Chapter 9

Hazards: Natural and Man-Made

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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.

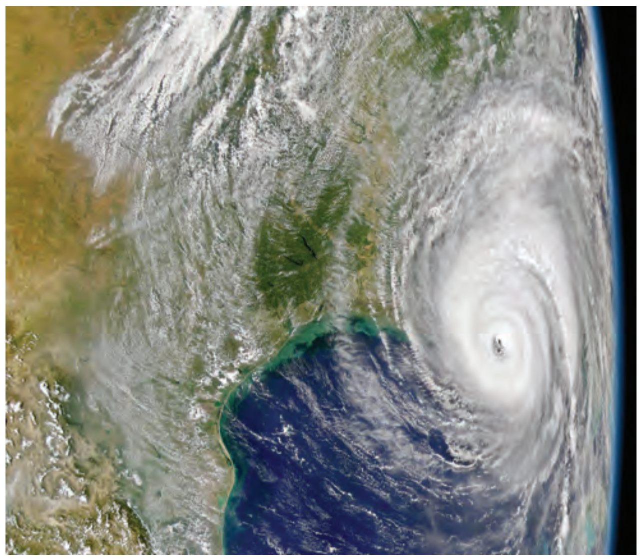

Figure 9.1 Hurricane Ivan over the Gulf Coast of the U.S, captured by SeaWiFS on 15 September 2004. Ivan attained Category 5 strength with winds reaching 270 km h^{-1}. (Credit: Ocean Biology Processing Group, NASA/GSFC and GeoEye).

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).

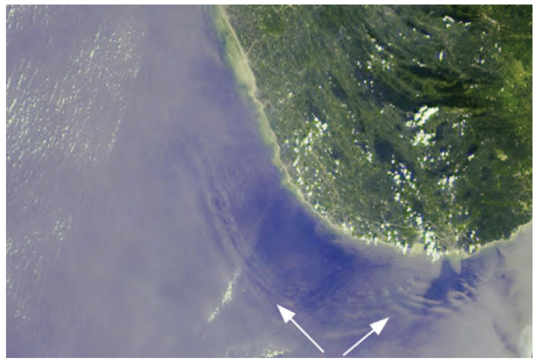

Figure 9.2 At approximately 05:15 UTC on 26 December, 2004, the Multi-angle Imaging SpectroRadiometer (MISR) aboard the Terra satellite captured this image of deep ocean tsunami waves about 30-40 km from Sri Lanka's south-western coast. (Credit: NASA/GSFC/LaRC/JPL, MISR Team).

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

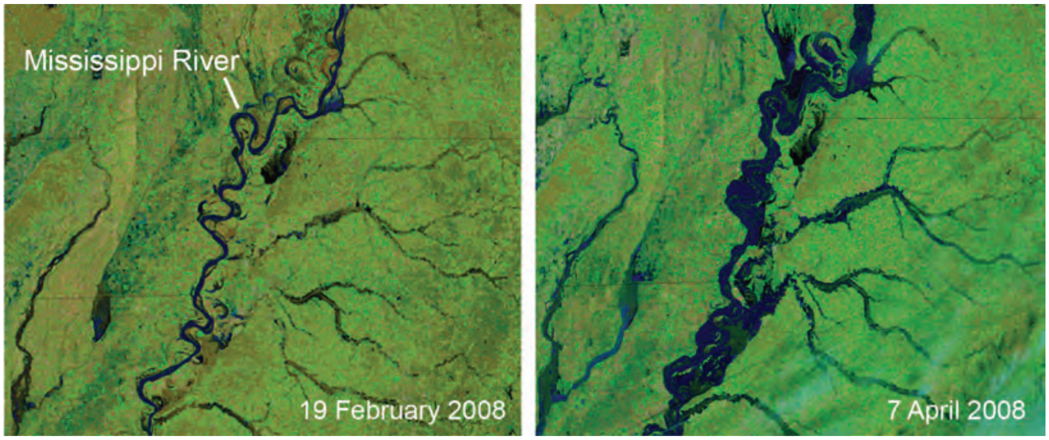

Figure 9.3 These photos were captured by NASA's MODIS-Terra sensor before and after the spring rains caused widespread flooding of the Mississippi River in March 2008. Water levels on the Mississippi River were still high on 7 April 2008 (Credit: MODIS Rapid Response Team, NASA/ GSFC).

