlorophyll a (μg l^{-1})**
Transparency /Secchi depth (m)	**Nitrate (NO$_3$-N, μg l^{-1})**
Salinity (psu)	**Ammonium (NH$_4$-N, μg l^{-1})**
Total Nitrogen (N, mol l^{-1})	**Nitrite (NO$_2$-N, μg l^{-1})**
Silicate (SiO$_2$, mmol l^{-1})	**Total phosphorus (P, μg l^{-1})**
Phytoplankton (number and species composition)	**Orthophosphate (P-PO$_4$, μg l^{-1})**

Optical remote sensing can contribute to the calculation of TRIX by providing chlorophyll values at a suitable frequency with respect to coastal and lake dynamics. However, as an index of primary productivity, the calculation of TRIX requires the knowledge of parameters not accessible from remote sensing. A regional application of TRIX based on remote sensing would require the area to be partitioned into dynamic ecological provinces, within which field-derived quantities can reasonably

be assumed to remain constant for a given time period (see Chapter 8).

In an attempt to characterize the probability of oxygen deficiency in shallow areas due to eutrophication, Druon *et al.*, (2004) defined an index (EUTRISK) that combines a proxy for primary production estimated from optical remote sensing with numerical modelling, providing information on the capacity to store and renew sea-bottom oxygen. Monthly maps of EUTRISK for the Adriatic Sea (Fig. 7.5) show variations in the sensitivity to eutrophication, with a high probability of bottom-water hypoxic events in spring and summer along the northwest coast of Italy.
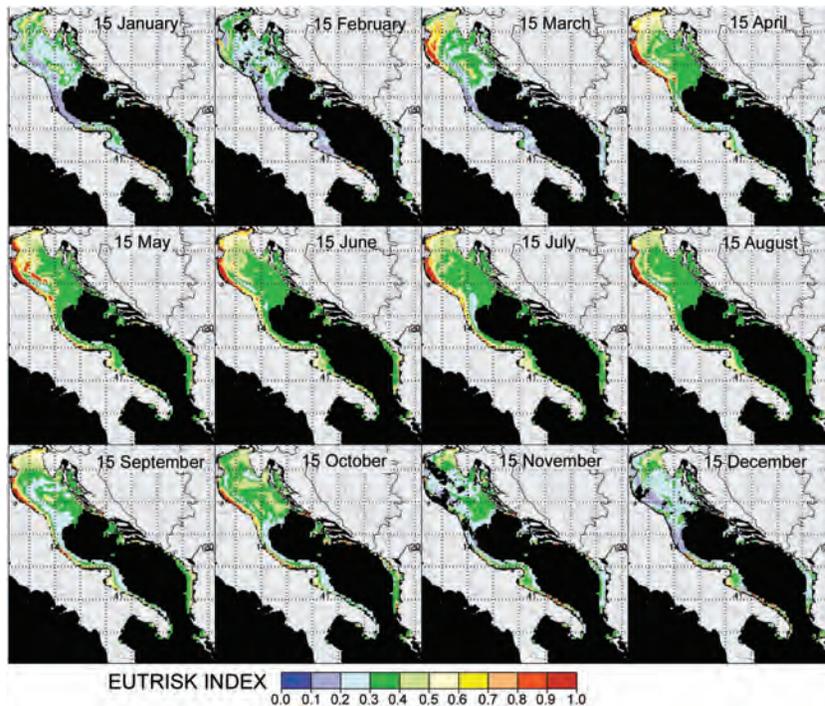
Figure 7.5 Monthly time series of EUTRISK index in the Adriatic Sea for the year 2002. The index is only applied to coastal waters, up to 100 m depth (*i.e.* black areas represent deep waters). (Source: Joint Research Centre, ECOMAR project, unpublished data). The index is scaled from 0 to 1.

7.3.2 Environmental Monitoring in the NW Pacific Region

Another Regional Seas programme of UNEP in the Northwest Pacific Region, NOWPAP (China, Japan, Korea, and Russia), has mandated the Special Monitoring and Coastal Environmental Assessment Regional Activity Centre (CEARAC) to use remote sensing techniques for environmental monitoring (NOWPAP CEARAC, 2005a; b). Ocean colour was identified as a useful tool for eutrophication monitoring and assessment of the NOWPAP coastal environment. CEARAC has recently published the 'Eutrophication Monitoring Guidelines by Remote Sensing' in support of the

implementation of an integrated marine environmental monitoring program in the region (NOWPAP CEARAC, 2007). It was also recommended that ocean-colour remote sensing techniques be used for case studies on harmful algal blooms as well as assessment of the eutrophication status in this region from 2008. Several web portal sites have been created at CEARAC showing the use of satellite remote sensing (`http://www.cearac-project.org/wg4/portalsite/`), oil spill monitoring (`http://cearac.poi.dvo.ru/en/main/about/`) and Marine Environmental Protection of the Northwest Pacific Region (`http://www.nowpap3.go.jp/jsw/eng/`).

7.4 Suspended Matter in the Coastal Zones

Plumes of turbid water are quite a frequent phenomenon in coastal waters, in particular in shallow soft bottom seas and in the mouth of rivers and estuaries (Fig. 7.6, see also Figs. 2.4 and 9.5). Turbidity is caused by a variety of particles in the

Figure 7.6 Envisat MERIS satellite image showing plumes of turbid water emanating from the mouth of the Yangtze River, China, on 15 March, 2008 (Credit: European Space Agency).

water, some of mineral origin, such as clay particles, and others of organic origin. Collectively, these particles are referred to as Suspended Particulate Matter (SPM) or Total Suspended Matter (TSM). The mineral portion primarily originates from the fine fraction of sediments, which are transported by rivers into the sea or, in shallow water, re-suspended from the sea floor by waves or tidal currents. SPM represents an extremely large amount of material, which is transported over long distances within

the coastal sea. Other sources of the inorganic fraction include dust from deserts or volcanoes, and fragmented skeletons of organisms such as coccolithophores, diatom shells *etc.*

The organic portion of suspended material, *i.e.* the detritus, is composed of decaying fragments of organisms or fecal material. The different particles can form complex flakes of an undefined structure, which act as a substrate for many microorganisms that colonize the surface and holes in the flakes, and live by decomposing and mineralizing the organic material. Due to the high organic content (including the attached microbes), detritus is an important food source for many benthic organisms. Furthermore, the complex large surface area of the flakes absorbs a number of different organic and inorganic trace substances, which are also transported with the suspended material. Finally, SPM absorbs and backscatters light and thus reduces the available solar radiance for photosynthesis by phytoplankton, benthic algae and seagrass.

Due to its diverse role, the formation and transformation, distribution and transport of SPM in the sea is of wide interest in various fields of marine science including marine biology and geochemistry, but also for monitoring the water quality, studying coastal erosion and the underwater light field and visibility. Due to the complex nature of SPM, transport and distribution cannot be observed in a representative way by ship cruises, nor can it simply be modelled as in the case of a conservative tracer like salinity. Only observations using aerial surveys and satellite data enable us to reveal the extremely complex distribution patterns and temporal variability. Thus, observations with a high spatial and temporal resolution are needed to map the distribution and analyze the transport mechanism. On the other hand, satellite observations are limited by clouds and show only the distribution of the upper few metres. To provide a complete view, as well as time series with a high temporal frequency, it is necessary to combine observations and simulations using data assimilation techniques.

ESA's MERIS sensor provides the potential to map SPM distributions in coastal zones due to its relatively high spatial resolution (300 nm) and 15 spectral bands in the visible and NIR spectral range. NASA's MODIS sensor provides more frequent coverage at a slightly higher spatial resolution (250 m), but has only one 250 m waveband centred in the visible, while SeaWiFS and AVHRR are also useful for mapping SPM distribution. The SPM component can be separated from the absorption by phytoplankton and dissolved organic matter using an artificial neural network which is currently used in the MERIS ground processor as the standard algorithm to determine SPM concentrations from the bi-directional water-leaving radiance reflectance (Fig. 7.7). These data have been used for assimilation into a SPM transport model for the North Sea.

The algorithm to determine SPM and other components from MERIS water-leaving radiance reflectance is based on an artificial neural network (NN) (Doerffer and Schiller, 2007). This NN in turn is trained with a large data set of simulated bi-
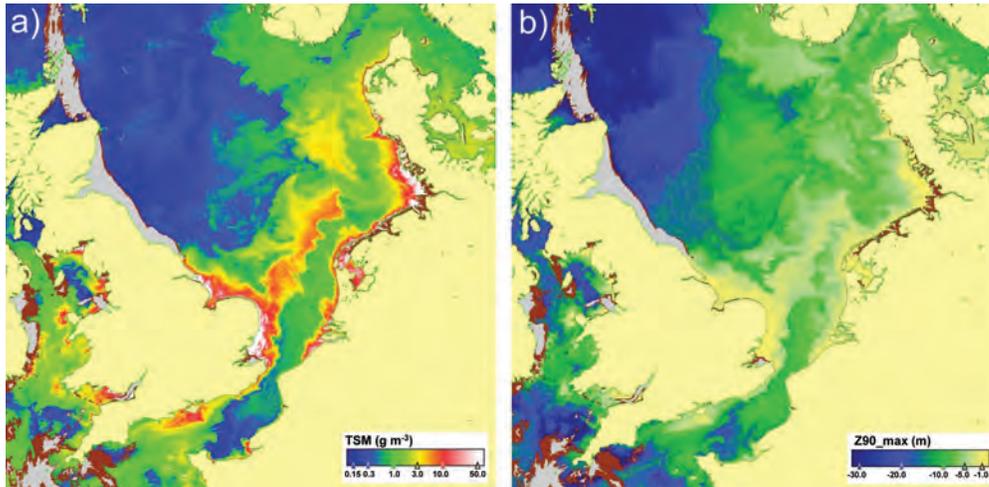
Figure 7.7 (a) Total suspended matter (TSM) derived from a MERIS scene over the North Sea on 27 March 2007, using the Case-2 R-BEAM processor, and (b) corresponding signal depth, $z90_{max}$. (Credit: Image provided by Roland Doerffer (GKSS, Germany), MERIS data provided by the European Space Agency).

directional radiance reflectances using Hydrolight (Mobley, 1994) as the radiance transport model. The underlying bio-optical model in turn is based on absorption and scattering measurements of a variety of coastal waters with concentrations of SPM up to 50 mg l^{-1}. Output of the NN are the three optical components (1) absorption coefficient of phytoplankton pigment, (2) absorption coefficient of dissolved organic matter (yellow substance plus detritus) and (3) scattering by all particulate matter (as defined by the pore size of the filter of ca. 0.2 - 0.45 μm). These coefficients are then used to compute the concentrations of chlorophyll and suspended matter using empirical relationships.

Another variable necessary to assimilate MERIS data into the model is the computation of the penetration depth. For this purpose, the maximum signal depth was computed using the optical properties of the three components. It is defined as the water depth of the surface water layer from which 90% of the water-leaving radiance originates, and is determined for each pixel from the three MERIS bands with the lowest downwelling irradiance attenuation coefficients. This depth was used to compare the concentrations from MERIS and the SPM transport model.

The SPM transport model is a hydrodynamical model. It includes tidal currents, waves and bioturbation as the most important processes, which determine sedimentation, re-suspension, transport and distribution in the coastal sea. A map of sediment distribution in the North Sea forms the basis for computing re-suspension. Important parameters such as the erosion depth and the vertical exchange coefficients were adjusted at the beginning of the development using satellite data of SPM from MOS (Modular Optical Spectrometer). The SPM model calculates distributions of three SPM fractions with different settling velocities in the water column and the
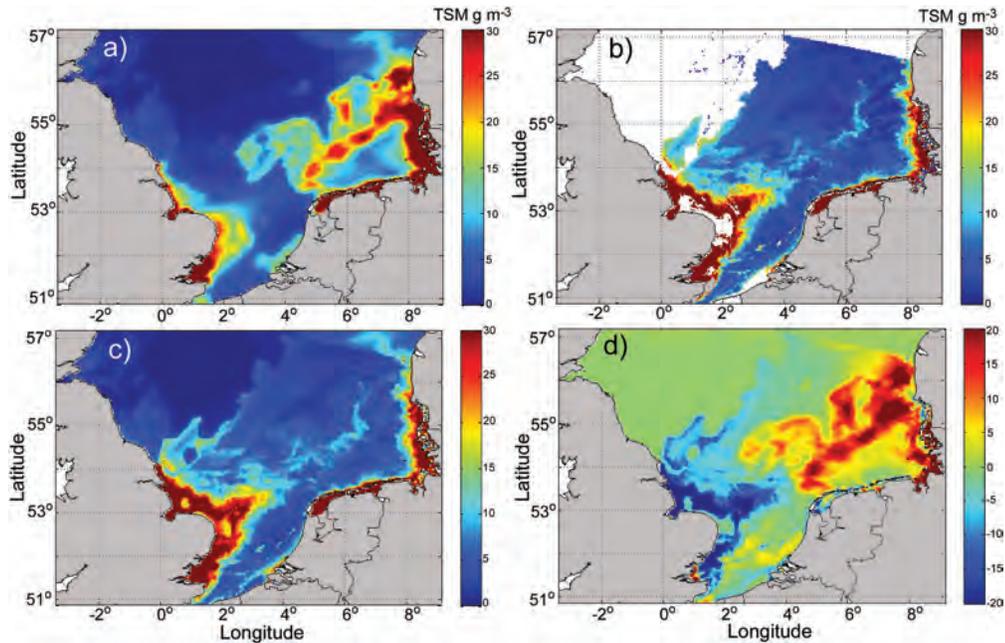
Figure 7.8 An example of data assimilation using the optimum interpolation method: a) surface concentration as calculated with the SPM transport model; b) surface sediment concentration derived from MERIS on 22 March 2003; c) model result after assimilating the MERIS data and d) difference between model results before and after data assimilation. (Credit: Image provided by Gerhard Gayer and Mikhail Dobrynin (GKSS, Germany), MERIS data provided by the European Space Agency).

corresponding fine sediment fractions in the first 20 cm from the bottom.

The results were compared to MERIS satellite data and to *in-situ* measurements, and a quality control system for the satellite data was developed. Next, the satellite data were assimilated into the model using a sequential optimum interpolation scheme (Fig. 7.8). The results show a significant improvement with assimilation. In particular, an overestimation of SPM is avoided (Fig. 7.9). However, further work is required to improve the assimilation procedure. From the point of view of satellite data providers, it is necessary to supply uncertainty estimates on a pixel-by-pixel basis. From the modeller's perspective, the weighting of satellite data with respect to these uncertainties, and in particular to the areas which are masked by clouds, have to be optimized.

