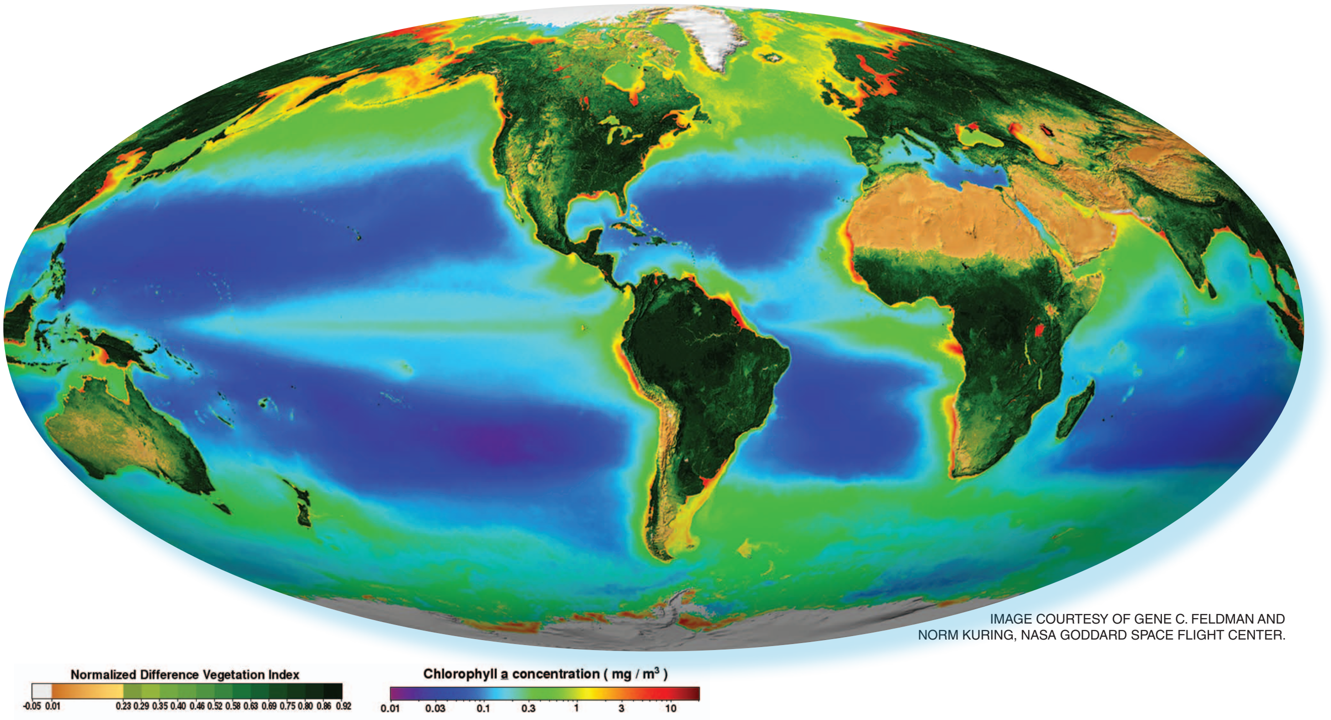
# Satellite Remote Sensing in Support of an Integrated Ocean Observing System



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*Abstract*—Earth observing satellites represent some of the most valued components of the international Global Ocean Observing System (GOOS) and of the Global Climate Observing System (GCOS), both part of the Global Earth Observation System of Systems (GEOSS). In the United States, such satellites are a cornerstone of the Integrated Ocean Observing System (IOOS), required to carry out advanced coastal and ocean research, and to implement and sustain sensible resource management policies based on science. Satellite imagery and satellite-derived data are required for mapping vital coastal and marine resources, improving maritime domain awareness, and to better understand the complexities of land, ocean, atmosphere, ice, biological, and social interactions. These data are critical to the strategic planning of in situ observing components and are critical to improving forecasting and numerical modeling. Specifically, there are several stakeholder communities that require periodic, frequent, and sustained synoptic observations. Of particular importance are indicators of ecosystem structure (habitat and species inventories), ecosystem states (health and change) and observations about physical and biogeochemical variables to support the operational and research

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communities, and industry sectors including mining, fisheries, and transportation. IOOS requires a strategy to coordinate the human capacity, and fund, advance, and maintain the infrastructure that provides improved remote sensing observations and support for the nation and the globe. A partnership between the private, government, and education sectors will enhance remote sensing support and product development for critical coastal and deep-water regions based on infrared, ocean color, and microwave satellite sensors. These partnerships need to include international research, government, and industry sectors in order to facilitate open data access, understanding of calibration and algorithm strategies, and fill gaps in coverage. Such partnerships will define the types of observations required to sustain vibrant coastal economies and to improve the health of our marine and coastal ecosystems. They are required to plan, fund, launch and operate the types of satellite sensors needed in the very near future to maintain continuity of observations.

## 1. INTRODUCTION, BACKGROUND, HISTORY, AND ACCOMPLISHMENTS

Coastal and ocean resources are fully interconnected through ocean, land and atmospheric physics, chemistry, biology and geology. Our global coastal communities share significant trade and culture that is based on living and non-living marine resources. These communities also share problems in terms of resource management, navigation and safety at sea, and the protection of life and property. Each coastal region has unique challenges associated with the safe extraction of resources and all support significant vessel traffic. Extreme events and environmental disasters, such as the Deepwater Horizon (DWH) accident in 2010 in the Gulf of Mexico, as well as the continuing challenges posed by extreme weather, fisheries management, and the impacts of urban and other land uses, require satellite remote sensing to track currents, map ocean productivity, assess winds and waves, and understand environmental forcing and variability. These situations require accessible, rapid, and frequent synoptic maps that are easily interpretable. The development, deployment, and use of satellites that complement ship-based observations, moored and other autonomous sensors, and models, will provide high-quality data more frequently, allowing for improved site-specific forecasts of weather, water conditions, and resource distribution.

Indeed, Earth observing from satellites is at the core of the United States' National Ocean Policy [1, 2]. Over the past twenty years, operational agencies, research institutions, and private industry have made great steps in advancing satellite remote sensing products and applications. There now exist significant collections of time series of processed and merged infrared, ocean color, and various microwave satellite imagery. The products are presently accessible in different formats and through different channels, albeit not always in a simple manner. Yet, there is still no centralized or coordinated distribution for the various satellite data products and applications available today, or for merged or interpreted data. For example, there still is no equivalent to the printed version of an 'atlas' that takes advantage of the interpretations of a dynamic ocean based on global, regional, or local multispectral satellite data available from the various different satellite types flown over the past 2–3 decades. There still is no dynamic map of resources that integrates across land use and land ecology, meteorology and atmospheric chemistry, ocean dynamics, biogeochemistry and ecology, and that includes a human geographic dimension.

