PAPER

The Sea from Space—Applying Remote Sensing to Societal Needs

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ABSTRACT

The use of satellite-based remote sensing systems for observing marine environments is presented. Satellite observations of the marine environment, including weather, support efforts in economic development, national defense, resource management, and policy making, and contribute to the comfort, health, and safety of the public. Several emerging uses of remote sensing, with applications beyond the scope of conventional marine environmental monitoring, are presented, including: maritime surveillance, international treaty enforcement, oil prospecting, and siting of offshore wind farms. As a tool, satellite remote sensing has great potential to contribute to the development of sound marine policy and informed decision making.

I. Introduction

The way we view the Earth has changed dramatically in the last several decades. Instead of a series of discrete parts, we now see the planet as an interconnected system that includes the land, oceans, atmosphere, and biosphere. Satellite-based observation systems have facilitated this understanding by providing a new spatial and temporal vantage point from which to view the Earth.

Current satellite-based remote sensing generally relies on electromagnetic radiation (typically visible, infrared, and microwave) to obtain information about the ocean without physical contact (Lillesand et al., 2004). Remote sensing systems can be located on many platforms (manned and unmanned aircraft, for example), but this article focuses on those systems located on satellites.

The sensors on board satellites fall into two basic groups: passive and active. Passive sensors record energy that is reflected or emitted from the sea at different spatial, spectral, and temporal scales. These types of sensors can image events such as phytoplankton blooms or measure sea surface temperature. Active space-born sensors, such as scatterometers and Synthetic Aperture Radar (SAR), transmit energy and record the energy reflected back to the sensor from the sea. They typically operate in the microwave spectrum and therefore are not constrained by the availability of daylight and cloud-free skies as are optical sensors (Robinson, 2004).

During the 1980s and 90s, satellite-based observing systems were developed and applied primarily to the study of natural phenomena (Martin, 2004). Since that time, new applications of remotely sensed data, many with direct benefits to society, have emerged. Satellite-based earth observation systems are improving public health, strengthening national security, and spurring economic growth. This paper discusses several marine applications of satellite remote sensing technologies. Though military and government efforts have sponsored many classified satellite missions, this paper focuses only on applications of non-military, unclassified satellite data.

Although the applications for satellite data are expanding, one criticism is that the data could be more useful if it were easier to locate and interpret by end users. But translating raw satellite data into useful information requires sophisticated interpretation techniques, significant funding, and interagency cooperation (NRC, 2003; 2005). This lack of synergy between research and operations has led to "transition failures" in which valuable data have been gathered but not applied appropriately by decision makers (NRC, 2003).

The useful application of remote sensing data is also threatened by decreased funding for the observation missions themselves. For example, the United States' extraordinary foundation of global observations is diminishing: between 2006 and the end of the decade, the number of operating missions will decrease dramatically and the number of operating sensors and instruments on NASA spacecraft, most of which are well past their lifetimes, will decrease by 40 percent (NRC, 2007).

II. History

It was recognized long ago that observing the ocean from an Earth orbit could free scientists and engineers from the limitations of studying the ocean using ships and buoys. Satellites generally provide greater geographic coverage at higher temporal and spatial resolutions than *in situ* measurements. In 1978, the U.S. launched three satellites that provided quantitative, calibrated measurements of the ocean. These three satellites included the Coastal Zone Color Scanner (CZCS), launched on board Nimbus-7, which was designed to make ocean color observations (NASA, 1996); the Advanced Very High Resolution Radiometer (AVHRR) on board the TIROS-N satellite, designed to measure sea surface temperature (NOAA, 1998); and several instruments on Seasat, the first satellite dedicated specifically to making oceanographic measurements (Born, 1979). Other countries such as Japan, France, Canada, and the nations of the European Space Agency (ESA) later initiated their own ocean satellite missions (Robinson, 2004).

To date, the number of nations that have launched ocean remote sensing satellites has grown to include at least eleven countries or groups of countries (Martin, 2004; Robinson, 2004). Ocean measurements routinely made from satellites include sea surface temperature; wind speed and direction; height and directional distribution of ocean waves; atmospheric water content and rain rate; sea surface height; extent and type of polar sea ice; and concentrations of sediment, phytoplankton and dissolved and suspended material (Gower, 2006; Martin, 2004; Robinson, 2004).

The availability of satellite imagery on the Internet generally, and Google Earth® specifically, has increased awareness of imaging the earth from space and facilitated new applications for satellite imagery including disaster relief, resource management, and tourism development. Remote sensing is a rapidly developing discipline and new techniques and sensors are constantly emerging. In particular, increases in spatial, spectral, and temporal resolution have resulted in a growing diversity of new applications.

III. Uses of Satellite Imagery Over the Sea: Some Recent Examples

Because a majority of remote sensing professionals were trained in the earth sciences and geography, most applications of remote sensing historically focused on environmental monitoring (NRC, 2001). But, as more satellites and instruments were launched, with ever expanding capabilities, applications of remote sensing beyond the scope of conventional environmental monitoring have emerged. In turn, societal benefits have expanded to encompass not only scientific research and environmental monitoring but public safety and human health, economic development, and global climate monitoring. A discussion of several emerging applications of remote sensing data and how these applications benefit society follows.

a. Oil Prospecting from Space

Commercially available remote sensing data can be useful for the exploitation of natural resources. For example, satellite-based SAR has been used to map large areas of the sea where potential oil and gas reserves might be found. Oil migrates naturally through cracks from deposits deep below the ocean floor, releasing oil into the world's surface waters. This oil can be seen in imagery taken by SAR sensors on board satellites such as the Canadian Space Agency's RADARSAT and the ESA's Envisat. The very thin oil layer on the water dampens the small (capillary) waves, and reflects the radar signal away from the satellite rather than toward it. This creates a discontinuity in the radar image that usually appears dark where there is a slick.

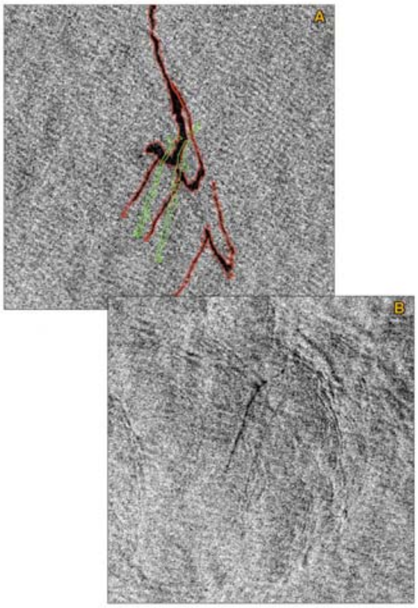
By examining the size and shape of the discontinuities on a SAR image along with other data such as bathymetric and gravity measurements, a skilled operator can often differentiate among ice, pollution, biogenic slicks, oil seeps, wind shadows, and oily bilge water. Once the presence of oil on the surface is ascertained, the natural seep can be traced back to its source on the seafloor.

Oil companies, such as Petrobras, the Brazilian national oil company, and PEMEX, Mexico's state oil and gas company, commonly use satellite-based SAR technology to identify areas with potential hydrocarbon deposits and to plan their seismic exploratory activities. This method has proven effective particularly in deepwater and has been used during exploration activities in Nigeria, Brazil, Angola, and the Gulf of Mexico (Wagner, 2006). Most recently, previously undetected oil seeps offshore Siberia and in the Barents Sea were found in SAR imagery. One advantage of using this radar survey technique is that it is less expensive than aerial or seismic surveys: a satellite survey costs tens of thousands of dollars, while a typical seismic survey of the same area has a price tag of hundreds of millions of dollars (NASA, 1999). Industry representatives report that a petroleum company can screen large areas of the ocean using SAR imagery for $0.50 per square kilometer—an economical method when one considers that a single satellite images can cover up to 500 square kilometers of ocean (Wagner, 2006).

