Report of the Ocean Observation Research Coordination Network In-situ-Satellite Observation Working Group

"A Modern Coastal Ocean Observing System Using Data from Advanced Satellite and *In Situ* Sensors – An Example."

J. Yoder, C. Davis, H. Dierssen, F Muller-Karger; Amala Mahadevan, Jay Pearlman; H. Sosik

June 1 2015

OCEAN RCN
OCEAN RESEARCH COORDINATION NETWORK

NSF

Table of Contents

A Modern Coastal Ocean Observing System Using Data from Advanced Satellite and *In Situ* Sensors – An Example.

I. Purpose

This report is intended to illustrate and provide recommendations for how ocean-observing systems of the next decade could focus on coastal environments using combined satellite and *in situ* measurements. Until recently, space-based observations have had surface footprints typically spanning hundreds of meters to kilometers. These provide excellent synoptic views for a wide variety of ocean characteristics. In situ observations are instead generally point or linear measurements. The interrelation between space-based and in-situ observations can be challenging. Both are necessary and as sensors and platforms evolve during the next decade, the trend to facilitate interfacing space and in-situ observations must continue and be expanded. In this report, we use coastal observation and analyses to illustrate an observing system concept that combines *in situ* and satellite observing technologies with numerical models to quantify sub-seasonal time scale transport of freshwater and its constituents from terrestrial water storage bodies across and along continental shelves, as well as the impacts on some key biological/biogeochemical properties of coastal waters.

II. Background

Operational agencies, research institutions, and private industry have generated many different products from satellite sensors for various applications. These include time series from individual sensors and products merged from multiple sensors, such as those that provide infrared, ocean color, and microwave observations. However, there has been only limited centralized or coordinated distribution of these products to support operational or research observing systems. This is changing now. In the US, the Integrated Ocean Observing System (IOOS) (US IOOS 2015) is an evolving focal point for US coastal water observations and data management/distribution. The work of the IOOS Regional Associations (US Regional IOOS, 2015) has focused on modeling of the coastal environment at a regional and local level, addressing issues from research to production of coastal marine environments. The Ocean

Observing Initiative (OOI, 2015) supports continental shelf and deep water science research. NOAA *CoastWatch* produces operational products for U.S. coastal waters. In Australia, the Integrated Marine Observations System (IMOS) (IMOS, 2015) supports an information infrastructure for marine observations and data. *MyOcean* (MyOcean, 2015) in Europe is producing a set of satellite-based products for SST, ocean optics and phytoplankton chlorophyll for European regional waters (e.g. the Mediterranean Sea) and for the global ocean at reduced spatial resolution. SeaDataNet (SeaDataNet, 2015) distributes data for Europe including in-situ observations.

With the increasing abundance of data, there is still no digital product 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 and multidisciplinary satellite data. Furthermore, and this is the main point of our report, satellite products need to be merged effectively and efficiently with *in situ* measurements from US and other ocean observing systems, and then distributed as a consistent and coherent package of observations (e.g. Gregg and Conkright 2001).

Coastal regions have a broad range of drivers and understanding their dynamics requires diverse data sets to be overlaid and merged. Many continental shelves are affected by rivers, ground water and other types of land-derived discharges, as well as upwelling of deeper waters. This creates important impacts on cross-shelf transport of chemicals, sediments, biological productivity and redistribution of larvae, and of other materials (Brink et al. 1992). Fresh water affects stratification and thus can influence rates of primary production, as well as the vertical distribution of oxygen. Influx of freshwater is generally time-dependent, particularly at temperate and higher latitudes, with important influences at days to seasonal time scales. River plumes can hug the coastline or spread farther offshore. Simple or complex numerical simulations do not always capture the important modes of variability owing to tidal impacts, topography, winds, coastal waves, and other influences on these environments. Surface water buoyancy can be increased by warming due to absorption of shortwave radiation by chlorophyll, detritus, and colored dissolved organic matter (Cahill et al. 2008), or buoyancy can decrease due to surface cooling, which can lead to strong convective mixing.

Recent studies show the importance of “bulge” circulation near river mouths. High discharge rates coupled with upwelling favorable winds can stimulate bulge circulation, which may keep large amounts of freshwater near river mouths for extended periods of time (Chant et al. 2008). Off the mouth of the Hudson River, for example, bulge circulation often transports freshwater to the left of the outflow rather that to the right as predicted (Chant et al. 2008). These circulation complexities make it difficult to predict the optimal placement of limited in situ observing platforms such as moorings. Yet, such sensors are required to observe important diurnal–to-seasonal time scale outflow events, and to quantify the fate of freshwater and its constituents once plumes form on the continental shelf.

Measurements to support modeling and understanding of the dynamic coastal environment include phytoplankton biomass and productivity, water quality and turbidity, nutrient concentrations, wind and forcing functions, current and eddies, salinity, temperature and sea level. Ultimately it will be important to obtain time series estimates of marine biodiversity across a variety of trophic levels.

A future observing system based on a combination of satellite observations, model predictions, and Lagrangian sensors should be an effective strategy to integrate such requirements and provide observations of many linked processes across a wide range of space and time scales. Such an effort has been successfully demonstrated in research programs (Chant et al. 2008 - (Figure 1), Chant, R.J. 2011). Sensors deployed on Lagrangian platforms are under development at a number of organizations. A Langrangian, profiling float for shallow coastal waters is a significant challenge. Nevertheless, profiling floats such as ARVOR-C/ARVOR-Cm developed by IFREMER and NKE (André et al., 2010) have been designed to sample the water column in shallow waters. Based on ARGO float design, they have been modified to land on the sea floor in coastal waters, and then to behave as virtual moorings with a limited drift. Combined with measurements-of-opportunity from low cost probes installed on fishing gear, these profiling systems make it possible to observe the evolution of stratification over multi-year periods (Charria et al., 2014).

III. Satellite Sensors for the Decade of the 2020s

There are a number of continuing and new Earth observation remote sensing missions that support the needs for ocean observations [Muller-Karger, 2013]. Some of the newer missions are in response to the National Imperatives for the Next Decade and Beyond decadal survey issued in 2007 (Decadal Survey 2007). Figure 2 shows relevant satellite altimeter missions and Figure 3 shows satellite ocean color radiometer missions. International satellite systems have contributed to our ocean knowledge (for example in ocean color and sea surface topography (Le Troan, 2007).

There are two general classes of orbiting space-based Earth-observing systems – those that are in equatorial orbit and those that have inclined orbits including polar orbits. In addition, a new generation of geosynchronous satellites can provide rapid repeating observations on a regional scale. Selected systems that provide enhanced capabilities for coastal observations are described in the balance of this section.

The Visible Infrared Imager Radiometer Suite (VIIRS) sensor, currently operating on NASA's Suomi National Polar-orbiting Partnership (NPP) system, although lacking the spectral resolution planned for NASA’s Pre-Aerosol, Clouds and ocean Ecosystem (PACE) mission and ESA’s Ocean Land Color Instrument (OLCI), is useful for locating and tracking larger plumes on the continental shelf. It could be effective in addressing major weather events that impact the ocean flows and environment.