As pointed out by the U.S. Commission on Ocean Policy in its 2004 report to the nation [2], achieving sustained observations from space presents daunting challenges. These challenges can only be met by implementing the vision of an integrated Global Earth Observation System of Systems (GEOSS). This will require continuing and very active international partnerships between government, industry, and academic sectors. The cost and long time frame for constructing and launching satellites requires that plans for sensors and missions be drafted five- to ten-years in advance to ensure that satellite observations will be available on a continuous basis. Multi-decadal records of observations also require space missions with sufficient overlaps to avoid gaps in data and allow intercalibration of successive generations of sensors. Lack of such coordination can seriously impair our understanding of changing marine environments and resources.

A fully integrated observing system needs mechanisms to link the remote sensing science community (academic, commercial, NGO and government) supported by research-driven government agencies, the stakeholders that require these observations, and the government agencies that are in a position to design and implement this type of large infrastructure. The effort will help the user community, including the space industry, to identify the most important space-based ocean observation needs. The strategy will include working with the international community to ensure that requirements for the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), and the Earth Observing System of Systems (GEOSS) are coordinated with U.S. plans for satellite remote sensing.

The ultimate objective is to help implement phased satellite missions and equipment replacement to maintain continuous and consistent data streams for the Regional Associations (RA's) mentioned in this white paper as a pathfinder for an Integrated Ocean Observing System (IOOS) to develop a strategy to serve the nation and the international community. This will help build the foundational data sets necessary for the global observing systems being developed to generate the ocean information services that will be at the heart of a healthy ocean and ocean economy.

## 2. TECHNICAL AND USER REQUIREMENTS

There are many stakeholder communities that require real-time, periodic, frequent, and sustained synoptic observations. Of particular importance are indicators of public health, ecosystem states (health and change), ecosystem structure (habitat and species inventories), and observations of physical and biogeochemical variables to support the operational (storm prediction/tracking) and coastal/ocean research communities, and industry sectors including oil and gas exploration, fisheries, and transportation. An emerging requirement is support of a Marine Biodiversity Observation Network or MBON [3, 4]. The requirements include:

- Surface phytoplankton biomass, including distribution and abundance of toxic phytoplankton, and of various phytoplankton functional types (PFT)
- Water quality including turbidity or transparency, and mapping of threats such as oil spills
- Spatial extent of living benthic habitats (coral reefs, seagrass beds, mangrove forests and tidal marshes) and ecological buffers to coastal flooding
- Distribution and condition of calcareous organisms (cold and warm water corals, coccolithophores and pteropods)
- Distribution and abundance of exploitable fish stocks
- Wind speed and direction
- Sea level variability
- Currents and eddies
- Sea Surface Temperature
- Salinity.

The academic, government, and commercial communities have led efforts to develop the scientific rationale for the application of satellite remote sensing observations of these variables, their impact, and processes that affect them [5–10]. Such requirements are in many ways defined from the bottom up, as various geographical regions, such as those organized under the US IOOS framework, recognize common problems that can only be addressed through large-scale observation. This includes the generation, validation, application, and distribution of real-time and historical regional sea surface temperature and meteorological maps, and assessments of the variability in ocean color and biogeochemical and coastal water quality parameters (Figure 1). Some of these efforts have led to successful industry applications in support of fishing and fisheries management, navigation and ship routing, oil and gas exploration and operations, search and rescue, and water quality monitoring (Figures 2 and 3). Some of the research and applications have been incorporated in critical government operations in the US and in many other nations.

These products have provided the necessary synoptic time-dependent surface observations needed to detect far-field forcing of the circulation, to interpret point observations collected by buoys and ships in a regional ecological context, and to enable more accurate numerical simulations of weather, the transport of heat and salts, of possible sources and sinks of carbon in the ocean, and of climate and of many other processes. This information is essential to support activities as varied as ocean mining and ship route planning, and is being used to develop new ecosystem-based management plans. Ultimately, this information is needed to sustain our economy and human health.

Stakeholders in each region need a basic level of service to obtain continuous access to near real-time and high-quality remote sensing products. Linking teams and infrastructure across coastal communities will help with coordination, increase efficiency and ensure scientific quality, and provide 24/7 coverage. Specifically, US national ocean policy needs to focus on setting the following goals, which are applicable to any coastal and sea-faring nation:

1) Co-production of scientific solutions. This requires developing a philosophy of partnerships for robust and mutual support between government agencies (providing funding and operations), academic research (providing research and development), and industry (providing value added and product marketing and commercialization).
2) Maintain current funding support for the groups that have established credible satellite remote sensing data products and information services. This includes academic research focused on new products, testing and validation, and support for real-time data capture (including direct broadcast receiving stations), data processing, and distribution of critical information, often in near real-time.
3) Organize "think tanks" among academic, government, commercial and operational remote sensing communities as well as data users and information service developers.
4) Design interactive workshops where remote sensing specialists present current and proposed products and elicit feedback from user groups to refine the existing satellite products. The team will assess requirements for real-time, climatological, and historical data sets covering the region and evaluate the cost-effectiveness of common sets of products.
5) Promote common entry points to data services offered by different groups that are designed to address local and regional needs, and that are replicated across the country and internationally. These may share a common look and feel to information. This addresses an important, long-standing goal of GOOS and IOOS planners and stakeholders. This is a requirement for participating in a viable and useful international system.
6) Develop robust products that are consistent and seamless across regions (imagery, GIS layers, and other value-added information) that complement and do not compete with industry. The IOOS and any international entity with a regional focus require a mechanism whereby stakeholder needs are communicated to the research community, and research products migrate to industry and to operations and