7.5   Concluding Remarks

In spite of the unresolved problems surrounding the quantitative interpretation of water colour in complex turbid water environments, optical remote sensing remains a unique and useful tool to assess water quality at synoptic scales. Its applications
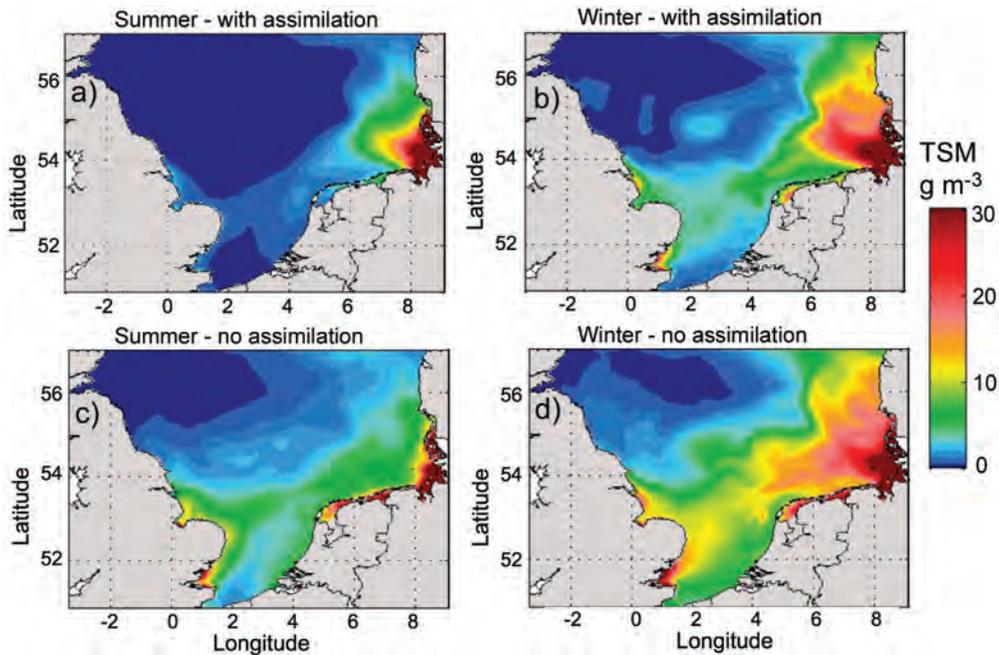
Figure 7.9 Seasonal mean TSM surface concentrations (g m^{-3}) calculated by the model with assimilation of satellite data for (a) the calm summer period, 15 April - 15 October, and (b) the winter period with more storms, 15 October - 15 April. The same calculation without data assimilation is shown in (c) for summer and in (d) for winter conditions. (Image provided by Gerhard Gayer and Mikhail Dobrynin (GKSS, Germany), MERIS data provided by the European Space Agency).

in operational management of aquatic environments are growing and capturing the interest of more end-users in different sectors. In parallel, the scientific and technical communities continue to search for better bio-optical models in optically-complex waters. Recent development of hyperspectral sensors (Bukata and Helbig, 2004; Dickey 2004) which provide coverage over the full spectrum of visible wavelengths, offer new opportunities to discriminate optical boundaries, and hence, to classify turbid waters and quantify individual components such as phytoplankton species and chemical compounds.

A Window on the State of the Marine Ecosystem

Trevor Platt and Shubha Sathyendranath

8.1 Ecological Indicators

There is a developing global consensus that management of the oceans should be ecosystem based, and that the integrity of the ecosystem should not be compromised (Garcia and Cochrane, 2005). A requirement has therefore developed for ecological indicators that quantify the elusive ecosystem properties of health, vigour and resilience. Indicators provide objective metrics of ecosystem properties that can be applied serially and operationally to detect changes that may occur in response to environmental perturbation.

A variety of ecosystem indicators have been proposed (reviewed by Rice, 2003; Platt and Sathyendrenath, 2008). These range from theoretically-simple indicator species, which, like the canary in a coal mine, convey information on the entire ecosystem, to quantitative attributes of the ecosystem revealed by ecosystem models. An ideal ecosystem indicator is objective, quantifiable in standard units, and has a non-contentious meaning. It should be available at high spatial and temporal resolution, in a cost-effective manner, to permit the construction of time series such that ecosystem change can be detected in a timely manner. Remotely-sensed, ocean-colour radiance data meet these stringent conditions. The retrieved variable, phytoplankton biomass, is an important property of the ocean ecosystem, broadly understood and expressible in standard units. Resolution in space and repeat frequency of sampling are beyond reproach.

Several metrics developed from serial ocean-colour data may prove to be useful indicators of the state of the ocean ecosystem (Table 8.1). Of course, it is not expected that ocean colour could provide indicators on all properties relevant to ecosystem-based management, but certainly it will provide, in an extremely cost-effective manner, objective indices of the near-real-time condition of the pelagic system. For example, autotrophic biomass and primary production, both of which can be estimated from ocean-colour data, are important pelagic ecosystem properties. The high frequency repeat sampling of ocean-colour data provides sufficient data to describe seasonal dynamics and make interannual comparisons

(Yamada and Ishizaka, 2006; Wu *et al.*, 2008a). The AVHRR series of SST is a source of complementary data about the physical environment, on the same scales of time and space.

Table 8.1 Ecological indicators of the pelagic ocean that can be derived from ocean-colour radiometry (Platt and Sathyendranath, 2008).

Indicator	Label	Dimensions
Initiation of spring bloom	b_i	[T]
Amplitude of spring bloom	b_a	[ML^{-3}]
Timing of spring maximum	b_t	[T]
Duration of spring bloom	b_d	[T]
Total production in spring bloom	b_p	[ML^{-2}]
Annual phytoplankton production	P_Y	[ML^{-2}]
Generalised phytoplankton loss rate	L	[ML^{-3}T^{-1}]
Integrated phytoplankton loss	L_T	[ML^{-3}]
Annual-scale f-ratio	f	Dimensionless
Spatial variance in biomass field	σ_B^2	[M^{2}L^{-6}]
Spatial variance in production field	σ_P^2	[M^{2}L^{-4}]
Phytoplankton functional types	NA	NA
Delineation of biogeochemical provinces	NA	NA
Phytoplankton size structure	s	Dimensionless

Ocean colour radiance data streams provide a rich resource for construction of time series, where serial images can be arranged to display the seasonal evolution of the chlorophyll fields, and the variations between years in these seasonal cycles (Platt and Sathyendrenath, 1988). The significance of these time series is that they offer a way to quantify the response of the ocean ecosystem to perturbation, natural or anthropogenic. They provide a rapid and cost-effective way to detect change in the magnitude and spatial distribution of a major ecosystem property, the autotrophic biomass.

8.1.1 Indicators Describing the Spring Bloom

In temperate latitudes, the spring phytoplankton bloom is the dominant component of the seasonal cycle. At each and every pixel in the region of interest, the spring bloom can be characterized with respect to amplitude (b_a), using the chlorophyll time series (Fig. 8.1, Table 8.1). Using satellite ocean-colour data we can also establish objectively, using threshold criteria, the time of the spring bloom initiation (b_i), the time of the maximum (b_t) and also the duration of the bloom (b_d). Because these indices (b_i, b_t and b_d) depend only on timing and not on absolute magnitudes (provided the threshold criteria are relative rather than absolute), they are not compromised by any problems arising from merging of different data streams. Using the time series, we can examine how these properties vary between years.
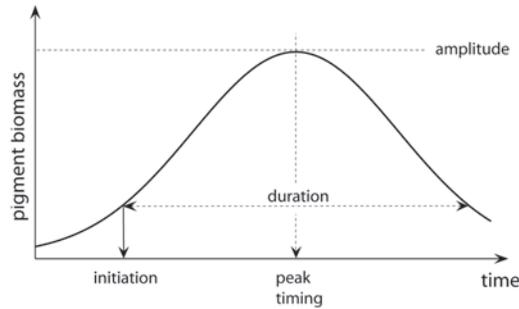
Figure 8.1 Objective characterization of the properties of a spring phyto-plankton bloom at a given pixel from time series of chlorophyll concentration. Defining characteristics are amplitude, initiation, timing of maximum and duration (from Platt and Sathyendranath, 2008).

The spring bloom is the most important event in the seasonal cycle of the ecosystem over much of the ocean. The reproduction of many organisms is timed to coincide with this event and fluctuations between years in its timing may have profound consequences for components of the ecosystem other than phytoplankton. For example, the Cushing-Hjort hypothesis, also known as the match-mismatch hypothesis, relates timing of blooms with timing of spawning and larval mortality of organisms higher in the food chain than phytoplankton. This hypothesis is very difficult to address using only ships as oceanographic platforms. However, it has proved to be more tractable using ocean-colour radiometry (Platt *et al.*, 2003). Thus, when we attempt to account for fluctuations in the abundance of marine species of commercial interest, we now have the possibility to consider the potential effect of changes in the ecosystem itself as a contributing factor.

8.1.2 Indicators Describing Phytoplankton Production

Ocean-colour data can be used to estimate phytoplankton production, also called primary production (Platt and Sathyendranath 1988; 1993; 1999) from which time series can be developed. An operational procedure is also available (Platt *et al.*, 2008). The primary production time series can also be used to describe the timing of the spring bloom. As a rate measurement, primary production can be integrated through time to estimate either the total production in the spring bloom (b_p) or total annual production (P_Y). These estimates of production are key measurements of ecosystem capacity. For example, the spring bloom production is a lower bound on the annual new production, where new production is that production supported by nitrogen supplied from outside the surface layer. Theoretically, the new production represents the nitrogen equivalent that can be removed from the pelagic zone in one year without impacting the overall productivity of the system. Further, the spring bloom production, as a minimal estimate of new production, can be used to calculate

the lower bound of the f-ratio (new production divided by total primary production) which is related to the ratio of production to biomass (Quiñones and Platt, 1991).

8.1.3   Indicators Describing Other Community Processes

Ocean-colour data also provide one of the very few ways we have available to estimate phytoplankton loss, which can be used in coupled ecosystem models and for solving the Sverdrup (1953) equation to forecast the initiation of the spring bloom. Loss terms, such as grazing, respiration, death by pathogens and sinking, are very difficult to estimate. To estimate loss using ocean-colour data, the chlorophyll biomass field is used to predict the biomass field at a later time, and the difference between the predicted and observed biomass fields is an estimate of the loss term (Platt *et al.*, 1991).

8.1.4   Indicators Related to Community Structure

Ocean-colour data can also be processed to yield metrics of phytoplankton community composition and functional groups, which can influence biogeochemical fluxes (Le Quéré *et al.*, 2005). Sathyendrenath *et al.* (2004) have developed an
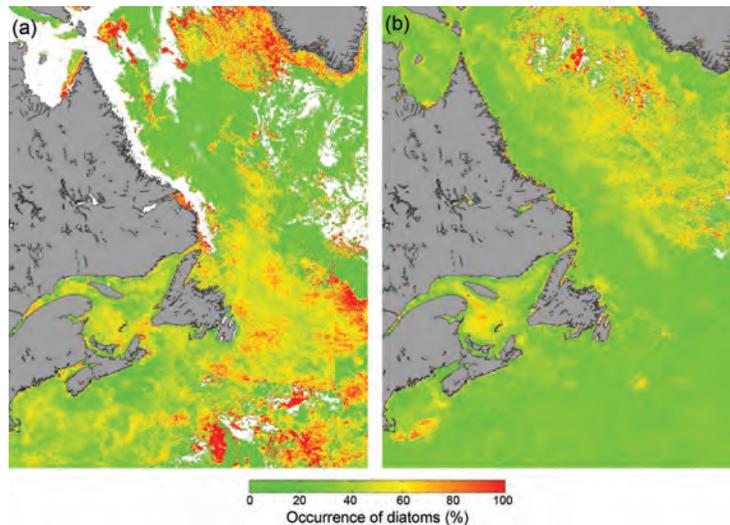
Figure 8.2   Satellite-derived maps showing the probability of occurrence of diatoms in the NW Atlantic, for a two week period in (a) spring (16-30 April 2006) and (b) summer (16-31 August 2006), generated from SeaWiFS data using the algorithm of Sathyendranath *et al.* (2004). Image provided by Emmanuel Devred, Dalhousie University, Canada.

algorithm to assess the dominance of diatoms in a phytoplankton community based on OCR data (Fig. 8.2). Diatoms are of particular interest because they have a high requirement for silicon and are an important flux of carbon to deep water (see
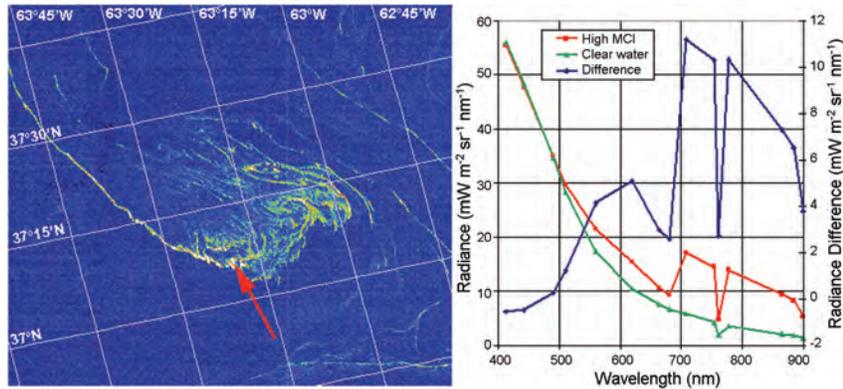
Figure 8.3 Left: Patterns of floating *Sargassum* in the Gulf Stream, imaged by MERIS (300 m resolution) on 22 October 2007 as MCI. Right: TOA radiance spectra for the *Sargassum* region indicated by arrow (red line), and for nearby clear water (green line). The difference (blue line, values on right axis) shows the 'red edge' characteristic of land vegetation, with a shift in wavelength that results in a high value of MCI (after Gower and King, 2008. Image data provided by the European Space Agency).

Chapter 5). Alvain *et al.* (2005) have also developed a procedure to index functional groups, estimates of which can be used in the most recent ocean carbon cycle models.

Given that it carries information on trophic status or chlorophyll biomass, ocean colour may also be indicative of the size structure of the phytoplankton community (Chisholm, 1992; Bouman *et al.*, 2005; Platt *et al.*, 2005), the more eutrophic water being dominated by larger phytoplankton than oligotrophic waters. Further, the absorption spectrum derived from ocean-colour data can also contain information on size structure (IOCCG, 2006). For example, Devred *et al.* (2006) used a two-component model in a variety of oceanic regimes, to estimate the proportion of picoplankton and nanoplankton (see also 'algal effective diameter', Fig. 9.8).

In another study, Gower and King (2008) made use of the MERIS Maximum Chlorophyll Index (MCI) to map of the distribution and movement of the floating seaweed, *Sargassum*, in the Gulf of Mexico and western Atlantic (Fig. 8.3, see also Chapter 7). Their data indicated strong growth early in the year in the Gulf of Mexico, with *Sargassum* moving out into the Atlantic each year in July and August.

8.1.5 Indicators Related to Variance in Chlorophyll Fields

There is a growing belief among those that study the population dynamics of fish, that only a small proportion of individuals contribute to recruitment of the next cohort (Berkeley *et al.*, 2004), with successful spawners being those that spawn in the time and place with the most favourable conditions for larval survival and growth. Berkeley *et al.* (2004) argue that networks of marine protected areas that protect a broad age structure and a broad range of habitats are necessary to conserve

marine populations. The location of these protected areas could be informed by the chlorophyll time series and the indices derived from these time series. Spatial and temporal variance in the chlorophyll time-series could inform the choice of marine protected areas. For example, we might want to protect areas where phytoplankton biomass or production is relatively high.

8.2 Spatial Structure of the Ocean Ecosystem at Large Scale Biogeographical Provinces

Many of the important applications of ocean colour deal with problems that are global in scope. An example is the role of the ocean in the planetary carbon cycle and its significance for climate change. Although the issues are global-scale in character, from an ecological point of view we cannot treat the ocean as being everywhere the same. We can perceive the ocean ecosystem as a suite of contiguous subsystems within each of which the internal interactions dominate over the interactions between subsystems. Thus, the central ocean gyres are different, ecologically, from upwelling regimes, and we expect that the ecophysiological rates in the two environments will be different. We call the regions, so defined, biogeochemical provinces (Platt and Sathyendrenath, 1988). In making global assessments of ecosystem performance, we may therefore adopt an approach in which the contributions of each province would be calculated separately and the results aggregated to the global scale.
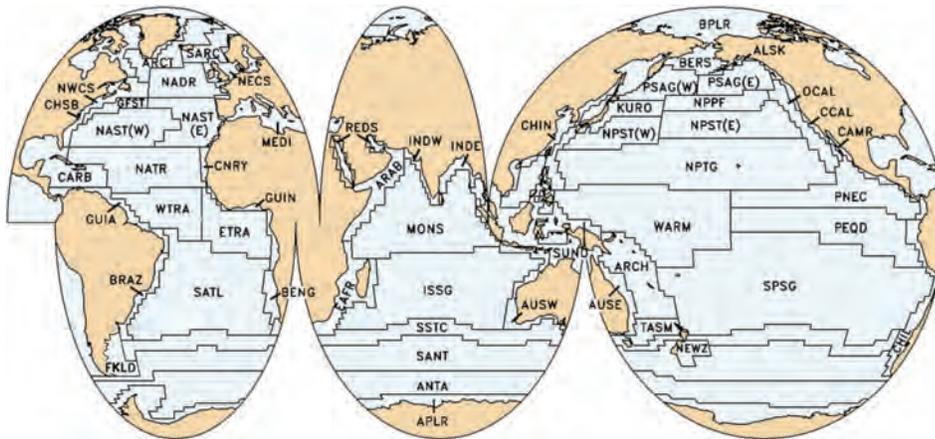
Figure 8.4 Biogeochemical provinces in the ocean, adapted from Longhurst (2006).

