The Global Ocean Observing System for Climate

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Annual Report

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Satellite Contributions to the Ocean Observing System for Climate, 2009 -2010

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Introduction

Coupling the ability of space-borne sensors to observe the global ocean frequently and at a fine spatial resolution with accurate in situ observations at the surface and at depth remains the key approach to increasing understanding of the global climate system. During 2009 and 2010, satellite observations continued to meet the continuity requirements for building climate data records (CDRs), but the challenges to sustaining this critical observing capability continued to grow as well. Existing instruments are aging and newer systems under development face delays. Since the last report, the White House announced a major restructuring of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), dissolving the three-way partnership between the U.S. Department of Defense (DOD), NASA, and NOAA. NOAA and NASA will now take primary responsibility for the afternoon orbit, and DOD for the morning orbit. NPOESS was designed to be the next generation of low earth-orbiting environmental satellites, and this restructuring into the Joint Polar Satellite System (JPSS) may have implications for the continuity of ocean observations from space.

Readers familiar with the past annual reports will notice that we again omit the historical descriptions and rationale for each of the parameter classes. Readers interested in those relatively static pieces of information may refer to earlier versions of this report. After an update on international efforts to coordinate satellite activities, we will include updates on the latest status, critical activities, and a look forward to the future for SST, ocean color radiometry, ocean surface topography, sea ice, and marine winds.

CEOS Virtual Constellations

Formed in 1984, the Committee on Earth Observing Satellites (CEOS) provides a forum for worldwide coordination of individual space agency efforts to observe the Earth System. CEOS works to maintain continuity of observations, minimize redundancy, identify and address information gaps, and build and sustain a global Earth observation network. In recent years, CEOS created a Virtual Constellation (VC) concept, designed to facilitate this coordination. The concept involves multiple satellites from multiple agencies working in harmony to improve temporal, spatial and spectral resolution, enhance system compatibility, and increase data availability. The CEOS VCs are envisioned as the space-component to the Global Earth Observing System of Systems (GEOSS).

At the center of the VC concept is a clear and common set of standards required for any mission's inclusion in the constellation, including guidance on the characteristics of the space and ground segments for that mission that would enable it to best satisfy the needs of the user community. Six VCs currently exist, including three with ocean applications. These include the Ocean Surface Topography Constellation, which is a joint NOAA and European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) effort designed to ensure continuity of sea level measurement; the Ocean Color Radiometry Virtual Constellation (OCR-VC), which will provide calibrated ocean color radiometry for ocean biology and biogeochemistry applications and currently has participation from more than 10 agencies internationally; and the Ocean Surface Vector Winds Constellation, which will improve operational marine warnings and forecasts through the use of satellite scatterometry and input from other VCs. In the fall of 2010, the Group for High Resolution SST (GHRSST) applied to CEOS, seeking to be formally designated as the VC for SST. The outputs of these VCs, when joined with in situ observations, will considerably improve the extent to which various agency programs can meet the continuity and accuracy requirements for climate monitoring of the oceans from space.

These ocean VCs have established goals and initiated progress toward meeting them. For example, the OCR-VC will provide long time series of calibrated ocean color radiance (OCR) at key wavelength bands from measurements obtained from multiple satellites. OCR-VC activities will include calibration, validation, merging of satellite and in situ data, product generation, as well as development and demonstrations of new and improved applications. Key priorities of the OCR-VC in the next several years include development of an inter-agency OCR Essential Climate Variable (ECV) implementation strategy and subsequent execution of this strategy, as well as concerted inter-agency efforts on activities relating to sensor inter-comparison and uncertainty assessment of datasets required for ECV generation. In this context, there are plans to develop an International Network for Sensor InTercomparison and Uncertainty assessment for Ocean Colour Radiometry (INSITU-OCR).

Sea Surface Temperature

Current Status and a Look Forward

SST remains one of the most critical parameters for ocean climate monitoring, with a continuous record of satellite monitoring dating back to 1981. Currently, the MODIS sensors on the NASA Terra and Aqua platforms continue to perform well and the Advanced Very High Resolution Radiometers (AVHRRs) on board Metop-A, NOAA-18, and NOAA-19 are in operational status. The Geostationary Operational Environmental Satellite (GOES) platforms, GOES-11, -12 and -13, continue to deliver SST measurements, with GOES-13 taking over coverage of the eastern United States from GOES-12, which now covers South America. The Republic of Korea's first Communication, Ocean, and Meteorological Satellite (COMS-1) achieved geostationary orbit in July of 2010, and is observing SST and ocean color for the Korean seas and surrounding ocean. The Advanced Along Track Scanning Radiometer (AATSR) on board the European Space Agency (ESA) ENVISAT satellite, the Tropical Rainfall Measuring Mission (TRMM) and its TRMM Microwave Imager (TMI), the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) on board the NASA Aqua platform, the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the Meteosat Second Generation (MSG) satellite series, the imagers on board the Japan

Meteorological Agency's MTSAT series, and other platforms all continue to deliver SST measurements as well.

Looking forward, the JPSS and its precursor, the NPOESS Preparatory Project (NPP), will carry the Visible-Infrared Imager-Radiometer Suite (VIIRS), the successor to the AVHRRs and the MODIS sensors. NPP and the first JPSS satellite are currently planned for launch in 2011 and 2015, respectively. The AMSR2 instrument on board the Japanese GCOM-W platform, expected to launch in 2012, will extend the time series of the current AMSR-E. EUMETSAT is planning for a 2012 launch of the second in the Metop series of satellites, Metop-B, which will carry the last of the AVHRR sensors. Finally, from ESA, the pair of Sentinel-3 satellites will each carry Sea and Land Surface Temperature Radiometer (SLSTR) instruments, designed to continue the AATSR time series after their launches beginning in 2013.

Critical Activities

As in the past, consistently reprocessing individual sensor observations, combining multiple contemporaneous observations from different sensors, and merging time series from individual sensors into a consistent record remain high priority areas for SST climate record development. As the satellite measurements have grown increasingly more accurate, a new emphasis is also now growing on the need for improved in situ SST observations. Since the time of the last report, there have been several important advances in these areas. International coordination of these activities has been achieved through GHRSST (Donlon et al., 2007), which produces and distributes over 30 commonly formatted daily SST products, all with error uncertainties (http://www.ghrsst.org). GHRSST has matured into a global operational "system of systems" and delivers both near real time operational products as well as retrospective, reprocessed data sets, with new products added every year. In the past year GHRSST added Level 2 data from the entire Along-Track Scanning Radiometer (ATSR) series, including ATSR-1, ATSR-2, and the Advanced ATSR (AATSR), with data back to 1991. Another new product this year is the daily, globally complete, one kilometer analysis product from the NASA Jet Propulsion Laboratory's (JPL) OurOcean project (Figure 1, Chao et al., 2009). To enable continued improvements to the satellite-based observations, GHRSST partnered with the Data Buoy Cooperation Panel to propose improvements in both SST and position accuracy in the drifting buoy array. Awareness of the need for in situ SST measurements tied to NIST standards has also been expressed by GHRSST, with calls for a larger number of NIST-calibrated in situ radiometer measurements across a broader range of oceanic conditions. Continued improvements in SST CDRs from space will require a greater emphasis on obtaining high quality in situ SST measurements from activities like these.