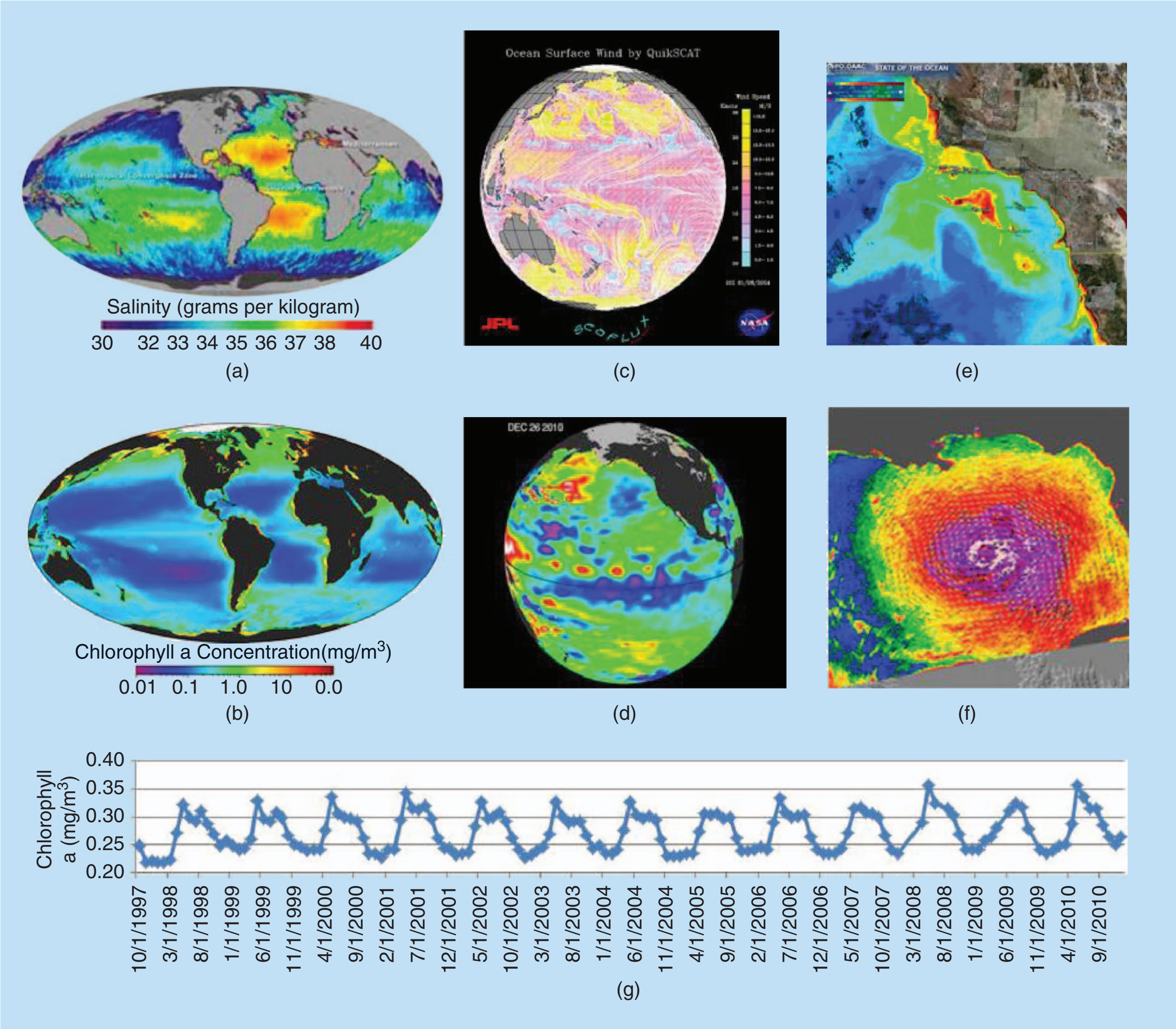


**FIGURE 1.** Sample synoptic observations from ocean-observing satellite sensors. (a) Global salinity fields from Aquarius, (b) Global chlorophyll average from SeaWiFS. (c) Pacific Ocean Winds from QuikSCAT, (d) Pacific Ocean sea surface topography anomaly. (e) Chlorophyll concentrations off California, (f) Hurricane Katrina wind speed and direction from QuikSCAT in the Gulf of Mexico. (g) Time series of global average chlorophyll concentrations from SeaWiFS (1997–2010). (Images courtesy of NASA. The time series was extracted using NASA's Giovanni online tool.)

are used to develop the next generation of ocean information services.

7) Build the ability to generate the same products at IOOS real-time stations for fail-safe service in case of station or other failure. This coordination needs to occur at an international level as well, since many countries don't have the technical expertise or capability to establish real-time data capture and processing stations. Collaborate with physical, biological, chemical and geological oceanographers to develop and deploy in situ real-time systems (acoustics, bio-optics, robotics, etc.) to provide high-quality biological and chemical observations that serve as ground truth, and as real-time concurrent anchor points to derive three-dimensional renderings, time series, and environmental assessments. An emerging field that would benefit from incorporating such products are Observing System Evaluations (OSE) and Observing System Simulation Experiments (OSSE).

8) Continue to develop applications for synoptic ecosystem, climate, and renewable/non-renewable energy siting assessments, and search and rescue and other operations. Examples of partnerships:
   a) Fisheries management community at the Federal, Regional, and State level to provide products needed in ecosystem based fisheries management
   b) Coastal zone management agencies
   c) National parks, sanctuaries, monuments, or other marine protected areas
   d) Commercial entities in need of value-added products to develop ocean information services.

9) Collaborate with numerical modelers to provide appropriate data for model validation and effective

utilization of satellite observations, including assimilation into numerical models.

10) Enhance product usefulness by integrating (fusing) ocean color, infrared, altimeter, scatterometer, Synthetic Aperture Radar (SAR), and in situ observations.
11) Develop a strategy and implement plans to prepare for new sensors and provide feedback to NASA, NOAA, USGS and international agencies on sensor operation, calibration, and product requirements.
12) Interact with NASA and NOAA in the US and with the many relevant agencies internationally to help define priorities for sensor and mission development. This is required as the present critical US fleet of NASA and NOAA satellite sensors age and operate beyond their planned life expectancy.

## 3. STATE OF THE OBSERVING SYSTEM AND TECHNOLOGY

Achieving continuity in satellite observations is essential for a national Integrated Ocean Observing System (IOOS) and for an international GOOS, GCOS, and GEOSS. In the US, NOAA operations can benefit from the substantial investments that other agencies make in developing new technologies and in advancing science. There is a substantial academic science community and commercial sectors that can help satisfy many of the needs that NOAA operations have for new and improved products, and to help generate value-added products and information services for the nation.

IOOS should help the U.S. and collaborators globally to plan for the proper sequence of satellites, infrastructure to generate and keep climate records, and train the people to generate and use these observations. This includes the technical know-how to create innovative products. Such bottom-up processes can be implemented around the globe under different administrative umbrellas. A critical element of this strategy will be to engage stakeholders and decision-makers as soon as possible to ensure the co-design for solutions to pressing problems in a near-future.

## 4. INTEGRATION WITHIN IOOS, MODELING, AND DMAC

An important objective is to improve the core services that a national observing system offers to the user/stakeholder communities for coastal U.S. areas including the research and operational users that require global coverage.

Foremost is the need for fundamental improvements in data management capabilities. IOOS will need to deliver raw data and useful analytical products in near-real time (i.e. less than one hour latency) to the community on an ongoing basis, reprocess data as appropriate calibration and ancillary data become available, and archive all incoming data in readily accessible formats for future assessments of environmental change.