The success of SAR imagery in detecting oil on the sea surface depends strongly on the environmental and weather conditions on the date of image acquisition, however. The effects of oil slicks on the sea surface can be confused with atmospheric effects due to wind shadowing and heavy rainfall (Gade et al., 1998; Trivero et al., 1998). Generally, slicks can be seen in SAR images only when the wind speed is not too high or too low. If the wind is too high, waves induced by the strong wind break and drag the oil below the surface where it cannot be detected. During periods of low wind speeds, the surface of the sea remains flat, making it difficult to differentiate between flat, calm water, and flat, oil-covered water. Integrating other data types such as meteorological and oceanographic data, both remotely sensed and *in situ*, aids in the interpretation of the satellite imagery and can help overcome these limitations (Bentz et al., 2004).

FIGURE 1

Naturally Occurring Oil Seeps. The top image outlines (in red) three seeps off the coast of Western Africa on December 12, 1997. Two seeps observed in the same location 47 days later (bottom image) are outlined in green. Source: RADARSAT-1 image © Canadian Space Agency 1997. Received by the Canada Centre for Remote Sensing. Processed and distributed by RADARSAT International. Image analysis and interpretation by Infoterra Ltd. (Color figures are available at http://www.mtsociety.org/publications/journal.cfm).



b. Pollution Monitoring and Treaty Enforcement

The same imagery that is used to exploit natural resources can also be used to protect them. Satellite-based radar is used to detect oil spills, forecast slick propagation, and to assess coastal and marine environmental impact from spills originating at offshore rigs. The use of the imagery is invaluable in determining the size of the spill and in monitoring its subsequent movements. Several operational automated slick detection systems are presently under development.

One automated system, run by Petrobras of Brazil, relies on emergency tasking of the satellite in the event of a spill (Wagner, 2006; Stephens, 2004; Bentz, 2001). After the area of interest is imaged by the satellite, the processed imagery is delivered in near real-time (generally in four hours or less from the time of acquisition) to Petrobras who then assimilates the data to extract the location and extent of the oil and integrate it into an oil spill model. This model then extrapolates the future movement and spatial distribution of the oil—information that is critical to a disaster response team. This application exemplifies a successful transition from raw data to operations—the data assimilation system and oil spill models utilize the raw data to make useful analyses and forecasts in a timely way.

These types of automated systems can also be used to identify illegal oil discharge from ships and prevent the introduction of pollutants. In this way, satellite imagery helps inform treaties such as the 1983 Bonn Agreement, a rigorously enforced multi-lateral agreement for dealing with pollution of the North Sea by oil and other harmful substances. Under this agreement, monitoring schemes were established to trace oil spills back to the ship from which they originated using SAR imagery in conjunction with vessel identification systems. Other satellite-based technologies such as infrared (IR) and ultraviolet (UV) sensors are used to determine spatial extent (de Sherbinin et al., 2002). This technique has proven useful for surveillance but, under the Bonn Agreement, photographic evidence is still required to prosecute a ship's owner.

Remote sensing can also help ensure compliance with international maritime agreements—it is used to monitor illegal ballast water discharge and prevent the introduction of aquatic nuisance species in support of the MARPOL Act (Pavlakis et al., 2001). As with oil, the discharge of ballast water creates a discontinuity in SAR imagery that can often be traced back to a ship (also visible in the SAR imagery). In this application, SAR not only locates marine pollution originating from ships, but more importantly, deters ship owners and operators from violating the agreements. The advantage of monitoring ships from space is that it provides greater coverage at a lower cost than traditional methods, and provides images of areas that can be difficult to reach.

Satellite imagery can also be used to evaluate and assess the effectiveness of existing international treaties or regimes. In this way, it has been used as an environmental monitoring tool to globally survey and assess wetlands in support of the 1971 international Ramsar Convention to protect wetlands (ESA, 2006b). On a political level, satellite imagery also plays an important role. It has been used to determine international water boundaries and surface water areas. By providing visual evidence of environmental problems, it can help generate commitments to new treaties and resolutions. Wide dissemination of satellite imagery can also build the public support needed for environmental treaties—one of the most important factors in treaty effectiveness. This in turn, can spur politicians to take action. In summary, data from remote sensing can help fill the gaps that often become obstacles to the development of sound environmental policy and solid, science-based decision making.

FIGURE 2

RADARSAT image of land-based spill off of Lebanon, 23 July 2006. Air strikes on 13 and 15 July 2006 hit a land-based oil-fueled power plant on the Lebanese coast 30 km south of Beirut. An estimated 30,000 tons of heavy fuel oil spilled into the Mediterranean where a combination of wind and currents pushed the oil out to sea and along the coast. Source: RADARSAT-1 image © Canadian Space Agency 2006.

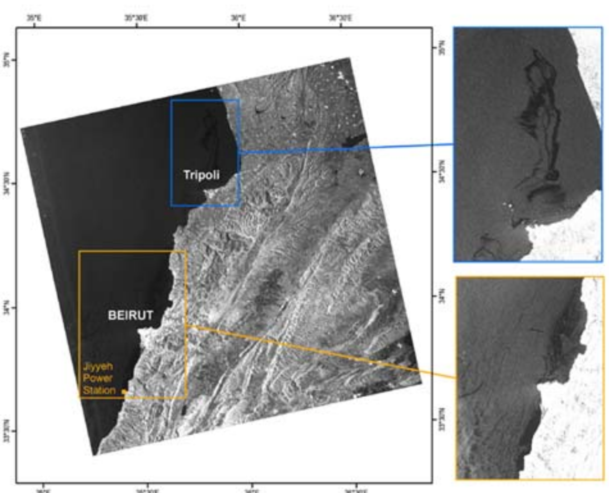
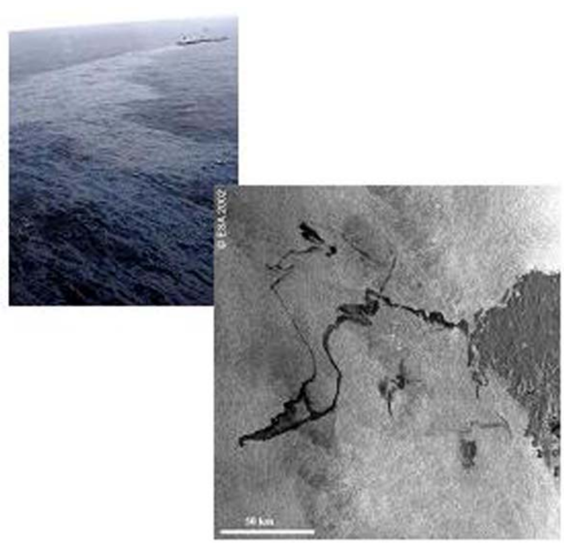


FIGURE 3

"Prestige" oil spill off the coast of Spain. The photograph shows the ship in the upper right-hand corner and the resulting slick. The ASAR image was created on 17 November 2002, 4 days after the ship started leaking. Source: images courtesy of European Space Agency © ESA 2002.



c. Protecting Fisheries and Economic Interests

Satellite data can be used to enforce compliance with international pollution-prevention treaties by identifying non-compliance. They can also be used to ensure that fishery privileges in the Exclusive Economic Zone (EEZ) are not violated.