The Landsat 8 Operational Land Imager has a moderate spatial resolution (15 m–100 m, depending on spectral band). It measures the Earth's terrestrial environment including the polar regions in the visible, near-infrared, short wave infrared, and thermal infrared. The improved spectral capability of Landsat-8 compared to previous Landsat missions provides greater capability for quantitative imaging of estuarine and coastal ocean waters. Imagery from all Landsat missions has limited applicability to dynamic ocean environments, as a given coastal region is imaged only about once per month owing to the long repeat cycle and typical cloud cover. In addition, current multichannel satellites do not reliably differentiate between water column and seafloor properties and methods rely on considerable prior knowledge of the locations of different types of habitats (Mumby et al. 2004). With only a few spectral channels in the visible, the green color produced by a phytoplankton bloom at the sea surface can appear similar to the green color produced by macroalgae covering a shallow coral reef. Hyperspectral capabilities, however, can differentiate dangerous blooms of cyanobacteria from healthy seagrass meadows.

Geostationary satellites can provide additional capability that complements lower altitude orbiting systems. Korea’s Geostationary Ocean Color Imager (GOCI) acquires imagery of the

East China Sea and adjacent waters every 60 min during daylight hours and is used to observe and track freshwater plumes from the larger rivers in that region (e.g., Yangtze, Yellow, and Xi rivers). Other space agencies are interested in launching ocean color imagers in geostationary orbit that would provide similar coverage for European, U.S. and Indian Ocean rivers. Applications of GOCI imagery have already emphasized the importance of high temporal frequency coverage for tracking events and processes in dynamic coastal waters (Figure 4) (Lou and Hu 2014).

Future planned missions relevant to coastal and shelf observation that support a more detailed understanding include NASA's Surface Water Ocean Topography Mission (SWOT) and Hyperspectral Infrared Imager (HyspIRI). SWOT will measure water storage changes in terrestrial surface water bodies and provide estimates of discharge of large (wider than 100 m) rivers, globally at sub-monthly, seasonal, and annual times scales (Jet Propulsion Laboratory 2012).

The HyspIRI mission, planned for launch after 2022, includes two instruments, flying together or possibly separately on satellites in Low Earth Orbit. One is an imaging spectrometer measuring from the visible to short wave infrared (VSWIR: 380 nm - 2500 nm) in 10 nm contiguous bands. The other is a multispectral thermal infrared imager measuring from 3 to 12 μm in the mid and thermal infrared (TIR). The VSWIR and TIR instruments both have a spatial resolution of 60 m at nadir. The VSWIR will have a revisit of 19 days and the TIR will have a revisit of 5 days. HyspIRI also includes an Intelligent Payload Module (IPM) that will enable direct broadcast of a subset of the data. Similar to Landsat, the HyspIRI long revisit intervals limit the applicability for dynamic coastal environments.

Hyperspectral imaging does have important advantages that derive from the superior characterization of spectral “fingerprints.” Benthic features from minerals to seagrass absorb and reflect different portions of the visible spectrum giving them unique spectral "fingerprints." These spectral fingerprints can be used to distinguish features that are not easily distinguished with simple color photography or multi-channel satellite imagery. In a coral reef environment, for example, the spectra from many different benthic features can be easily discriminated with peaks and dips across the visible spectrum. Using these detailed spectral fingerprints, airborne imagery with 10 nm or finer spectral resolution can map not only the presence or absence of features on the seafloor, but the health and bleaching of corals, leaf area index and primary productivity of seagrasses, and different types of floating vegetation and slicks of oil (Hochberg et al. 2003; Mumby et al. 2004; Hill et al. 2014).

Airborne hyperspectral sensors have been shown to classify reefs with 98% accuracy, while narrowband multispectral sensors overestimated coral cover by 11–15%, and broadband sensors like Landsat overestimated coral cover by 24–103% (Hochberg and Atkinson 2000). Full-resolution airborne imagery provides very good spectral separation of the bottom-types that cannot be achieved from current satellite assets.

Improved methods are being developed to simultaneously model the bathymetry, bottom depth and water column optical properties from hyperspectral imagery (Dekker et al. 2011). New inversion approaches are being refined that can discriminate phytoplankton functional types including the presence of harmful algal blooms (Palacios 2012).

Lessons learned from satellite remote sensing show that careful calibration and orbital considerations are necessary to make meaningful use of satellite data (see National Academy Report). Otherwise postprocessing to handle contamination by sun glint and the presence of complex absorbing aerosols make it very challenging to interpret imagery.

Looking to the next generation of satellites, the higher spectral resolution and higher performance of NASA's PACE (Pre-Aerosol, Clouds and ocean Ecosystem) mission and ESA's Ocean Land Color Instrument (OLCI) radiometers on the Sentinel-3 satellites will be used to quantify the large-scale (1.0 – 1.2 km resolution imagery) impacts on shelf processes. Full-resolution OLCI imagery has 300-m pixel resolution for improved mapping of coastal features and thus will be able to image river plumes at relatively (<1km) high spatial resolution. The PACE sensors that may be considered could also have higher spatial resolution intended for better observations of processes in coastal regions and shelf waters.

NASA's GEO-CAPE (Geostationary Coastal and Air Pollution Events) radiometer, because of its stable positioning over the Earth, will provide imagery of particulate and dissolved water constituents acquired every 30 min during daylight for U.S. coastal waters (Fishman et al. 2012). Data from GEO-CAPE can be used to map freshwater plumes emanating from the larger U.S. rivers and track their movement across and along the continental shelf at hourly time scales during daylight hours. Ocean color radiometers in geostationary orbit (IOCCG, 2012) are promising new satellite technologies for coastal observations. Because geostationary orbits allow many images during a single day (e.g., Figure 3), the derived products, which could include phytoplankton chlorophyll a, harmful algal bloom indices, water transparency, particulate carbon/particulate matter, and colored organic matter, enable analyses of trends and shorter scale dynamic events. This is of particular interest for flood pulses that can occur in estuaries and river-ocean interfaces.

In addition to government-sponsored systems, the number of privately funded earth imaging systems that are useful for coastal observations is growing and by the 2020's, there will be several different systems available. These new commercial satellites offer higher resolution imagery that is directly relevant to imaging and understanding the small spatial and temporal scales associated with river outflow including frontal dynamics and mixing processes. DigitalGlobe launched WorldView-3 (Digital Globe 2015) in August 2014 and its mission duration will keep it operating past 2020. This system includes eight-band multispectral imagery with 1.24 m resolution as well as CAVIS (Clouds, Aerosols, Vapors, Ice, and Snow) data at 30 m resolution. Startup companies SkyBox Imaging and Planet Labs are offering systems that will provide both high spatial and high temporal resolution imagery (SkyBox 2015) As more private systems become available, the cost of imagery is expected to drop considerably by the 2020's, thus making the data available to the scientific community studying coastal processes.

IV. Key data contributions from satellite and *in situ* systems to meet the requirements for coastal observations

1. Phytoplankton Functional Types (PFT)

Satellites: Identification of phytoplankton functional types (PFT) may be based on algorithms using spectral absorption (*a*) and scattering properties (*b*) from advanced ocean color sensors such as PACE (nominally 1 km X 1 km pixels, but also possibly higher resolution) and OLCI (0.3 X 0.3 km pixels). Landsat-8 and HyspIRI can provide occasional higher spatial resolution imagery to derive similar properties at 0.030 X 0.030 km resolution, but with longer repeat cycles.