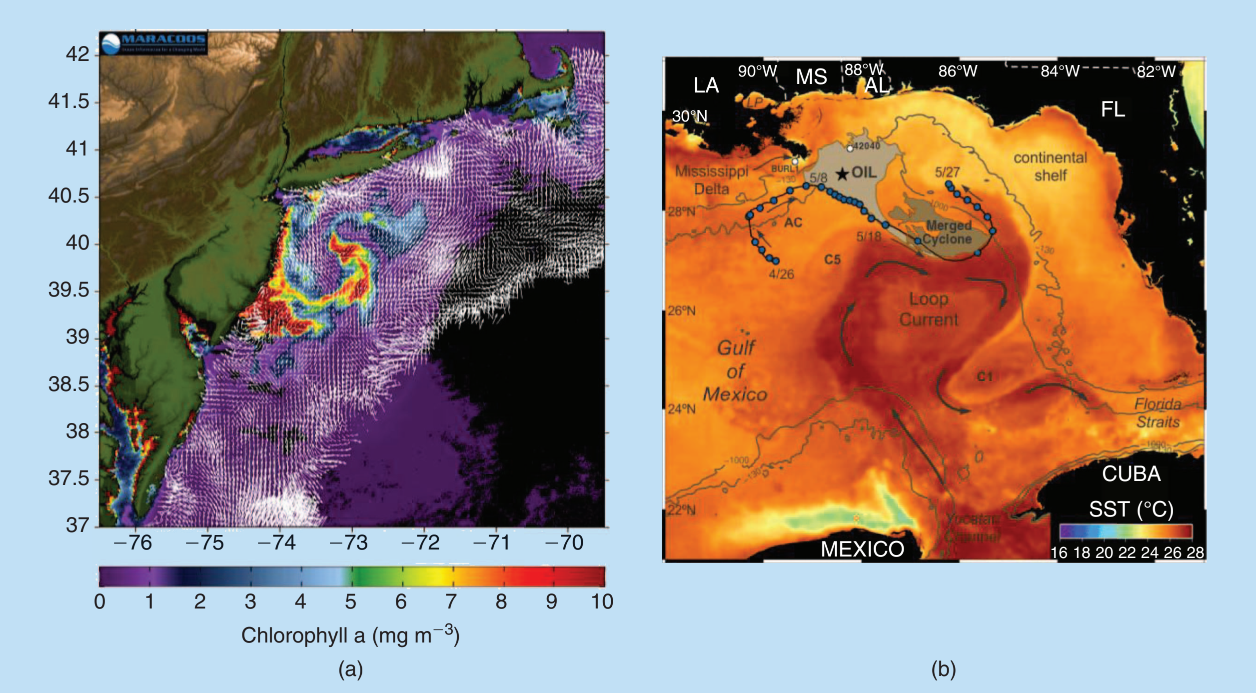
An IOOS remote sensing team should be constituted to work closely with various agencies and elements of the IOOS (Stakeholders, DMAC, Product and Services, and Education and Outreach committees). This team should include representatives from all regional associations or other relevant body of the IOOS. Regional problems should be identified through regional community assessments, interviews, and questionnaires. Product focus teams should oversee the development of real-time satellite image products, including integrating data from multiple platforms and climatological data sets and data sets that will enable the next generation of ocean information services. An important process will be product review, validation, and feedback, guided by metrics.

The team should collect disparate real-time data sets presently available from geographic areas of interest but from various unrelated observing systems and in different formats, and integrate them into coherent information products. A set of synoptic, regionally calibrated, consistent set of products covering coastal zones to the deep ocean should be generated using a variety of operational and research satellite sensors (see Section 5). The precise type, format, and product distribution mechanisms will result from consultations between government resource managers, industry providers, and other stakeholders including the scientific research community. Further, this pilot activity will help organize the remote sensing community in the region. The activity includes active outreach efforts to help people understand the remote sensing products available from different providers and to enable the development of innovative ocean information services.

## 5. THE ROLE OF THE NON-GOVERNMENTAL SECTOR

In most cases, governments are the only entities that have the financial and political power, the responsibility, and the capability to develop, launch and operate complex satellite systems for Earth observation. Yet government agencies need access to the science to develop new products to protect life and property and promote economic growth in a constantly changing world. In many cases, commercial and academic entities can generate value-added products at a lower cost and with more flexibility than government entities. Commercial and academic groups also serve an important role in promoting international collaboration, often stimulating collaboration between countries that governments are unable to promote due to political considerations. As part of this process, governments also need to work hard to avoid duplication and competition in areas not related to their primary mission.

An example of a partnership that includes government, academic, and industry partners focuses on research designed to inform the management of Atlantic bluefin tuna fisheries. Industry, academic researchers, and government managers from the United States, Mexico, and Spain work together with private industry and academia to integrate satellite remote sensing and many other types of observations to evaluate the impacts of disturbance such as the Deepwater Horizon oil spill [12, 13] and of potential



(a)

(b)

**FIGURE 2.** Sample synoptic observations from ocean-observing satellite sensors. (a) An ocean color image of chlorophyll a collected on 23 August 2011 off the eastern US coast showing a large phytoplankton bloom, combined with HF CODAR (white arrows). The satellite data was critical to the New Jersey water quality managers and university field researchers for coordinating sampling of the phytoplankton bloom over time as they were associated with significant declines in bottom water quality. (b) Application of satellite data for tracking the DWH oil spill using SAR radar images to detect surface oil and GOES-E Sea Surface Temperature (SST) to resolve the Loop Current and eddies on 17 May 2010 in the Gulf of Mexico. (Source for image (b): [11].).

shifts in habitat due to climate change in the Gulf of Mexico [14], the Caribbean Sea, and in the Mediterranean.

The IOOS and GOOS can facilitate such partnerships and stimulate the development of a robust data collection and distribution backbone. The support of enhanced and value-added information contributes to economic growth. In its essence, one may view this partnership as having three integrated elements, in which government organizes and coordinates large infrastructure to generate the raw materials (data), academia helps provide creative solutions (technology, algorithms, new products), and industry provides a capability to generate value-added products and to finance the feedbacks between these components (i.e. through taxes and direct funding of academic research, in addition to deriving profit). Private organizations provide additional benefits through the creation of jobs.