French authorities, for example, have reported a 95% reduction in fish piracy in the Southern Ocean's Kerguelen Islands since SAR satellite surveillance was initiated in February 2004 (Losekoot and Schwab, 2005). To combat illegal fishing of the Patagonian toothfish, a SAR receiving station was located on Kerguelen Island to monitor the region around the clock and in all weather conditions. SAR provided an ideal monitoring tool because the French Exclusive Economic Zone includes almost one million square kilometers of ocean, an area too large to effectively survey with ships. The SAR images are received at Kerguelen in real time and automatically processed to extract the radar signature of ships in the area. These radar signatures along with each ship's position are sent to French authorities on Reunion via satellite link. Illegal vessels can then be quickly identified because authorized vessels are required to have an Argos satellite transmitter aboard which broadcasts the ship's location and identification. These ship's positions are then matched with radar signatures to discriminate illegal vessels whose locations are sent to French navy patrol boats who can intercept the rogue vessels. Just a few months after its installation, the system celebrated a major success when it identified a Honduran vessel with an illegal catch of 60 tons aboard (ESA, 2005).

d. Finding Fish with Satellites

Remote sensing is used not only as a tool to regulate fisheries, but also to exploit them. Satellite imagery can direct fishing fleets to large schools of fish by tracking currents, ocean features, and weather fronts.

Numerous private companies promote satellite imagery as a road map to guide fishing vessels towards a catch. For example, ORBIMAGE SeaStar Fisheries Service provides data collected from its own multispectral (8 channel) OrbView-2 satellite, launched in 1997 (see www.orbimage.com). ORBIMAGE provides several types of products. A single-layer image or dataset of chlorophyll *a* for a 512 x 512 km area costs on the order of $500 for a single-user license. These data include plankton concentration, plankton frontal analysis, sea surface temperature, sub-surface temperature, near real-time surface currents, sea surface height anomalies, complete weather information, and fish location recommendations provided by ORBIMAGE's oceanographers. Other products include maps that cover an approximate area of 2,000 km^2 and are delivered directly via email to fishing vessels. ORBIMAGE also provides specialized services, such as the SeaStar Albacore Service, which provides fish-finding maps customized for seasonal albacore trolling fleets. The direct download license for this service costs approximately $100,000 per year and can be used with one's own high-resolution picture transmission antenna. It offers direct access to OrbView-2 data for a circular region of approximately 4,000 km in diameter.

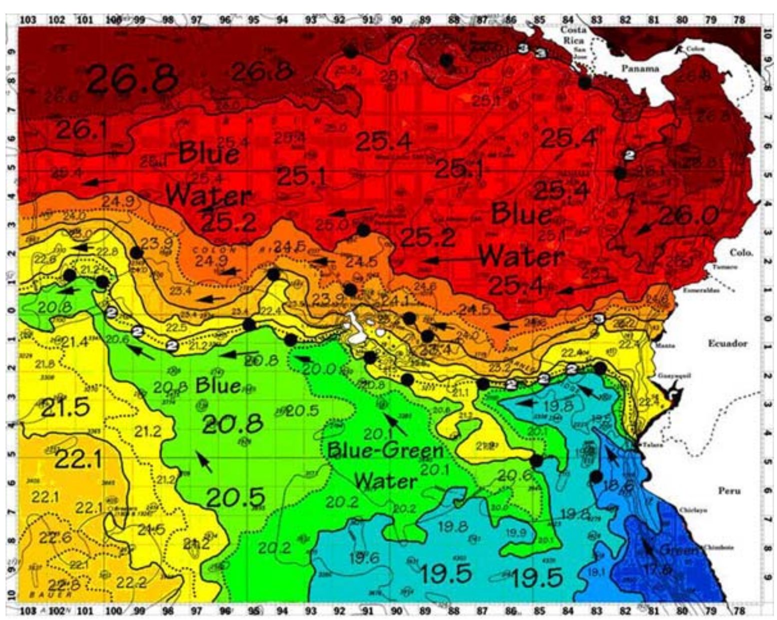
Roffer's Ocean Fishing Forecasting Service, Inc. (ROFFS) provides a similar service (www.roffs.com). Founded in 1987, ROFFS sells satellite-derived environmental data to commercial and recreational fishers from the Northeast Atlantic to the Gulf of Mexico. Combining ship and buoy data with imagery from NOAA's AVHRR sensors, the National Aeronautics and Space Administration's (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, and satellite-based altimeter data, ROFFS fishing analyses incorporate: water temperature, water color, bottom topography, history of ocean fronts, orientation of local currents, biological quality of the water, forage preference of the target species, availability of forage, and habitat preference of the forage and target species to predict optimal regions for fishing (Figure 4). An unlimited seasonal plan for a selected area costs on the order of $2000, while a single analysis costs around $64.

e. Habitat Mapping and Ecosystem Modeling: Coral Reefs

Remote sensing can also help monitor sites of natural productivity in the ocean, like coral reefs. Around the world, coral reefs are threatened by increasing ocean temperatures and human activities, such as fishing (Bellwood et

FIGURE 4

Roffs fisheries oceanographic analysis for the Ecuador area. Created on October 18, 2001 using data from the previous three days. Based on a multiple factor analysis, the symbols (black dots) mark the areas where bait concentrations are expected and where fishing action is anticipated to be better compared with other (non-marked) areas. Source: Mitchell Roffer, Roffer's Ocean Fishing Forecasting Service, Inc.



al., 2004). For some reefs, these stresses have led to massive die-offs at rates unparalleled in the last 10,000 years. As coral reefs change dramatically, remote sensing has emerged as an effective way to measure, document and track these sensitive ecosystems.

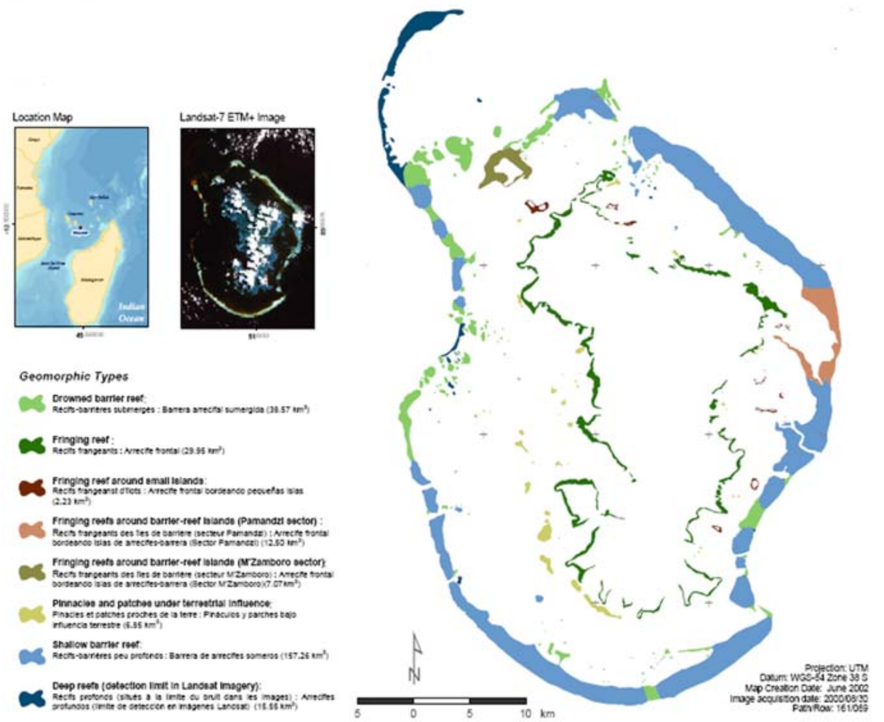
The Millennium Coral Reef Mapping Project, run by the Institute for Marine Remote Sensing at the University of South Florida, aims to map and classify coral reefs worldwide using over 1,700 high resolution (30 m) multispectral Landsat 7 images acquired between 1999 and 2003. The project, funded by NASA's Oceanography Program, will provide the first ever uniform global map of shallow water reef systems. This baseline map will allow researchers to examine the structure and extent of shallow reef ecosystems in the Caribbean-Atlantic, Pacific, Indo-Pacific, and Red Sea. The work allows for an examination of the similarities and differences between reef structures on a scale much greater than that obtained from traditional field studies.