In situ: Advanced sensors for identifying PFTs are based on optics, flow cytometry/microscopy, and genomics. These capabilities are identified in a recent NOAA/NASA/BOEM RFP for Demonstration of a U.S. Marine Biodiversity Observation Network (http://explore.noaa.gov/Science/BiodiversityProjects.aspx and http://www.nopp.org/wp-content/uploads/2010/03/BON_SynthesisReport.pdf) and European Framework "Oceans of Tomorrow projects for ocean sensors such as NeXOS. [http://www.nexos-project.eu] Observations on coastal ARGO floats could also include bio-optical sensors (IOCCG 2011), such as transmissometers (water clarity), chlorophyll fluorometers (phytoplankton biomass), and scattering meters (back-scattered solar spectral irradiance to compare with satellite-derived measurements). Oxygen sensors are also increasingly common on ARGO floats. Oxygen sensors on a coastal version of the float would be very useful for assessing the potential for anoxic conditions, particularly in bottom layers beneath river plumes. This could follow the emerging developments of the SOCCOM project (SOCCOM 2015) which is focused on an observational component consisting of ~180 Argo vertical profiling floats equipped with nitrate, oxygen, and pH sensors.

2. Water quality including turbidity or transparency

Satellites: Spectral diffuse attenuation (*K*), *absorption* and *scattering* are accessible at regional spatial scales and with temporal resolution of days for PACE and OLCI and hours to days for GEO-CAPE, GOCI, and potentially other imagers on geostationary satellites. For coastal regions with potentially significant cloud cover, the frequency of image time series can be unpredictable.

In situ: Moored transmissometers, spectral absorption and scattering meters, and sensors for downwelling spectral irradiance can be deployed in coastal environments. With advances leading to smaller sizes, reduced power demand, and increased control of biofouling, these types of sensors will be more readily accessible in the next ten years. (NeXOS 2015, SenseOcean 2015) Moored instruments provide limited spatial resolution, although temporal scales can range from minutes to years. Increasingly these types of sensors can also be deployed on autonomous vehicles and drifting profilers, adding greatly to potential spatial resolution.

3. Wind speed and direction

Satellites: Currently scatterometers are of limited use for observing coastal winds because of interference from land features creating a need for high spatial resolution. The Ku band pencil beam scatterometer to be launched by Indian Space Research Organization (ISRO) onboard Oceansat-3 in 2017 will be useful in measuring winds in the coastal seas.

In situ. In many cases, wind speed and direction are monitored with moored meteorological packages. These provide point measurements and are thus a local observation.

4. Sea level variability

Satellites: The NASA altimeter SWOT (Srinivasan, 2015) will be an important tool to study watersheds and the coastal ocean. SWOT will have a nominal average revisit time of 11 days at low latitudes, and somewhat more frequent coverage at mid-to-high latitudes. As with other radar altimeters, SWOT coverage is not affected by cloud cover. Thus, most of the coastal ocean off the continental U.S. should get coverage at least 3 times per month with higher frequency coverage for Alaskan and north Atlantic coastal waters. SWOT may be capable of measuring the “bulge” effect on sea level of large freshwater discharges as they move onto the continental shelf along with other processes such as the currents and eddies in the coastal region.

In situ: Sea level changes along the U.S. and other coastlines are monitored by tide gauges. A network of sensors has been created by different countries and agencies. The data are aggregated under the Global Sea Level Observing System (GLOSS) (http://www.gloss-sealevel.org).

5. Currents and eddies

Satellites: Recent research indicates the importance of eddies for re-circulated river flows near the coast. As mentioned above, SWOT will have the resolution to observe sea level changes associated with coastal currents and eddies. In addition, time series from GEO-CAPE and other geostationary imagers (ca. 30-60 min resolution) can track sub-daily flows of river plumes during daylight hours. At high latitudes, some of these rapid observations can be available from polar-orbiting satellites in certain circumstances.

In situ. Current meter moorings provide Eulerian measurements of coastal currents. Other sensors provide information on mixing between saltier and fresher waters. High

Frequency (HF) radar is used to measure surface currents with maximum resolution of 1 km and maximum range of 200 km (range and resolution being inversely proportional), and with temporal resolution of an hour. (Harlan 2010*)*. Current vectors derived from these measurements show mesoscale features, such as coastal eddies, which are resolved with much greater accuracy than possible with an array of current meters.

6. Temperature and Salinity

Satellites. Salinity sensors on current satellites (e.g., *Aquarius, SMOS*) are of limited use for measuring sea surface salinity (SSS) near the coast owing to their large footprint (>> 300 km) and low temporal resolution (monthly). However, seasonal plume patterns of low salinity waters from large rivers (e.g. Amazon, Mississippi) are measurable by *Aquarius*. Sea surface temperature (SST) imagery at resolutions comparable to the satellite ocean color scanners is routinely available for research and operational users. Data from NOAA/AVHRR and MODIS (~ 1 km resolution) are useful in constructing SST fields. The thermal IR data from the new OCM-3 will also be useful to determine the sea surface temperature. The payload will have two views for better retrieval accuracy. The Ground Sampling Distance (GSD) will be 360 m for OCM-3 and 1080 m for thermal IR. Swath of the Payload will be 1440 km.

In situ. Temperature (T) and salinity (S) sensors are routinely deployed on current meter moorings. T and S sensors are obvious measurements for small profiling floats and/or gliders designed for shallow coastal waters. A new technology for monitoring the fate of river plumes and their impacts in shelf water is an ARGO float for shallow water. Such a float is under development but not yet operational [Haraguchi, 2014]. A critical feature is that the float senses the bottom by striking it, so that profiles from the surface to the bottom are possible. Thus, the float can operate and collect data without re-programming in coastal environments characterized by rapidly changing bottom depths. Keeping the float at depth between profiles significantly decreases the chances of a beach stranding. An example of such a float is the ARVOR-C (Temperature, Salinity, Depth) /ARVOR-Cm (Temperature, Salinity, Depth, Turbidity, Dissolved Oxygen, Fluorescence) profilers. At the present time, this float is operated in a "virtual mooring mode" (the profiler lands on the sea bottom between two profiles), instead of a "drifting mode" that would be difficult to manage in dynamic coastal regions. The multi-parameter

(ARVOR-Cm) was in development phase in 2014 with final tests planed at the end of the 2014). [Charria, 2014) One operational scenario to optimize collecting high priority data is to release floats at different stages of river discharge events or in high discharge seasons.

Table 1 summarizes the above lists. Since there is a large variation in satellite and in situ capabilities, this table summarizes the general categories of required capabilities**.**

7. Identification of Potential Fishing Zones (PFZ)

The high resolution sea surface temperature (~ 1.1 km) and ocean color (chlorophyll at spatial resolution of 360 m) data are regularly used to identify the PFZ in the coastal waters (mainly on the shelf and slopes) based on the features like meandering flows, eddies, filaments, etc. which are identifiable using high resolution satellite data. Data from NOAA/AVHRR and MODIS (~ 1 km resolution) are useful in constructing SST fields and the 8 channel Ocean Color Monitor (OCM) data (~ 360 m) are useful in visualizing chlorophyll distributions. The Indian Space Research Organization has planned to launch Oceansat – 3, in continuation of the existing Oceansat – 2. Oceansat-2 is an interesting example of impacts and benefits to the fishing industry. At an IOCCG meeting a few years ago, the ISRO representative said that the Indian fishing using satellite imagery had saved more in fuel costs than it cost to build and launch Oceansat-2.