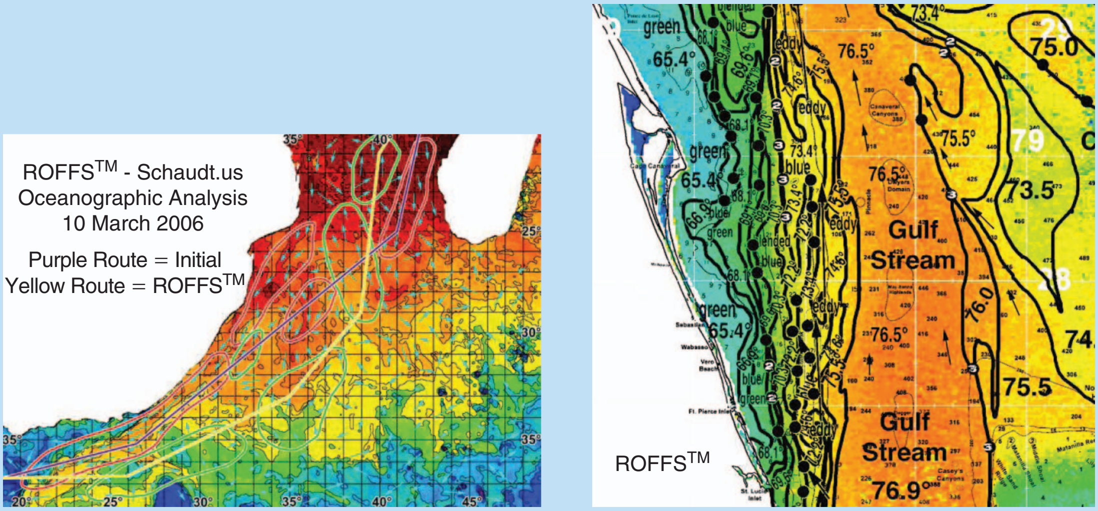
## 6. INTERNATIONAL COOPERATION

A coherent vision for international cooperation has emerged with the implementation plan (2005–2015) for a Global Earth Observing System of Systems (GEOSS) [http://www.earthobservations.org]. GEOSS seeks to link international resources and facilities to address the needs of information for the benefit of a globalized society. The ‘system of systems’ provides a framework to link existing and planned observing systems around the world. The GEOSS would be owned by member nations, and each would control its own assets. A GEOPortal would provide an Internet gateway to the GEOSS products.

As GEOSS develops, many groups are making significant advances either through bilateral international agreements, or under other larger umbrellas. Drinkwater et al. [5] provide examples of important efforts, such as those organized under the Global Ocean Data Assimilation Experiment (GODAE; http://godae.org/) [9] and the Group for High Resolution Sea Surface Temperature (GHRSST; https://www.ghrsst.org/) [10]. Several other such large-scale international efforts exist, either to distribute observations or to help define strategies for international collaboration in specific areas of ocean remote sensing, such as the International Ocean-Colour Coordinating Group (IOCCG; http://www.ioccg.org/). Many of these organize through facilitation of the Committee on Earth Observation Satellites (CEOS; http://www.ceos.org/), which coordinates international civil space-borne observations of the Earth.

## 7. THE WAY FORWARD FOR THE NEXT TEN YEARS

Focusing on the needs in the United States as an example, a good model on which to build the IOOS is the partnership between the National Weather Service (NWS) and the private sector. We propose a partnership between academia, industry and the government that will result in general and tailored forecasts of physical, biological,



(a)

(b)

**FIGURE 3.** (a) Oceanographic analysis for oil industry ship routing off southeast Africa. An example of how private industry integrates infrared and ocean color satellite data to visualize ocean currents. Arrows indicate the current direction. Areas where the currents are particularly favorable and unfavorable to ship routing are outlined in green and red, respectively. The purple line indicates the pre-cruise routing and the yellow line indicates the advised routing based on the location of the favorable currents. (Image courtesy of ROFFS™-schaudt.us.) (b) An oceanographic analysis produced by private industry for the fishing industry (recreational and commercial) and for researchers off the east coast of Florida, USA. Infrared and ocean color data are integrated to map water mass boundaries. Black dots indicate where ocean convergence occurs over specific bottom topography (e.g. reefs, wrecks, gradients) to generate "favorable" fishing conditions. Numbers inside the dots indicate the number of consecutive days of relevant convergences. (Image courtesy of ROFFS™.)

geological, and chemical ocean conditions and warning products that are acknowledged as valuable. These products have applications ranging from scientific research to public safety, transportation, agriculture, and daily forecasts of weather, coastal and ocean currents, water quality, and many other environmental conditions of interest. These IOOS products should be wide-ranging and based on the needs of regional and local organizations and communities, as well as national needs. They should support and not interfere with the competitive nature of private industry and should enable new information services to emerge, just as in the meteorological services industry.

An important path to pursue will be to develop stronger links between land cover and land use change assessments and coastal research and resource management. On the one hand, fluxes of carbon and other materials, and human impacts on these processes within the land-ocean continuum must be considered to correctly assess global terrestrial and ocean material budgets. Roughly 1/3 of the carbon buried in the ocean is derived from terrigenous sources and is delivered to the coast via rivers; 70% of it is buried within continental margins. Managing sediment that may end up in rivers should be managed to understand impacts on resources such as coral reefs. Many pollutants also make their way to the coast in dissolved or particulate form and will have an impact on the health of coastal communities, or markets that depend on those coastal resources. Remote sensing is also required to understand the impacts of rapid and episodic flushing events.

The IOOS can play a pivotal role in the co-development of solutions for pressing social and environmental challenges. It can coordinate activities such as calibration and validation efforts, developing new research and applications, refining a vision for Earth observation, and distributing science-quality, real-time and archived products and timely information. The IOOS can help create efficiencies in regional infrastructure and capitalize on the human knowledge of each region. It can also help ensure that these systems are secure and properly backed up so that the necessary information is available even during emergencies.

### *7.1. CORE REMOTE SENSING PRODUCTS*

The IOOS requires the concurrent availability of the standard suite of sea surface temperature (SST), chlorophyll, wind, and sea surface height products generated over the past decade by NOAA and NASA. New products are now required that include regionally calibrated and de-clouded SST, wide swath altimetry and winds, and advanced coastal ocean surface reflectance values based on higher spectral resolution data.

The connections between the watershed, wetlands, coastal floodplains and other areas prone to flooding should be considered when defining critical remote sensing products. The IOOS system will focus on variability and stress that may result due to combined effects of contamination, ocean acidification, and temperature extremes, for example, on various marine ecosystems.

Some of these new measurements will bring very exciting new scientific advances that are directly applicable to living resource management. For example, hyperspectral ocean color data will help define how the biodiversity of the phytoplankton and particle size distributions change over large areas of the ocean. Chlorophyll fluorescence line height (FLH) is of critical importance in this process, to identify phytoplankton blooms in coastal, estuarine, and shelf waters where the traditional algorithms for chlorophyll concentration based on blue to green radiance ratios often give erroneous values. This will help quantify global ocean ecosystem structure and biodiversity from space for the first time. It will also bring a revolution to how ocean color data are applied in coastal zones. These advanced sensors will also provide improved "true-color" imagery enhanced to highlight aquatic features, and estimates of total suspended sediment concentration (TSS), turbidity, absorption coefficient of the colored dissolved organic matter (CDOM), the diffuse attenuation coefficient (K_490), and water clarity/Secchi Disk Depth. One such advanced concept is NASA's Pre-Aerosol, Clouds, and Ecosystem Mission (PACE) mission, planned for development over the next decade to monitor whether and how different biogeographical seascapes change and how they respond to disturbance. In the meantime, ESA's Sentinel-3 mission, expected to launch in 2014-2015, will also provide important information toward this goal.