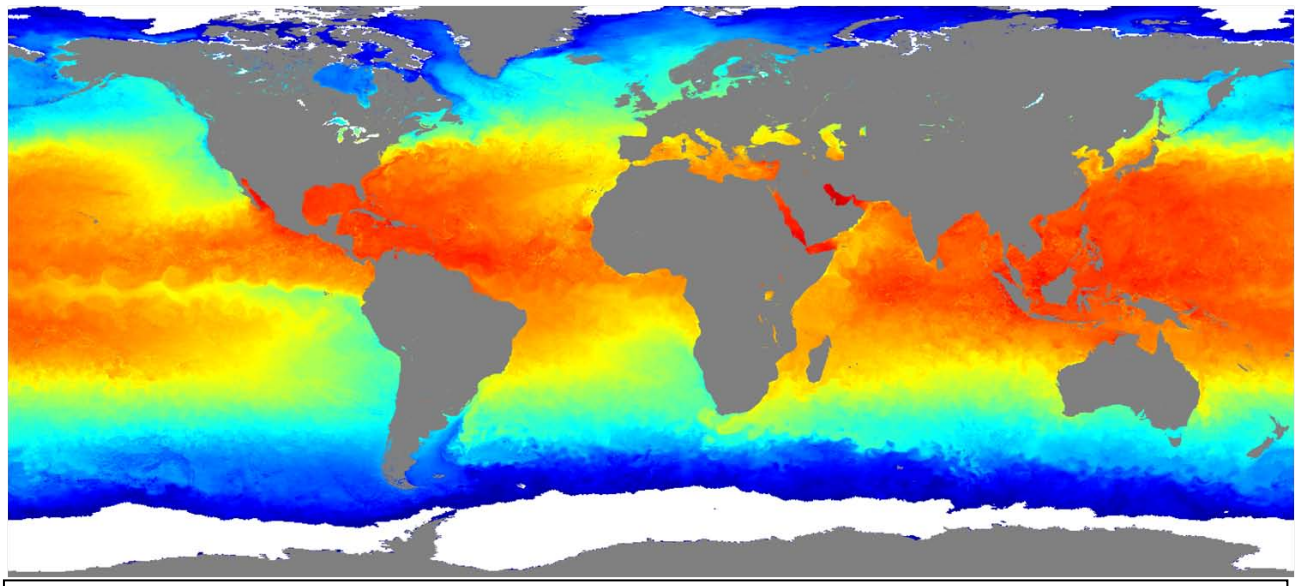

Figure 1: G1SST Sea Surface Temperature Analysis for September 15, 2010, from the GHRSST program. G1SST is a daily, global, Level 4 gap-free analysis product produced by the NASA JPL OurOcean project, and has a spatial resolution of 1 km.

NOAA's National Oceanographic Data Center (NODC) and the University of Miami continue to maintain and develop the AVHRR Pathfinder data set, the single-sensor series reprocessing effort focused on creating global SST CDRs from the AVHRRs on the NOAA polar orbiters (http://pathfinder.nodc.noaa.gov). Pathfinder SSTs are available for 1981-2009 on multiple averaging periods (daily, 5-day, 7-day, 8-day, monthly, and yearly) with corresponding climatologies. Efforts are now focused on the transition to AVHRR Pathfinder Version 6, which will feature key improvements over Version 5, including a higher resolution reference field. This improved reference field will increase data retention in coastal and high gradient regions and in regions where meandering or feature advection is present. Also, output from Version 6 will adhere to the international GHRSST content and format standards, including uncertainty estimates, which are an important requirement for a CDR.

Ocean Color Radiometry

Current Status and a Look Forward

Satellite-based ocean color radiometry data are invaluable in climate studies; they are crucial to improving our understanding of ocean biology and biogeochemistry and the significant role of the ocean in the global carbon cycle. Ocean color radiometry (OCR) data also help to evaluate and assess the impacts of climate change on coastal and ocean ecosystems, including influences of climate on primary productivity, living marine resources and fisheries, water quality, harmful algal blooms, and protected habitats. Accurately measuring ocean color properties remains, however, a demanding task, particularly in the coastal ocean region. Key challenges include the need for robust calibration (accurate ocean color products require top-of-atmosphere radiance be calibrated to ~0.1%) and correcting for significant atmospheric and ocean surface effects, as well as to accurately discriminate optical constituents like phytoplankton, suspended particulate matter, and colored

dissolved organic matter, particularly in complex and dynamic coastal waters. The ability of the OCR community to address these issues and other associated needs for climate studies such as regular reprocessing and merging data from multiple OCR sensors continues to improve, and there has been a continuous climate-quality ocean color time series since 1997.

However, the continuity of this climate-quality OCR time series is currently at risk, primarily as several key OCR sensors are all beyond design life and aging: SeaWiFS, MODIS-Aqua, and MERIS. SeaWiFS had been operating in "safe haven", a non-imaging mode, for much of 2008 and 2009 as a result of internal telemetry and navigation anomalies. Further, the spacecraft had experienced significant orbit drift. Routine operating performance has been significantly better in 2010, however, and there was recently a successful orbit raising campaign. Evidence still shows, however, that the sensor is indeed aging, including recent drift in the lunar calibration, particularly for the 412 nm band and the 443 nm band to a lesser extent. Since SeaWiFS is commercially owned, availability of SeaWiFS data depends on purchasing licenses. NASA has maintained access to delayed, reduced resolution global data (~4 km); NOAA has extended the license for access to the high resolution (~1 km) SeaWiFS Merged LAC (MLAC) data for contiguous US and adjacent waters into 2012.

Ocean color observations from MODIS-Aqua have been fully calibrated and now provide global data with quality comparable to SeaWiFS; the Aqua ocean color time-series runs from 2002 to the present. As demonstrations, Figure 2 displays MODIS-Aqua 1 km ocean color map in Chesapeake Bay; Figure 3 shows time-series of MODIS-Aqua mean chlorophyll and standard deviation from May 1, 2005 to September 10, 2010, which are produced operationally by NOAA CoastWatch. Recently, efforts continue to improve performances of MODIS-Aqua ocean color products. The higher resolution (0.25 or 0.5 km) MODIS ocean color operational products will be available in late 2012 and cover the Chesapeake Bay, Puerto Rico, Southern California, Mississippi Delta, Texas Coast, and Florida Shelf CoastWatch regions. Frontal information from MODIS-Aqua chlorophyll data will be used to provide fundamental information needed for ecosystem-based fishery management. The chlorophyll frontal operational products are expected to be available in late 2011 or early 2012. Operational products of global *Emiliania huxleyi* bloom distribution are expected to become available late 2011. One important area where MODIS differs from SeaWiFS is that it also has short-wave infrared (SWIR) bands, which enable more accurate ocean color retrievals in turbid coastal waters (Wang, 2007); NOAA ocean color radiometry products that utilize this technique will become operational in 2012. In addition to the MODIS-based ocean color products, efforts continue to address issues that have been identified with use of MODIS-Terra for ocean color applications (Franz et al., 2008); progress is being made in this area (see Figure 4).

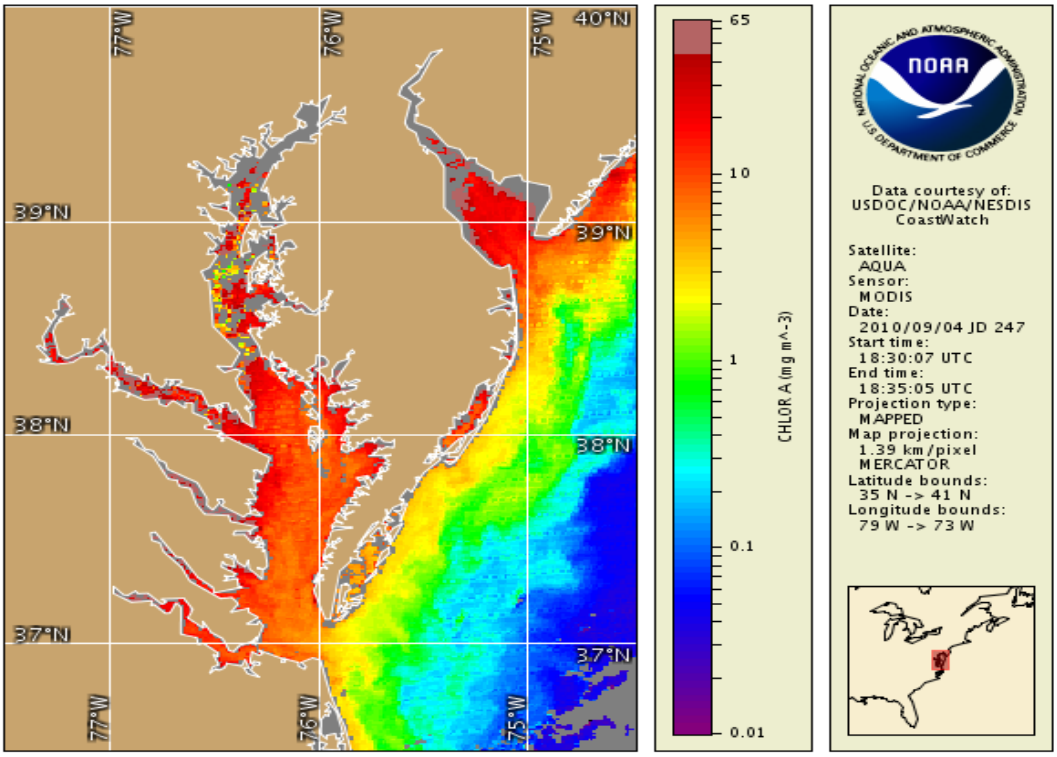

Figure 2: MODIS/AQUA 1km ocean color map in Chesapeake Bay produced operationally by NOAA CoastWatch.