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).

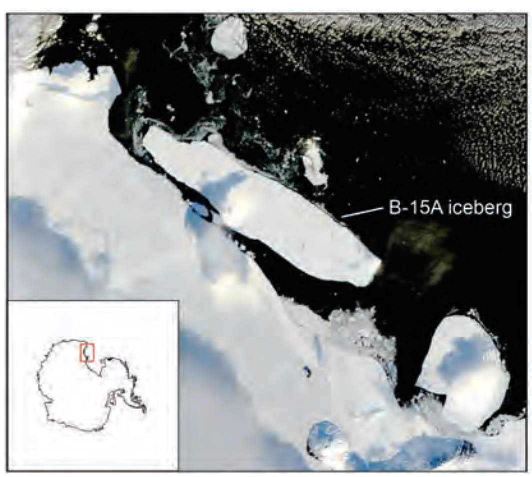

Figure 9.4 True-colour image of the iceberg B-15A in McMurdo Sound, Antarctica, captured by NASA's MODIS-Terra satellite on 13 December, 2004 (Credit: Jeff Schmaltz, MODIS Land Rapid Response Team at NASA GSFC).

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* (2^{nd} on top), *Dinophysis fortii* (3^{rd} on top) and *Dinophysis acuminata* (2^{nd} 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

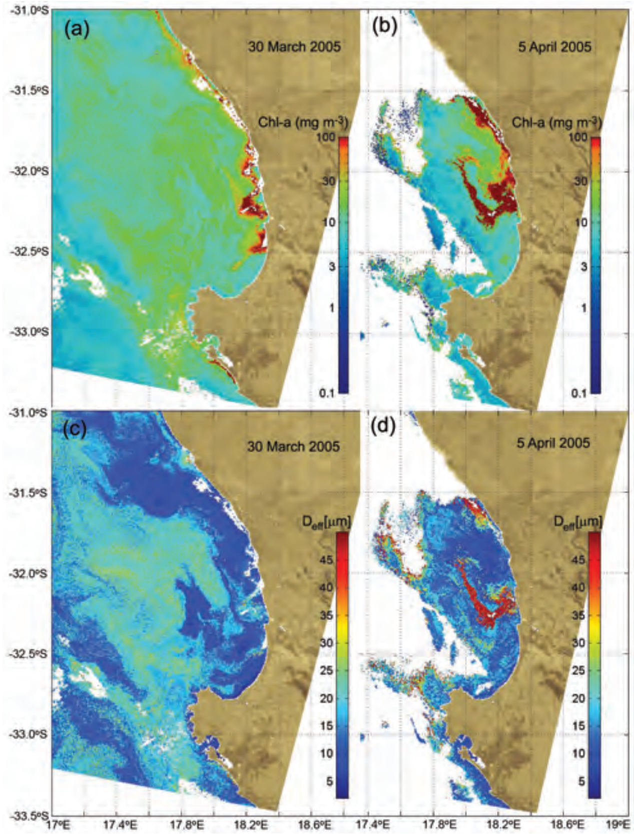

Figure 9.8 Experimental analytical reflectance products showing the complex spatial distribution of a high biomass HAB event in the southern Benguela, and a change in the HAB assemblage in response to environmental conditions. Panels (a) and (b) show Chl-a concentrations approximately one week apart, 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