In related work, a global team of researchers used the imagery from the Millennium Coral Reef Mapping Project to estimate how many reefs are within Marine Protected Areas (Mora et al., 2006). The study overlaid the Millennium Project's Landsat maps and other reef imagery, with GIS layers of Marine Protected Areas (MPAs). The researchers found that only 18.7 percent of the world's reefs are located within MPAs, and less than two percent of all reefs are within MPAs that actively limit human activities that can damage them. This type of large-scale ocean management analysis was made possible by the widespread availability of remote sensing data.

Satellite altimeters, like the American-French collaborative mission called Jason-1, can also provide useful information concerning threats to coral reefs. The ocean has varying surface topography: in short, when water warms, it expands, pushing the surface level up in some areas. An altimeter maps the surface height of the ocean and is extremely useful for looking at broad ocean currents and providing an indication of subsurface temperatures. From its vantage 860 miles above the ocean, Jason-1 can measure ocean surface topography to an accuracy of 3.3 cm. As coral reefs are known to be highly sensitive to

FIGURE 5

Map of Mayotte's Reef in Indian Ocean derived from Landsat-7 Enhanced Thematic Mapper. Source: Millennium Coral Reef Mapping Project, University of South Florida.



changes in temperature, altimetry data used in conjunction with AVHRR data is useful for reef monitoring and assessing reef habitat on a global scale.

f. Commercial Shipping: Tracking Ice Flows

Knowing the location of icebergs and sea ice is essential to operators of tankers, oil rigs, icebreakers, and military vessels in polar waters. In the Canadian Arctic, navigation is limited to a brief season between July and October, when the ice is weaker and open water is present. Competitive sailors also require ice data—the Volvo Ocean Challenge is just one of several professional sailing races that rely on satellite ice tracking to help navigate southern waters (ESA, 2006). Commercial fisheries, such as the Alaskan snow crab industry in the Bering Sea, require information on ice edge to know where to set their traps. Ice data are also used to help manage hydropower generation by determining hydropower potential of a glacier system and calculating seasonal runoff. Finally, ice analysis is increasingly used as a record of ice conditions to support climate change studies.

Sea ice can be tracked via satellite with instruments such as passive microwave sensors and scatterometers (which provide low spatial resolution but high temporal acquisition frequency) and satellite-based active sensors such as SARs (which provide high spatial resolution but low temporal acquisition frequency). Other sensors used in ice tracking include the AVHRR, originally developed for meteorological applications but useful for ice monitoring due to its frequent temporal coverage and ready availability. In addition to visible imagery, the thermal bands of the AVHRR provide an indication of ice type and age at a resolution of 1 km even in times of polar darkness. Another source of ice data is the US Defense Meteorological Satellite Program (DSMP) which uses the Operational Line Scan System (OLS) to provide visible and thermal imagery at a resolution of 0.5 km. Passive microwave imagery from the Special Sensor Microwave/Imager (SSM/I) instrument on the DSMP satellites provides microwave radiometry over a swath of 1394 km at a coarser resolution (12.5 km to 25 km). However, approximately 70% of the time, cloud cover or fog typically ob-

FIGURE 6

Icebergs in the Southern Ocean as imaged by ASAR. Source: European Space Agency.

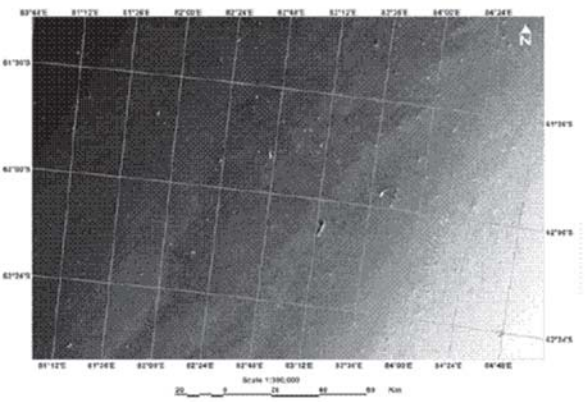
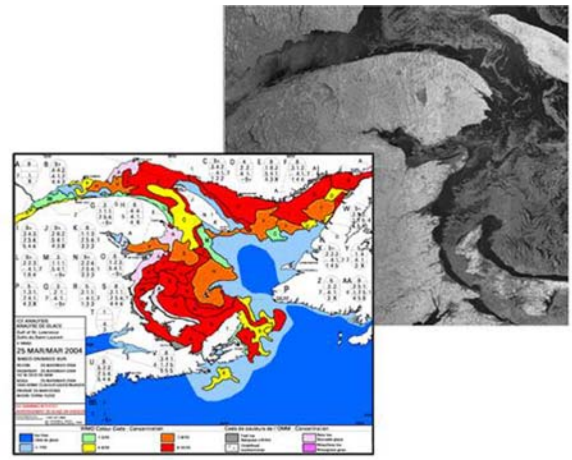


FIGURE 7

Ice analysis in the Gulf of St. Lawrence for 25 March 2004. This analysis incorporates data from the black and white RADARSAT SAR image shown above and also includes imagery from reconnaissance flights and optical data from NOAA AVHRR, Envisat MERIS, and TERRA's MODIS sensor. Source: Canadian Ice Service. RADARSAT-1 image © Canadian Space Agency 2004.



scures the part of the ice pack of greatest concern to ship traffic. For this reason, SARs on board the Canadian Space Agency's RADARSAT, ESA's Envisat, and ESA's Remote Sensing Satellite series (ERS 1/2) are optimal for sea ice mapping because of their all-weather, day/night and high-resolution imaging capabilities (Flett, 2003).

Radar data can aid in determining ice concentration and type, identifying ice features and icebergs, and tracking ice motion. Information on total ice concentration, location of the ice edge, ice type and thickness, ice topography, the state of ice decay, and iceberg and ice island location can be derived directly from radar imagery. From these data, detailed maps are created that provide accurate and timely information about ice conditions in the waters for navigators.

The use of SAR in monitoring ice flow is operational in many countries including the U.S., Canada, Denmark, and several other European nations. It is estimated that over 10,000 scenes of SAR data are collected annually for use in operational ice monitoring (Bertoia et al., 2004). This results in substantial cost savings due to the reduction of aircraft reconnaissance and the use of more efficient ship transit routes.