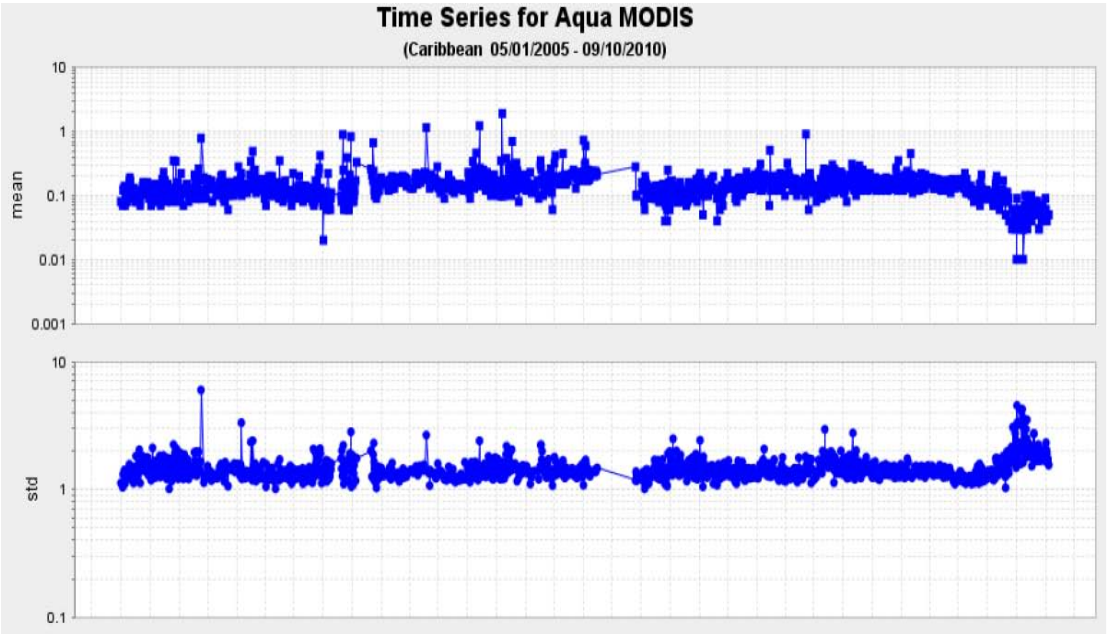

Figure 3: Time series of MODIS-Aqua mean chlorophyll and standard deviation from May 1, 2005 to September 10, 2010, which is produced operationally by NOAA CoastWatch.

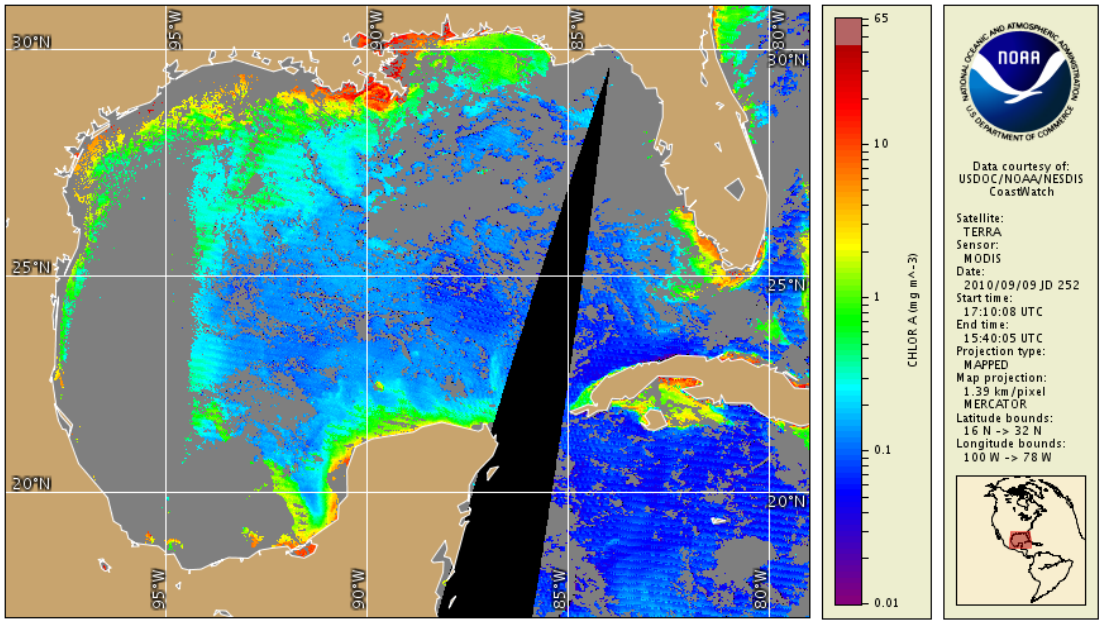

Figure 4: MODIS-Terra 1km ocean color map in Gulf Mexico produced operationally by NOAA CoastWatch.

In Europe, the Medium Resolution Imaging Spectrometer (MERIS) on Envisat-1 has been operating since 2002 and is still providing high quality data for a variety of applications. NOAA began generating CoastWatch ocean color products operationally for U.S. coastal waters from MERIS reduced resolution (1 km) data in January 2009 (Figure 5), and more recently MERIS full-resolution (300 m) OCR data products for U.S. coastal waters are being distributed by CoastWatch on an experimental basis. A follow-on to MERIS is being developed: the Ocean and Land Colour Instrument (OLCI) on the Sentinel-3 platforms, the first anticipated for launch in 2013. These missions will be considered operational, with free and open access to data.

Two new ocean color sensors were launched in 2009-2010, expanding the ocean color radiometry VC. The Oceansat-2 platform from the Indian Space Research Organization (ISRO) with the Ocean Color Monitor-2 (OCM-2) sensor (a follow-on to the OCM sensor on OceanSat-1) was launched into low Earth orbit in September 2009; these data are presently being evaluated. Further, in a particularly exciting development, the Korean COMS-1 satellite, carrying the Geostationary Ocean Color Imager (GOCI), reached orbit in July 2010 and is now providing ocean color observations from geostationary orbit for the first time. The geostationary vantage point affords significantly enhanced temporal revisits that should prove quite useful for improved understanding and monitoring of dynamic and frequently cloud-covered coastal and adjacent waters.

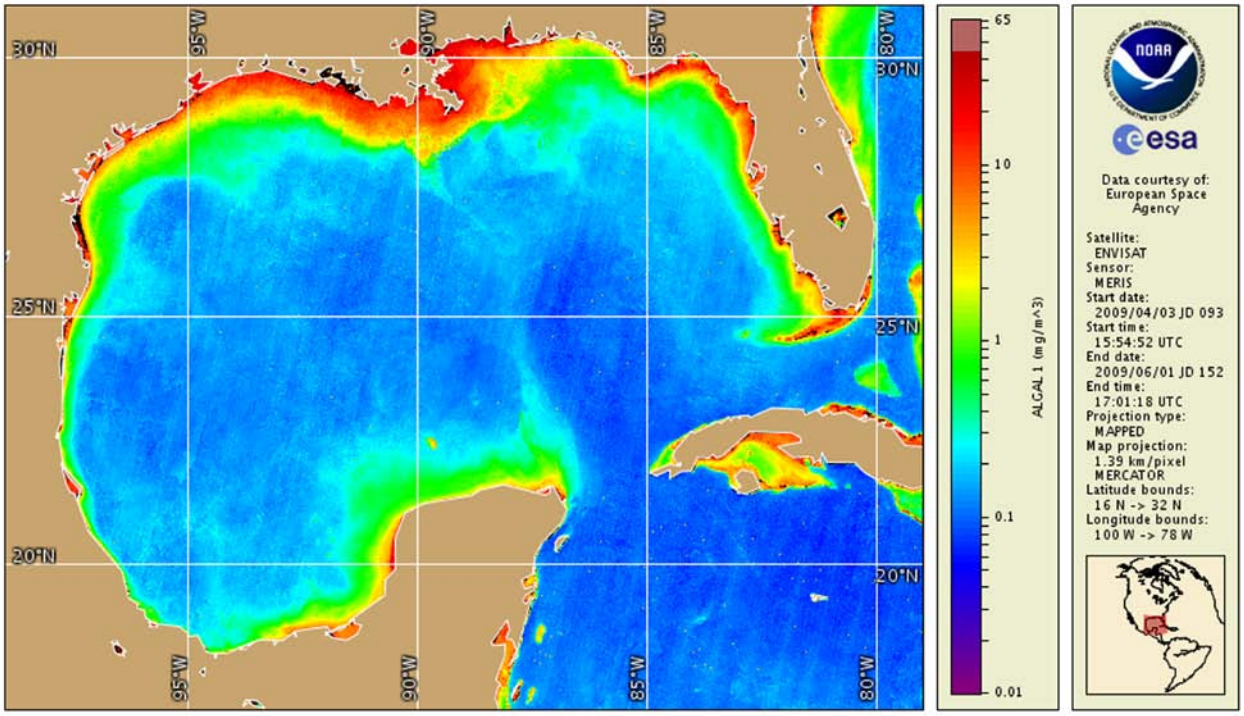

Figure 5: MERIS 1 km ocean color produced operationally by NOAA

Toward continuity of U.S. ocean color radiometry observations, the VIIRS instrument will fly on JPSS environmental satellites, starting with the planned launch of the NPP spacecraft in 2011. Following well-documented quality concerns due to manufacturing anomalies and other issues (see NRC, 2008, for further details), efforts continue toward the goal of having VIIRS-NPP data meet heritage performance. A comprehensive, supporting VIIRS ocean calibration/validation plan continues to be executed as a U.S. government agency and academic partnership. As with SeaWiFS and MODIS, the intent is to use data from the Marine Optical Buoy (MOBY) for vicarious calibration. The NPP follow-on JPSS-1 platform will provide continuity in the afternoon orbit, and is planned for launch by 2015. As with MODIS above, the SWIR bands on the VIIRS instruments will enable improved OCR retrievals in complex coastal environments.