The new OCM-3 will have 13 channels in visible and near IR in addition to two split window channels in thermal infrared. The narrow bands (10-20 nm) in OCM-3 are expected provide better estimates of chlorophyll, CDOM, inorganic suspended material, etc. The thermal IR data will be useful to determine the sea surface temperature. The payload will have two views for better retrieval accuracy. The Ground Sampling Distance (GSD) will be 360 m for OCM-3 and 1080 m for thermal IR. Swath of the Payload will be 1440 km.

V. Functionality of the Observing System – focusing on fate of river plumes

A fully integrated future observing system to determine the fate of major river plumes once they reach the U.S. continental shelf (incl. Gulf of Alaska) requires a combination of observations, models, and analyses of the background data of the watershed and adjacent coastal ocean. To focus assets at crucial times during the year and at key locations requires knowledge of historical patterns of sub-seasonal to interannual variability of freshwater storage in terrestrial reservoirs within the coastal region of interest. Of particular interest are the time lags between the storage and major discharges into coastal waters. For the U.S., this information can be determined in part from analyses of the stream flow records maintained by the U.S. Geological Survey. For lakes, reservoirs, and wetlands that exceed 250 m^2, and for rivers whose width exceeds 100m, SWOT will also measure the storage change in terrestrial surface water bodies at sub-monthly, seasonal, and annual time scales. SWOT can also provide an estimate of the change in river discharge at the same time scales (Jet Propulsion Laboratory, 2012).

A regional-scale numerical model that is forced by realistic tides and winds, has realistic bottom topography, vertical and horizontal resolution appropriate for its application, and is capable of producing the fields of interest, including ecological and biogeochemical tracers, is required as an integrative and predictive tool. The model will be particularly useful if it can be run in near real-time and is capable of assimilating basic meteorological fields and some ocean physical observations, such as vertical structure.

To support such a model, buoy winds, surface air temperature, and incoming solar radiation are the minimum meteorological measurements required as a complement to the physical ocean measurements outlined above. Combining knowledge of historical trends with near-real time SWOT imagery should provide important boundary conditions for models to predict the generation and fate of river plumes that originate with significant discharge events. SWOT data will also provide ca. 3 snapshots per month of sea surface height (SSH) for any given coastal region. SSH variability, in combination with coastal circulation models, may prove useful for detecting coastal eddies, currents, and bulge circulation.

As mentioned earlier, ocean color radiometers in geostationary orbit (IOCCG, 2012) are promising new satellite technologies for coastal observations; the advantage of geostationary orbit is that many images of a single region are possible during a single day (e.g., Figure 3). Quantitative measurements of derived products may not be possible when waters are highly turbid, although the backscattering and absorption characteristics would still allow tracking the fate of plumes and other features associated with river discharge events. Under ideal conditions, the derived products would help determine plume impacts on water clarity, as well as phytoplankton carbon, chlorophyll, and productivity. These measurements when combined with other information would, for example, lead to predictions for bottom layer oxygen content. Further measurements for modeling of river plumes and the near shore impacts include high spectral resolution of PACE and HyspIRI, including bands in the UV and near UV. These will provide significant improvements for measurements of in-water constituents beneath the complex atmospheres of coastal regions. Resolving taxonomic composition at the phytoplankton class level, as well as determining dominant phytoplankton size classes may also be possible (e.g., IOCCG 2014). Such information is necessary for predicting rates of nutrient utilization, sinking rates of organic matter, and other information that can be used to predict whether the lower layer of stratified waters beneath plumes will become deprived of oxygen, thereby affecting the health of living resources such as shellfish. In the future a new range of in situ sensors (discussed earlier in the paper) can be coupled with the satellite observations; particularly of interest here are the *in situ* bio-optical measurements from mooring or drifting sensor packages. More sophisticated (and expensive) sensors can make detailed biological measurements, at least at a few sites, while comparatively simple biological/biogeochemical sensors can be deployed on floats (Amaral-Zettler et al. 2010; Duffy et al. 2013).

The high spatial and temporal resolution of emerging commercial imaging systems will provide opportunities to study the fine-scale process controlling river plumes. These systems are optimized for land feature imaging but their planned capabilities will allow for imaging of coastal ocean features. SkyBox Imaging, for example, launched its second satellite in July 2014 and plans to have 24 satellites in orbit by 2018. This system includes multispectral imaging at 2m resolution over a 8km swath and will have revisit rates well below one hour through a constellation of 24 satellites. While these commercial systems are not expected to provide the absolute precision of science mission satellites, the high spatial-temporal resolution can provide context for multi-scale variability and in situ data interpretation that is essential for river plume process studies.

VI. Data Integration

The components of an observing system for understanding the fate of river plumes as they reach and interact with the waters of the continental shelf, and their impacts on biological and biogeochemical processes could be integrated in the following way:

- For a given regional observing system, real-time stream gauge data and analyses of historical patterns are used to predict the timing of high discharge conditions. These predictions could be improved using a watershed model such as the Soil and Water Assessment Tool (SWAT) [reference: http://swat.tamu.edu] that assimilates SWOT and similar satellite data, providing measures of terrestrial reservoir water storage.
- The results of analyses/models are used to determine when to deploy coastal ARGO floats near river mouths. Coastal currents are tracked using time series of float locations, surface current vectors from coastal radar, and periodic (ca. every 10 days) snapshots of coastal sea level from SWOT. A coastal circulation model would be used to assimilate these data and provide more complete time/space coverage.
- Plumes are tracked by the time series of float locations using the float salinity measurements to confirm that any given float is actually in the plume. Plumes could also be tracked using imagery from a geostationary satellite such as GEO-CAPE, particularly when river waters are more turbid, and thus more strongly reflective, than surrounding continental shelf waters.
- The impacts of river plumes are determined from bio-optical instruments on the floats, data from PACE, HypsIRI, GEO-CAPE, and possibly other satellites, as well as moored instruments that could include more sophisticated sensors for detailed biological measurements and mobile systems such as gliders, AUVs and ARGO floats. Biological/biogeochemical measurements should include phytoplankton biomass, primary productivity, dominant phytoplankton types, genetic composition of both microorganisms and higher trophic levels (such as through eDNA technologies), water transparency, sediment concentration, particulate carbon concentration, nutrient concentrations, and oxygen content. Calculations and products based on the measurements would include phytoplankton productivity, across-shelf carbon and sediment flux, and an index related to the potential for anoxia of bottom waters. Since

these ecosystems are complex, additional sensors may need to be included to refine the understanding of habitats.

The discussion above is meant to illustrate an approach for using observations that combine satellite, in situ sensors, and numerical models for one coastal application. One can envision many other applications for a combination of satellite and in situ measurements of the coastal ocean. Those applications could include assessing the temporal and spatial variability of benthic habitats (coral reefs, mangroves, marshes) and how they might be undergoing long term change, and assessing the effects of other physical phenomena of coastal environments, such as upwelling circulation, and their effects on nutrients, oxygen, and phytoplankton dynamics.