New high resolution altimeter observations will offer higher performance both in terms of spatial and vertical resolution and better coverage closer to coastal zones. In addition, animations of time sequence imagery along with water mass boundary analyses will be offered to track water masses, algal blooms, river water, and oil plumes.

It will be critical to link satellite imagery at a variety of spatial, temporal, and spectral resolutions, and interpreted products derived from them. For example, coastal resource managers may require rapid access to 'climatological' temperature and water quality indices, an assessment of anomalies and an analysis of whether these represent extremes that occur because of synergy between different environmental variables, and an ability to 'zoom in' from synoptic 1 km satellite observations to landscape imagery at the 30 m or 2 m afforded by Landsat (Figure 4) or commercial-class satellite imagers such as WorldView-2. The Millennium Global Coral Reef Map, based on Landsat data for the year 2000 [15, 16], is an example of a product developed by researchers that is widely used by managers and other scientists on a global basis.

We can't overstress the importance of regional calibration. The present worldwide calibrations provided by NOAA and NASA are not adequate for providing the best available satellite data products. IOOS needs to be leading the development of strategies to have the best standardized quality control procedures to ensure the availability of science-quality data.

One area of concern is cloud cover and relatively isothermal conditions for several months a year in some areas. Thus, an IOOS remote sensing team needs to investigate new ways to perform cloud screening, cloud reduction, and removal of sunglint, especially as pertains to chlorophyll and other products based on Visible and Short-Wave-Infrared optical measurements.

The IOOS remote sensing project should develop composite images over varying time periods and across different technologies (infrared and microwave, in situ). Products should span a range scales, allowing analysis of daily or better variations but also include averages over time scales longer than synoptic (e.g. 12 hours, one week, monthly, annual and corresponding 'climatologies' and anomaly products).

Different academic and industry data providers operate dedicated downlink sites for NOAA, NASA, ESA, and other sensors. Including these operators in the IOOS framework will enable faster turn-around in the processing and availability of imagery provided to stakeholders.

To advance these objectives in the U.S., for example, the list below provides a basic set of core products that should be developed in a seamless manner and in common format for different parts of the country, including its territories. Similar products and tools to use them to support decision-making should be developed jointly at the international level. The IOOS needs to address both the real-time requirements of stakeholders but also provide sufficient historical observations to provide context, define baselines and compute anomalies, and assess variability and uncertainty.

## *REMOTE SENSING HIGH, MEDIUM AND LOW SPATIAL RESOLUTION SATELLITE PRODUCTS AND RELEVANT SENSORS*

### CORE PRODUCTS: (< 2 M, 30 M, 250 M, 500 M, 1-KM, 25–60 KM PIXELS)

- Coastal zone and shallow benthic resource maps
    - Beaches, estuaries, mangroves, wetlands, coral reefs
- High spatial resolution coastal watershed, land use, and wetlands assessments, temperature, heat and thermal inertia products (many of these will serve as inputs to mesoscale marine atmospheric sea-breeze and coastal ocean "coupled" models)
- Coastal ocean surface spectral reflectance values in the visible
- Total suspended sediment concentration (TSS)
- Turbidity
- Colored dissolved organic matter (CDOM) absorption coefficient
- Chlorophyll concentration
- Water clarity/Secchi Disk Depth
- Chlorophyll fluorescence line height (FLH)
- Sea surface height, sea surface height anomaly and geostrophic currents
- Wind speed and direction
- Synthetic Aperture Radar imagery (including wind vector and directional wave fields)

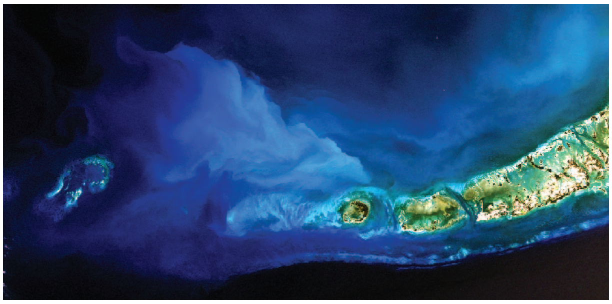


**FIGURE 4.** Landsat 5 image (29 March 2008) highlighting the Dry Tortugas (patch of islands toward the left of the image) and the Lower Florida Keys, Florida, USA. (Image modified from [17].) The image shows a large plume of sediment (light blue color) that extends seaward to the west-northwest from the Marquesas Keys (center, bottom). This region experiences strong currents that set up dynamic and rapid sediment and temperature changes. The area is also affected intermittently by large blooms of phytoplankton and turbid water advected from the west-northwest, i.e. from Florida Bay and from the southwest coast of mainland Florida. These changes, and the large distance from large human population centers, helps maintain robust coral reef communities around these remote islands.

- Sea surface temperature and de-clouded sea surface temperature and composites on various time scales.

### SATELLITE SENSORS: US AND INTERNATIONAL

#### US: HISTORICAL/CLIMATOLOGIES AND CURRENT/REAL-TIME

- MODIS (Moderate Resolution Imaging Spectroradiometer; Terra and Aqua)
- AVHRR (Advanced Very High Resolution Radiometer; NOAA 15, 16, 18, 19, MetOp_A)
- GOES-East geostationary imagery
- VIIRS (Visible Infrared Imaging Radiometer Suite)
- Aquarius (NASA/CONAE) and suite of salinity products
- Suite of altimeter products
- Suite of wind scatterometer products
- Suite of wind passive radiometer observations
- Landsat, ASTER
- Worldview/Digital Globe, GeoEye-class imagery
- SAR
- Historical: sensors including Sea-viewing Wide Field-of-view Sensor
- International: Sensors of similar categories as shown above, including ENVISAT, ERS, SPOT, the upcoming Sentinel series, etc.

### 7.2. APPLICATIONS

The use of oceanographic satellite data by groups outside of the scientific research community has been limited for a number of reasons. One is the relatively low spatial and temporal resolution of the sensors designed to examine global ocean processes. To be useful to coastal resource managers, spatial resolution of observations needs to drop below the 300–500 m threshold, in particular for the routine study and assessment of coastal, shelf, and estuarine resources. Such capabilities should be incorporated into the new generation of ocean color sensors, for example, along with the capability to separate sediment and bottom reflectance from river plumes and phytoplankton blooms, using bands sensitive to the natural fluorescence of phytoplankton. Finer spatial resolution data of high radiometric resolution and quality, collected at the near-daily level, would revolutionize coastal zone assessments and the management of living and non-living marine resources.