In addition to these current and planned ocean color sensors, which include the first operational OCR sensors, efforts are underway to develop the next generation of space-based ocean biology and biogeochemistry missions (e.g., hyperspectral instruments), as existing capabilities do not entirely meet the needs of the research and application user communities (see IOCCG, 2008; NRC, 2008). Next-generation OCR sensors, both research and operational, will likely provide improved spatial, temporal and spectral resolution and coverage. For a comprehensive list of other current and planned sensors providing ocean color data of various resolutions and quality, see the International Ocean Colour Coordinating Group (IOCCG) website (http://www.ioccg.org). It should be noted that cross-calibration will be critical for climate applications, and also that not all sensors have been fully calibrated to meet the standard of SeaWiFS data quality.

Critical Activities
Given the concern over continuity of climate-quality OCR data, there is a National Academies study presently underway in the U.S. for "Assessing Requirements for Sustained Ocean Color Research and Operations", supported by NOAA, NASA, the National Science Foundation, and the U.S. Navy's Office of Naval Research. This study, whose final report is anticipated by mid-2011, will identify the research and operational needs and the associated sensor and system requirements for a sustained, systematic capability to observe ocean color from space; review the capability of current and planned national and international ocean color radiometry sensors - including VIIRS and foreign alternatives - in meeting these requirements; and assess the gaps and options for filling gaps between the current/planned sensor capabilities and the requirements. As a prelude to this study, NOAA generated an "Ocean Color Radiometry Satellite Continuity Mitigation" Plan in 2009 to ensure that it's operational and users needs continue to be met during this period of uncertainty; this plan could potentially be augmented by a more comprehensive Analysis of Alternatives study within NOAA as needed following completion of the above National Academies study. Other critical activities for OCR include continued emphasis on the work of the OCR-VC to develop and execute an ECV implementation strategy and conduct inter-agency sensor inter-comparison and uncertainty assessments.

Ocean Surface Topography

Current Status and a Look Forward
Sea level rise (SLR) is clearly one of the most publicly recognizable aspects of the global warming phenomenon. It directly threatens coastal infrastructure through inundation, increased erosion, more frequent storm-surge flooding, and loss of habitat through drowned wetlands. The only feasible way to resolve the spatial variability needed to accurately determine SLR globally is by means of satellite altimetry, specifically the systematic collection of sea level observations initiated by TOPEX/Poseidon in 1992 and continued today by the on-going Jason series of satellite missions, including Jason-2, launched on 20 June 2008. Jason-2 represents an important step toward the routine measurement of sea level for climate, involving four partners: NASA and CNES are primarily responsible for building and launching the satellite, while NOAA and its operational partner EUMETSAT are primarily responsible for collecting and processing the near real-time data.

In January 2009, Jason-2 and Jason-1 completed a seven-month tandem calibration phase, during which time the two satellites made nearly simultaneous measurements (1 minute separation) along the same orbit. This calibration phase is necessary for identifying subtle performance differences in the many instruments aboard the two satellites and ultimately for creating a sea level climate data record. After a short period of maneuvers, Jason-1 was moved to an interleaved orbit, effectively increasing the resolution of the pair of satellites from 300 km to 150 km in horizontal track spacing and from 10 to 5 days in time. Studies done after two years of operation indicate that Jason-2 is performing at least as well as Jason-1 (Leuliette and Scharroo, 2010).

Along with Jason-1 and -2, there is presently only one other functioning altimeter in orbit: ESA's Envisat, the successor to ERS-1 and ERS-2. Envisat continues to provide useful sea level data after

8 years of operation although the failure of one radio frequency (RF) chain has reduced the satellite to single frequency operation. Starting in October 2010, Envisat will continue its mission, from a lower orbit, through 2013. The Navy is actively seeking a replacement mission, GFO-2, hopefully to be launched in 2013. The next planned altimeter is Altika, an experimental Ka-band mission jointly supported by CNES and the Indian space agency, ISRO. Altika is scheduled for a mid-2011 launch. ESA is planning to launch the first of two Sentinel-3 missions, which includes a replacement for the Envisat altimeter, in 2013. Finally, NOAA and EUMETSAT are currently in the process of securing funds for a joint Jason-3 mission to be launched in 2013-14 to overlap with Jason-2 and using the same mission design. For the era beyond Jason-3, NOAA, EUMETSAT, and ESA are also planning a Jason-CS (Continuity of Service) series that will use a new platform and orbit.

Because current altimeters provide height measurements only at the nadir location along their ground track and not a 'swath' of data (as is typical of other satellite instruments) there is a trade-off between spatial and temporal resolution. Fortunately, for the large-scale processes generally of interest for climate observations, a single high-accuracy altimetry mission such Jason-2/OSTM is sufficient. Shorter space and time-scale phenomena at the ocean's mesoscale are not adequately sampled by a single altimeter, but the present configuration of three altimeters in complementary orbits does capture most of the signals of interest. Applications such as ocean eddy monitoring, surface current analyses, and ocean heat content for hurricane intensity forecasting require this higher resolution sampling (see http://ibis.grdl.noaa.gov/SAT for more information on altimetry research and applications). In the next two years, however, it is possible that Envisat and Jason-1 will fail, leaving possibly only Jason-2 operating in until Altika's launch in 2012. The requirement for high spatial resolution coverage may be satisfied by NASA's proposal to fly a swath altimeter (SWOT), but not before 2020.

Critical Activities

By paying careful attention to instrumental and environmental (e.g. path delay) corrections normally applied to an altimeter's range measurements, it is possible to construct a consistent record of global mean sea level change over the past 18 years from the TOPEX, Jason-1, and Jason-2 altimeter missions. As shown in Figure 6, the overall trend for this interval is 2.9 mm/year, roughly 1.6 times greater than the 20th century rate and 3 times greater than the late 1800s – early 1900s rate, both determined from tide gauge observations (Scharroo et al., 2006). Whether the present higher global rate reflects a true long-term change or simply decadal variability is currently unknown.

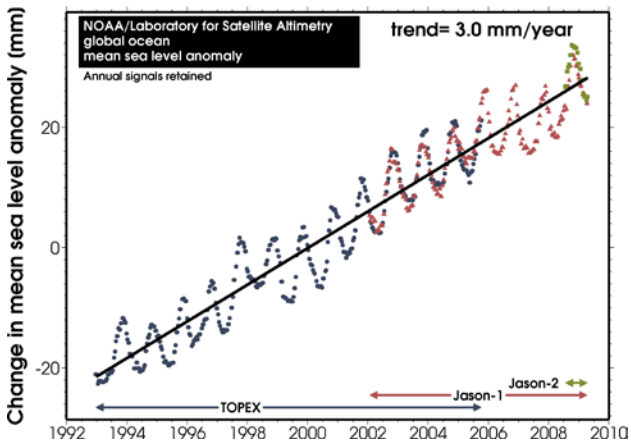

Figure 6: Global mean sea level trend from TOPEX, Jason-1, and Jason-2.