Ultimately, the choice of issues, the data and the models required to address those issues to understand the dynamics of the ocean environment rely heavily on the stakeholder community of scientists engaged in ocean and coastal research. Integration of the stakeholders into the process of planning, specifically assessing needs early on and working with them to define deliverables, schedules, particular products leads to a more capable, useful and, ultimately, a more comprehensive and better funded program of ocean observation. The issues are broad, ranging from satellite capabilities to having access to data in easily used formats that are interoperable. Even data formats can be a barrier. Many community repositories maintain data in their formats that are not consistent across disciplines. When using data from in situ and space-based observations, some form of interoperability support is typically required. The Ocean Data Interoperability Platform (ODIP) has developed three case studies using either standards or broker middleware (ODIP, 2015). Brokering has been used in GEOSS to translate data formats across disciplines. An EarthCube project “Broker Building Block” is evaluating data and model interoperability in estuaries and coastal waters (BCube 2015). Data interoperability and availability also rely on the ability to interface sensors with platforms and having access to the data in commonly available formats for use. Standard interfaces between sensors and platforms have been recently proposed (e.g. PUCK) and introduction of web services for data access is maturing. In all cases, monitoring of sensors conditions and having appropriate metadata are recognized as important steps in increasing the value of data and supporting data integration.

While the focus of this discussion has been on sensors, observations and models, there is an underlying assumption that a strong science capability will be sustained over the next decade as the satellite and advanced in situ systems become operational. This requires education and training both in science disciplines of oceanography and a broader outreach across the sciences. The training should certainly follow the traditional education patterns, but may need to be extended by including more cross-disciplinary training and research.

VII. Recommendations

The above discussion leads to recommendations for combining and expanding satellite and in situ measurements, particularly for applications in the coastal environment. The recommendations cover four areas:

- Satellite Observations/Missions
- In situ Observations
- Data, Analyses and Modeling
- Education

While the recommendations have been grouped into the above four areas, we recognize that there are needs of the end to end processes that reach across the areas, where, for example, satellite products need to be merged effectively and efficiently with *in situ* measurements from ocean observing systems across the globe, and then distributed as consistent and coherent data sets for modeling and analyses. A future observing system based on a combination of satellite observations, model predictions, and Lagrangian sensors will be an effective strategy to address ocean science requirements and provide observations of many linked processes across a wide range of space and time scales. In achieving this, satellite products need to be assessed in terms of their accuracy in complex coastal waters with in situ measurements from US and other ocean observing systems, incorporated into oceanographic and climate models and then distributed as a consistent and coherent package of observations to stakeholders.

Ultimately, good, high-resolution base maps of the ocean environments are needed to provide a foundation for analyses of state, dynamics of the environment and trends in both the short and long term. These include habitats, the chemical and physical environments and other key characteristics overlaid on bathymetric maps for all the data collected from the field devices mentioned in this report. While this is a challenge, such innovation can provide tremendous leverage in understanding the ocean and the ocean-land interactions.

1. Satellite Observations

- Satellite data of key ocean variables (SST, ocean color, winds, altimetry, etc.) are only valuable if they are well calibrated and comparable between sensors and over years to decades. Therefore we strongly support the timely launch of new satellite systems to assure continuity of satellite observations and the careful cross calibration of data across missions for coastal science.

- Geosynchronous and polar satellites provide unique and complimentary views of the coastal ocean. Geosynchronous satellites provide high repetition data for lower latitude but do not cover from 50 degrees to the poles, while polar orbiters can cover these latitudes at high frequency and all latitudes at potentially higher spatial resolution. For this reason we support a balanced system of geosynchronous and polar satellites. As a longer-term objective, we support the development of a constellation of small satellites covering all latitudes at high frequency (1-3 hours) and adequate spectral and spatial resolution for the coastal ocean.

- As the next generation of earth-observing satellite sensors progress through design and implementation phases, it will be important to highlight appropriate priorities for integrated coastal ocean observing. For each upcoming U S satellite sensor (e.g., PACE, GEO-CAPE, HyspIRI, SWOT, etc.), there will be trade-off considerations amongst temporal repeat frequency, spatial resolution, spectral resolution, mission cost, and payload size. Additional capabilities with higher temporal/spatial resolution and sensitivity/signal to noise are also needed that provide stable and well-calibrated data. Well-justified and quantifiable needs for coastal problems will be critical to ensure the most effective mission capabilities for integration with *in situ* observations and model results.

- Improve satellite data interoperability to allow ready access to and use of the satellite data regardless of the user's technical background or discipline. To do this, we recommend leveraging interoperability guidelines being developed under NASA [Practical Data Interoperability for Earth Scientists Version 1.0 Christopher Lynnes, Ken Keiser, Ruth Duerr, Terry Haran, Lisa Ballagh, Bruce H. Raup, Bruce Wilson Earth Science Data Systems Working Group -

https://earthdata.nasa.gov/sites/default/files/field/document/PracticalInteropforEarthSci_v1_0.pdf] and https://earthdata.nasa.gov/esdswg] and the NSF [(http://earthcube.org/) and http://en.wikipedia.org/wiki/Data_Infrastructure_Building_Blocks_(DIBBs)] .

2. In situ Observations

- ARGO floats have greatly improved our view of the internal structure of the global ocean and been essential for validation of basin scale physical and bio-optical properties measured with satellites. For the coastal ocean we recommend more active development and implementation of the new generation of coastal ARGO floats that include bio-optical sensors (IOCCG 2011), including transmissometers (water clarity), chlorophyll fluorometers (a rough indicator of phytoplankton biomass under ideal conditions), oxygen monitors and backscattering meters (back-scattered solar spectral irradiance to compare with satellite-derived measurements). For data compatibility, instrumentation should be the same or similar to that already available on open ocean ARGO floats and gliders (this includes miniaturized nutrient, as well as pH and carbon sensors to further study the effect of water discharge to coastal waters). To have widespread application of such sensors and systems, issues of cost, expected lifetimes, operability must be addressed on a global scale.

- Further development and use of gliders and AUVs for the coastal ocean is also needed. These platforms will complement coastal ARGO floats by providing more synoptic and extended horizontal coverage, as well as having the potential for larger sensor payloads.

- New forms of communication and sensor control are becoming available and should be further supported. For example, sensor webs allow real time control of sensors and implementation of standards such as OGC "PUCK" provide plug and play sensor/platform interfaces to improve the use of sensors in multiple platforms.

- Expand the use of targets (i.e. platforms) of opportunity –Invest in programs for optimal use of platforms-of-opportunity (fishing vessels, ferries, transport ships, energy industry infrastructure, etc.) to enable cost-effective ocean sampling. This should include development of appropriate sensor systems that can be deployed and maintained readily on a variety of platforms. This approach can complement autonomous research platforms such as gliders and floats, with advantages including lower cost and logistical challenges and greater potential for sensor payload (e.g., more demanding biological and chemical sensors).

3. Data Analyses and Modeling

- All coastal data (*in situ* and satellite) needs to be quality assured, and made available in a consistent format in near-real time.