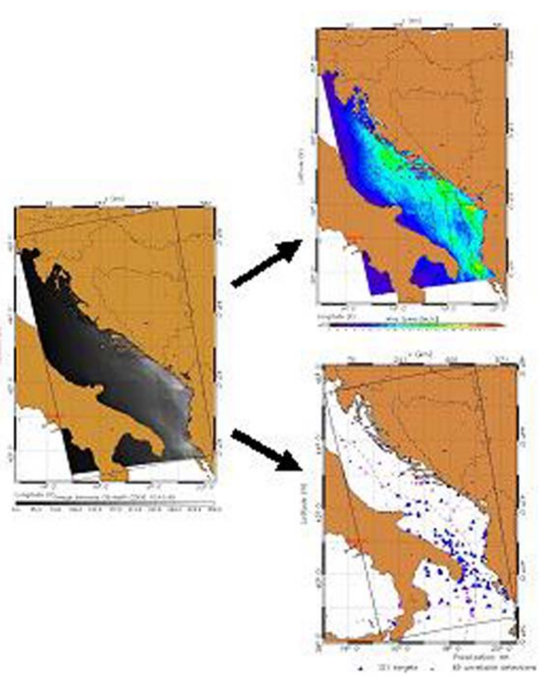
g. Defense: Maritime Surveillance and National Security

Measurements of wind speed and direction near the ocean surface are critical for predicting weather patterns and planning military operations. Historically such surface wind measurements were made by instruments on ships and buoys, but their coverage was insufficient to provide a global wind map. Now the QuikSCAT satellite can provide daily near-global coverage at spatial resolutions of 25 km. This satellite uses a scatterometer called Seawinds, a unique circular scanning active sensor, which yields more robust wind measurements than in the past. Winds can also be derived from SAR imagery available from satellites such as RADARSAT-1 and Envisat's ASAR.

A project at the NATO Undersea Research Centre derives wind speeds and other environmental information from SAR imagery over large areas to support efforts in operational oceanography—the coupling of models, satellites, and *in situ* observations in order to describe the state of the ocean and to provide a predictive capability (Teixeira et al., 2007).

FIGURE 8

Derivation of wind speed and ship locations in SAR Image. Source: RADARSAT-1 image © Canadian Space Agency 2006. Received and processed by the NATO Undersea Research Centre Remote Sensing Group. Image analysis and interpretation by Boost Technologies.



The project involves down linking SAR data in real-time and deriving wind speed at higher spatial resolutions than have previously been possible. Moreover, from the same image, strategic information about the location, speed, and direction of ships can be derived. Therefore, from one SAR image, a synoptic view of the sea over a large area is created, which provides not only environmental data but also operational information such the location and direction of vessels in the area. (See Figure 8).

Data from other satellites such as NASA's AQUA and TERRA can be used to derive horizontal underwater visibility, an important parameter for covert diver operations. Additional data from *in situ* sensors, models, and other sources is also incorporated in a process known as data fusion. The integration of these data contribute to an overall awareness of the region, known as Maritime Situational Awareness (MSA), essential information for NATO troops. This information can be provided in near real-time and is vital for planning and conducting search and rescue missions, naval refuelings, beach landings, studying ocean basin circulation, and locating frontal regions in support of NATO maritime operations (Alvarez et al., 2000).

Another example of ocean surveillance, funded under the auspices of ESA, is known as the MARISS program (European Maritime Security Services). This effort is developing an automated system for detecting vessels that integrates satellite data with coastal surveillance radar, automatic identification systems (AIS), and vessel traffic management systems. This allows for surveillance of vessels in the territorial waters of Europe and has applications to national security, border control, and the prevention of illegal trafficking (Silvestri, 2006).

h. Energy: Planning Offshore Wind Farms

The development of offshore wind farms is progressing rapidly, particularly in Europe. Construction of wind farms in clusters is especially attractive because grid connections and maintenance costs can be shared. However, the distance between wind farms must be carefully calculated to avoid the reduction of wind speed caused by wind turbines, known as shadowing. Accurate estimates of wind characteristics, specifically shadowing (also known as the wind farm wake effect) are critical, particularly during the development stages of the project. However, the spatial variability of wind distribution has historically been difficult to capture with conventional *in situ* methods. For this reason, satellite platforms such as RADARSAT-1 and the ESA's ERS-1, ERS-2, and Envisat provide wind speed estimates at resolutions of a few square kilometers that are accurate to within +/- 2 m/s. These satellite-based SARs provide measurements that are precise enough to enable the early stages of wind farm planning, before higher-accuracy on-site measurements are required.

The two largest offshore wind farms in the world are located at the Danish sites Horns Rev and Nysted, which became operational in 2002 and 2003 respectively. Recently, micro-siting and environmental impact studies were carried out in both locations, as the development of two additional wind farms has been scheduled in the vicinity (Schneiderhan et al., 2003). To carry out the impact studies, a series of satellite and airborne SAR images were analyzed to determine the downstream distance over which the two wind farms impact the marine wind climate. High-resolution ERS-2 SAR and Envisat ASAR imagery was used in conjunction with data from Germany's Experimental airborne SAR (E-SAR). The E-SAR data had a much higher spatial resolution (2 m) than the satellite SAR images (25 m) but a longer acquisition time (2-4 minutes per scene), resulting in fluctuations in wind speed and direction within a single E-SAR scene. Wind maps were generated from the SAR images and spatial averages of wind speed were obtained upstream, within, and downstream of the wind turbine arrays. Shadowing of up to 20% of the ambient wind speed was found 5-20 km downstream of the wind farms. The use of SAR imagery in the planning stages of wind farm development makes the essential "shadowing" analysis more efficient and cost-effective.

i. Aquaculture: Siting Offshore Fish Farms

Global fisheries worldwide are declining, while demand for seafood is rising. A recent study found that, based on the current trajectory, a complete collapse of all species presently fished could occur within forty years (Worm et al., 2006). Aquaculture may be a way to stem the tide: already, it is the fastest growing food production industry (FAO, 2006). Satellite imagery is proving to be a useful tool for this fast-growing agribusiness. Fish farmers can assess the chemical, biological and physical characteristics of potential fish farm sites without the need to conduct on-site surveys.

Temperature is one of the most important factors in selecting an economically viable fish farm site. Water temperatures above or below the optimum temperature can adversely affect reproduction, mortality, feeding, and growth rates of fish. In a recent study, scientists from the Institute of Aquaculture in Scotland used NOAA-AVHRR imagery to pinpoint optimum locations for off-shore floating pens of sea bass and sea bream near the island of Tenerife in the Canary Islands (Pérez et al., 2005). Over a 3-year period, approximately 135 radiometrically corrected images were used to determine average sea temperature (SST). Each image was analyzed to calculate SST from algorithms that use channels 4 and 5 of the AVHRR. The SST data were then averaged and the areas with the optimal SST values were selected as most favorable sites for fish pens. For sea bass and sea bream, higher temperatures (within a range) produce higher growth rates and shorter reproduction cycles. And for a fish farmer, this means greater profit.

j. Coastal Development

Monitoring changes in bathymetry and sediment transport regimes caused by coastal development is an important commercial application of satellite imagery. Externalities due to dredging and other construction activities include the erosion of beach and dune areas, increased turbidity over vital ecosystems such as coral reefs and sea grass beds, and erosion of tourist beaches. As a result, construction and dredging activities must be constantly monitored to determine their environmental impacts through all phases of a project. To do so, *in situ* measurements are typically carried out using turbidity meters and water samples which can determine suspended sediment concentration. However, this type of analysis is expensive and time consuming. Remote sensing data provides greater coverage at a lower cost.