Key to understanding long-period sea level variability is continued monitoring of the sea level rise budget. Changes in total sea level should be equal to the sum of the changes in the components of

sea level rise — thermal expansion and salinity changes within the ocean and mass added to the oceans from continental ice sheets. Recent research (Leuliette and Miller, 2009) compared total sea level from Jason-1 altimetry to steric (density) changes in sea level measured by Argo profiles of temperature and salinity and mass variations from the GRACE gravity mission and demonstrated that the budget can be closed in the near-global region where measurements from all three observing systems are available. An update to Leuliette and Miller for 2004 to 2010 shows that the sea level trend over the period is +1.6 mm/year, while the trend in the global mean steric component is +0.5 mm/year and the estimate of the trend in the global mean mass component is from +0.9 mm/yr. For comparison, the 20th century sea level budget was roughly one-third (0.4 mm/yr) steric increase and two-thirds (1.4 mm/yr) mass increase (Miller and Douglas, 2004). Note that in the budget calculation, the trend in total sea level from Jason-1/Jason-2 is not global because values near coasts are excluded. The trend for the full global coverage is 2.4 mm/year, 50% larger than the value used to evaluate the budget. The Indonesian Throughflow, in particular, has seen a large rise during 2005-2010 that significantly changes the rate when it is excluded.

To ensure accuracy and value of altimeter observations for climate studies, particularly for the global sea level rise problem, it is important to have a period of overlap between satellite missions. Only by directly comparing the average heights between missions is it possible to accurately detect and correct for biases and thereby extend the global sea level record over multiple decades. An overlap is also useful for identifying subtle instrument-dependent problems, such as a drift in one of the environmental corrections to the range measurements. A problem of this type was detected in the Jason-1 microwave radiometer measurements, during the 4-year overlap between the Jason-1 and TOPEX/Poseidon missions, and a recalibrated wet troposphere correction has eliminated the drift.

The value of satellite altimeter observations for climate studies is also greatly enhanced by the operation of two in-situ ocean observing systems supported by the NOAA Office of Climate Observations (OCO): a global network of GPS-controlled tide gauge stations, and the Argo profiling drifter array. Relative sea level observations from more than 80 tide gauge stations are currently providing an independent, ground-based check on the bias and drift errors of each altimeter mission. Routine comparisons between gauge and altimeter measurements show that altimeter-measured trends are accurate within ±0.4 mm/year and any drift in the TOPEX/Jason-1/Jason-2 time series is statistically insignificant (Figure 7). Thus, the 2.9-mm/year trend observed over the past 18 years by satellite altimetry is significantly higher than the gauge-measured trend over the past century. The gauge measurements may also provide a critically needed solution to the problem of how to deal with gaps in the global mean time series caused by instrument failure or the delay of a follow-on mission.

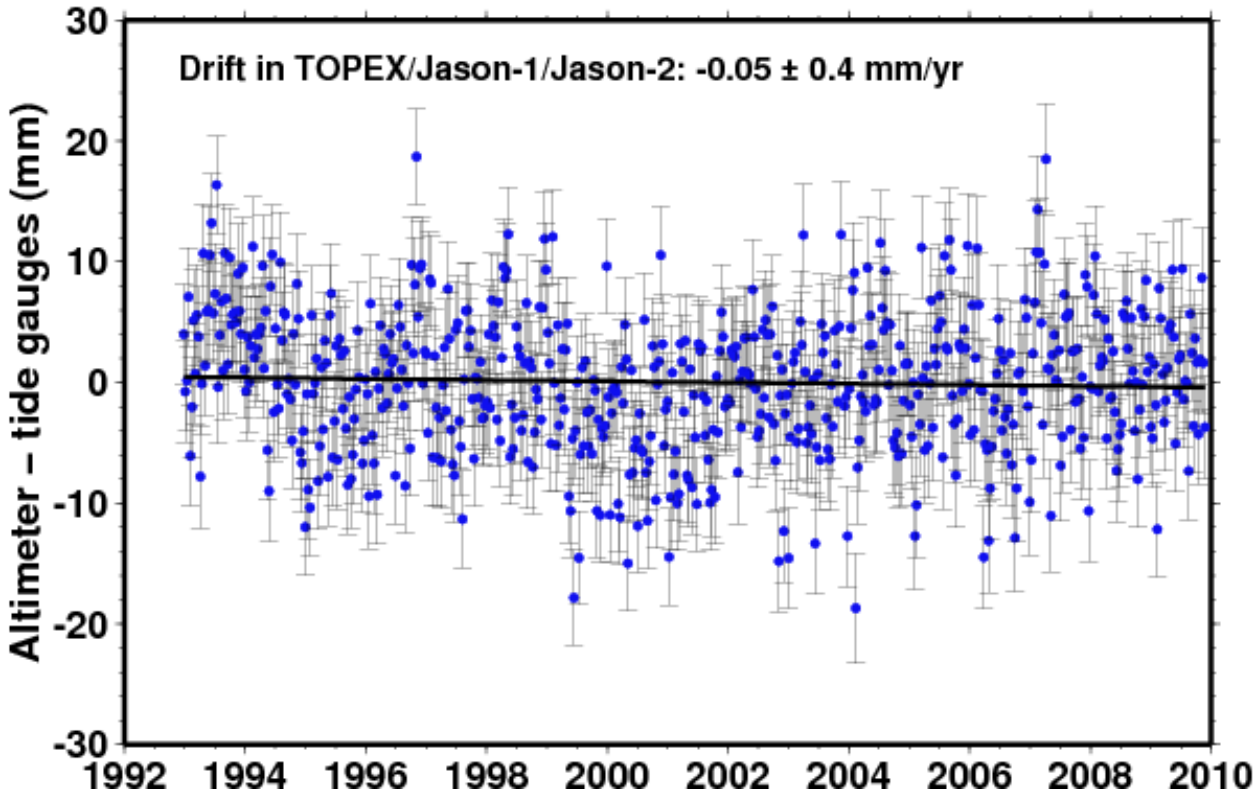

Figure 7. Multi-satellite tide gauge analysis for TOPEX/POSEIDON, Jason-1, and Jason-2

Sea Ice

Current Status and a Look Forward

Monitoring sea ice changes provides a critical climate indicator, and building momentum toward greater commercial activity in the Arctic highlights the need for long-term, continuous observations. The series of passive microwave imagers that began with the NASA Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) in 1978 and extends through the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) now continues to the present with the DMSP Special Sensor Microwave Imager/Sounder (SSMIS). These passive sensors allow for the determination of sea ice extent (areal coverage), but not thickness. Both extent and thickness are needed, however, to determine sea ice volume, which is of fundamental importance to understand the role of the polar regions in global climate.

Only satellite altimetry measurements of ice freeboard offer a way to obtain estimates of ice thickness that are of the spatial and temporal scale needed for basin-scale ice volume estimates. After almost seven years of collecting ice and snow elevation measurements over polar regions, from February 2003 to October 2009, the NASA Ice, Cloud and land Elevation Satellite (ICESat), launched January 13, 2003, was decommissioned on August 14, 2010 and reentered earth's atmosphere on August 30, 2010. The follow-on mission, ICESat-2, will exploit a micro-pulse multi-beam approach to create a denser sampling geometry and enable better measurements of sea ice

thickness. ICESat-2 has a scheduled launch date in late 2015. Shortly after ICESat collected its last science data, ESA successfully launched the CryoSat-2 satellite on April 8, 2010. CryoSat-2 carries the SAR/Interferometric Radar Altimeter (SIRAL) for measuring ice sheet elevations and sea ice thickness. SIRAL became operational on April 11, 2010. ESA will complete the commissioning phase of CryoSat-2 in the fall of 2010.

The National Snow and Ice Data Center (NSIDC) provides a climate record of sea ice extent through the supporting data for the Sea Ice Index (http://nsidc.org/data/seaice_index/). The Sea Ice Index (SII) itself combines near-real-time data and historical data that have undergone more thorough quality control in a routinely updated information product of current Arctic and Antarctic ice extent (daily data) with trends and anomalies (based on monthly mean data, Figure 8). The value of the Sea Ice Index is that it provides a near-complete consistent record of sea ice for over three decades that is necessary for tracking long-term change and variability. The Sea Ice Index is the ice extent data source for NSIDC's Arctic Sea Ice News and Analysis (http://nsidc.org/arcticseaicenews/), a site that provides scientific discussion of how the ice cover is changing to the scientific community and the general public. The Sea Ice News and Analysis site is regularly updated through the year, but interest peaks over the course of each summer's melt season when the site has hundreds of thousands of unique users each month. The NOAA-supported SEARCH Sea Ice Outlook collaboration among the scientific community to improve seasonal prediction of Arctic sea also makes use of the Sea Ice Index ice extent values as a baseline for comparison of contributed outlooks.