- High-resolution (<< 1 km) coupled physical bio-optical models of the coastal ocean are essential for the merging of these disparate data sets into a coherent picture of the coastal ocean and must be an integral part of any coastal observing system. Like the weather system for atmospheric measurements, validated model outputs will be the primary format that is used by other scientists and the general public.

- Improved interoperability between sensors and between relevant data/information infrastructures would aid in supporting incorporation of measurements into models. This is particularly true for coastal and river observations and modeling as the hydrological models are developed by disciplines that are usually separate from the ocean research community. New techniques such as interoperability through brokering and multi-disciplinary standards under development by NSF should be considered and validated for coastal observations and modeling.

4. Education

- We anticipate the need for expanded education at the undergraduate and MS level to provide the professionals to create and operate the Coastal Observing System and work in formal and informal coastal ocean education.

- There needs to be an educational capability that helps people learn the uses and benefits of ocean observation technology and also recruits new talent into science fields

VIII. References

Ahn, Y. H., and Shanmugam, P., 2006. Detecting the red tide algal blooms from satellite ocean color observations in optically complex Northeast-Asia coastal waters. Remote Sensing of Environment, 103, 419–437.

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

André, X., S. Le Reste, J.-F. Rolin, Arvor-C., 2010 A Coastal Autonomous Profiling Float, Sea Technology, 51(2), 10-13.

BCube, 2015. [http://www.odip.org/media/odip/org/documents/promotion/odip%20poster_2014.pdf].

Brink, K.H. ,J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.E. Hammond, S.M. Henrichs, C.S. Marens, C.A Nittrouer, D.P. Rogers, M.R. Roman, J.D. Roughgarden, R.L. Smith, L.D. Wright, and J.A. Yoder, 1992. Coastal Ocean Processes:A Science Prospectus. Woods Hole Oceanog. Inst. Tech. Rept., WHOI-92-18. Woods Hole Oceanographic Institution, Woods Hole, MA.

Cahill, B., O. Schofield, R. Chant, J. Wilkin, E. Hunter, S. Glenn, and P. Bissett, 2008. Dynamics of turbid buoyant plumes and the feedbacks on near-shore biogeochemistry and physics. Geophysical Research Letters, 35 , doi:10.1029/2008GL033595.

Chant, R.J., J. Wilkin, W. Zhang, B.-J. Choi, E. Hunter, R. Castelao, S. Glenn, J. Jurisa, O. Schofield, R. Houghton, J. Kohut, T.K Frazer, and M.A. Moline, 2008. Dispersal of the Hudson River Plume in the New York Bight: Synthesis of Observational and Numerical Studies during LaTTE. Oceanography 21: 148-161.

Chant, R.J. 2011 Interactions between Estuaries and Coasts: River Plumes – Their Formation, Transport, and Dispersal, Reference Module in Earth Systems and Environmental Sciences, from Treatise on Estuarine and Coastal Science, Volume 2, Pages 213-235

Charria, G., M. Repecaud, L. Quemener, A. Ménesguen, P. Rimmelin-Maury, S. L'Helguen, L. Beaumont, A. Jolivet, P. Morin, E. Macé, P. Lazure, R. Le Gendre, F. Jacqueline, R. Verney, L. Marié, P. Jegou, S. Le Reste, X. André, V. Dutreuil, J.-P. Regnault, H. Jestin, H. Lintanf, P. Pichavant, M. Retho, J.-A. Allenou, J.-Y. Stanisière, A. Bonnat, L. Nonnotte, W. Duros, S. Tarot, T. Carval, P. Le Hir, F. Dumas, F. Vandermeirsch, F. Lecornu,Previmer, 2014. A contribution to in situ coastal observing systems, *Quarterly Newsletter MERCATOR-Ocean*, 49,.

Charria, G., 2014 private communication, see also http://www.nke-instrumentation.com/products/profilers/products/arvor-c.html

Decadal Survey, 2007. Earth Science and Applications from Space:

National Imperatives for the Next Decade and Beyond (2007), National Research Council, ISBN: 978-0-309-14090-4 (http://www.nap.edu/catalog.php?record_id=11820 and http://decadal.gsfc.nasa.gov/PACEmtg2_Mar2012.html).
Digital Globe. 2015. http://worldview3.digitalglobe.com/

Duffy, J. E., Amaral-Zettler, L.A., Fautin, D.G., Paulay, G., Rynearson, T.A., Sosik, H.M., Stachowicz, J.J., 2013. Envisioning a Marine Biodiversity Observation Network. Bioscience. http://www.aibs.org/bioscience-press-releases/resources/DuffyREV2.pdf

Fishman, J, L. T. Iraci , J. Al-Saadi, K. Chance, F. Chavez, M. Chin, P. Coble, C. Davis, P. M. DiGiacomo, D. Edwards, A.Eldering, J. Goes, J. Herman, C. Hu, D.J. Jacob, C. Jordan, S. R. Kawa; R. Key, X. Liu, S. Lohrenz; A. Mannino; V. Natraj, D. Neil, J. Neu, M. Newchurch, K. Pickering, J. Salisbury, H. Sosik, A. Subramaniam, M, Tzortziou, J. Wang, and M. Wang, 2012. Progress report on NASA's GEO-CAPE mission: Fulfilling the mandate and meeting the challenges of the nation's next generation of atmospheric composition and coastal ecosystem measurements. Bulletin of the American Meteorological Society.10.1175/BAMS-D-11-00201.1

Gregg, W.W. and M.E. Conkright, 2001. Global seasonal climatologies of ocean chlorophyll: Blending in situ and satellite data for the Coastal Zone Color Scanner era. J. Geophys. Res. 106, 2499-2515.

Haraguchi K., 2014 , Tecsrg Company, Japan, private communication

Harlan, J., et al. 2010. The Integrated Ocean Observing System High-Frequency Radar Network: Status a Local, Regional and National Application. Marine Technology Society Journal, 44, 122-132.

Horner-Devine, A.R., 2009. The bulge circulation in the Columbia River plume Continental Shelf Research 29, 234–251

IMOS, 2015. http://www.imos.org.au

IOCCG, 2011. Bio-optical sensors on Argo Floats. Claustre, H. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 11, IOCCG, Dartmouth, Canada.

IOCCG, 2012. Ocean-Colour Observations from a Geostationary Orbit. Antoine, D. (ed.). Reports of the International Ocean-Colour Coordinating Group, No. 12, IOCCG, Dartmouth, Canada.

IOCCG, 2014. Phytoplankton Functional Types from Space. Sathyendranath, S. (ed.). Reports of the International Ocean-Colour Coordinating Group, No. 15, IOCCG, Dartmouth, Canada. 156 pp.

Jet Propulsion Laboratory (JPL), 2012. Surface Water and Ocean Topography mission (SWOT). Science Requirements Document, Second Release (v1.1). Jet Propulsion Laboratory, California Institute of Technology..

Jet Propulsion Laboratory. HyspIRI Mission Study. http://hyspiri.jpl.nasa.gov/

Le Troan, P-Y., 2007. Principles of satellite radar altimetry, http://earth.eo.esa.int/dragon/ocean_training/Lecture_Material/DAY5-19Oct2007/D5_L1-2_letraon_lecture1_2.pdf.