To implement this approach, we need first a scheme for partitioning the ocean into a suite of biogeochemical provinces. An example is that produced by Longhurst (2006). Here, the assumption is that phytoplankton ecology is under the control of physical forcing and the partition is made according to the large-scale patterns in the forcing that is relevant to the phytoplankton. The resultant partitioning yields some

sixty provinces at the global scale (Fig. 8.4). In his original publication, conceived with imagery from CZCS, the boundaries between these provinces were rectilinear and schematic in character. It was understood that the boundaries would shift with seasonal progression and between years, in other words that the boundaries would be dynamic. If we want to delineate the boundaries at any particular moment,
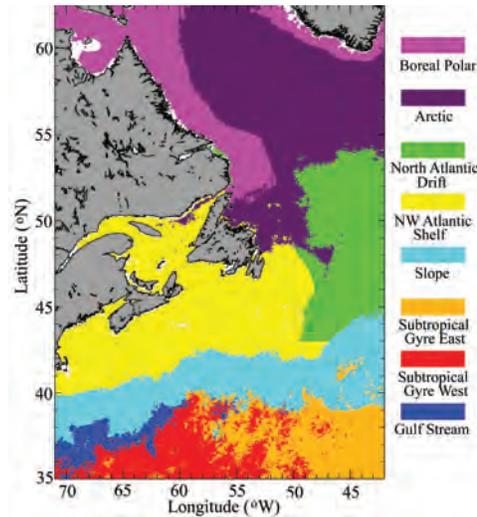
Figure 8.5 Biogeochemical provinces of the Northwest Atlantic Ocean for the year 2006, determined objectively using OCR data. (Image provided by Emmanuel Devred, Dalhousie University, Canada).

remotely-sensed data on ocean colour provide the most useful resource, given that they afford a global-scale view of the pelagic ocean (Platt and Sathyendrenath, 1999; Platt *et al.*, 2005; Devred *et al.*, 2007). In the first instance, OCR is the key by which we can translate the diagrammatic scheme of Longhurst into a less-rigid scheme that reflects the reality of the day (Fig. 8.5). Further, serial study of ocean-colour imagery allows us to see the shifts in the province boundaries between seasons (Fig. 8.6) and between years.

A partition of the ocean constructed in this way has many applications in oceanography and biogeochemistry. It provides an oceanographic context for understanding particular findings. It gives a framework for implementation of algorithms that proceed by weighted integration over diverse spatial blocs. It allows the rich data set acquired by remote sensing to complement the sparse data acquired using ships. Further, it also provides the ideal template for the placement of marine protected areas, which as Berkeley *et al.* (2004) argue, may be most beneficial if placed in different habitats within biogeographical and oceanographic regions.

The development of these methods has been stimulated strongly by the availability of ocean-colour data, and their implementation would be very difficult, if not impossible, without access to ocean-colour data. The first partitioning scheme by Longhurst was inspired by the synoptic chlorophyll fields derived from CZCS,
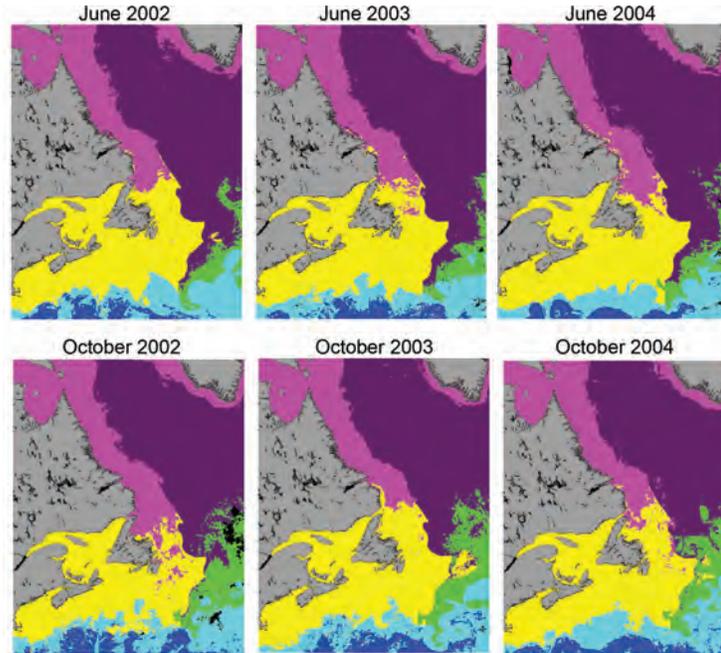
Figure 8.6   Dynamic borders of biogeochemical provinces in the NW Atlantic in June and October over 3 years (2002-2004). Colour scheme is the same as for Fig. 8.5 (Image provided by Emmanuel Devred, Dalhousie University, Canada).

and its refinement to incorporate short-time variability is achievable only through currently-flying sensors. To this extent, the disaggregation of the ocean into a suite of biogeochemical provinces as an aid to research and understanding can be seen as a major contribution of the ocean-colour initiatives undertaken some thirty years ago.

8.3   Conclusions

Even with only two remotely-sensed variables (chlorophyll and temperature), a rich set of ecological indicators can be derived (Table 8.1). Access to ancillary *in situ* data improves the interpretation of ocean-colour time series. Although one of the defining advantages of the use of ocean colour in the development of ecosystem indicators is the potential to provide indicators on an operational basis, further research holds promise of improved understanding of the ecosystem and indicators of health, integrity and resilience. With an emphasis on quality control, remotely-sensed data can be useful for construction of time series. Time series provide cost-effective basis for development of ecological indicators, averaged at appropriate time and space scales. The 10-year series of SeaWiFS has already yielded some interesting results, and we should strive to maintain continuity of a reliable ocean-colour data stream.

Hazards: Natural and Man-Made

Heidi Dierssen, James Acker, Stewart Bernard and Grant Pitcher

Ocean basins, regional seas, and coastal margins are subject to a variety of hazards that can occur suddenly, periodically, or slowly resulting from changes to climate and the environment. Broadly defined by the United States Department of Defense, a hazard is "Any real or potential condition that can cause injury, illness, or death to humans; damage to or loss of a system, equipment or property; or damage to the environment". Episodic hazards can restructure the coastal zone, greatly impacting marine and estuarine ecosystems as well as residential communities residing along the coasts. Over one-third of the total human population, nearly 2.4 billion people, lives within 100 km of an oceanic coast, a fact emphasized by the devastating tsunami in the Indian Ocean in 2004. Hazardous events, such as hurricanes and tsunamis, often originate in areas distant from where they eventually have the most significant impact, and occur on space and time scales that can only be resolved from satellite imagery. While some hazards are considered 'natural' in origin (*e.g.*, earthquakes, storms), anthropogenic changes to the environment have increasingly contributed to the frequency, magnitude, and duration of many hazards confronting humans and the environment.

The human population is growing; more people are living closer to the ocean and the human footprint on the oceans, particularly the coastal zone, is markedly increasing. In order to better evaluate relationships between natural and anthropogenic hazards, the following sections categorize hazards based on their relative time scales. Hazards can be broadly divided into two categories: acute versus chronic (Table 9.1). Some examples of acute hazards include tropical storms, flooding and river runoff, earthquakes leading to tsunamis, spills of toxic or noxious substances, harmful or toxic organisms, and icebergs. Long-term or chronic hazards facing marine ecosystems include increasing sea surface temperature, acidification (lower pH), increased sea level, changing water properties *e.g.* due to influx of glacial melt-water, and increased eutrophication due to nutrient fertilization in the coastal zone. Chronic changes to the ocean environment provide new conditions to which marine organisms must acclimate for survival, and new habitats for water-borne pathogens to be spread. Chronic hazards also have the potential to contribute to acute hazards. For example, increased sea surface temperatures can increase the

frequency and intensity of tropical storms (Emanuel, 2005; Webster *et al.*, 2005). Table 9.1 presents a list of some known hazards that confront the world's oceans and the resulting impacts on the oceanic ecosystems, both to physical characteristics and the ecosystems.

Table 9.1   Selected hazards impacting the ocean.

Hazard	Impact
Acute Hazard	
Tropical storm	Sediment plumes, beach erosion, loss of benthic habitats, resuspension of toxins, increased pathogens
Tsunami	Sediment plumes, beach erosion, loss of benthic habitats, resuspension of toxins, increased pathogens
Chemical spill	Toxic plumes, mortality of plankton/nekton
Flooding/river runoff	Sediment plumes, anoxia, hypoxia, harmful algal blooms, increased toxins and pathogens
Iceberg	Navigation problems, altered sea ice patterns and associated food webs
Chronic Hazard	
Chronic sea surface warming	Altered thermohaline circulation, coral bleaching, delay or prevention of sea ice formation, seasonal timing altered, increased tropical storms with associated impacts, altered food web, increased pathogens
Increasing acidity	Prevention of calcification (corals, pteropods, etc.), altered food web
Rising sea level	Coastline changes, altered benthic habitats
Glacial melt-water	Stabilized water column, prevention of deep-water formation/circulation, decreased light penetration, increased productivity, altered food web
Nutrient fertilization	Harmful algal blooms, anoxia, hypoxia, loss of benthic habitats, altered food web

The following sections present the potential uses of ocean-colour radiometry for detecting episodic hazards and the impacts of both acute and chronic hazards on marine ecosystems. Impacts on the terrestrial environment and human life and property are not directly discussed here, but the oceans are the largest publicly-shared domain and consequences on marine ecosystems affect all spheres of life.

9.1   Monitoring Hazards with Ocean-Colour Radiometry

Ocean-colour sensors are not specifically designed to make the very detailed observations required for high temporal tracking of episodic events and high spatial resolution to resolve fine-scale features. Many acute hazards, however, can be observed using the current suite of ocean-colour satellites. Polar orbiting ocean-

colour sensors have repeat global coverage every 2-3 days at the equator, with daily coverage at higher latitudes. In the mid-latitudes, hurricanes can be tracked nearly daily via the SeaWiFS, MODIS and MERIS sensors (Fig. 9.1). These true colour images can be derived at 250 m resolution, a finer resolution than available from geostationary platforms like the current weather satellites (*e.g.*, GOES). Such high resolution imagery can resolve the track and spatial extent of intense storms with greater accuracy and aid in development of better predictive storm models.

Figure 9.1 Hurricane Ivan over the Gulf Coast of the U.S, captured by SeaWiFS on 15 September 2004. Ivan attained Category 5 strength with winds reaching 270 km h^{-1}. (Credit: Ocean Biology Processing Group, NASA/GSFC and GeoEye).

Earthquakes that occur along the ocean bottom can displace the seafloor several metres and result in large oceanic waves called 'tsunamis.' Tsunamis can move at roughly 640 km hr^{-1} across the seafloor. The waves slow down when they reach shallow water near land and the accompanying reduction in speed and wavelength results in increased height and steepness as the wave's energy is condensed in a smaller water volume. As evident in the December 2004 tsunami that struck southeast Asia, massive tsunami waves have been among the deadliest natural disasters in modern history. Remotely-sensed imagery of tsunamis is more difficult to obtain from traditional satellite platforms due to their rapid speed and fine spatial scale. Moreover, nadir-viewing ocean-colour imagery does not necessarily detect wave fields, unless they are associated with corresponding shifts in ocean colour. However, multi-angle imagers, like the MISR (Multi-angle Imaging SpectroRadiometer) instrument aboard the Terra satellite, have been used to detect roughness patterns on the sea surface associated with large waves. The waves are made visible due to the effects of changes in sea-surface slope on the reflected sun-glint pattern. For example, imagery of wave patterns and wave-breaking associated with the devastating

December 2004 tsunami, were observed with MISR's 46-degree forward pointing camera, but were invisible to MISR's nadir (vertical-viewing) imager (Fig. 9.2). MODIS-Aqua data were used to assess the post-tsunami effects on chlorophyll and turbidity in the area (Tan *et al.*, 2007).
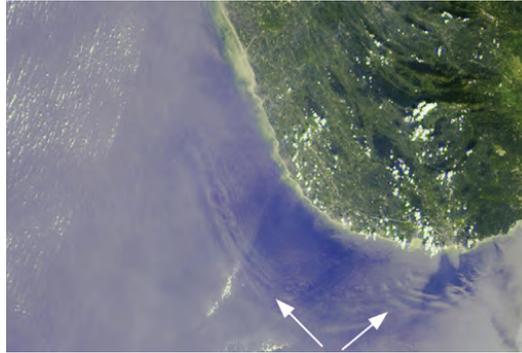
Figure 9.2 At approximately 05:15 UTC on 26 December, 2004, the Multi-angle Imaging SpectroRadiometer (MISR) aboard the Terra satellite captured this image of deep ocean tsunami waves about 30-40 km from Sri Lanka's south-western coast. (Credit: NASA/GSFC/LaRC/JPL, MISR Team).

Episodic flooding of coastal regions due to intense storms or tsunamis can also be observed with ocean-colour imagery. Land surfaces overlain by water have lower spectral reflectance and the spectrum is generally limited to visible wavelengths; separation of the land from water can thus be accomplished with relatively simple techniques. To date, most of the remote sensing analyses of floods have primarily been done with true or false colour images derived from the sensors aboard satellites or portable airborne sensors, including airborne active lidars, and are verified with time-series of images taken before and after a major flood event. Flood water can be difficult to see in true colour satellite images, particularly when the water is muddy. A combination of visible and infrared light can be used to make floodwaters more obvious (see Fig. 9.3).

From the recent accomplishments in radiative transfer modelling in optically-shallow water (as discussed further in the following sections on shallow water bathymetry and benthic habitat characterization), potential exists for estimating the water depth and water properties of flood regions using high resolution ocean-colour imagery.