NSIDC also distributes sea ice climatologies based on the U.S. National Ice Center (NIC) sea ice charts. NIC charts are produced through the analysis of several satellite passive and active data sources. The NIC Arctic climatologies for the period 1972- 2007 are presently available at http://nsidc.org/data/g02172.html. A new Navy-funded NIC effort to produce an information product parallel and complementary to the passive microwave-based SII, but making use of operational data, is underway at NSIDC. The new product, known as the Multisensor Analyzed Sea Ice Extent (MASIE), is based on output from the NIC Interactive Multisensor Snow and Ice Mapping System (IMS, http://www.natice.noaa.gov/ims/). The MASIE will be produced by NSIDC using the sea ice component of the IMS 4 km daily products. The new product will benefit users who may need a more accurate daily ice edge location than that provided by passive microwave data solely. These users include department of defense, homeland security, and commerce planners, the general public, scientists interpreting other data acquired near the ice edge, and researchers seeking to quantify the error in the passive microwave product.

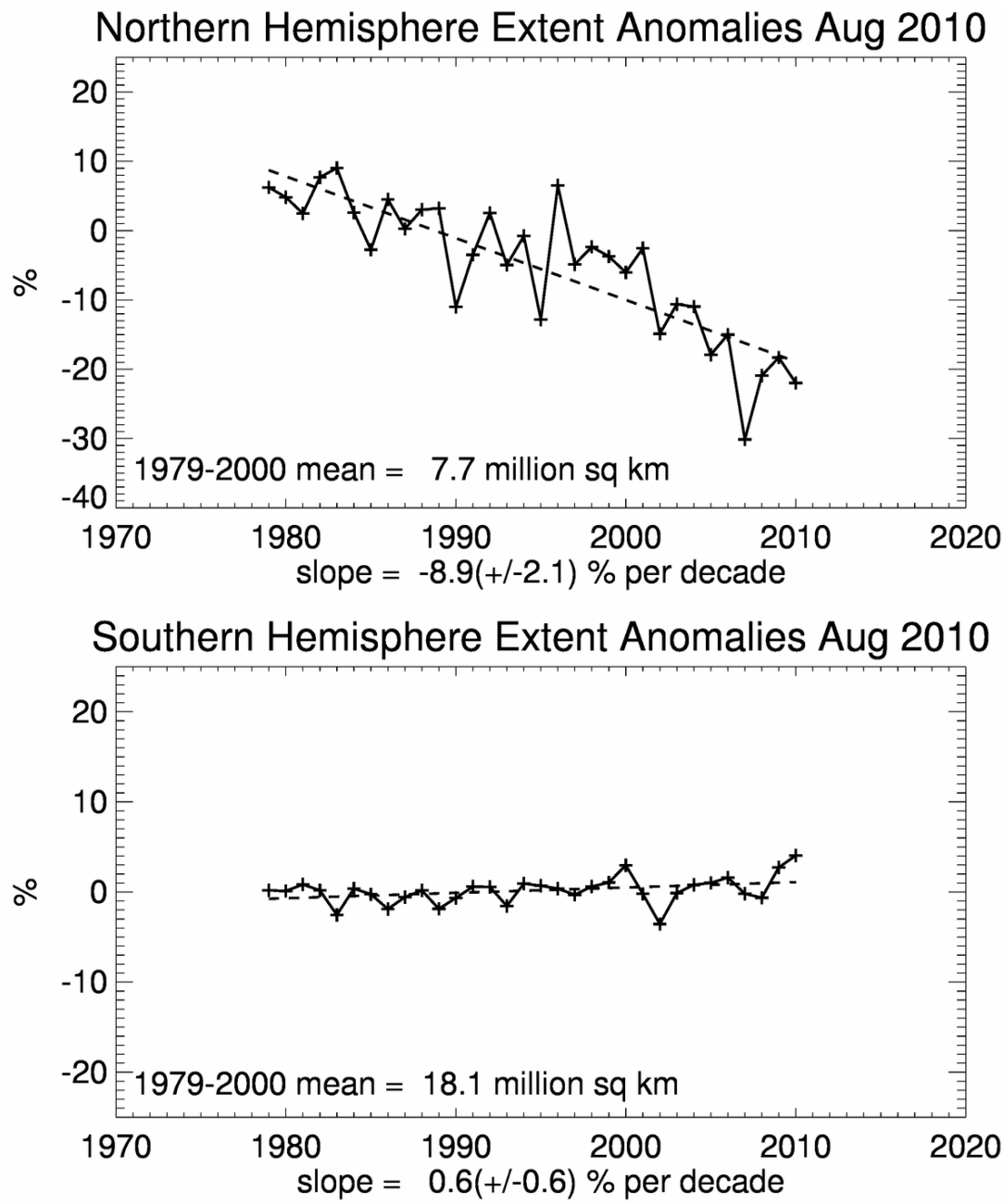

Figure 8: Northern Hemisphere (left) and Southern Hemisphere (right) sea ice extent trends for June from the Sea Ice Index (nsidc.org/data/seaice_index/), based on satellite passive microwave sea ice retrievals.

Although not originally intended for monitoring of sea ice, due to its long time series and ability to distinguish between ice of different ages, QuikSCAT served as an important tool for monitoring the fast changing Arctic sea ice cover in the last decade. For example, Nghiem et al. (2007 and 2008) used QuikSCAT to study the extent of Arctic perennial sea ice, the year-round ice cover, and found that it was reduced between March 2005 and March 2007 by 23% with a new record loss in 2008.

The rate of loss became more rapid in the 2000s, when QuikSCAT observations were also available to verify the model results. QuikSCAT data have revealed potential mechanisms contributing to the perennial-ice extent loss: ice compression toward the western Arctic, ice loading into the Transpolar Drift together with an acceleration of the Transpolar Drift carrying excessive ice out of Fram Strait, and ice export to Baffin Bay. Unfortunately, the QuikSCAT conical scanning sensor failed in November 2009 ending a unique data stream that has provided significant support to sea ice research and operational charting efforts globally. While the scanning has stopped, the scatterometer's radiometer itself continues to collect data, albeit over a very narrow swath. An attempt to exploit this very limited collection to produce a monthly product is taking place at NASA JPL. More significantly, a push is underway to mitigate the loss of QuikSCAT data by obtaining access to the ISRO Oceansat-2 scatterometer operational data stream, which is similar to that provided by QuikSCAT. A letter of intent between ISRO, NASA, and NOAA to provide OceanSat-2 operational data was signed on 18 November 2009. Initial test datasets have been provided to the U.S. for testing and validation with full access to OceanSat-2 data expected by the end of 2010.

Critical Activities

The dynamic nature of sea ice and the logistical difficulties of conducting in situ measurements make validation of satellite sea ice freeboard measurements challenging. To validate these satellite measurements, joint NOAA/NASA flight campaigns were carried out in 2006, 2009, and 2010 using instrumented NASA P-3 and DC-8 aircraft to underfly Envisat and ICESat satellites. NOAA validation studies from the 2006 Arctic Aircraft Altimeter (AAA) Campaign demonstrated excellent agreement between freeboard heights derived from Envisat radar altimeter (RA2) observations and corresponding estimates made with NASA's Airborne Topographic Mapper (ATM), a well calibrated airborne laser altimeter (e.g. Figure 9). Similarly, excellent agreement has been found in comparisons of airborne laser altimeter measurements with ice and snow elevation estimates from the ICESat GLAS instrument (e.g. Figure 10).

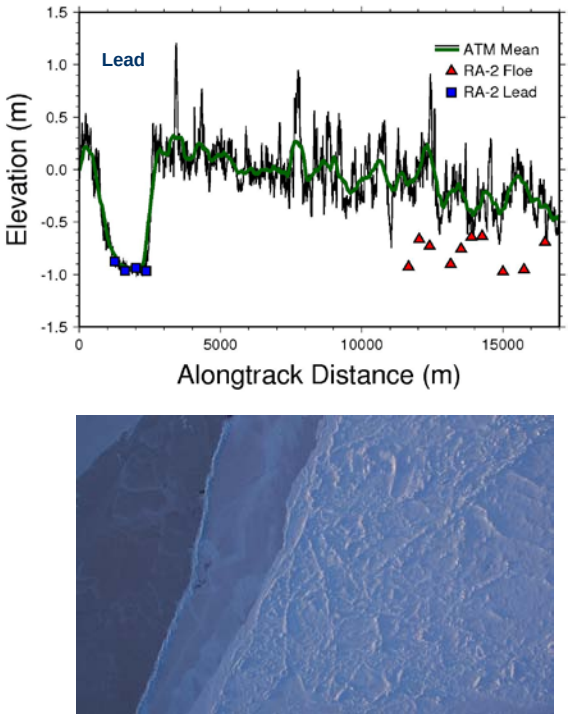

Figure 9. Top panel shows ATM elevation profile along a 17 km Envisat ground track. Blue squares denote Envisat lead locations and red triangles denote ENVISAT sea ice floes. Lower panel illustrates a digital photograph of the lead-floe transition of the upper panel (black box).