Lou, X., and C. Hu, 2014. Diurnal changes of a harmful algal bloom in the East China Sea: Observations from GOCI. Remote Sensing of the Environment. 140: 562-572.

Muller-Karger, F.; Roffer, M.; Walker, N.; Oliver, M.; Schofield, O.; Abbott, M.; Graber, H.; Leben, R.; Goni, G., 2013. Satellite Remote Sensing in Support of an Integrated Ocean Observing System. Geoscience and Remote Sensing Magazine, IEEE , vol.1, no.4, pp.8,18,. http://dx.doi.org/10.1109/MGRS.2013.2289656.

MyOcean, 2015. http://www.myocean.eu

NeXOS, 2015. http://www.nexosproject.eu

Ocean Observatories Initiative. 2010. Final Network Design. http://www.oceanobservatories.org/wp-content/uploads/2012/04/1101-00000_FND_OOI_ver_2-06_Pub.pdf.

Ocean Observatories Initiative 2015, Current Status, http://oceanobservatories.org

ODIP, 2015. [http://www.odip.org/media/odip/org/documents/promotion/odip%20poster_2014.pdf].

Rong, Z., Li, M., 2012. Tidal effects on the bulge region of Changjiang River plume. Estuar. Coast. Shelf Sci. 97, 149–160.

SeaDataNet, 2015, http://www.seadatanet.org.

Senseocean. 2015. http://www.senseocean.eu

SkyBox. 2015. (http://spectrum.ieee.org/aerospace/satellites/9-earthimaging-startups-to-watch).

SOCCOM, 2015. The Southern Ocean Carbon and Climate Observations and Modeling project. (http://soccom.princeton.edu)

Srinivasan, M, A. Andral, M. Dejus, F. Hossain, C. Peterson, E. Beighley, T. Pavelsky, Y. Chao, B. Doorn, E. Bronner, L. Houpert., 2015. Engaging the Applications Community of the Future Surface Water and Ocean Topography (SWOT) Mission, The International Archives of the

Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W3, 2015 36th International Symposium on Remote Sensing of Environment, 11–15 May 2015, Berlin, Germany

U.S. Integrated Ocean Observing System (U.S. IOOS), 2013 Report to Congress, http://www.ioos.noaa.gov/about/governance/ioos_report_congress2013.pdf.]

U.S. Regional IOOS, Associations 2015, http://www.ioos.noaa.gov/regional.html

IX. Figures and Tables

Table 1: Summary of sample observations for the coastal environment

Attribute	Satellite observation	In situ observation
Phytoplankton Functional Types (PFT)	PACE, Landsat 8, HyspIRI	Optics, flow cytometry/microscopy, and genomics
Water quality	PACE, OLCI, GEO-CAPE, GOCI	Moored transmissometers, spectral absorption and scattering monitors, and sensors for down welling spectral irradiance.
Wind speed and direction	ISRO Oceansat -3	Moored metrological packages
Sea level variability	SWOT	Tide gauges, GLOSS (JCOMM network)
Currents and eddies	SWOT, GEO_CAPE	Current meter moorings, high frequency radar
Temperature and salinity	Aquarius (large bodies)	Argo shallow water floats,
Potential Fishing Zone identification Ocean Color and SST	AVHRR/MODIS, Ocean Color Monitors	

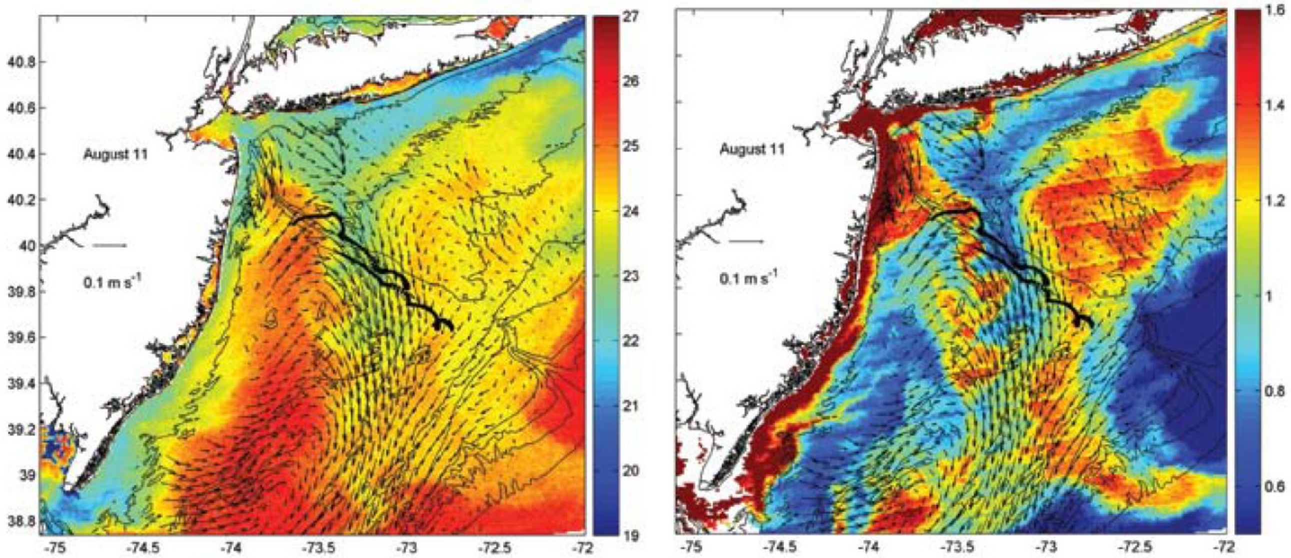


Figure 1. Integration of multiple observational strategies has provided unique insights into the dramatic ways US continental shelf waters off New York are influenced by freshwater outflow from the Hudson River. Both panels show surface currents derived from coastal radar systems (CODAR); the left panel shows satellite-observed SST (°C) while the right panel shows chlorophyll a (mg m^{-3}). Both images are from 11 August 2006. Also shown are drifter trajectories (heavy black lines) from 26–28 July 2006. Together, the observations suggest an offshore transport of cold water and high chlorophyll a by the mid-shelf jet just inshore of the Hudson Shelf Valley. Reproduced from Chant et al. (2008).