As snow accumulates on polar landmasses, it compacts and forms ice. As ice builds up, it flows outward into floating shelves and is sloughed off or 'calved' from the front of the glacier as an iceberg. Global warming has apparently increased the rate of ice stream flow in Greenland (Zwally *et al.* 2002) and led to the disappearance of Antarctic ice shelves. Icebergs can hinder navigation along shipping lanes and significantly alter the water column properties. In addition, icebergs can disrupt sea ice patterns, phytoplankton blooms and survival of higher trophic levels, such
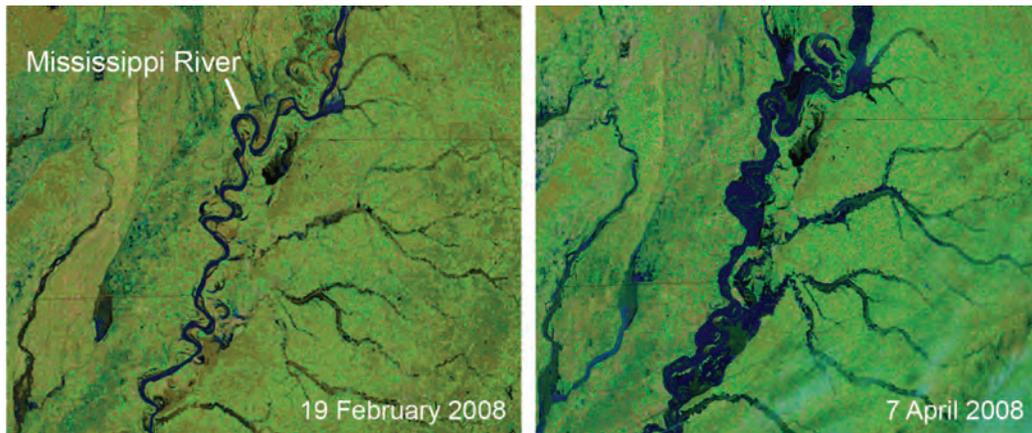
Figure 9.3 These photos were captured by NASA's MODIS-Terra sensor before and after the spring rains caused widespread flooding of the Mississippi River in March 2008. Water levels on the Mississippi River were still high on 7 April 2008 (Credit: MODIS Rapid Response Team, NASA/ GSFC).

as pteropods (pelagic snails) and penguins (Arrigo *et al.*, 2002; Seibel and Dierssen 2003). Ocean-colour imagery has been employed to identify and track the path of icebergs. In March 2000, one of the largest icebergs ever recorded calved from the eastern Ross Ice Shelf, Antarctica. In a few weeks the iceberg, named B-15, split into several pieces, the largest of these being B-15A which has persisted in McMurdo for several years (Fig. 9.4). Even this fragmented iceberg, approximately 160 km in length and 200-270 m in thickness along its centerline, contained enough drinking water to supply the world for several months. SeaWiFS imagery was also used to assess the impact of icebergs on phytoplankton biomass (Schodlok *et al.*, 2005).
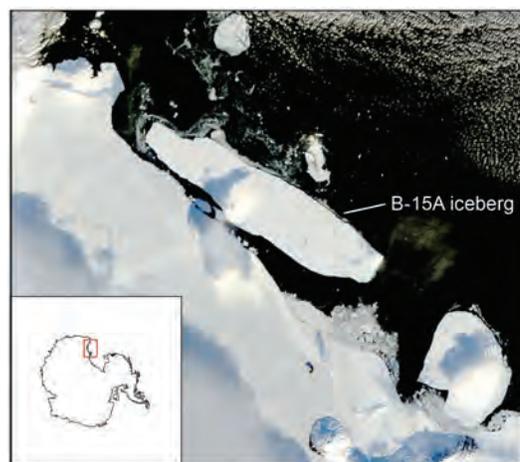
Figure 9.4 True-colour image of the iceberg B-15A in McMurdo Sound, Antarctica, captured by NASA's MODIS-Terra satellite on 13 December, 2004 (Credit: Jeff Schmaltz, MODIS Land Rapid Response Team at NASA GSFC).

In addition, input of glacial melt-water into the coastal regions can change the water clarity and enhance reflectance due to the addition of fine particles (*i.e.*, 'glacial flour'), add potentially limiting nutrients like iron, enhance the stability of surface waters, and impact sea ice cycles. The input of pulsed inputs of melt-water was shown to increase productivity up to hundreds of kilometres offshore along the Antarctic Peninsula (Dierssen *et al.*, 2002).

Harmful impacts of phytoplankton blooms are often associated with the release of biotoxins by certain species present in the algal assemblage. Marine biotoxins, such as domoic acid, saxitoxins and okadaic acid are some of the most potent toxins in the world and extremely dangerous. For some compounds, doses at the level of μg kg^{-1} are more than sufficient to kill. Ocean colour cannot directly monitor chemical compounds such as biotoxins in the water column. However, as discussed later in this chapter, ocean-colour radiometry does have utility in monitoring harmful algal blooms (HABs).

Some of the chronic hazards listed in Table 9.1, such as increases in sea surface temperature and height, can be tracked by satellites. However, most of the chronic hazards themselves are not directly observable with ocean-colour sensors. Parameters like pH and nutrient concentration cannot be monitored directly from space, but may be correlated to parameters derived from ocean colour. Sea surface nitrate, a required nutrient for phytoplankton primary production, for example, can be estimated indirectly from remotely-sensed sea surface temperature and chlorophyll (Goés *et al.*, 2000). As discussed in the following section, ocean-colour parameters may be used to evaluate many of the impacts of chronic hazards, including sediment plumes, alterations in food webs, harmful algal blooms, and changes to ocean circulation.

9.2 Assessing the Impact of Hazards with Ocean-Colour Radiometry

Hazards can impact the biology, chemistry, physics, and geology of the world's oceans with diverse and frequently deleterious impacts on marine ecosystems. Here we outline a few potential impacts arising from both acute and chronic hazards (*e.g.*, sediment plumes, harmful algae blooms and loss of benthic habitat) and the potential for using ocean-colour imagery to monitor and assess these changes to the ocean environment.

9.2.1 Sediment Plumes

Precipitation events, storm surges and high wind conditions may transport sand, mud and other debris into coastal waters creating sediment plumes which can be distinguished by their reflective characteristics. Such plumes may cover expansive

regions of the coastline. These plumes play a significant role in the overall terrestrial sediment discharge into the coastal regime and the development of bottom topographic features. In addition, flood events can spread pollutants and alter biological productivity. Sediments contain chemical elements such as carbon, copper, and phosphorus, which affect the chemistry of the oceans. Sediments also impact shallow reef communities by reducing light penetration and burying rocky substrate favourable to algal and invertebrate colonization. Plumes of sediment can also occur from catastrophic collapse of benthic vegetation that serves to stabilize sediments (Stumpf *et al.*, 1999). The spread of plumes is contingent upon the mesoscale circulation that includes gyres, meanders, filaments, and fronts from tens to hundreds of kilometres in size and from days to months in duration.

Sediment-laden water is so distinct from typical coastal water that many plumes can be delineated using simple Red-Green-Blue (RGB) true-colour images from space (Fig. 9.5). Such true-colour images have been used to locate intense plumes after

Figure 9.5 This image of the Rio de la Plata estuary (South America) was acquired by the MERIS sensor on 17 April 2004, and shows the thick sediment plume transported by the Paraná and Uruguay Rivers into the estuary. (Credit: European Space Agency).

rainstorms or other turbidity events, and are useful for delineating the extent and aerial dimensions of a sediment plume. This visual analysis can be done with single channel sensors or even uncalibrated photographs.

In addition to the identification of plumes, the spectral information from ocean-colour imagery can also be used to quantify the amount of suspended material, also referred to as total suspended sediment (TSS), total suspended matter

(TSM), suspended particulate matter (SPM), or suspended particulate inorganic matter (SPIM) (see also Section 7.4). When major discharge events occur along the coast, the bio-optical properties of the water column become decoupled from the phytoplankton and the majority of the water-leaving radiance is attributed to light backscattered from suspended sediment. Minerals have a large refractive index and high backscattering and can produce reflectance spectra that are several orders of magnitude greater than water with other constituents, particularly in the near-infrared portions of the spectrum.

Algorithms developed to estimate the amount of suspended sediment, reaching up to several hundred mg l^{-1}, are numerous and vary in complexity and accuracy. By far the most widely published approaches are simple empirical relationships between suspended sediments and absolute reflectance at one or more combination of wavelengths or empirical combinations of wavelength ratios. The underlying statistical architecture of these models can include logarithmic and/or quadratic forms. Other approaches rely on libraries of reflectance spectra and suspended matter coupled with various mathematical techniques, such as spectral mixture analysis (Warrick *et al.*, 2004) or neural networks (Schiller and Doerffer, 1999, Chapter 7). Due to the variability in colour, shapes, and size distributions of sediment particles, however, global models for remotely estimating sediment concentrations are still elusive. Optical approaches based on inherent optical properties, *i.e.*, that include estimates of the index of refraction from the backscattering ratio and the spectral slope of the particulate attenuation coefficient, which can be related to particle size distribution, may hold the most promise for a global model for quantifying sediment. Regional algorithms have currently proven to be far more successful than a single global suspended sediment concentration algorithm.

Over the past 30 years, suspended sediment has been quantified in coastal regions throughout the world using various ocean-colour sensors from the nominal 1-km resolution satellite sensors to higher resolution satellite imagers with less spectral information including MODIS (250 m), Landsat series (30 m), Quickbird, IKONOS, to airborne imagers such as the Airborne Visible-Infrared Imaging Spectrometer (AVIRIS), PHILLS, and CASI. The ideal instrument for mapping future plumes would have high spatial resolution, high spectral resolution, and a frequent revisit time.

In the search for global models to enumerate sediment concentration, the underlying accuracy of the retrieved sea spectral reflectance cannot be stressed enough. Traditional oceanic approaches for atmospheric correction rely on the near infrared portion of the spectrum to correct for atmospheric aerosols (Gordon and Wang, 1994). As described above, however, sediment contributes significantly to reflectance at these wavelengths. Reliable, repeatable approaches to estimate sediment concentrations from satellites and aircraft, therefore, will rely on accurate atmospheric correction of the imagery, including an understanding of coastal aerosol plumes that also absorb and backscatter light and glint from the air-water interface, as well as an understanding of other backscattering constituents in the water such

as phytoplankton, detritus, bubbles, and seafloor reflectance, when applicable.

9.2.2 Altered Food Webs

Many of the acute and chronic hazards discussed above can alter the species composition of phytoplankton populations and thereby impact higher trophic levels. Various approaches for using ocean-colour imagery to identify specific phytoplankton species, taxonomic groups, or cell sizes rely on the specific absorption and backscattering properties of the phytoplankton. Chlorophyll-a, the dominant pigment found in all photosynthetic organisms, absorbs light broadly in the blue (400 to 470 nm) region of the visible spectrum, and narrowly in the red (660 nm) region. However, other accessory pigments found in phytoplankton, such as chlorophylls-b and -c, phycobiliproteins, and carotenoids, allow organisms to harvest more of the incident blue and green light. Phytoplankton from different taxa generally have unique sets of accessory pigments that differentiate them from one another and can result in unique absorption spectra that could impact the spectral nature of water-leaving radiance. When evaluating the total absorption spectra, however, many diverse phytoplankton groups share similar spectral shapes (Sathyendranath *et al.*, 1987; Morel, 1988). This is especially true when the differences are reduced to the spectral resolution available in most current ocean-colour satellites which have only 6 to 8 visible available spectral channels (Dierssen *et al.*, 2006).

However, several phytoplankton groups have been distinguished from satellite imagery based on their unique optical properties and/or regional tuning of algorithms using knowledge of the local phytoplankton composition. Select examples illustrating the various approaches are presented below and are not meant to be inclusive of all the research in this growing field (see also Chapter 8). The NASA Ocean Biogeochemical Model (Gregg, 2007) uses ocean-colour imagery from SeaWiFS coupled with a physical-biogeochemical model for diagnostic identification of phytoplankton functional groups. Another global model recently developed differentiates between four major groups of phytoplankton from ocean-colour imagery (Alvain *et al.*, 2005). Global distributions of nitrogen-fixing cyanobacterium, *Trichodesmium*, have been mapped using ocean-colour imagery (Westberry and Siegel, 2006). Approaches have also been developed to estimate the concentrations of nuisance cyanobacteria in turbid eutrophic waters from ocean-colour satellite imagery (Simis *et al.*, 2005). Local algorithms have been developed to estimate species in a variety of regions worldwide (*e.g.*, concentrations of diatoms in the North West Atlantic, Sathyendranath *et al.*, 2004). Blooms of the toxic dinoflagellate, *Karenia brevis*, in the Gulf of Mexico are routinely monitored using species-specific algorithms applied to ocean-colour imagery coupled with ancillary information such as wind stress, field observations, and weather forecasts (Stumpf *et al.*, 2003). Highly backscattering phytoplankton, such as surface-dwelling coccolithophores and the detached coccoliths, can also be observed using OCR data (Balch *et al.*, 1999; 2005).

In natural communities, the cell size of the dominant phytoplankton organism, varying from picoplankton (<2 μm), ultraplankton (2-5 μm), nanoplankton (5-20 μm), to microplankton (>20 μm), can explain over 80% of the variability of the spectral shape of the phytoplankton absorption coefficient (Ciotti *et al.*, 2002). Large microplankton absorb less light per mg of chlorophyll than small picoplankon. Correspondingly, recent efforts have been directed at estimating phytoplankton cell size directly from ocean-colour imagery (Ciotti and Bricaud, 2006). Such an approach can be useful in detecting shifts in ocean ecosystems from larger microplankton, such as diatoms, to predominantly picoplankton, such as *Prochlorococcus*, which would have significant implications for the trophic web.

Responses of coastal regions linked to terrestrial changes can also be observed with ocean-colour imagery. For example, warming of the Eurasian landmass has led to enhanced productivity in the water column (Goés *et al.*, 2005). In a similarly dramatic example, agricultural runoff from fields in Mexico was shown to stimulate large phytoplankton blooms in the Gulf of California (Berman *et al.*, 2005). Such large blooms stimulated by terrestrial forces distant from the region can alter water clarity, change the trophic structure of the water column, and potentially lead to anoxic conditions.

9.2.3 Harmful Algal Blooms

Ocean-colour radiometry offers cost-effective, frequently acquired, synoptic data pertaining to phytoplankton biomass in surface waters, and is thus of considerable value in monitoring and better understanding harmful algal blooms (HABs). These are an increasingly frequent occurrence in coastal waters around the globe, often resulting in severe negative impacts to local marine ecosystems and communities, in addition to commercial marine concerns such as aquaculture operations (Hallegraeff, 1993). Harmful impacts of algal blooms, often composed of a variety of dinoflagellate species (Fig. 9.6), are associated primarily with the toxicity of some species present in the algal assemblage, or the high biomass such blooms can achieve in highly eutrophic systems. Upwelling systems provide dramatic examples of these impacts, where collapse of high biomass blooms through natural causes such as nutrient exhaustion can lead to hypoxic events and in extreme cases, the production of hydrogen sulphide, causing extensive mortalities of marine organisms (Fig. 9.7).

Ocean-colour radiometry can play an important role in effective ecosystem management with regard to HABs: routinely acquired synoptic data relating to phytoplankton dynamics allows both a greater understanding of the variability of HABs as ecologically prominent phenomena, in addition to a means of detecting and monitoring blooms in real time (Ryan *et al.*, 2002).

All phytoplankton are intimately connected to their physical environment and are subject to horizontal transport. The ability to understand HAB growth and movement in coastal systems depends fundamentally on understanding not only causative

Figure 9.6 The majority of harmful algal blooms are attributed to dinoflagellate species, and the harmful impacts are associated with either their high biomass or toxic properties. Depicted in this figure are some of the bloom-forming dinoflagellates common in the Benguela upwelling system, including *Alexandrium catenella* (2nd on top), *Dinophysis fortii* (3rd on top) and *Dinophysis acuminata* (2nd on bottom), three of the most common toxic species in the Benguela. (Image provided by Grant Pitcher, Marine and Coastal Management, South Africa).

biological processes and typical patterns of phytoplankton species succession, but also the physical environment in which HABs occur. Time series of ocean-colour products, in conjunction with other remotely-sensed data such as sea surface temperature, can improve understanding of regional forcing and transport mechanisms. Analyses such as these not only improve our understanding of why and when HABs are likely to occur, but also greatly improve our ability to predict HAB occurrence operationally (Stumpf *et al.*, 2003; Pitcher and Weeks, 2006).