An effort funded by ESA included the development of a prototype commercial service to monitor the impact of human activities on the coastal zone. The aim of the project, known as MOCCASSIN, was to measure changes to bathymetry and sediment transport caused by port development by producing maps of suspended sediment concentration and high-resolution bathymetry (Hesselmans et al., 2000). The project relied on satellite imagery from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (to measure total suspended sediment); SAR (to measure bathymetry in shallow areas); and the Modular Optoelectronic Scanner (MOS) on board the Indian Satellite IRS-P3 (to measure total suspended matter). The bathymetry and sediment concentration data were then integrated with data from *in situ* sensors to provide a complete picture of the changes to the sediment transport regime.

k. Human Health: Mitigating the Effects of Phytoplankton Blooms

When exposed to certain conditions, algae reproduce at high rates, causing an "algal bloom." Some types of algae can produce neurotoxins that can kill the animals that eat it, or can bio-accumulate in prey and kill higher level organisms. Humans may be poisoned by eating seafood caught in an area experiencing a harmful algal bloom. Blooms can also lead to depletion of available oxygen in the water, which can then kill fish and other organisms. Not only do blooms pose a health threat, they are costly: harmful algal blooms are estimated to produce $82 million in economic losses each year in the U.S. alone—$38 million in commercial fishing losses, $37 million in public health costs, $4 million in tourism impacts, and $3 million in coastal monitoring and management (Hoagland and Scatasta, 2006).

In 1998, Congress passed the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA), which explicitly calls for research to advance the ability to predict and detect harmful blooms. Advanced warning is considered key to minimizing costs and risks of harmful algae blooms and remote sensing has proven to be a powerful forecasting tool.

In 2004, NOAA developed a Harmful Algal Bloom Forecasting System to forecast and detect blooms using satellite imagery in conjunction with other monitoring techniques.

Specifically, SeaWiFS provides data on the scattering of sediments in the water, which can be translated into accurate chlorophyll concentrations using a special algorithm (NOAA, 2006). The imagery can also be used to distinguish some species of algae from others because their cellular features produce unique optical signatures discernable through satellite imagery. But chlorophyll concentrations are just one input to the forecasting system—*in situ* sampling is also required to ground-truth the satellite data and confirm the type of algae present. Because algal blooms have caused shellfish closures, fish kills, marine mammal deaths and respiratory problems in humans, the ability to effectively predict and monitor such blooms not only protects humans, but also minimizes the costs associated with such events.

FIGURE 9

This SeaWiFS image of the northeastern Gulf of Mexico from March 1, 1999 shows a nearshore concentration of an algal bloom in light blue-green. Source: NASA, Goddard Space Flight Center.

IV. Discussion

The growth in satellite systems has been driven partly by advances in technology and partly by societal needs. The monitoring of weather conditions and global warming, fisheries management, offshore oil and gas exploration, national security, commerce, public health, and recreation and leisure activities have all benefited from remote sensing. Moreover, approximately 50 percent of the world's population lives within 50 km of the coast, making half the world's population particularly vulnerable to natural hazards such as hurricanes and tsunamis. Satellite remote sensing is playing an increasingly important role in addressing these societal concerns.

Remotely sensed data are generally accurate and objective, provide consistent coverage over long time periods, can focus on various scales, and present large amounts of information without infringing on national sovereignty. As a tool for scientists, it provides nearly instantaneous coverage of very large areas of ocean space at high repetition rates and high resolution. Scientists have long recognized the power of remote sensing; however, the use of remote sensing for other disciplines such as policy development and treaty enforcement remains underexploited. The under-use of this technology can be traced to the fact that many environmental policymakers and social scientists have no experience with remote-sensing technologies. The technical expertise required to process and interpret remote sensing imagery is extensive and the data and the tools required (imagery, hardware and software) can be costly (NRC, 2003).

a. Technical Limitations

From a technical standpoint, there are several shortcomings with satellite sensors and the resulting imagery. For sensors, these include anisotropy or hysteresis, cloud and haze cover which can limit the use of optical sensors, difficulties in making atmospheric corrections and calibrating sensors, and spacecraft anomalies. For imagery, problems include difficulties in image registration, highly variable interpretation of some types of imagery, and the challenges inherent in working with very large data sets.

Moreover, remote sensing alone cannot be a substitute for *in situ* data: ground truthing is required for validation purposes. A recurring theme throughout this article is the need for multiple sensors: Satellite data from one sensor is often used in conjunction with data from airborne sensors, *in situ* instruments or data from another satellite. This synergistic use of multiple sensors with varying spatial, temporal, and spectral resolutions, particularly the fusion of active and passive data (such as radar with optical images) provides an extremely powerful tool.

Finally, as the number of ground stations that can receive satellite imagery in real time has increased, so have the distribution channels for the processed data. The Internet has become a primary portal which provides access to remotely sensed data and metadata—some sites offer data, others offer tools for visualizing the imagery. The ability to download megabytes of imagery has made it feasible for many more people to display, manipulate, and interpret satellite imagery. With this widespread dispersal of data, however, comes a loss of control. It is therefore essential to ensure that the data are accurate, reliable, and include the necessary metadata. Furthermore, in many cases highly skilled users are required to interpret the data and understand the methodologies that produced the images.

b. Legal Limitations

In addition to technical issues, considerable legal and political issues are involved in the use of remote sensing over the sea. These include distribution and copyright practices, and the determination of funding and maintenance costs, which must be agreed upon in the case of joint ventures. But perhaps the most controversial issue resulting from the growing use of high spatial resolution imagery concerns privacy. In the case of ocean remote sensing, concerns over privacy are not as critical as on land because few areas of the ocean are privately held. Nevertheless, the globalization of remote sensing has created a flow of data outside traditional jurisdictional and national boundaries, thus placing it beyond traditional methods of legal control (Crowsey, 2007). Several commentators have observed a remarkable lack of comprehensive policy development with respect to legal and ethical concerns over privacy and the use high-resolution remote sensing technologies (Slonecker et al., 1998).

c. Economic Limitations

Historically, data rights, pricing, and distribution polices were determined by the governments owning the satellites. As a consequence, users had little choice in the market for imagery. However, the control and distribution of satellite imagery is migrating from the government to the private sector, creating an economic restructuring of the entire remote sensing community (Baker et al., 2001). Thirty-three percent of the satellites in orbit by the end of 2007 will be commercial. Sales by the satellite-based commercial remote sensing industry are expected to reach $2 billion by 2010 and prices are expected to drop as the number of commercial sources proliferates (Storey, 2006; NRC, 2003). This trend towards commercialization of satellite imagery, in combination with the rise of a global information infrastructure (i.e., the Internet), has created a fundamentally different world of remote sensing in the last ten years.

V. Trends/Looking Ahead

a. Technological Progress

Methods for observing the ocean from space are moving ahead on all fronts, but the maturity of the techniques varies. Emerging trends include the use of multiple-look angle data and the development of imaging spectroscopy, a technique that samples hundreds of narrow and contiguous spectral bands ranging from visible to infrared (Toselli, 1991). Change detection is another application of satellite data that holds great promise as a tool to map glacier and sea-ice variations (Canty, 2006). More powerful computers have resulted in enhanced image processing and as data exchange becomes routine and automated, data distribution channels are becoming faster and more widespread. This high-speed data transfer results in near real-time (NRT) delivery of imagery which allows for rapid decision making. As linkages between raw data and decision makers become stronger, remote sensing will play a more important role in the field of "enviromatics"— the use of computer modeling to analyze the Earth's environment, predict future trends, and improve decision making in resource management (Roush, 2005).