Figure 2. Figure showing current and future satellite altimeter missions (Figure courtesy of the Committee on Earth Observation Satellites, http://www.ceos.org/)

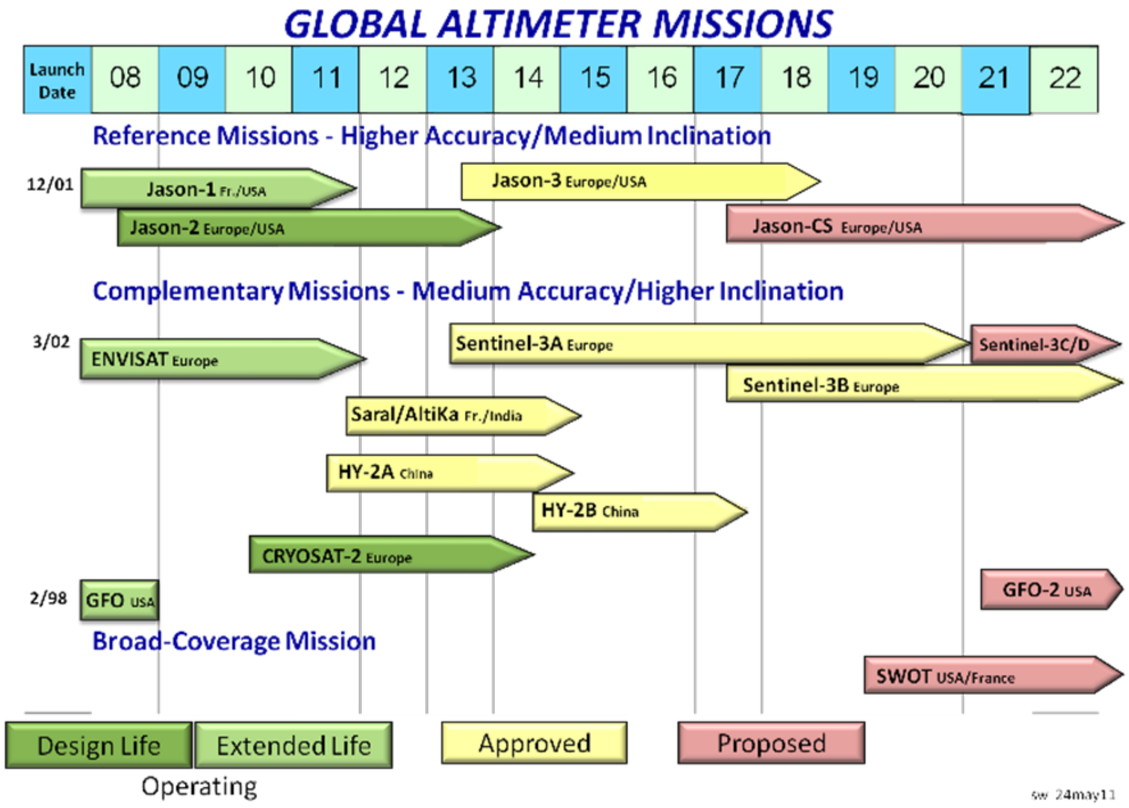
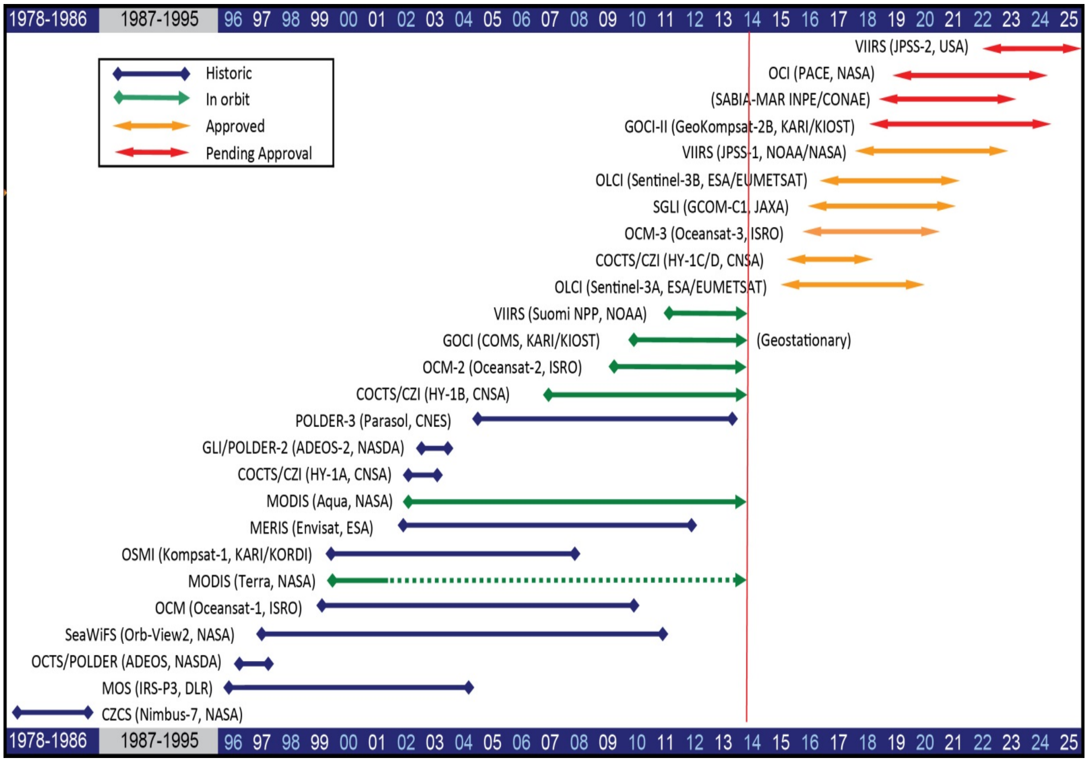


Figure 3. Figure showing current and future ocean color missions (Figure courtesy of the International Ocean Color Coordinating Group, www.ioccg.org)



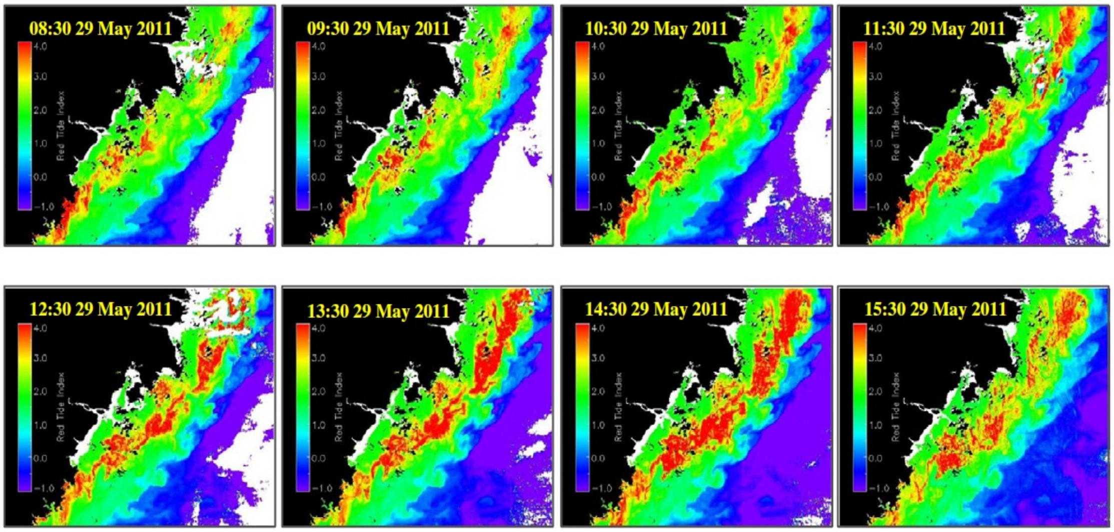


Figure 4. False color images from GOCI measurements of coastal waters of the East China Sea on 29 May 2011, showing values of the “red tide index” (RI) developed by Ahn and Shanmugam (2006) and modified by Lou and Hu (2014). In these images, high RI values (> 2.8, yellow-red colors) correspond to a rapidly evolving harmful algal bloom attributed to the dinoflagellate *Prorocentrum donghaiense* . Reproduced from Lou and Hu (2014).