Natural resource managers and public health officials need better tools to detect and monitor HAB events so that mitigation actions can be effectively taken. Bio-optical systems, including remotely-sensed ocean-colour data, offer a cost-effective means of obtaining real-time data relating to the algal assemblage using a variety of platforms, sensor systems, and processing techniques ranging from standard empirical products to the use of sophisticated analytical inversion algorithms (a recent synopsis of available techniques can be found in Glen *et al.*, 2004). Analytical reflectance inversion algorithms in particular offer the ability to derive information on the type of algal assemblage present in the water, in addition to gross algal biomass (IOCCG, 2006). Such algorithms also allow the derivation of other water constituents, such as sediment concentrations and algal degradation products, which may be of utility in assessing environmental control mechanisms. An example of the approach can be seen from MERIS images of southern Benguela (Fig. 9.8), showing

Figure 9.7 Many marine mortalities are attributed to harmful algal blooms and associated with either hypoxic or toxic events. The above stranding of 2,000 tons of rock lobster on the South African west coast was caused by declining oxygen concentrations to below detectable levels following the decay of a bloom of the dinoflagellate *Ceratium furca*. (Credit: Grant Pitcher, MCM, South Africa).

the detection of the change of dominant assemblage during a high biomass bloom event. *In situ* sampling confirmed that the dominant HAB species had changed from the small dinoflagellate *Prorocentrum triestinum* to the large celled *Ceratium furca*. The approach also offers a significant advantage in that it allows the derivation of equivalent geophysical products from *in situ*, airborne, or space-based sensors. This offers the ability to use analogous multi-platform derived data measured on a variety of temporal and spatial scales, *i.e.*, Eulerian high frequency mooring-derived data and daily synoptic satellite-derived data.

There is a great need for satellite observations at higher spatial resolution to monitor near-shore regions, estuaries and fjords where fish farms or shellfish beds are frequently located. NASA's MODIS-Aqua sensor has the capability to capture data at both 250 m and 500 m spatial resolution, although only two of the 500 m bands and one 250 m band have centre wavelengths in the visible spectrum. Shutler *et al.* (2007) recently developed a dynamic atmospheric correction approach to use these bands to retrieve chlorophyll. ESA's MERIS sensor currently offers the best capability with a 300 m resolution for all 15 wavebands, and 1-3 day revisit time. Figure 9.9 shows a MERIS image of a bloom of harmful *Karenia mikimotoi* to the east of the Orkney Isles, Scotland. MERIS 300-m resolution data are now available in near-real-time via a rolling archive over Europe and North America, which should enhance the use of ocean-colour data in near-shore environments.

Improving and expanding the forecasting capabilities offered by remote sensing technologies will provide rapid and spatially-broad information. This information
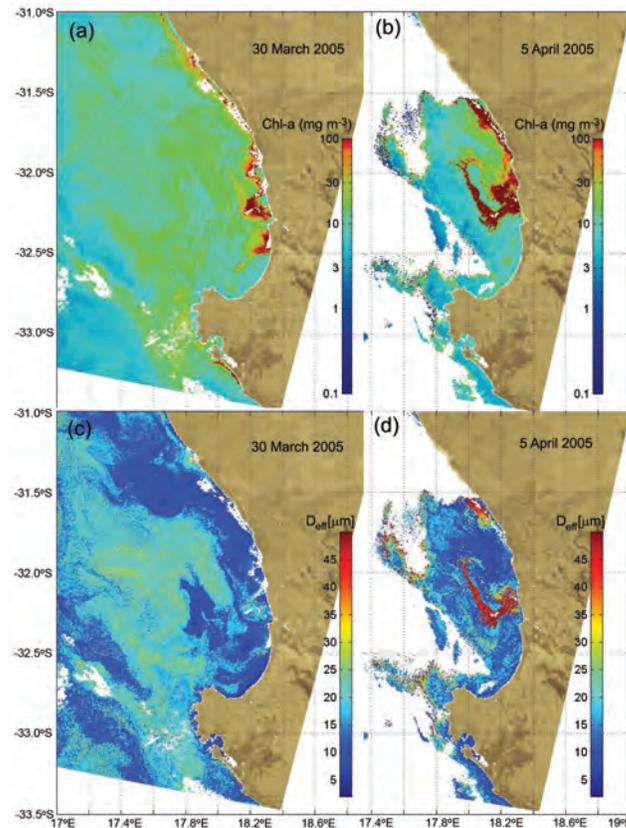
Figure 9.8 Experimental analytical reflectance products showing the complex spatial distribution of a high biomass HAB event in the southern Benguela, and a change in the HAB assemblage in response to environmental conditions. Panels (a) and (b) show Chl-a concentrations approximately one week apart, while (c) and (d) depict the algal effective diameter, indicating a change to a large-cell dominated assemblage in (d). (Credit: Image provided by Stewart Bernard, CSIR-NRE, South Africa, MERIS data provided by the European Space Agency).

will permit monitoring of the environmental conditions that promote HAB formation as well as the tracking of HABs as they transit through a region. Making user-focussed ocean colour and other remotely-sensed products more widely available and easy to use is central to the more effective use of ocean colour for HAB applications. The ChloroGIN programme (Chlorophyll Globally Integrated Network), under the auspices of GEO (Group on Earth Observations) and GOOS (Global Ocean Observing System) aims to play a key role in making HAB-related products more accessible to a wide variety of users though web-based dissemination systems. Ocean-colour algorithm development is also of considerable importance, as information on assemblage type in addition to biomass are vital for HAB applications, and such research is ongoing internationally.

Remote sensing has an important role to play in improving our understanding
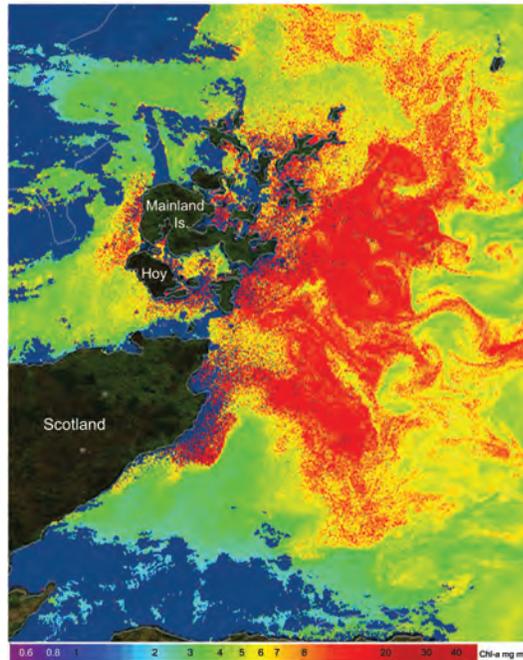
Figure 9.9 A bloom of harmful *Karenia mikimotoi* to the east of the Orkney Isles, Scotland captured by MERIS in full-resolution mode (300 m) on 31 July 2006. (Credit: Image provided by Steve Groom, Plymouth Marine Laboratory, UK. MERIS data provided by the European Space Agency).

of HAB ecology, and will be of greater value if used as part of an integrated ecological approach to understanding HABs. The efforts of the international scientific programme, the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB, 2001), are central to these efforts, and the GEOHAB comparative approach across coastal ecosystems will do much to improve global understanding of the ecology of potentially harmful phytoplankton blooms. Such an integrated approach is also needed for the development of a predictive ability for HABs through a wide variety of ecosystems, and these HAB forecasting abilities will have considerable societal benefit. Ultimately, it would be hoped to establish forecasting structures operating in key areas around the globe in near real-time, utilising probabilistic ecological and nested 3D physical models in conjunction with data from a variety of multi-sensor observation platforms. Ocean-colour data will form a critical component of these structures.

9.2.4   Shallow Water Bathymetry

Shallow water is a hazard to navigation, and remote sensing can be a valuable tool to update charts when depths are changed by storms or floods. Accurate shallow water bathymetry is technically achievable using ocean-colour data. The 0 to 20 m

water depth is frequently lacking in most coastal databases because hydrographic survey vessels do not navigate in these near-shore regions. Remote sensing has the capability to monitor coastal benthic features and associated water column properties, using sensors that have spatial resolution of few metres (*e.g.* SPOT-HRV, Landsat TM). These sensors have a limited set of wavelengths in the visible, but the spectral contrast between various bottom structures can be used to construct classification algorithms based on differential reflectance (Andréfouët *et al.*, 2001; Hochberg *et al.*, 2003).

9.2.5 Benthic Habitat Loss

Ocean-colour remote sensing is an emerging tool for characterizing changes to benthic habitats in water where the reflectance of the seafloor can be observed or detected from above the water's surface, often referred to as 'optically-shallow water'. Traditionally, the products obtained from ocean-colour satellites have focused on unicellular phytoplankton in the surface layers of the world's oceans, but the imagery can also be used to characterize seafloor reflectance and hence bottom type in optically-shallow water. Understanding of benthic optical properties and light propagation in optically-shallow waters has advanced significantly in recent years and many algorithms have been developed and applied to identify benthic ecosystems. By definition, benthic environments in optically-shallow waters are within the photic zone and receive enough sunlight to support photosynthesis by seagrasses, macroalgae, kelps, and even zooxanthellae living symbiotically with corals. Ocean-colour remote sensing offers a cost-effective approach for mapping and potentially quantifying benthic substrate that is highly repeatable and cost-effective for detecting large scale changes in the benthos, particular in large homogenous regions (Dekker *et al.*, 2006).

Stumpf *et al.* (1999) used AVHRR data, with only one visible channel (580-680 nm) to investigate water column turbidity events and potential presence/absence of seagrasses. Single channel radiometers provide limited information that can be used to uncouple water column constituents (*e.g.*, phytoplankton and sediments) from bottom albedo. Regions of low reflectance were associated with dense seagrasses and/or phytoplankton blooms, while regions of high reflectance were either turbid waters or optically shallow waters with highly reflective bottoms.

Remote sensing has also been used to document resilience in benthic features to hurricanes and other large scale disturbances. Seagrass distributions observed with high resolution imagery from the Portable Hyperspectral Imager for Low Light Spectroscopy (Ocean PHILLS) were analyzed in the eastern portion of the Bahamas Banks near Lee Stocking Island. Meadows varied from sparse (leaf area index <0.5) to very dense (leaf area index >2) over metre scales (Dierssen *et al.*, 2003). Analysis of airborne imagery was analyzed before and after Hurricane Floyd passed directly across the study region. Although this storm inflicted significant damage to

structures on the adjacent island, turtlegrass distributions in this region were found to be virtually undisturbed.

Coral reefs are also amenable to remote sensing techniques and are amongst the most threatened coastal ecosystems worldwide (Pandolfi *et al.*, 2003). The photosynthetic products from the symbiont zooxanthellae contribute to coral growth and calcification in healthy corals. Under stressful conditions, such as increased water temperature or decreased salinity, the coral host expels the zooxanthellae and the colour of the corals become white or 'bleached.' (Fig. 9.10). Massive global coral bleaching events that occurred in 1998 and 2002, for example, were attributed to increased temperatures after the climatological fluctuations known as El Niño Southern Oscillation (ENSO) periods (Aronson *et al.*, 2000). Increases in remotely-derived sea surface temperature have been used as important indicators of potential bleaching events, but ocean-colour imagery can be used to detect the whitening itself through enhanced benthic reflectance across the visible spectrum (Andréfouët *et al.* 2005, Dekker *et al.*, 2005). Finer spatial resolution than that available with the current suite of ocean-colour satellite sensors is generally required to detect characteristic metre-scale features of coral reefs, but high spatial resolution airborne imagery has been used to discriminate coral reef substrates (Karpouzli *et al.*, 2004) and to document mortality in corals due to bleaching (Mumby *et al.*, 2001), as well as high spatial resolution satellite sensors with only a few visible bands, such as IKONOS, Quickbird and Landsat (Elvidge *et al.*, 2004; Andréfouët *et al.*, 2005). Radiative transfer approaches for detecting coral bleaching events require reflectance measurements of healthy and bleached corals and are aided by *in situ* knowledge of seafloor bathymetry and water optical properties.

Figure 9.10 High-resolution Quickbird-2 satellite image acquired on 22 February 2004 showing coral-bleaching off Heron Island, Capricorn Bunker Group, Southern Great Barrier Reef, Australia. Image provided by Stuart Phinn and Chris Roelfsema, Center for Remote Sensing and Spatial Information Science, University of Queensland (Copyright DigitalGlobe).

Various methods have been used to assess benthic environments from space that include empirical, semi-empirical, and analytical methods. Analytical and radiative

transfer-based forward and inverse models have many advantages over empirical approaches. The future vision is to develop methods that are repeatable, robust and can be transferred to the diverse capabilities of future ocean-colour sensors. The further advancements in ocean-colour remote sensing techniques in optically shallow water will aid in our ability to detect and model temporal and spatial variability in benthic features and help develop hypotheses for understanding factors that control the distribution, density, and productivity of these ecosystems and develop appropriate responses to hazardous events.

9.2.6 Changes in Ocean Circulation

Marine ecosystems rely on patterns of ocean circulation that influence the physical and chemical properties of the water column. Long-term climatic trends, as well as other short-term climatic modes, such as interannual and decadal-scale variabilities, play an important role in determining ecological species distributions. Climatic warming has been demonstrated in the top 3000 m of the global ocean since 1950 (Levitus *et al.*, 2001), but the resulting shifts to the geographical distributions of many marine species through selective mortality, migrations, and changes in reproductive behaviour have only begun to be enumerated. Physical processes, such as upwelling, are essential for phytoplankton growth and sustenance of the complex trophic web built on these rich stocks of upwelling-induced phytoplankton (Fig. 9.11). Goés *et al.*
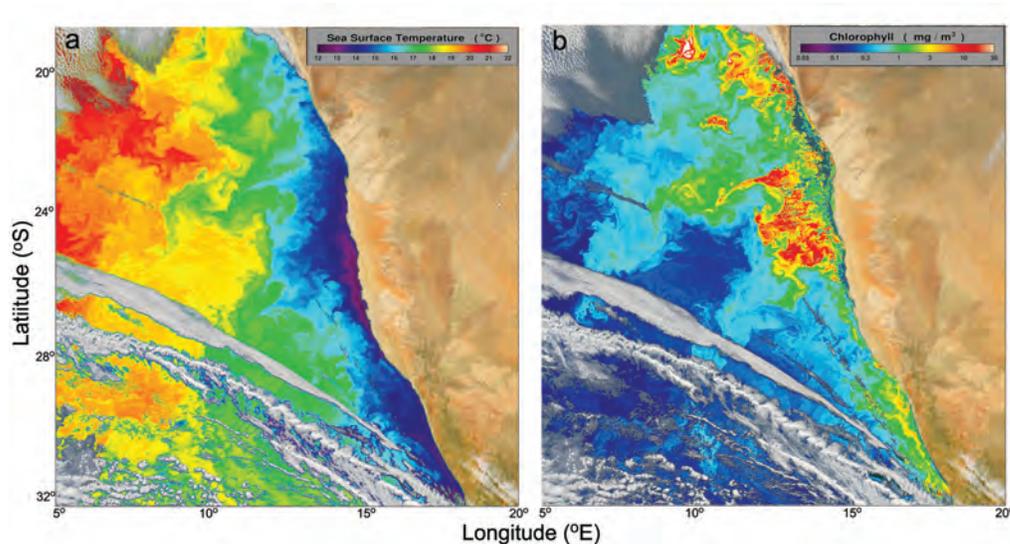
Figure 9.11 MODIS-Aqua SST and chlorophyll images from 17 June 2007 showing a) upwelling of cold (shown in blue) nutrient-rich water off the coast of Namibia, southern Africa and b) the associated high chlorophyll concentrations (shown in red) from a dense phytoplankton bloom (Credit: Ocean Biology Processing Group, NASA/GSFC).

(2005) documented how the warming Eurasian landmass has escalated the intensity of summer monsoon winds and strengthened upwelling in the western Arabian Sea. This coupled atmosphere-land-ocean phenomenon was linked to enhanced satellite-derived chlorophyll concentrations in the surface waters of the Arabian Sea using imagery from both the ADEOS-1 Ocean Colour Temperature Sensor (OCTS, Japan) and SeaWiFS. Regional changes in productivity, such as this example, can lead to altered fish stocks, oxygen concentrations in the water, and the significant shifts in the trophic status of these waters.