A revolution in the size of satellites is also taking place. These new "micro-satellites" are small, low-cost spacecraft, often launched in constellations that function in all the same ways as much larger satellites. Some of these smaller satellites may provide higher resolution than previously available (Baker et al., 2001). In addition to lower costs, constellations of smaller satellites have the advantage of greater temporal resolution (i.e., reduced revisit intervals).

b. Domestic and International Satellite Programs

Historically the U.S. led the way in satellite remote sensing but in spite of past superiority, the U.S. satellite program is now perceived to be "severely deficient" (NRC, 2005). "Recently, six NASA missions with clear societal benefits and the established support of the earth science and applications community have been delayed, de-scoped, or cancelled." (NRC, 2007). Not only is the U.S. losing ground, but it is not making the investment required to keep pace in the future. For example, presently there are 5 space-based radars in orbit, and 9 are expected by the end of 2011 (Stoney, 2006). None of them, however, is American.

While the number of U.S. government-funded missions is decreasing, international efforts in satellite remote sensing are on the rise (Baker et al., 2001). Since the 1980s, the number of countries and multinational organizations that have launched imaging satellites has grown steadily. Presently, at least 21 nations own imaging satellites including Israel, Canada, India, and Japan (Ibid.; Stoney, 2006b). Moreover, many other nations are developing extensive expertise in using satellite imagery without operating their own spacecraft.

c. Commercialization

One trend that is observed both domestically and internationally is the emergence of a nascent marketplace for satellite imagery. This trend is due to a combination of several factors—economic, technological, and political (Baker et al., 2001). Market conditions have improved due to advances in smaller, more affordable satellites combined with a relaxation of restrictions on public access of imagery (Ibid.). Furthermore, enabling technologies such as more affordable computing power, larger capacity data storage systems, and user-friendly image processing software reduced the technical and price barriers for a wider range of customers. But commercial imagery remains a small percentage of satellite data. In the U.S., it is expected that commercial sources of satellite imagery will be an "important and high-leverage adjunct to government systems, [but] not as a general replacement" (NRC, 2007).

An important distinction can be made in the way commercialization is taking place. In Europe, Canada, and Russia, civilian (government-owned) satellite enterprises such as ESA, are increasingly focused on selling data commercially. In the U.S., on the other hand, commercial (government licensed but privately owned) companies, such as Orbimage, are relying on U.S. government agencies as their biggest customers (Baker et al., 2001; NRC, 2002). Thus, it is reasonable to expect the imagery business will continue to be government-sponsored and/or subsidized in one way or another for the foreseeable future.

VI. Transitioning from Research to Societal Benefits

Over the past several decades, the use of remote sensing has increased dramatically. Some of the first proponents of satellite imagery emphasized early on that such systems should serve the needs of society beyond the narrow limitations of environmental science (NRC, 2003b; 2005). Yet, in spite of the use of remote sensing in an increasing number of disciplines and the growing distribution channels of satellite data, there has been much criticism of the slow transition of satellite data from researchers to operational users. The importance of transitioning satellite imagery and coupling it with appropriate decision-making systems was tragically emphasized in the aftermath of the 2004 Asian tsunami, which was detected by space-born and *in situ* sensors that were not coupled to an appropriate warning system (NRC, 2005).

There are many cases in which satellite data with societal benefits are not being used operationally (for a list of several case studies see NRC, 2003). For example, between 1980 and 1997, more than a dozen airplanes were damaged or lost engine power after flying through volcanic ash (USGS, 1997). An instrument known as the Volcanic Ash Mapper Instrument (VOLCAM), designed to track volcanic ash and measure other compounds using UV and other sensors, was proposed as an add-on to existing spacecraft (NRC, 2003).

The concept was strongly endorsed by the relevant federal agencies and a proposal was drafted which assigned responsibilities to several of them—NASA for mission development, flight hardware, software development, and scientific research; NOAA for data ingest, processing, and analysis; the Federal Aviation Administration for aviation control planning and education; and the U.S. Geological Survey for eruption prediction and diagnosis (Ibid.). But though the project had strong operational potential and garnered interagency enthusiasm, VOLCAM remained non-operational. The National Research Council suggests its failure was due to the fact that no single agency took the lead (Ibid.). In summary, VOLCAM "demonstrated strong operation potential but, despite substantial effort and interest in both the research and operational communities, *has not successfully been transitioned* to operational status" (Ibid.).

This case illustrates a common problem with establishing remote sensing systems that have clear societal benefits: the transition from the research community to the operational community often requires the involvement of several government agencies and stakeholders, none of which may have the resources needed to take the lead. In the U.S., these potential leadership roles are spread across agencies. Internationally, the problem can be even more complex for efforts that involve multinational agencies such as ESA.

VII. Conclusion

The assimilation of environmental data by policymakers and the public is arguably more important now than ever before. Tracking the changes associated with global warming and its effects—including ice melt, sea level rise and extreme weather events—and using that data to inform policy will be crucial for mitigating the effects of climate change (IPCC, 2007; Moore, 2007). Remote sensing provides an invaluable tool for understanding global warming, but its value will be undermined if the data are not appropriately linked to decision making.

Fundamental improvements need to be made to existing remote sensing systems because they presently only loosely connect three essential elements: (1) the raw data; (2) the analyses, models, and forecast that provide timely syntheses of information; and (3) the decision processes that use those analyses and forecasts to produce actions with direct societal benefits (NRC, 2003).

This paper presented new applications of satellite remote sensing technologies with clear societal benefits and discussed several transitions of satellite measurements from research to operational use. Further efforts are in place to bridge the gap between data and decision-making systems, but there remains a clear need to develop more useful end products. A key factor in addressing this shortcoming remains the need to reconcile long-term research funding (curiosity-driven) with short-term funding (societal benefits). A recent NAS report warned that "the scientific community must focus on meeting the demands of society explicitly, in addition to satisfying its curiosity about how the Earth system works" (NRC, 2007). One tool—remote sensing—gives us the ability to do both.

Acknowledgments

The authors wish to thank the anonymous reviewers for their very thoughtful and constructive comments. We would also like to acknowledge the valuable input from Chuck Trees and Joao Teixeira at the NATO Undersea Research Centre in La Spezia, Italy.

References

Alvarez, A. et al. 2000. A satellite based ocean forecasting system to support naval operations in crisis situations. SACLANTCEN Report SM-375, La Spezia, Italy. SACLANT Undersea Research Centre.

Baker, J.C., K. O'Connell and R. Williamson, (eds). 2001. Commercial observation satellites: at the leading edge of global transparency. Rand Corporation Report MR-1229.

Bellwood, D.R., T.P. Hughes & M. Nystrom. 2004. Confronting the coral reef crisis. Nature, 429: 827-833.

Bentz, C.M. et al. 2004. Multi-sensor synergistic analysis of mesoscale oceanic features: Campos Basin, south-eastern Brazil. Int J Remote Sensing. 25(21):4835-4841.

Bentz, C.M. and F.P. Miranda. 2001. Application of Remote Sensing Data for Oil Spill Monitoring in the Guanabara Bay, Rio de Janeiro, Brazil. Geoscience and Remote Sensing Symposium, 2001. IGARSS '01. IEEE 2001 International. Vol. 1, p. 333 – 335.

Bertoia, C., et al. 2004. Synthetic Aperture Radar for Operational Ice Observation and Analysis at the U.S, Canadian, and Danish National Ice Centers, in Synthetic Aperture Radar Marine User's Manual, U.S. Department of Commerce.