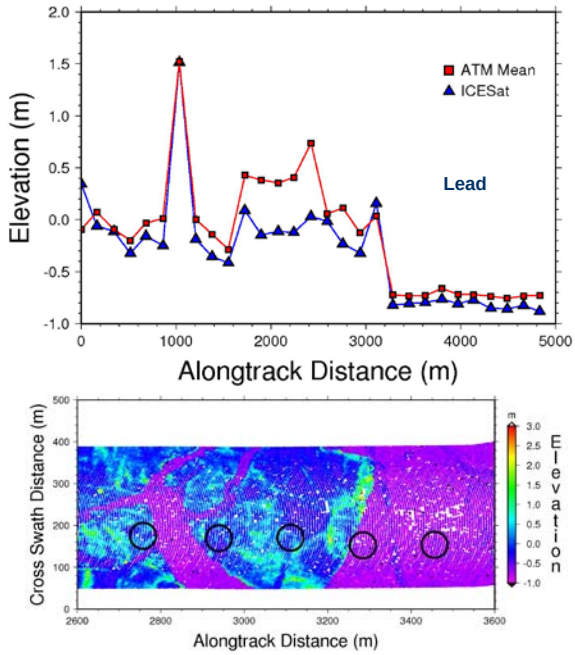

Figure 10. Top panel shows mean ATM elevations (red) and individual ICESat footprint elevations (blue) along a 5 km ICESat ground track. Lower panel illustrates the ATM swath measurements in the sea ice floe – lead transition region bounded by black box in upper panel. The ICESat footprints are denoted as black circles.

A follow on joint NOAA-NASA airborne and in situ experiment was carried out in April of 2009 and included a satellite altimeter under-flight along an Envisat track over sea ice in the Canada Basin west of the Queen Elizabeth Islands and over-flights of the Danish GreenArc Ice Camp off the northern coast of Greenland. This Canada Basin Sea Ice Thickness (CBSIT) Experiment was designed to more thoroughly and precisely validate RA2 and GLAS ice freeboard observations and is a NOAA contribution to NASA's Operation Ice Bridge (OIB), an ongoing mission of airborne measurements of Arctic and Antarctic ice intended to help fill the data gap between the ICESat and ICESat-2 satellite missions. The OIB data sets are managed and distributed by the NASA DAAC at NSIDC.

On April 5, 2010 NOAA helped plan and coordinate another Envisat underflight that employed a NASA DC-8 following the same flight (and Envisat orbit) track as that of the AAA 2006 experiment. During this same Spring 2010 IceBridge campaign, researchers at the NOAA Laboratory for Satellite Altimetry (LSA) coordinated ESA CryoSat-2 satellite operations with NASA IceBridge flight planning to help bring about a highly opportunistic NASA DC-8 underflight of the Cryosat-2 satellite. The fully instrumented NASA DC-8 underflew Cryosat-2 on April 20,

2010, just 12 days after the satellite's launch. The satellite and airborne data sets cover a 670 km track (see Figure 11) and are nearly coincident in space and time. These IceBridge data sets should prove valuable for validating CryoSat-2's capabilities over sea ice. IceBridge data from this underflight and from other missions are available from NSIDC (http://nsidc.org/data/icebridge/index.html)

Activities of the GCOS SST-SI Working Group are critical to improving concentration estimates from passive microwave data for model assimilation, especially at the ice edge. An algorithm called the Enhanced NASA Team or NASA Team 2 uses the higher frequency channels available on SSM/I and later sensors to overcome weather and snow effects, and is being used for AMSR-E sea ice concentration standard product. NSIDC has received funding from the NOAA Climate Data Record (CDR) Program to improve consistency between SMMR-SSM/I and AMSR-E products, develop data quality fields, and improve metadata and preservation standards. These steps are required to have sea ice extent and concentration meet NRC requirements for CDRs.

Extending the SSM/I-derived record into the operational life of the JPSS program's Microwave/Imager Sounder (MIS) instrument is another critical activity. Future MIS sea ice products should be prototyped using AMSR-E in close collaboration with sea ice algorithm and remote sensing experts. The current Aqua satellite has sufficient fuel to operate until 2017. Barring instrument failure, AMSR-E data will be available until then. The Japanese Aerospace Exploration Agency (JAXA) is currently developing an AMSR-E follow-on sensor, AMSR2, to be flown aboard the JAXA Global Change Observing Mission-Water (GCOM-W) satellite, whose launch is currently scheduled for late-2011 or early-2012. NSIDC is a member of the AMSR2 science team and is collaborating with JAXA on algorithm development and data management issues. JAXA and NOAA are working together to make the GCOM-W widely available. However the scientific community is still concerned about a data gap should JPSS be delayed or should MODIS-Aqua or GCOM-W fail.

Synthetic aperture radar (SAR) data and imagery is another valuable tool for monitoring sea ice in near-real time, as well as assessing its seasonal and interannual variability in the context of climate variability and change. While there are currently numerous satellite sensors such as ASAR on Envisat and PALSAR on ALOS providing such data to users, and likewise plans for continuity internationally (e.g., Sentinel-1, Radarsat constellation), routine and sustained access to data for U.S. research and applied users is an ongoing concern as the U.S. does not currently have its own SAR sensor or mission.

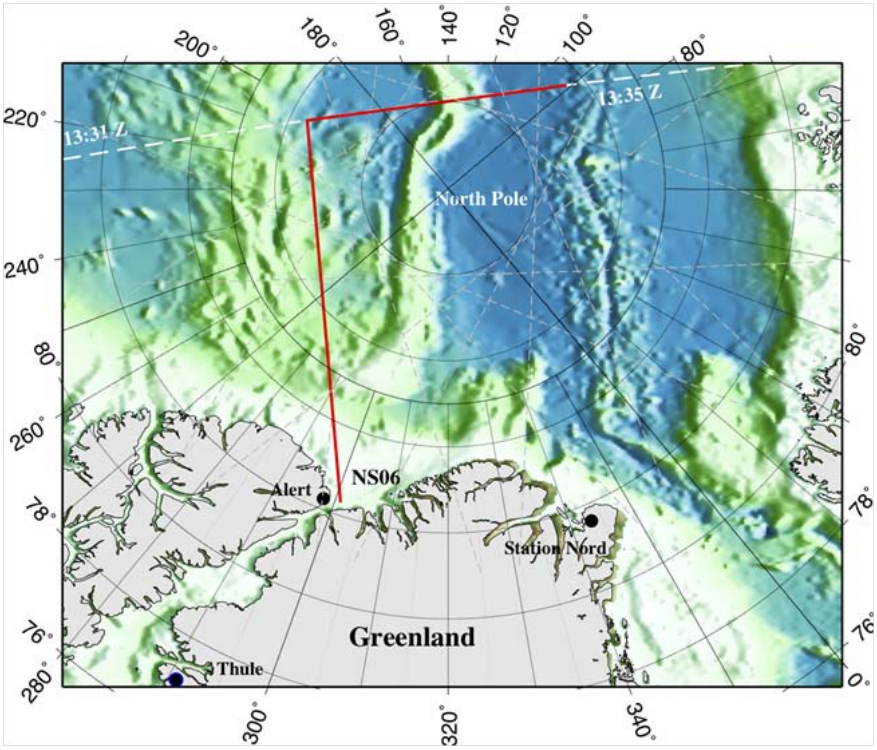

Figure 11. CryoSat-2 ground-track (dashed white) and IceBridge DC-8 track (L-shaped, red). The April 20 sea ice survey began at NS06 flying north to and along the CryoSat-2 track. CryoSat-2 overpass times (GMT) on April 20, 2010 are shown in white. DC-8 flew back and forth along the CryoSat-2 track between 13:47 and 15:58 GMT.

Marine Winds

Current Status and a Look Forward

Winds over the ocean are the largest source of momentum for the ocean surface, and as such they affect the full range of ocean movement - from individual surface waves to complete current systems. Ocean surface vector winds (OSVW) also play key role in regulating the earth's water and energy cycles by modulating air-sea exchanges of heat, moisture, gases like carbon dioxide, and particulates. This modulation regulates the interaction between the atmosphere and the ocean, which establishes and maintains both global and regional climates. The advection and offshore transport of nutrients and fresh water can be linked to the life cycle and annual variability in fish stocks. Ocean surface winds can be linked to upper ocean mixing, which is easily linked to ocean, atmospheric, cryospheric, and terrestrial climate change. Thus OSVW measurements are needed to 1) document heat uptake, transport, and release by the ocean; 2) document ocean carbon sources and sinks (ocean surface vector winds modulates air-sea exchanges of gases such as CO_2) and 3) document the air-sea exchange of water and the ocean's overturning circulation (Figure 12 and 13).