Moreover, the timing, onset, and intensity of coastal upwelling is critical for species whose life histories are closely tuned to the annual cycle. Some studies have suggested that rising ocean temperatures have contributed to decreased upwelling in certain regions. In turn, the dwindling plankton populations have significant influences on the marine ecosystem, including seabird communities (Hyrenbach and Veit, 2003). Marine bird concentrations have been shown to be positively correlated to primary productivity in the water column. Upwelling regions, such as Point Conception, California, appear to be important 'hot spots' of sustained primary productivity and marine bird concentrations (Yen *et al.*, 2006). For example, in 2005 coastal ocean temperatures were 2 to 5 degrees above normal throughout the west coast of the United States and Canada, apparently caused by a lack of upwelling that brings cold, nutrient-rich water to the surface. These warmer ocean temperatures were linked to decreased fish stocks (*e.g.*, salmon and rockfish) and decreased nesting success and mortality of seabirds (*e.g.*, cormorants and auklets) which require high marine productivity in the spring months for successful breeding. These shifts in upwelling are not only observed in North America, but have been observed globally including Antarctica and Europe.

9.3   Future Directions

As demonstrated above, ocean-colour imagery has been used successfully to document hazardous events and to determine the impacts of acute and chronic hazards on the oceans. Such imagery is currently being used to track the course of tropical storms and hurricanes, document coastal erosion and sediment re-suspension events, harmful algal blooms, and to identify changes to benthic habitats and the trophic food web throughout the world's seas. Many of these methods are qualitative and show only those impacts that can be observed visually from a true colour image, such as the apparent extent and duration of a sediment plume. However, the considerable research into the optical properties of the water column and benthos, coupled with radiative transfer modelling, has led to the development of more advanced methods for characterizing these changing environments. The use of ocean-colour imagery to assess hazards is an emerging field. For example, further research is needed to integrate the various relevant measurements required

to understand intense algal bloom development and the propensity of these blooms to produce toxins. As storm surges erode coastlines, we also need better methods to identify the amount of eroded material and depth of flood waters in inland areas. Modelling flood water properties will require an understanding of the water's optical properties.

Quantifying hazardous events and changes to the world's ocean resources requires higher temporal, spatial, and spectral resolution imagery than currently available. Analytical and semi-analytical methods for evaluating this imagery will require that both the magnitude and spectral shape of the retrieved sea surface reflectance are accurate. Hence, new atmospheric correction approaches must be developed that handle significant amounts of near-infrared reflectance and absorbing aerosols common to the coastal zone. Research is also needed to develop algorithms that are not merely site-specific empirical regressions, but which can actually determine the quantity and composition within the surface waters and on the seafloor. Integrated modelling and data assimilation efforts will be required to tie together *in situ* measurements and a variety of remote-sensing data including sea surface temperature and bathymetry.

Ocean Colour and Climate Change

Nick Hoepffner, Cara Wilson and Samantha Lavender

The longest currently-operating ocean-colour sensor (SeaWiFS) was launched in 1997, so it is not possible to detect decade-scale variability using SeaWiFS data alone. Newer and overlapping missions such as MODIS-Aqua and MERIS (launched in 2002) will hopefully ensure unbroken observations and provide global ocean-colour products up to 2012, with an increased spatial coverage. In the meantime, long-term changes can be observed by comparing climatological SeaWiFS/ MODIS/ MERIS data against data from the Coastal Zone Colour Scanner (CZCS), which operated between 1979 and 1985. The following section focuses on a few recent applications using these ocean-colour time-series to detect long-term trends in marine biology due to climate change. Notwithstanding the current limitation of ocean colour in obtaining a data set with a time frame of several decades, ocean colour is identified as an Essential Climate Variable (ECV) within the Global Climate Observing System (GCOS) action plan to support the United Nations Framework Convention on Climate Change (UNFCCC) and the work carried out by the Intergovernmental Panel on Climate Change (IPCC), representing a unique synoptic-scale view of the pelagic ecosystem. As such, it is absolutely essential to avoid any temporal gaps in the ocean-colour record, which has already suffered considerably from the ~10-year gap between the CZCS and SeaWiFS missions. Moreover, the provision of a single and consistent data stream of ocean-colour products from multi-platform devices would optimize the use of ocean-colour radiometry (OCR) data in climate research.

10.1 Long-Term Changes in Phytoplankton Biomass

Gregg *et al.* (2002) and Antoine *et al.* (2005) conducted a comprehensive re-analysis of CZCS data using similar methods and algorithms (as far as possible) to those used for current sensors, such that comparison of ocean-colour data sets from both eras could be achieved with a reasonable level of confidence. This analysis of decadal changes between CZCS and SeaWiFS data sets yielded an overall increase of 22% in the global ocean chlorophyll concentration (Antoine *et al.* 2005). Using only 6 years of SeaWiFS data, Gregg *et al.* (2005) also observed a slight increase in global ocean

chlorophyll concentration (4.1%).

Although the global average ocean chlorophyll concentration is observed to be increasing, some regions of the ocean show a decrease. For the oceanic carbon cycle and ecosystem assessment it is important to understand where these changes are occurring. The largest positive changes between CZCS and SeaWiFS data sets are observed in the inter-tropical regions, whereas the oligotrophic gyres are becoming even more impoverished (Antoine *et al.*, 2005). Using a 9-year time series of SeaWiFS data, Polovina *et al.* (2008) demonstrated that in the North and South Pacific and North and South Atlantic, outside the equatorial zone, areas of low surface chlorophyll waters have expanded at average annual rates from 0.8 to 4.3% yr^{-1}. According to the authors, the expansion of low chlorophyll waters is consistent with global warming scenarios, implying increased vertical stratification in the mid-latitudes. The rates of expansion as observed with satellite data, however, greatly exceeds recent model predictions. Vantrepotte and Mélin (2008, subm.) also reported a decline in chlorophyll concentrations in the subtropical gyres at rates ranging from 1 to 5% per year, based on a decade of SeaWiFS data (1997-2007, Fig. 10.1).
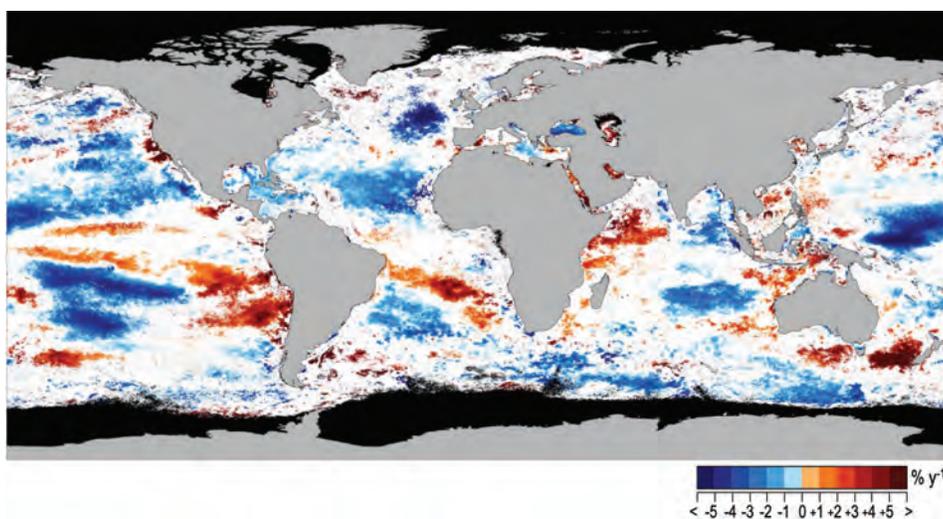
Figure 10.1 Linear changes in SeaWiFS-derived chlorophyll concentration from September 1997 to December 2007 (in % per year). Only the pixels for which a significant linear trend was detected, are reported ($p < 0.05$, Student-t test). (Image provided by Vincent Vantrepotte, Joint Research Centre, EC).

Positive changes, *i.e.* increases in chlorophyll concentrations, seem to be confined in coastal regions and upwelling areas. Several lines of evidence show an increasing strength of the seasonal upwelling in different systems over several decades, using other data sources (Bakun 1990; Snyder *et al.* 2003) and would explain the subsequent rise in chlorophyll in these regions. Likewise, using 11-years of data from SeaWiFs and its predecessor OCTS, Kahru and Mitchell (2008) found that bloom magnitudes have increased significantly in eastern boundary upwelling systems, as well as in a

number of areas known to be sensitive to eutrophication (*e.g.* enclosed and semi-enclosed basins, outflow areas of large rivers). Some of the observed trends in bloom magnitude could be attributable to the strong El Niño of 1997-98 at the start of the time series. However, bloom magnitudes have increased in many areas even after this event.

Long-term changes in phytoplankton biomass could be reflected in the global ocean primary production and the entire carbon cycle. Comparing the CZCS record with 6 years of SeaWiFS data, Gregg *et al.* (2003) demonstrated a slight decrease of 6.3% in the global marine primary production, most of the decline being observed at mid- to high-latitudes. In contrast, low latitude and equatorial areas showed an increase in primary production between the CZCS and SeaWiFS eras. Using 9 years of SeaWiFS imagery (1997-2006), Behrenfeld *et al.* (2006) showed a decrease in net primary production over the years after an initial boost in 1998 due to the El Niño event.

Despite the different methodologies used, a certain level of consistency emerges from these OCR investigations, indicating that phytoplankton chlorophyll and primary production in large regions of the ocean (mid-latitude gyres) are decreasing over a multi-year period. Considering the limited ocean colour time-series being used (mainly SeaWiFS era), any interpretation of the changes as representative of longer term trends possibly linked to global warming would be speculative. Yoder and Kennelly (2003) documented a significant relationship between the inter-annual variability of chlorophyll and the large ENSO (El Niño Southern Oscillation) event which took place in 1997, and had global impacts for many years. Behrenfeld *et al.* (2006) also underline the striking correspondence between changes in primary production and a Multivariate ENSO Index, which would relate observed trends in chlorophyll and primary production to climate variability, rather than climate change.

10.2 Fisheries and Climate

The 1997/98 El Niño was one of the strongest ENSO events of the century. Ocean colour satellite data, in synergy with data from an extensive array of moorings across the equatorial Pacific, have contributed enormously to our understanding of ENSO dynamics and their ecosystem impacts. Deepening of the thermocline, and cessation of upwelling along the equator and in the coastal ecosystems lowers ocean productivity and causes significant depression of the anchovy fisheries of Peru and Chile (Alamo and Bouchon, 1987; Escribano *et al.*, 2004). However, other species are positively impacted by El Niño, for example increases are observed in the biomass of sardine and mackerel (Bakun and Broad, 2003; Niquen and Bouchon, 2004). Satellite ocean-colour data have demonstrated that the effects of El Niño are not constrained to just the equatorial and coastal upwelling regions, but extend throughout most

of the Pacific Ocean. For example during the 1997/98 event the Transitional Zone Chlorophyll Front (TZCF) was shifted ∼5° south of its regular position (Bograd *et al.*, 2004), and lower chlorophyll values occurred across most of the subtropical Pacific (Wilson and Adamec, 2001).

On a longer time scale, the present wintertime position of the TZCF in the Pacific, as observed with SeaWiFS data set, is about 5° further north than it was during the CZCS time period (Fig. 10.2). This shift has also been seen in SST data used as a proxy for the TZCF (Bograd *et al.*, 2004). Data from the CZCS and SeaWiFS sensors have also been used to identify regions of the ocean which have experienced significant changes in the concentration of chlorophyll and rate of primary productivity in the past twenty years (Gregg and Conkright, 2002; Gregg *et al.*, 2003).
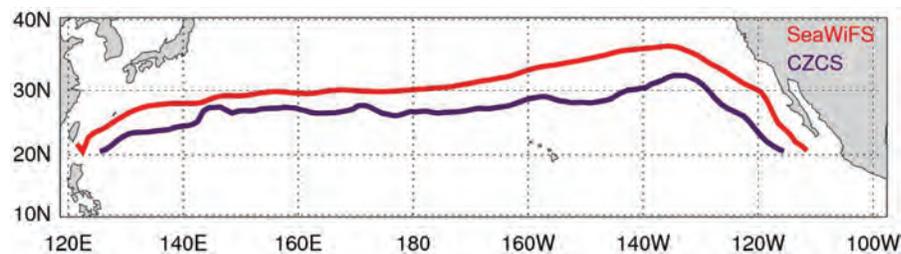
Figure 10.2   Interannual variation in the position of the TZCF indicated by the mean January position from CZCS data (1979-1985) in purple, and from SeaWiFS data (1998-2004) in red. The winter TZCF is presently ∼5° further north from its position during the CZCS era. (Credit: Cara Wilson, unpublished data)

There is significant long-term temporal variability in fish stocks, and for over 150 years scientists have been trying to differentiate the effects of interannual variability, overfishing and long-term changes such as regime shifts, which are characterized by relatively rapid changes in the baseline abundances of both exploited and unexploited species (Polovina, 2005). Long-term variations in ecosystems often follow trends or patterns also observed in ocean and atmosphere properties (Mantua *et al.*, 1997; Hare and Mantua, 2000; Peterson and Schwing, 2003). For example, a shift in the North Pacific in the 1970's between a shrimp-dominated ecosystem to one populated primarily by several species of bottom-dwelling groundfish species coincided with a regional change from a cool to a warm climate (Botsford *et al.*, 1997; Anderson and Piatt, 1999; Fig. 10.3). Although similar phenomena have been seen for many different stocks, and in all ocean basins, the mechanisms that link large-scale ocean and atmosphere dynamics to changes in population abundances are not always clear (Botsford *et al.*, 1997; Baumann, 1998) and the relationships are not always constant over time (Solow, 2002). Ecosystem changes related to regime shifts are not in themselves harmful to the ecosystems as a whole (Bakun and Broad, 2003), but to maintain sustainability, management practices must be flexible enough to recognize and accommodate them (Polovina, 2005). Chassot *et al.* (2007) used satellite-derived primary productivity data together with catch data from European seas for the

period 1998 to 2004, and found significant positive relationships between primary production and yield, suggesting a strong linkage between marine productivity and fisheries production. This is relevant in the context of climate change, because variations in primary production linked to global warming could strongly modify fisheries production in the future.
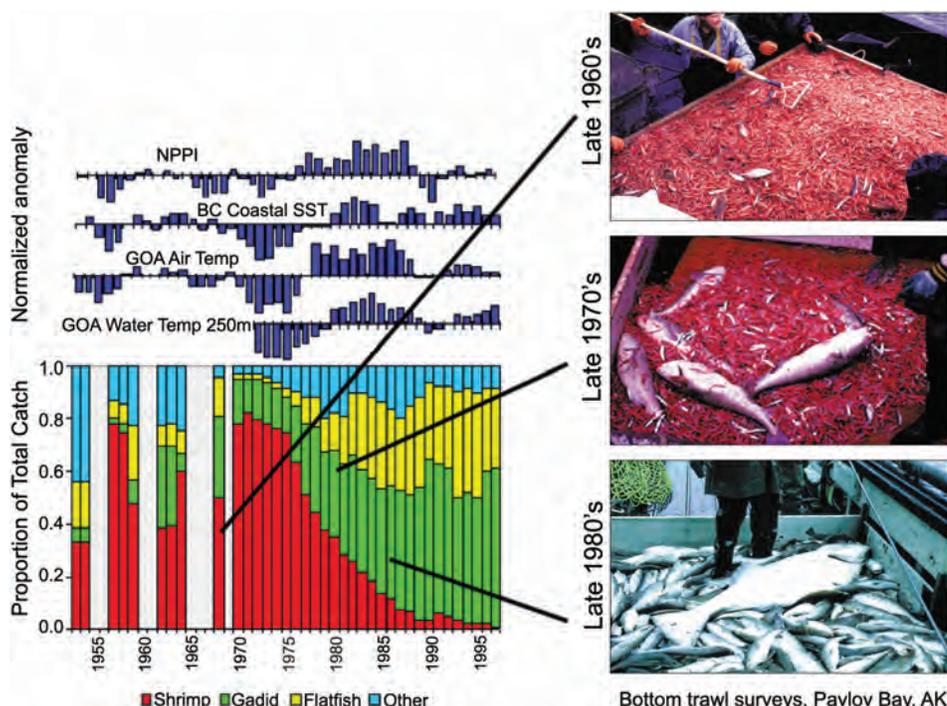
Figure 10.3 Changes in the composition of small-mesh trawl catches in the Gulf of Alaska (GOA) between 1953 and 1997, in relation to climate indices. Chart data expressed as normalized anomalies (NPPI: North Pacific Pressure Index; BC: British Columbia), and shown visually in photos of small-mesh bottom trawl surveys in Pavlov Bay, Alaska (right). Figures adapted from Anderson and Piatt (1999) and Botsford *et al.* (1997). Reprinted with permission from AAAS.