Another reason the data have not been used is the lack of algorithms to address coastal issues, including important metrics of water quality, water motion, bathymetry, habitat mapping, and so on. New algorithms are needed and this will require a concerted, international effort and much collaboration.

Perhaps among the most important reasons that ocean satellite data remain under-utilized is the lack of tools to use the data. Each data set or product comes in a variety of different and complicated data file formats. Different sensors cover different time periods. The data are also available from many different sources and there is no portal that facilitates collection of such multidisciplinary data.

Planning requires a vision of concurrent observations from multiple satellites across a wide range of time scales, spatial scales, and also spectral scales (from the ultraviolet to the microwave). Ultimately, it will be important to develop a set of distributed applications for different platforms including desktop and mobile media to make the products accessible, and which include a minimum of basic applications tools to extract information from these data. These applications should be simple and can address specific tasks without trying to accomplish everything for everyone.

### 7.3. MANAGEMENT

In the US, IOOS needs to constitute a Strategic Remote Sensing Planning team comprised of end user stakeholders, scientific experts, and managers of multi-institutional remote sensing and oceanographic programs. This Planning Team would be responsible for defining the product suite to be generated at each site and for developing a cost-efficient failsafe server mirroring plan. Major decisions about calibration, atmospheric correction, geometric registration, scheduling, deadlines, composition of focus teams, assignment of overall tasks, and planning to ensure the timely, efficient, and competent accomplishment of all work for the project would be the responsibility of the Planning Team. The project strategy would be guided through consultations with national agencies including NASA, NOAA, the USGS, and with international agencies, private industry, and by engaging the best scientists and engineers from academic research institutions.

The major tasks proposed for such a planning team include:

- Hold interactive workshops and surveys to obtain feedback from users/stakeholders and educational experts on current products and formats, as well as "needs" (i.e. "what is missing").

- Support critical dialogue among remote sensing specialists to discuss technical issues (calibration, geocorrection, file formats, geographic coverage, cloud-masking, etc.).
- Improve the quality of data delivered to the users. This would include composited imagery for cloud-removal, animation products, and historic archives and climatologies, as well as fail-safe production in case of emergencies such as hurricanes that affect a site.
- Offer training workshops to enhance the use of remote sensing data into research, operations, and education efforts outside the main research activities of the investigators.
- Support users that require new product specifications.
- Collaborate with NASA, NOAA, USGS, and other US agencies.
- Collaborate and coordinate with relevant regional and international entities requiring and/or providing regional synoptic coverage.

### *7.4. OUTREACH AND EDUCATION*

The IOOS planning team program should work with education and outreach experts across Federal and State government entities to help users and the general public understand the concept of integrated ocean observing and its applications, including science, research, and decision-making. The team will engage operational, research, commercial and recreational resource users (fishermen, tourists) to help these members of the public understand the value of coastal and ocean resources and the utility of the observations collected through the IOOS system. Formal and informal education activities need also be aimed at the K-16 level and state and federal legislators.

A critical need for scientists and resource managers trained in the use and application of ocean remote sensing products will be satisfied by coordinating investments from different agencies in this area.

Access to these synthesized products will facilitate research, education, as well as outreach and extension to public groups including emergency managers along with the Office of Homeland Security, Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEM), U.S. Coast Guard, FEMA, and to the various NOAA line offices. The observations will have similar applicability in agencies within other countries, and will be of value also to international agencies and non-governmental users.

The program will have a multi-cultural approach regarding diversity and outreach to under-represented groups.

## 8. COSTING AND INVESTMENT

In its report to the United States government and the nation in 2004, the U.S. Commission on Ocean Policy [18] emphasized the importance of proper planning to ensure the availability of a healthy space-based observing system component to satisfy the high demand for timely knowledge anywhere around the world, at any time. This blue ribbon commission recognized the challenges of sustaining these observations. The Commission emphasized long-lead planning for funding, planning for overlap between missions to avoid gaps in data and to allow cross-reference of the calibration of sensors, and planning for wide access to science-quality data to enable far-reaching applications of the multiple observations collected by space-based sensors regionally and globally. Clearly, closer coordination between our agencies in the executive branch and a well-informed congress are critical elements to address these challenges. The budget planning in the U.S. also needs better cooperation between relevant agencies on maintaining present missions and planning future missions, including coordinated budgets for sensor design, mission planning and launch, sustaining high-quality observations, and data management, including archive, fusion, and distribution. Again, these processes need to be based on a solid education and capacity building strategy that reaches across all ages.

## 9. CONCLUSIONS

Satellite imagery and satellite-derived data comprise a key element of the IOOS observing system in the US. It is a cornerstone technology for local as well as for large-scale and international environmental assessment, research, and commercial applications. The US IOOS can play a pivotal role in activities such as calibration and validation efforts, developing new research and applications, refining a vision for Earth observation, and distributing science-quality, real-time and archived products and timely information. The IOOS can help create efficiencies in developing a regional infrastructure and capitalize on the human knowledge of each region. It can also help ensure viability of systems during emergencies. Ultimately, the IOOS can learn from international programs and also provide training opportunities to the international community.

A number of core remote sensing products are required by a broad range of stakeholders in the industry sector, and in operational and research communities. Basic products include sea surface temperature (SST), chlorophyll, wind speed/direction, salinity, and sea surface height. Newer products to be added include indices of water quality, coastal and marine high spatial resolution habitat maps (status and trends), and biological diversity assessments. Many of these products, however, require the launch of a new generation of satellites.

IOOS requires a strategy to coordinate the human capacity, and to fund, advance, and maintain the infrastructure that provides improved remote sensing observations and support for the nation and societies around the globe. A partnership between the private, government, and academic sectors (Universities) will enhance remote sensing support and product development for critical coastal and deep-water regions based on infrared, ocean color, and microwave satellite sensors. This white paper emphasizes the need for IOOS to inform operational and research agencies in the United States of the types of observations and observing platforms required, including what types of satellite sensors need to be launched in the future to maintain continuity of observations, and the types of new observations required. Similar requirements of agencies and other stakeholders in other countries may be satisfied through collaboration with the IOOS or similar regional entities.

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## REFERENCES

[1] National Ocean Policy Implementation Plan. [Online]. http://www.whitehouse.gov/administration/eop/oceans/implementationplan

[2] U.S. Commission on Ocean Policy, "An ocean blueprint for the 21st century," in "Final report of the U.S. Commission on ocean policy," Washington, D.C., Tech. Rep., 2004.