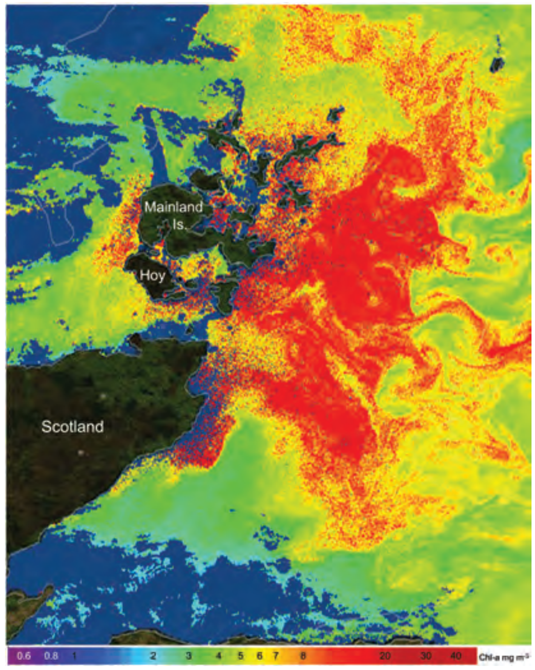

Figure 9.9 A bloom of harmful *Karenia mikimotoi* to the east of the Orkney Isles, Scotland captured by MERIS in full-resolution mode (300 m) on 31 July 2006. (Credit: Image provided by Steve Groom, Plymouth Marine Laboratory, UK. MERIS data provided by the European Space Agency).

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.

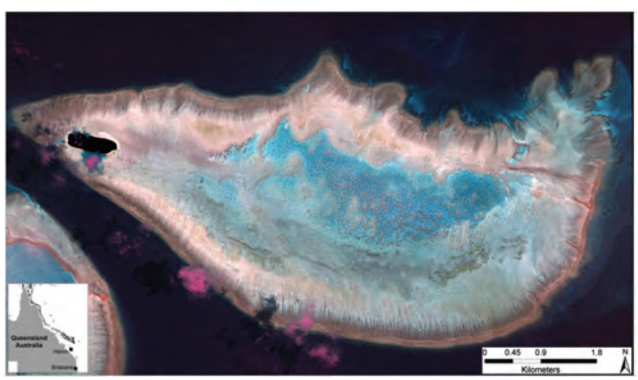

Figure 9.10 High-resolution Quickbird-2 satellite image acquired on 22 February 2004 showing coral-bleaching off Heron Island, Capricorn Bunker Group, Southern Great Barrier Reef, Australia. Image provided by Stuart Phinn and Chris Roelfsema, Center for Remote Sensing and Spatial Information Science,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

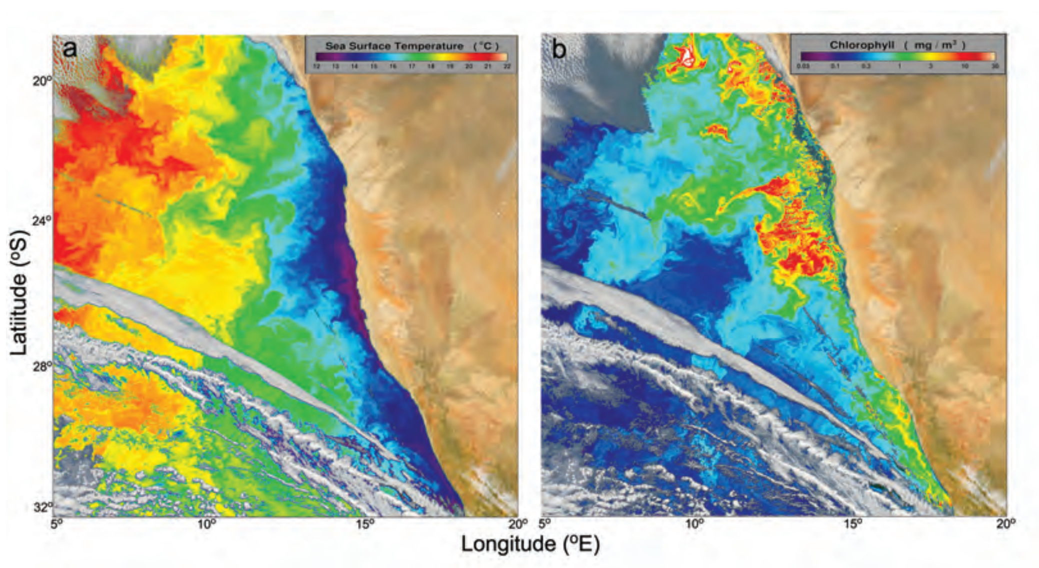

Figure 9.11 MODIS-Aqua SST and chlorophyll images from 17 June 2007 showing a) upwelling of cold (shown in blue) nutrient-rich water off the coast of Namibia, southern Africa and b) the associated high chlorophyll concentrations (shown in red) from a dense phytoplankton bloom (Credit: Ocean Biology Processing 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.