One of the current limitations of satellite data is the relatively short time-span of the data series. For fisheries applications it is crucial that climate-quality records of ocean colour be maintained so that existing satellite records will be able to serve as a benchmark against which to gauge future changes.

10.3 Toward a Long-Term and Consistent Ocean-Colour Time Series

To examine long-term changes in ocean colour for climate monitoring purposes, ocean-colour data sets need to be based on individual sensors with a significant historical archive, or a time-series of several overlapping, well-calibrated sensors that

can be combined to produce a consistent, well-calibrated merged data set. Individual sensors typically have a nominal lifetime of 5 years, but in reality their operating period can be much shorter (*e.g.* OCTS which provided data for 8 months prior to a power failure), or longer (*e.g.* SeaWiFS currently in its 11th year of activity). Currently, no operational satellite ocean-colour missions are designed to provide multi-decadal observations of the marine biological field, such as the NOAA-AVHRR series for measurement of sea surface temperature. However, ESA's Sentinel-3 series of operational satellites, the first of which is scheduled for launch in 2012, are designed to provide an uninterrupted flow of robust global data products. At the moment, the ocean-colour community has to rely on a number of individual missions launched by various space agencies, with radiometric sensors that differ in their technical specifications. Multiple overlapping missions, such as the current SeaWiFS, MODIS and MERIS missions, have the advantage of increasing the spatial coverage of the global ocean, which is more limited with a single sensor due to the effects of sun-glint and clouds (IOCCG 1999). The challenge is to maximize the information available by combining data from individual sensors, such that a reasonably consistent and well calibrated data stream of ocean-colour products can be generated independently of sensor characteristics and satellite orbital schemes.

NASA's Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies (SIMBIOS) Program was conceived in 1994 to examine the technical challenges of combining ocean-colour data from an array of individual missions to form consistent and accurate global bio-optical time-series products. A specific objective of the program was to develop appropriate methods for merging data from sensors with different viewing geometries, resolution (spectral, spatial and temporal), and other radiometric features. Several merged ocean-colour data sets have become available in recent years:

❖ NASA OBPG merged Chl-a data set based on SeaWiFS and MODIS-Aqua,
❖ NASA REASoN merged Chl-a, Colour Dissolved Material (CDM) and particulate backscattering (b_{bp}) data sets based on SeaWiFS and MODIS-Aqua,
❖ ESA DUE GlobColour multi-parameter (19 variables) data set based on SeaWiFS, MERIS and MODIS.

The merging of data from individual sensors not only provides a long time-series, but also increases the temporal coverage (see Table 10.1) and error characterisation of the final data set. The averaged daily coverage by individual sensors ranges from ~8% for MERIS to ~16% for SeaWiFS. The combination of two sensors increases the global ocean coverage to ~20-25% per day, and to ~30% per day with the combination of three sensors (IOCCG, 1999).

The GlobColour Project was initiated and funded by the ESA Data User Element (DUE) Programme in 2005 to develop a satellite-based ocean-colour data set to support global carbon-cycle research, and to satisfy the scientific requirement for a long time series of consistently calibrated global ocean-colour information with the

Table 10.1 Ocean-colour sensor average daily coverage plus standard deviation for 2003 (produced by Stephane Maritorena and based on the GlobColour Chl-a data).

Sensor(s)	Coverage (%)	Standard Deviation (%)
SeaWiFS	16.65	2.01
MODIS-Aqua	13.76	1.15
MERIS	8.51	1.48
SeaWiFS/MODIS-Aqua	24.22	1.94
SeaWiFS/MERIS	22.24	2.40
MODIS-Aqua/MERIS	19.92	1.74
SeaWiFS/MODIS-Aqua/MERIS	28.85	2.24

best possible spatial coverage. This was achieved by merging data from the SeaWiFS, MODIS-Aqua and MERIS missions. The project provides global daily, 8-day, and monthly merged data products at 4.6-km resolution for the time period 1997-2007, and is freely available to the scientific user community (`http://www.globcolour.info`).

Future Perspectives

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11.1 Current Situation and Future Directions

Today we find ourselves standing on the threshold of profound breakthroughs in ocean biological sciences. By virtue of the opportunities provided by the first generation of ocean-colour satellite missions during the past decade, we have realised major advances in our ability to resolve multiple in-water constituents from remote sensing data, related these to key components and processes within ocean ecosystems, and integrated this new information into advanced prognostic models. Over this same period, we have also seen major technological developments that can enable the new measurements necessary to address the remaining top priority questions in environmental policy and ocean science.

The focus on science in service of societal needs is supporting the elaboration of extended requirements among environmental protection and other operational agencies throughout the world for marine environment monitoring, as well as putting structures in place for enhanced exchange of marine information. Furthermore, these operational communities acknowledge a critical reliance on continued research to improve understanding of oceanic processes and their interaction with our health and well-being. At the same time, commercial operators are increasingly affected by environmental considerations and are adopting more innovative techniques to collect, process and analyse the information necessary to support safe, efficient and sustainable commercial practices.

As a result, a wide range of user communities have ambitious plans to use satellite ocean-colour radiometry (OCR) for research, operational and commercial applications. Space agencies are responding to these evolving requirements with a set of OCR mission scenarios. In this chapter we consider the factors driving increased demand for ocean-colour radiance measurements, the responses from the space community and the technical issues to be addressed over the coming years to ensure that the advances fostered by the ocean-colour community over the last decade continue.

11.2 Evolving Needs for OCR Measurements

The research, operational and commercial user communities each have very different requirements for ocean-colour derived information over the coming years.

11.2.1 Research Challenges in Ocean Colour

Of key importance in a world with a changing climate is a better understanding of the Earth System. For example, the key research challenges in relation to ocean-colour radiometry measurements, as elaborated by ESA in consultation with a group of leading international Earth Scientists, and which are consistent with the science goals of the other space agencies, include:

- ❖ quantifying the interaction between variability in ocean dynamics, thermohaline circulation, sea level and climate;
- ❖ quantifying primary production and its role in the ocean carbon cycle;
- ❖ understanding physical and bio-chemical air/sea interaction processes;
- ❖ understanding internal waves and mesoscale variability in the ocean, its relevance for heat and energy transport and its influence on primary production;
- ❖ quantifying marine-ecosystem variability and its natural and anthropogenic physical, biological and geochemical forcing;
- ❖ understanding land/ocean interactions in terms of natural and anthropogenic forcing;
- ❖ providing reliable model and data-based assessments and predictions of past, present and future states of the ocean.

Research users are particularly interested in using ocean-colour imagery to help detect and quantify the response of coastal and marine ecosystems to climate change. Plankton are good indicators of climate change and documenting the timing, magnitude and distribution of changes in their biomass and productivity on regional to global scales over an extended time period offers a unique tool to monitor and assess the effects of climate change on the aquatic ecosystem. This will likewise have significant societal impacts and benefits associated with improved understanding and insights gained from research.

11.2.2 Operational Use of OCR Data

Operational agencies responsible for managing society's use of ocean and coastal ecosystems, sustaining natural resources, protecting public health and ensuring safe navigation are increasingly adopting ocean-colour derived information services for routine monitoring and assessment tasks, and to help fulfil the mandate to optimise use and protection of coastal and ocean resources. In Europe, for example, the Global Monitoring for Environment and Security (GMES) initiative has fostered

strong user acceptance of the operational use of ocean-colour data for water quality monitoring. At the same time, new policies such as the Water Framework Directive and the Marine Environment Strategy drive operational users to adapt their routine monitoring programmes within the budgets available, and in such situations the cost-effectiveness of satellite-based ocean-colour information is increasingly recognised. This creates a parallel set of challenges to be addressed. Greater integration of ocean-colour derived information into a wider operational monitoring and analysis will drive requirements on spatial and radiometric resolution, data continuity, quality control and validation in complex coastal environments.

Satellite ocean-colour data represent a powerful tool to assess the effectiveness of policies and practices and support their application and enforcement. For example, implementing ecosystem-based approaches to management with associated integrated ecosystem assessments will increasingly rely on routine and synoptic measurement of aquatic biological activity via satellite remote sensing. Improved satellite OCR data and products will support a more timely and effective decision making process, and enhance the ability of operational agencies to optimally manage and protect the marine and coastal environment.

In the USA, Federal and state agencies share coastal ocean protection and management responsibilities including fisheries management, water quality monitoring, protection of marine sanctuaries and marine mammal habitats, and assessing storm event effects. These management responsibilities require an improved understanding of context and change through time and space. This requires inter-calibration of ocean-colour sensors and calibration to provide stable time series. Calibration and Validation (Cal/Val) are therefore key activities for satellite remote sensing of ocean optical, biological and biogeochemical properties in support of both research and operations/applications, and will require an even greater focus in the future in the context of virtual ocean-colour constellations and associated data exchange.

Beyond routine water quality and general ecosystem health and productivity assessments, operational uses of satellite ocean-colour data will continue to grow and include new and improved developments and applications in support of user needs. Some potential new operational applications include:

❖ **Creation of habitat suitability maps** - establishing boundaries of marine sanctuaries; managing commercially and recreationally important living marine resources; directing *in situ* sampling efforts, and locating targeted organisms such as Harmful Algal Blooms (HABs).

❖ **Ecological prediction** - forecasting year-class survival or growth rate of a species based on the timing of the spring phytoplankton bloom; initialising and validating results of numerical ecological models; improving ecological forecasts through data assimilation; and nowcasting or forecasting the fate and transport of pollutants and pathogens.

❖ **Extended use for climate change and impact assessments** - to better estimate

the spatio-temporal distribution of the air-sea CO_2 flux and ocean acidification, especially in the coastal zone where riverine inputs and productive filaments can degrade the accuracy of estimates based only on sea surface temperature and scatterometer-derived wind speeds; providing data on the long term changes of surface biomass in response to climate change and other human activities.

Finally, new and improved operational products will benefit from the continued infusion, transition and integration of research and technology developments into operational practices.

11.2.3   Commercial Use of OCR Data

Commercial operators are also realising the value of ocean-colour derived information, and its utilisation among private sector customers is expected to increase significantly over the coming years due to a greater demand for marine environment information and high sensitivity to the cost effectiveness of the different data gathering approaches. The aquaculture industry in Europe and South America is probably the most advanced private sector user of ocean colour but at present this is for relatively simple products (*e.g.* detection of algal blooms). In parallel with the expansion of this industry, the demands for information are also growing. The ocean-colour community has the opportunity to respond with new products such as water mass delineation (*e.g.* to provide warnings of strong salinity variations, oxygen concentration and the presence of harmful jelly fish), environmental impact assessment and improved characterisation of algal bloom events. In addition to aquaculture, commercial tour operators and sport fishing, marine engineers and shipping operators are all demonstrating increased interest in the commercial use of ocean-colour derived information such as transparency, sediment concentration and chlorophyll concentration. One of the main evolution requirements from the commercial sector is a robust capability to extract information close to the coast in complex optical and geographic environments (*e.g.* high sediment loads, fjords and estuaries, coral reefs).

11.3   Technical Developments for Wider OCR Utilization

The different user groups are setting strong challenges for the ocean-colour community. For example, biological and ecosystem modelling requires quantification of variables which are not yet calculated from ocean-colour radiometry measurements. The lack of these data imposes constraints on model development and validation. The response from the ocean-colour community may be improved algorithms for processing existing data, enhanced data assimilation, new mission concepts, new instruments and new infrastructure for enhanced data exchange. The ocean-science

community also has significant expectations for the contribution of ocean colour as a unique data stream for assimilation into coupled physical-biogeochemical models and in support to the Global Climate Observing System (GCOS) Implementation Plan as an Essential Climate Variable.

Research and operational users investigating and monitoring coastal and inland waters require observations with improved spatial, temporal and spectral resolution and coverage. In addition, there is a continuous requirement from the operational user community for improved reliability of measurements and the capacity to extract new parameters in optically complex, highly variable coastal areas. To respond effectively, the ocean-colour community must develop new or improved capabilities in at least the following key areas:

- ❖ separation of in-water constituents (*e.g.*, organic and inorganic substances) in global waters, which requires advanced corrections for atmospheric effects on satellite ocean measurements as well as new, advanced algorithms for characterising the parameters of interest;
- ❖ resolution of coastal phenomena and mapping of coastal habitats using high temporal and spatial resolution measurements;
- ❖ active assessments of plant physiology and the function of different groups of plants in aquatic ecosystems; and
- ❖ determining environmental variability of the surface ocean, including the depth of the mixed layer.

At instrument level, the engineering focus must be on enhanced spatial and spectral resolution while the space agencies together can ensure improved temporal resolution.

Improved Spatial Resolution (200 - 300 m): Higher spatial resolution can provide improved measurements for estuaries, bays and lakes, which are often used for aquaculture applications, and can potentially also provide information for coral reef and other near-shore ecosystems that are currently poorly resolved. Further, finer spatial resolution ocean-colour data will improve the capability to track ocean features and processes that influence migration, feeding, spawning and recruitment of commercially important fish populations and many protected species. Clearly this will also improve water quality monitoring and assessments through enhanced detection of (harmful) algal blooms, freshwater run-off (often containing pollutants and pathogens) and other phenomena and processes of interest.

Improved Spectral Resolution: River run off, suspended sediments, coloured dissolved organic matter, large phytoplankton blooms and bottom reflectance in shallow water all add to the optical complexity of coastal waters. Research has shown that additional bands in the infrared and short wave infrared (SWIR) can improve atmospheric correction, while additional bands in the red to near infrared can aid identification of phytoplankton. Bands at the "red edge" from 680 to 709 nm have been used in methods to detect harmful algal blooms and the distribution

of *Sargassum*, while narrow spectral bands centered around 665 nm and 680 nm are frequently used to measure the height of the chlorophyll-a fluorescence peak. SWIR bands in particular are needed for turbid coastal waters. Additional ultraviolet bands (UV) show potential for improving atmospheric correction and phytoplankton discrimination, and also for better quantifying ocean organic and inorganic materials. In the coastal regions, aerosol vertical profile information is needed, *e.g.* data from the CALIPSO measurements. Most current and planned sensors do not measure in enough different wavelengths to optimise separation of components in optically-complex waters and none provide enough bands for optimal atmospheric correction. Higher spectral resolution (narrower/more bands) and greater spectral coverage, from the UV to SWIR with the required sensor signal-to-noise ratio (SNR) values will allow for improved discrimination of aquatic and atmospheric optical constituents (particularly in coastal regions), enhance detection of harmful algal blooms and help quantify more accurately sediment loads, river discharges and other water quality indicators.

Improved Temporal Resolution: The present once-per-day frequency limits the utility of coastal area observations. Cloud cover can be a significant problem, particularly in highly variable coastal regions and can result in large areas having little or no coverage. Multiple looks per day will help mitigate this problem and improve our ability to monitor and manage ecosystem health and water quality. More frequent OCR observations are also required to resolve diurnal and tidal cycle effects. Currents driven by diurnal and semi-diurnal tides reverse approximately every 6 hours. Furthermore diel winds (such as land-sea breezes), river run-off, upwelling, tides and storm winds also contribute to strong coastal currents. More frequent sampling is required to track features driven by these coastal currents including water masses containing harmful algal blooms, freshwater run-off, oil/sewage spills and other hazardous materials. More frequent imagery will also aid in the development of ecosystem models to support the management of marine sanctuaries and protected areas, provide hazard warnings and improve management of fisheries using the Essential Fish Habitat approach for key commercial and sport fish stocks.