[3] L. Amaral-Zettler, J. E. Duffy, D. Fautin, G. Paulay, T. Rynearson, H. Sosik, and J. Stachowicz. (2010). Attaining an Operational Marine Biodiversity Observation Network (BON) Synthesis Report. [Online]. Available: http://www.nopp.org/wp-content/uploads/2010/03/BON_SynthesisReport.pdf

[4] J. E. Duffy, L. A. Amaral-Zettler, D. G. Fautin, G. Paulay, T. A. Rynearson, H. M. Sosik, and J. J. Stachowicz. (2013). Envisioning a marine biodiversity observation network. *Bioscience* [Online]. *63(5)*, pp. 350–361. Available: http://www.aibs.org/bioscience-press-releases/resources/DuffyREV2.pdf

[5] M. Drinkwater, H. Bonekamp, P. Bontempi, B. Chapron, C. Donlon, J.-L. Fellous, P. DiGiacomo, E. Harrison, P.-Y. LeTraon, and S. Wilson, "Status and outlook for the space component of an integrated ocean observing system," in *Proc. OceanObs: Sustained Ocean Observations and Information for Society*, Venice, Italy, Sept. 21–25, 2009, vol. 1.

[6] H. Bonekamp, F. Parisot, S. Wilson, L. Miller, C. Donlon, M. Drinkwater, E. Lindstrom, L. Fu, E. Thouvenot, J. Lambin, K. Nakagawa, B. S. Gohil, M. Lin, J. Yoder, P.-Y. L. Traon, and G. Jacobs, "Transitions towards operational space based ocean observations: From single research missions into series and constellations," in *Proc. OceanObs'09: Sustained Ocean Observations and Information for Society*, Venice, Italy, Sept. 21–25, 2009, vol. 1, p. 6.

[7] E. Lindstrom, M. A. Bourassa, L.-A. Breivik, C. J. Donlon, L.-L. Fu, P. Hacker, G. Lagerloef, T. Lee, C. L. Quéré, V. Swail, W. S. Wilson, and V. Zlotnicki, "Research satellite missions," in *Proc. OceanObs: Sustained Ocean Observations and Information for Society*, Venice, Italy, Sept. 21–25 2009, vol. 1, p. 28.

[8] J. Yoder, "Ocean colour radiometry: Early successes and a look towards the future," in *Proc. OceanObs: Sustained Ocean Observations and Information for Society*, Venice, Italy, Sept. 21–25 2009, vol. 1, p. 43.

[9] P. L. Traon, M. Bell, E. Dombrowsky, A. Schiller, and K. W. Becker, "GODAE oceanview: From an experiment towards a long-term international ocean analysis and forecasting program," in *Proc. OceanObs: Sustained Ocean Observations and Information for Society*, Venice, Italy, Sept. 21–25 2009, vol. 2.

[10] C. J. Donlon, K. S. Casey, C. Gentemann, P. LeBorgne, I. S. Robinson, R. W. Reynolds, C. Merchant, D. Llewellyn-Jones, P. J. Minnett, J. F. Piolle, P. Cornillon, N. Rayner, T. Brandon, J. Vazquez, E. Armstrong, H. Beggs, I. Barton, G. Wick, S. Castro, J. Hoeyer, D. May, O. A. Arino, D. J. Poulter, R. Evans, C. T. Mutlow, A. W. Bingham, and A. Harris, "Successes and challenges for the modern sea surface temperature observing system," in *Proc. OceanObs'09: Sustained Ocean Observations and Information for Society* Venice, Italy, Sept. 21–25 2009, vol. 2.

[11] N. D. Walker, C. T. Pilley, V. V. Raghunathan, E. J. D'Sa, R. R. Leben, N. G. Hoffmann, P. J. Brickley, P. D. Coholan, N. Sharma, H. C. Graber, and R. E. Turner, "Impacts of a loop current frontal eddy cyclone and wind forcing on the 2010 Gulf of Mexico oil spill," in *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise* (AGU Monograph Series vol. 195), Y. Liu, A. MacFadyen, Z. Ji, and R. Weisberg, Eds., 2011, pp. 103–116.

[12] B. A. Muhling, M. A. Roffer, J. T. Lamkin, G. W. Ingram Jr., M. A. Upton, G. Gawlikowski, F. E. Muller-Karger, S. Habtes, and W. J. Richards, "Overlap between Atlantic bluefin tuna spawning grounds and observed Deepwater Horizon surface oil in the northern Gulf of Mexico," *Mar. Pollut. Bull.*, vol. 64, no. 4, pp. 697–687, 2012.

[13] B. A. Muhling, J. T. Lamkin, and M. A. Roffer, "Predicting the occurrence of bluefin tuna (Thunnus thynnus) larvae in the northern gulf of mexico: building a classification model from archival data," *Fish Oceanogr.*, vol. 19, no. 6, pp. 526–539, 2010.

[14] B. A. Muhling, S.-K. Lee, J. T. Lamkin, and Y. Liu, "Predicting the effects of climate change on bluefin tuna (Thunnus thynnus) spawning habitat in the Gulf of Mexico," *ICES J. Mar. Sci.*, vol. 68, no. 6, p. 1051, 2011.

[15] S. Andréfouët, F. E. Muller-Karger, J. A. Robinson, C. J. Kranenburg, D. Torres-Pulliza, S. Spraggins, and B. Murch, "Global assessment of modern coral reef extent and diversity for regional science and management applications: A view from space," in *Proc. 10th Int. Coral Reef Symp.*, Okinawa, Japan, June 28–July 2, 2004, pp. 1732–1745.

[16] S. Andréfouët, E. Hochberg, C. Chevillon, F. E. Muller-Karger, J. C. Brock, and C. Hu, "Multi-scale remote sensing of coral reefs," in *Remote Sensing of Coastal Aquatic Environments: Technologies, Techniques and Application*, R. L. Miller, C. E. Del Castillo, and B. A. McKee, Eds., New York: Springer-Verlag, 2005, pp. 297–315.

[17] B. B. Brian, C. Hu, B. A. Schaeffer, Z. Lee, D. A. Palandro, and J. C. Lehrter. (2013, July). MODIS-derived spatiotemporal water clarity patterns in optically shallow Florida Keys waters: A new approach to remove bottom contamination. Remote Sens. Environ. [Online]. *134*, pp. 377–391. Available: http://dx.doi.org/10.1016/j.rse.2013.03.016

[18] U.S. Commission on Ocean Policy. (2004). An ocean blueprint for the 21st century. Final Report of the U.S. Commission on Ocean Policy. Washington, D.C., Tech. Rep. [Online]. Available: http://govinfo.library.unt.edu/oceancommission/documents/full_color_rpt/welcome.html#final

**GRS**