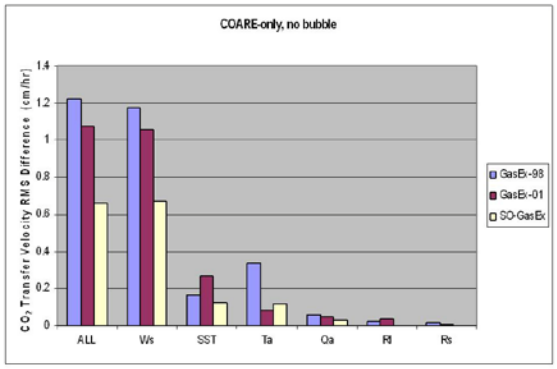

Figure 12. Jackson and Wick (2009) examined differences between satellite and ship-computed CO_2 replacing one parameter at the time with satellite measurements. There results show that nearly 95% of the uncertainty in computed transfer velocity can be contributed to the errors in wind speed. The next largest contributor is SST.

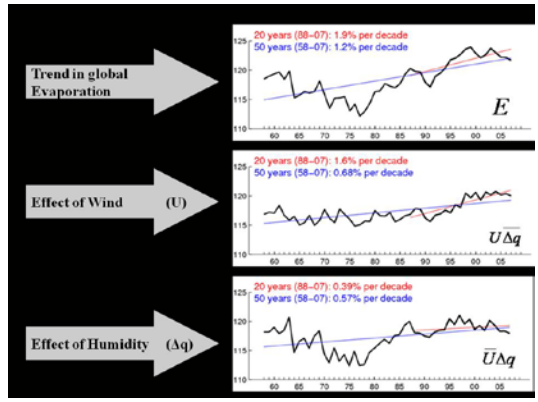

Figure 13. L. Yu 2009 analysis of 50-yr evaporation (E_{vp}) time series shows a distinct transition from a downward trend to an upward trend around 1977–78 with most dramatic increase during 1990s. The analysis suggested a dominant role of the wind forcing in the decadal change of both E_{vp} and humidity (dq).

Scatterometers are currently considered to be the most practical satellite OSVW instruments (Bourassa et al., 2010). The 18 year long history of OSVW observations, shaped by the U.S. (SeaSat, NSCAT, SeaWinds on QuikSCAT, SeaWinds on ADEOS2) and European (AMI on ERS-1 and ERS-2, and ASCAT on METOP-A) scatterometer instruments, greatly facilitated the study of decadal wind variability. In October 2009, ISRO launched the OceanSat-2 satellite with the OSCAT scatterometer on board. This instrument is still in its calibration and validation phase, and the suitability of OSCAT wind measurement for climate studies is yet to be determined.

The QuikSCAT scatterometer alone provided more than a decade of high quality global ocean vector wind observations with better sampling than any other scatterometer. These unique measurements enabled a number of climate studies. For the first time, a number of satellite-based wind vector climatologies have been developed to help characterize winds over the ocean:

- The 7-year high wind monthly atlas reveals how frequently high winds occur over the open ocean all over the world (Sampe and Xie, 2007). High winds play an important role in Earth's climate; they remove heat from the ocean, leading to the formation of "deep water" cold, salty, dense water that helps drive global ocean circulation patterns. High winds also help exchange gases, such as carbon dioxide, between the oceans and the atmosphere, mix different types of ocean water, and pump nutrients up from the deep sea for plankton to feed on. For example, high winds occur more than twice as often over the warmer than the colder flank of the Gulf Stream, and over the poleward than equatorward meanders of the Antarctic Circumpolar Current.
- The first climatology of available wind power over the oceans derived from QuikSCAT data was generated by Liu et al. (2008). This data set revealed regions of high wind power associated with flow distortions by land, wind channeled by land topography, and buoyancy effect on turbulent stress driven by ocean fronts. These results are of importance for generation of electricity by ocean wind farms and the placement of wind farms.

- A notable oceanographic climate result enabled by the long QuikSCAT time series was presented by Lee and McPhaden (2008), who studied the implications of the QuikSCAT and ERS winds and altimeter sea surface height observations to decadal variability and the connections of oceanic and atmospheric circulations in the Indo-Pacific region. The scatterometer and altimeter data suggest an anti-correlated decadal variability of the meridional overturning circulations (MOCs) and heat transports in the Pacific and the Indian Oceans, such that the Pacific- and Indian-Ocean MOC play opposite roles in regulating tropical heat content that is important to interannual and decadal climate variability. The observations also highlight the oceanic tunnel via the Indonesian throughflow and atmospheric bridge through the Walker Circulation in connecting the Indo-Pacific variability.
- Milliff et al. identify an El Niño/Southern Oscillation warm events (WE) precursor signal in strong WE years which occurs just after the so-called Spring Predictability Barrier, providing very early warning of an ensuing ENSO WE.
- Another one of the key discoveries of the QuikSCAT mission has been the realization that Sea Surface Temperature (SST) fronts play a key role in modulating the winds, and wind stress (Risien and Chelton 2006, 2008). Minobe et al. (2008) studied the climatic influence of the Gulf Stream, which transports large amounts of heat from the tropics to middle and high latitudes, on the free atmosphere above the marine atmospheric boundary layer. Minobe et al. consider the Gulf Stream's influence on the troposphere, using a combination of operational weather analyses, satellite observations, including QuikSCAT, and an atmospheric general circulation model. Their results reveal that the Gulf Stream affects the entire troposphere.

QuikSCAT ceased to operate in November 2009, leaving a gap in the high quality climate data record. The European Advanced Scatterometer (ASCAT) is currently operational; however, it has approximately half the sampling of QuikSCAT and the two instruments have not been intercalibrated. ASCAT uses a different microwave frequency: c-band vs. QuikSCAT's Ku-band. Proper intercalibration of these two types of instruments is an ongoing effort. Current findings are that QuikSCAT retrievals are slightly noisier than ASCAT retrievals; however, QuikSCAT is much more sensitive at low wind speeds (<4ms-1) and high wind speeds (>15ms-1). The ISRO OceanSat-2 scatterometer had three weeks of overlap with QuikSCAT. Preliminary indications show significant problems in the OceanSat-2 scatterometer calibration that will need to be addressed before these data would be able to help mitigate the climate data gap.

In an effort to establish sustainable OSVW measurement for operational community as well as provide continuation of quality ocean wind vector CDRs, NOAA is currently pursuing collaboration with JAXA, where NOAA would provide a Dual-Frequency Scatterometer (DFS) system to fly aboard JAXA's GCOM-W2 and GCOM-W3 missions.

Critical Activities

QuikSCAT provided an unprecedented ten years of continual operation that supported operational weather forecasting and warning and climate studies and monitoring, but there is currently no plan in the U.S. to implement a sustained satellite OSVW observing system capability.

With a goal of defining the nation's OSVW climate requirements and provide recommendations for path forward NOAA, NASA and JAXA held workshop on scatterometry and climate in Washington

DC in August 2009. There was a general consensus among participants that the primary products from scatterometers such as ocean vector winds, stress, sea-ice cover, are key climate observables that require long term monitoring. The main workshop conclusions and recommendations are listed bellow:

- While QuikSCAT has provided the first indications of a climate signal, a 10-year record is still insufficient for assessing decadal climate variability.
- Aside from scatterometry, there is no demonstrated method of measuring the surface wind or stress from space with the appropriate accuracy and coverage for climate studies.
- The highest ranked recommendation was for the continuity of the climate data set, with an emphasis on minimizing data gaps and ensuring that successive missions could be cross-calibrated against each other.
- The second ranked recommendation was for improvements in the temporal coverage of space-borne measurements
    - Diurnal variability can significantly mask the climate signatures from satellites collecting data at the same time of day. In order to appropriately sample diurnal variability, a constellation of coordinated scatterometers will be required. Maximum benefit of the satellite observing system can be achieved through international collaboration on data sharing, orbit planning (i.e., temporal sampling), in situ calibration, and intercalibration.
- Appropriate sampling of many climate signatures will require better coverage and resolution at high wind speeds and under rain than current capabilities.

Looking toward the future, the continuity of ocean surface vector wind CDRs requires a commitment to a series of fine spatial resolution, broad swath scatterometer systems that will provide accurate wind vector retrievals from calms to the strongest hurricane force winds, including within the coastal zone where significant ocean upwelling occurs. The realization of DFS on GCOM-W2 and GCOM-W3 will be a significant step toward a sustained wind vector CDR capability, where DFS provides both the C-band and Ku-band channels and improved spatial resolution.

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