Born, G.H., J.A. Dunne and D.B. Lamb. 1979. Reports: Seasat mission overview. Science 204:1405-6.

Canty, M.J., 2006. Image Analysis, Classification and Change Detection in Remote Sensing. New York, CRC Press, 348 pages.

Crowsy, R. 2007. Examining the legality of a bird's eye view. Earth Imaging Journal, May/June.

de Sherbinin, Alex et al. 2002. Remote sensing data: valuable support for environmental treaties. Environment. 44(1):20.

European Space Agency. 2005. Envisat radar surveillance protects endangered prehistoric fish, 17 November 2005. http://www.esa.int/esaCP/SEMPLU638FE_Protecting_0.html.

European Space Agency. 2006. Satellites ensure safe passage through treacherous waters in volvo ocean race, March 6, 2006. http://www.esa.int/esaCP/SEMF02NVGJE_index_0.html 6.

European Space Agency. 2006b. Ramsar and remote-sensing experts tackle threats to wetlands, 7 November 2006. http://www.esa.int/esaEO/SEMVA8PFHTE_index_0.html.

FAO Fisheries Technical Paper 500. 2006. State of World Aquaculture 2006. Rome: Food and Agriculture Organization of the United Nations, p 1.

Flett, D.G. 2003. Operational use of SAR at the Canadian ice service: present operations and a look to the future. In: Proceedings of the Second Workshop on Coastal and Marine Applications of SAR, 2003. Svalbard, Norway: European Space Agency.

Gade, M. et al. 1998. The imaging of biogenic and anthropogenic surface films by the multi-polarisation SIR-C/X-SAR. J Geophys Res. 103:**18866-18866. [[CHECK PAGES #S]]**

Gower, J.F. 2006. Remote Sensing of the Marine Environment. Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 338 pages.

Hesselmans, G.H.F.M. et al. 2000. Monitoring changes to bathymetry and sediment transport regimes caused by port development (MOCCASSIN). European Space Agency Report.

Hoagland, P. and S. Scatasta. 2006. *The economic effects of harmful algal blooms.* In E. Graneli and J. Turner (eds.), Ecology of Harmful Algae. Ecology Studies Series. Ch. 30, pp. 391-402. Dordrecht, The Netherlands: Springer-Verlag.

Intergovernmental Panel on Climate Change (IPCC). 2007. Summary for Policymakers. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Lillesand, T.M. et al. 2004. Remote Sensing and Image Interpretation, 5th edition. New Jersey, US, John Wiley and Sons, 763 pages.

Losekoot, M. and P. Schwab. 2005. Operational use of ship detection to combat illegal fishing in the Southern Indian Ocean. In: IGARSS '05. Proceedings, Geoscience and Remote Sensing Symposium, 2005, Vol. 3: 1767- 1771. Seoul, Korea: IEEE International Geoscience and Remote Sensing Society.

Martin, S. 2004. An Introduction to Ocean Remote Sensing. Cambridge, UK: Cambridge University Press, 426 pages.

Moore, B. 2007. Congressional Hearing on National Imperatives for Earth Science Research before the US Senate Committee on Commerce, Science and Transportation. March 7.

Mora, Camilo et al. 2006. Coral reefs and the global network of marine protected areas. *Science* 23 June 2006: 312(5781):1750–1751.

National Aeronautics and Space Agency. 1996. GES DISC DAAC Data Guide: Coastal Zone Color Scanner (CZCS) Instrument Guide, Version 2.0, September 1996, http://disc.gsfc.nasa.gov/guides/GSFC/guide/CZCS_Sensor.gd.shtml

National Aeronautics and Space Agency. 1999. Slick technology helps detect oil. Innovation, Vol. 7, Number 1, Jan/Feb.

National Oceanic and Atmospheric Administration, NOAA Polar Orbiter Data User's Guide, November 1998. Available at: http://www2.ncdc.noaa.gov/docs/podug/cover.htm.

National Research Council of the National Academies Report. 2001. Transforming Remote Sensing Data into Information and Applications. Washington, D.C.: National Academies Press.

National Research Council of the National Academies Report. 2002. Toward New Partnerships in Remote Sensing: Government, the Private Sector, and Earth Science Research. Washington, D.C.: National Academies Press.

National Research Council of the National Academies Report. 2003. Satellite Observations of the Earths' Environment—Accelerating the Transition of Research to Operations. Washington, D.C.: National Academies Press.

National Research Council of the National Academies Report. 2003b. Using Remote Sensing in State and Local Government: Information for Management and Decision Making. Washington, D.C.: National Academies Press.

National Research Council of the National Academies, Space Studies Board Report. 2005. Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation. Washington, D.C.: National Academies Press.

National Research Council of the National Academies, Report. 2007. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. Washington, D.C.: National Academies Press.

NOAA Technical Report NOS CO-OPS 047. 2006. Annual Report of the Gulf of Mexico Harmful Algal Bloom Operational Forecast System (GOM HAB-OFS): October 1, 2004 to September 30, 2005 (Operational Year #1)

Pavlakis, P., D. Tarchi and A. Sieber. 2001. On the monitoring of illicit vessel discharges, European Commission Document, EUR 19906 EN.

Pérez, O.M., T.C. Telfer and L.G. Ross. 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. Aquac Res. 36(10): 946–961.

Robinson, I.S. 2004. Measuring the Oceans from Space. Chichester, UK: Praxis Publishing, 669 pages.

Roush, W. 2005. Enviromatics. Technol Rev, May.

Schneiderhan, T. et al. 2003. SAR wind fields for offshore wind farming. In: Proceedings of the Second Workshop on Coastal and Marine Applications of SAR. Svalbard, Norway: European Space Agency.

Silvestri, S. et al. 2006. MARISS GMES services element consolidation for maritime security. In: Proceedings SeaSAR 2006, Advances in SAR Oceanography from ENVISAT and ERS missions. Frascati, Italy: European Space Agency.

Slonecker, E. et al. 1998. Emerging legal and ethical issues in advanced remote sensing technology. Journal of the American Society for Photogrammetry and Remote Sensing, 64(6):589.

Stephens, K. 2004. Brazilian oil company continues to use RADARSAT-1, Earth Imaging Journal, 23 March.

Stoney, W.E. 2006. ASPRS Guide to Land Imaging Satellites. In: NOAA Commercial Remote Sensing Symposium, September 2006. Washington, DC: National Oceanic and Atmospheric Administration.

Stoney, W.E. 2006b. Markets and opportunities. Earth Imaging Journal, 2006. Available at http://www.eijournal.com/Markets_Opportunities.asp.

Teixeira, J., E. Coelho and E. McCarthy. 2007. Real-time high resolution atmospheric prediction at the NATO undersea research centre. NURC Report (in press). La Spezia, Italy.

Toselli, F. and J. Bodechtel (eds). 1991. Imaging Spectroscopy: Fundamentals and Prospective Applications. Boston, MA: Kluwer Academic Publishers, 280 pages.

Trivero, P., B. Fiscella, F. Gómez and P. Pavese. 1998. SAR detection and characterization of sea surface slicks. Int J Remote Sensing, 19(3):543-548.

USGS (U.S. Geological Survey). 1997. Volcanic Ash—Danger to Aircraft in the North Pacific. USGS Fact Sheet 030-97. USGS, Reston, Va.

Wagner, M. 2006. Drilling deep for energy: radar imagery improves oil exploration success. Earth Imaging Journal, 2(5):10-15.

Worm, B. et al. 2006. Impacts of biodiversity loss on ocean ecosystem services. *Science* 314(5800): 787-790.