There is also the need to further develop and improve bio-optical algorithms and products. The accuracy of satellite measured products compared to *in-situ* products needs to be continuously improved. This is partly achieved through improved atmospheric corrections in coastal waters and the development of regional bio-optical algorithms, as well as robust and sustained supporting cal/val efforts. However, in the longer term it will also depend on the appropriate channels being available on future instruments. Finally, the ocean-colour community must continuously engage in developing new products. This may be customisation of mature capabilities for particular user groups, or it may be the development of entirely new products, for instance, there is a strong demand for anomaly products to identify changes over time, which is not yet satisfied by the ocean-colour community.

11.4 Scheduled OCR Missions

The short term outlook for the ocean-colour community is very good. MODIS, MERIS and potentially SeaWiFS are all expected to continue providing data over the coming years. For MERIS, it is planned to optimise Envisat orbit maintenance to extend mission operations until the launch of Sentinel-3, thus ensuring continuity of the ocean-colour data stream, and the establishment of a long-term, consistent, climate quality data set which will play a critical role in assessing how climate change and human population pressures will impact marine resources and biogeochemical cycles. Increased adoption of ocean-colour based information services is critically dependent on the space community guaranteeing operational continuity of ocean-colour data streams with sufficient performance and quality. A number of ocean-colour missions are currently approved or in advanced planning stages.

❖ **ISRO Oceansat-2:** ISRO's Oceansat-2 mission is scheduled for launch in early 2009, and will add to the number of data streams immediately available. Oceansat-2 will carry three instruments including the OCM-2 ocean-colour sensor. OCM-2 is similar to OCM-1 apart from the 765 nm band being moved to 740 nm to avoid O_2 absorption, and the 670 nm band being replaced by 620 nm for better quantification of suspended sediments. Modes of operation would include local area coverage at 360 m (real time transmission) and global area coverage at 4-km (on-board recording).

❖ **U.S. Integrated Program Office (IPO) VIIRS:** The Visible Infrared Imager Radiometer Suite (VIIRS) is a multi-purpose instrument which includes an ocean-colour capability. The first VIIRS will fly on the NPOESS Preparatory Project (NPP) with a scheduled launch in 2010. VIIRS is designed to have similar capabilities for ocean colour as the current MODIS instruments. However, VIIRS on NPP does not appear capable of providing climate-quality ocean-colour data, and thus will be less capable than MODIS-Aqua. Subsequent VIIRS instruments are anticipated to have better performance than VIIRS on NPP with NPOESS-C1 being the first platform opportunity for VIIRS following NPP. NPOESS-C1 is scheduled for launch no earlier than 2013.

❖ **ESA Sentinel-3:** Sentinel-3 will substantially improve the ability to provide, on a sustained basis, reliable, frequent, consistent, timely and long-term collections of remotely-sensed OCR and other ocean data of uniform quality. The Sentinel-3 payload comprises a Cryosat-derived Radar Altimeter and two imagers, a MERIS-like Ocean and Land Colour Instrument (OLCI), and an AATSR-like Sea and Land Surface Temperature Radiometer (SLSTR). The OLCI provides similar but enhanced ocean colour capabilities as MERIS. Two satellites are planned (Sentinels-3A and -3B), each designed with a 7-year lifetime, with the first satellite scheduled for launch in 2012 and the second in 2015. It is anticipated that other satellites will be added to the series in the future. Sentinel-3 has a

high-inclination sun-synchronous frozen orbit with 14+7/27 revolutions per day with a mean altitude of 815 km and a local equatorial crossing time of 10:00 am enabling near-complete global coverage and mitigating sun glint, morning haze and cloud-cover impact. The baseline of two satellites simultaneously in-orbit with 180° dephasing supports full imaging of the oceans within 2 days.

❖ **JAXA GCOM-C:** The next Japanese ocean-colour mission is the Global Change Observation Mission for Climate research (GCOM-C). The mission will consist of three satellite series for 13 years from early 2014. GCOM-C will carry the second-generation Global Imager (SGLI) which is a radiometer of 380-12,000 nm wavelength, 1150-1400-km swath width, and 10:30 am descending orbit. Features of SGLI are 250 m spatial resolution (500 m for thermal infrared) and polarization/along-track slant view channels (red and near-infrared), which will improve coastal ocean, land, and aerosol observations.
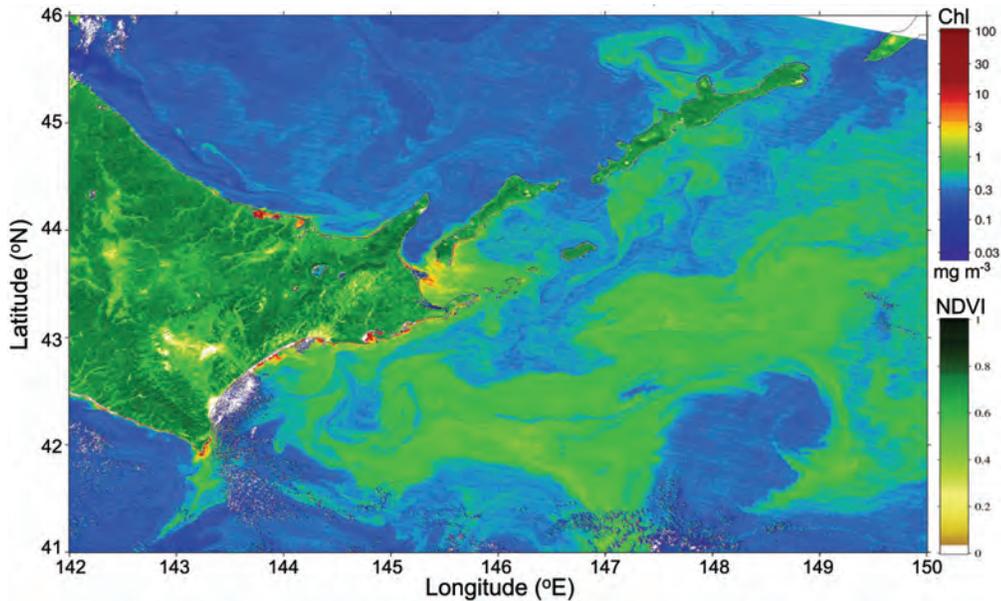
Figure 11.1   Chl-a concentration east of Hokkaido Japan, one of the fish nursery areas in the Oyashio Current, estimated by the GLI sensor onboard ADEOS-II on 24 September 2003, using the 250 m resolution channels.

❖ **KARI/KORDI Geostationary Ocean Colour Imager (GOCI):** The Korean COMS satellite, carrying the world's first ocean-colour imager in a geostationary orbit, is scheduled for launch in mid-2009. GOCI has the unique capability of observing the ocean and coastal waters with a high spatial resolution (500m) and a very high temporal resolution (refresh rate: 1 hour), owing to its geostationary orbit. The GOCI mission concept includes eight visible-to-near-infrared bands and a 2500 km×2500 km swath centered at 36°N and 130°E. GOCI will provide multiple views of many locations within the fixed region during a single day

(*i.e.* 8 images per day). This will allow examination of short-term biophysical phenomena in oceanic and coastal waters, such as harmful algal blooms, mesoscale process studies and fishing ground information.

❖ **EnMAP:** The Environmental Mapping and Analysis Programme is a German hyperspectral mission, scheduled for launch in 2012. The imager has 200 channels covering the spectral range from 420 nm to 2450 nm. It has a ground resolution of 30 m and a swath width of 30 km. The mission is intended to support research and demonstration applications in geology, land degradation, agriculture, forestry and coastal and inland waters. Key scientific objectives with respect to coastal and inland waters include improved chlorophyll quantification, differentiation between ecologically important phytoplankton groups and dissolved organic compounds, monitoring of potentially toxic algal blooms in eutrophic coastal and inland waters and the estimation of processes such as primary production in inland and coastal waters.

Oceansat-2, Sentinel-3 and GCOM-C all ensure improved coverage and revisit at 250-300 m spatial resolution, while the modification of particular channels will enhance the measurement capability for parameters such as suspended sediment concentration. In addition to these missions already under development, the space agencies are also working on new capabilities and concepts to extend the range of parameters extracted from ocean-colour data, to enhance the quality of the information generated. Priority concepts presently under review by various agencies include:

❖ Global hyperspectral imaging radiometer in sun synchronous orbit for accurate separation of in-water constituents and correction of the contribution of aerosols;
❖ Global hyperspectral imaging radiometers in geostationary orbit, which will enable global and regional observations of dynamic and complex coastal and shelf processes and discrimination of in-water constituents on sub-daily time scales, and at high spatial resolution (200 m or better) at nadir;
❖ Multi-spectral, high spatial resolution imager to observe coastal habitats and ecosystems at unprecedented scales and accuracies;
❖ Deployment of active approaches for probing plant physiology and functional composition from polar satellite orbit using laser technologies;
❖ Implementation of portable sensors on suborbital platforms;
❖ Development of new technologies for the assessment of ocean mixed-layer depth from satellite orbit; and
❖ Development of new technologies to obtain ocean particle profiles and aerosol column distributions.

11.5   A Bright and Colourful Future

Over the last decade, the ocean-colour community has achieved significant advances in building the level of acceptance of satellite-based OCR data for research, operational and commercial purposes. The integration of ocean-colour derived information with conventional measurement technologies is continuously expanding. A vigorous set of research activities is widely supported by a broad range of organisations including space agencies, marine environment institutions and research centres. Long term continuity of ocean-colour data streams is being addressed by space agencies such as ESA, JAXA and NOAA and the ocean-colour community is working to ensure that data and information products meet the requirements of the different user communities.

In support of the Group on Earth Observations (GEO) objectives, the Committee on Earth Observation Satellites (CEOS) established the concept of Virtual Constellations, to help coordinate the design, operation and exploitation of future systems to meet a range of Earth observation requirements. An Ocean Colour Radiometry-Virtual Constellation (OCR-VC) was recently proposed by the IOCCG, with the aim of providing an unbroken stream of calibrated ocean-colour radiances at key wavelength bands. The OCR-VC will address a number of GEO tasks under the societal benefit areas of health, climate, ecosystems and agriculture, and will also provide Essential Climate Variables (ECV) for the Global Climate Observing System (GCOS). Ultimately, the OCR virtual constellation will help agencies avoid duplication and overlap in Earth Observation efforts, and will help to close emerging data gaps, thus facilitating the establishment of a globally sustained Earth Observation network of ocean-colour sensors.

In the next 25 years, the international ocean-colour community can take a leadership role in creating new observational capabilities for marine environment management and ocean sciences as aids to informed stewardship of our blue planet. In doing so, we can expect great strides towards lifting the veil on the "Unseen World" of the ocean to discover new knowledge of its functioning as a result of close cooperation and cross fertilization between the remote sensing and the oceanographic communities. Now we need to act. In cooperation with the space agencies, we can ensure that the appropriate data streams are made available to the research, operational and commercial user communities. Together with these user communities we can continue to develop the necessary knowledge, techniques and competence, and learn how to better manage and protect these precious oceanic resources for future generations.

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Acronyms

ADEOS	Advanced Earth Observing Satellite
AO	Arctic Oscillation
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible-Infrared Imaging Spectrometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CASI	Compact Airborne Spectrographic Imager
CDM	Coloured Detrital Material
CDOM	Coloured Dissolved Organic Matter
CDR	Climate Data Records
CEARAC	Coastal Environmental Assessment Regional Activity Centre
CEOS	Committee on Earth Observation Satellites
ChloroGIN	Chlorophyll Globally Integrated Network
CZCS	Coastal Zone Color Scanner
DAM	Dynamic Area Management
DIC	Dissolved Inorganic Carbon
DMS	Dimethyl Sulfide
DOM	Dissolved Organic Matter
DON	Dissolved Organic Nitrogen
DUACS	Developing Use of Altimetry for Climate Studies
ECV	Essential Climate Variable
EEZ	Exclusive Economic Zone
EnMAP	Environmental Mapping and Analysis Program (German hyperspectral satellite mission)
ENSO	El Niño Southern Oscillation
Envisat	Environmental Satellite (ESA)
EOF	Empirical Orthogonal Function
ERSEM	European Regional Seas Ecosystem Model
ESA	European Space Agency
EUTRISK	Eutrophication Trophic Index
FAO	Food and Agriculture Organization
FRRF	Fast Repetition Rate Fluorometer
GCOS	Global Climate Observing System
GCOM	Global Change Observation Mission (Japan)
GEO	Group on Earth Observation
GEOHAB	Global Ecology and Oceanography of Harmful Algal Blooms
GES-DISC	Goddard Earth Sciences - Data and Information Services Center
GHRSST	Global ocean data assimilation experiment High-Resolution Sea Surface Temperature
Giovanni	GES-DISC Interactive Online Visualization and Analysis Infrastructure
GMES	Global Monitoring for Environment and Security (EC)
GOES	Geostationary Operational Environmental Satellites

GOCI	Geostationary Ocean Colour Imager
GOOS	Global Ocean Observing System
GSFC	Goddard Space Flight Center
HAB	Harmful Algal Bloom
HNLC	High-Nutrient, Low-Chlorophyll
IBGP	International Geosphere-Biosphere Programme
ICES	International Council for the Exploration of the Seas
IKONOS	Commercial high-resolution satellite (Greek word for "image")
INCOIS	Indian National Centre for Ocean Information Services
IRS-P4	Indian Remote Sensing Satellite
IOCCG	International Ocean-Colour Coordinating Group
IOP	Inherent Optical Properties
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
KARI	Korea Aerospace Research Institute
KORDI	Korea Ocean Research and Development Institute
LME	Large Marine Ecosystem
LOICZ	Land-Ocean Interactions in the Coastal Zone
MERIS	Medium Resolution Imaging Spectrometer (ESA)
MISR	Multi-angel Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer (USA)
MOS	Modular Optical Spectrometer (Germany)
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
NOAA	National Ocean and Atmospheric Administration (USA)
NOWPAP	Northwest Pacific Action Plan
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
OBPG	Ocean Biology Processing Group (NASA)
OCM	Ocean Colour Monitor (on IRS-P4)
OCR	Ocean-Colour Radiometry
OCR-VC	Ocean Colour Radiometry - Virtual Constellation
OCTS	Ocean Colour and Temperature Scanner (Japan)
OECD	Organization for Economic Cooperation and Development
OGCMs	Ocean General Circulation Models
PAR	Photosynthetically Available Radiation
PDO	Pacific Decadal Oscillation
P-E	Photosynthesis-Irradiance
PFZ	Potential Fishing Zone
PHILLS	Portable Hyperspectral Imager for Low Light Spectroscopy
PIC	Particulate Inorganic Carbon
POC	Particulate Organic Carbon
PON	Particulate Organic Nitrogen
PP	Primary Production

PPWG	Primary Productivity Working Group
Quickbird	Commercial high-resolution satellite
SAM	Seasonal Area Management
SD	Secchi Depth
SeaDAS	SeaWiFS Data Analysis System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SGLI	Second generation Global Imager (Japan)
SNR	Signal-to-Noise Ratio
SPIM	Suspended Particulate Inorganic Matter
SPM	Suspended Particulate Matter
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SWIR	Shortwave Infrared
TOA	Top-of-Atmosphere
TOPP	Tagging of Pacific Pelagics
TRIX	Trophic Index
TSM	Total Suspended Matter
TSS	Total Suspended Sediment
TZCF	Transitional Zone Chlorophyll Front
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultra-violet
VIIRS	Visible Infrared Imager Radiometer Suite