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NOAA's NESDIS SATELLITE OCEANOGRAPHY

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ABSTRACT

Satellite oceanography within the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) focuses on observation retrieval and applications to address the NOAA missions of environmental assessment, prediction, and stewardship. The Satellite Oceanography Division encompasses three functional areas: satellite ocean sensors, ocean dynamics / data assimilation, and marine ecosystems / climate. The breadth of scientific investigation includes sea-surface temperature, sea-surface height, sea-surface roughness, ocean color, surface vector winds, sea ice, data assimilation, and operational oceanography.

1. INTRODUCTION

The Satellite Oceanography Division of the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) focuses its efforts on applications research and development to address the NOAA missions of environmental assessment, prediction, and stewardship. Specifically, the Satellite Oceanography Division's efforts entail research to address the NOAA strategies of monitor and observe, understand and describe, assess and predict, and engage, advise, and inform in pursuit of NOAA's four primary mission goals: Ecosystems, Climate, Weather and Water, and Commerce and Transportation.

The NESDIS mission, to provide timely access to global environmental data from satellites and other sources to promote, protect, and enhance the Nation's economy, security, environment, and quality of life, further shapes the focus of the division. Specific NESDIS themes guiding the division are: improving weather products and services, extending climate services, improving coastal services, providing operational ocean services, and saving lives and property through hazards support. Within this framework and the context of satellite ocean remote sensing, the Satellite Oceanography Division strives to be a national focal point for satellite oceanography by building on the research done by federal, state, and local agencies, academia, and the private sector to extend NOAA's investment in understanding the ocean and processes/events affected by the ocean, http://orbit-net.nesdis.noaa.gov/orad/index.html. In pursuit of this goal, the Satellite Oceanography Division seeks to provide national and global leadership in civilian operational oceanography through the development of new satellite sensors, improved collection of current ocean data, and capacity building that develops infrastructure, trains new ocean scientists, and provides outreach tools using the latest technology. In its efforts, the Division promotes the optimal use of data to ensure realization of benefits environment applications with new and improved algorithms, enhanced data assimilation, and development of long-term data sets. Divisional efforts directly support producing the highest quality products in a timely manner to facilitate the prediction and assessment of the state of the environment and the promotion of widespread availability of environmental data and information. The Division further supports NOAA research goals by developing quality-assured coastal and ocean applications that fully utilize and integrate current and emerging satellite data and by developing products using satellite data. In addition, the Division focuses on transforming observations into useful climate information; improving the use of satellite data in numerical weather prediction models; and improving the use of NOAA satellite data for disaster reduction support.

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2. STRUCTURE

Within the Satellite Oceanography Division, there are three functional areas: satellite ocean sensors, ocean dynamics / data assimilation, and marine ecosystems / climate. These functional areas are augmented through cross-cutting efforts of science teams investigating the areas of sea-surface temperature (SST), sea-surface height (SSH), sea-surface roughness (SSR), ocean color, ocean surface winds, and sea ice. The goal is end-to-end science, from sensor development and observation retrieval through the development of applications and the implementation of operational products for significant observable ocean parameters, including those parameters derivable through the fusion of different observed parameters. The science teams' efforts translate to four common themes: calibration and validation, operational satellite ocean remote sensing, climate, and data assimilation.

Within the functional area of satellite ocean sensors, the division's research principally focuses on developing sensor-level measurements into instrument-specific geophysical products. The research explores the physics that describe the relationships between sensor observations and geophysical products. This effort involves developing and validating model functions used to retrieve the geophysical parameters and understanding the uncertainties associated with the various components and parameterizations invoked. The research addresses instruments that span the visible, infrared, and microwave spectral regions, focusing on ocean color physics and biology, sea-surface temperatures, and ocean surface winds. Research areas include the development of: *in-situ* optical instrumentation and bio-optical algorithms for the calibration/validation of products derived from satellite ocean color sensors; sea-surface temperature retrievals from infrared and microwave instruments in both geostationary and polar orbits; and ocean surface winds derived from active and passive microwave sensors. The fundamental objective is to provide science-quality satellite and *in-situ* data sets with traceable uncertainties. The division also develops, monitors, and maintains time-series observations for assessing the long-term stability of the data sets.

For the functional area of ocean dynamics and data assimilation, the division researches and develops operational applications relevant to physical oceanography and marine geophysics using combinations of satellite data and *in-situ* ocean observations.
This functional area exploit sdata fusion as a technique for developing new observational products of derived dynamical parameters, such as ocean surface currents (radar altimetry/scatterometry) and near-surface ocean heat content (radar altimetry/sea-surface temperature) to determine aspects of the general ocean circulation and its variability. Additionallly, this functional area employs radar altimetry data to examine the marine gravity field, bottom topography, and sea-level rise. Results are interpreted in the context of supporting numerical models for oceanic/atmospheric prediction and studying climate change. In cooperation with agencies in the United States and abroad, the division ensures that operational processing of satellite data meets national requirements for assimilation in predictive models and monitoring of various ocean dynamic phenomena, e.g. El Niño. The division also is a focal point for facilitating and promoting satellite ocean remote sensing data assimilation within the interagency (Department of Defense, National Aviation and Space Administration (NASA), NOAA) Joint Center for Satellite Data Assimilation. Data Assimilation is a rapidly growing area of focus. The Satellite Oceanography Division has long contributed to the National Weather Service's data assimilation of SSTs, SSHs, and ocean vector winds. With the recent formation of the Joint Center for Satellite Data Assimilation (JCSDA) between NOAA, Navy, Air Force, and NASA, data assimilation has become a principal focus for environmental modeling. The Satellite Oceanography Division is making a commitment of both scientific and operational support for satellite data assimilation for numerical environmental prediction, including climate investigations. The scientific support involves providing sufficiently accurate data with known error characteristics and assisting the incorporation of the data into models.

The functional area of marine ecosystems and climate encompasses research and development of operational satellite remote sensing applications for oceanic, coastal, and estuarine areas. Satellite data (e.g., sea surface temperature, ocean color, surface winds) are processed and analyzed to resolve aspects of marine ecosystems important to NOAA's objectives for monitoring habitats, protecting species, maintaining human health, and promoting sustainable development. This functional area also works to develop an understanding of observable and derivable satellite ocean remote sensing parameters in the context of climate change. The division works with domestic and foreign agencies to ensure that operational processing of satellite data meets ecosystem-monitoring and climate-quality data record requirements.

3. SCIENCE ACTIVITIES

Formal science teams cut across functional areas to address the science issues and product development for specific categories of satellite ocean remote sensing parameters, subject to prioritization based on user requirements. As a public-interest government agency and unlike academia, NOAA/NESDIS must remain focused on the end value of its efforts, products, and services. The current science teams are: sea-surface temperature, sea-surface height, sea-surface roughness, ocean color, ocean surface winds, and sea ice. Science activities, by science team are discussed below.

3.1 Sea-surface Temperature

Sea-surface temperature investigations address both geostationary and polar-orbit observations and involve SST retrieval with thermal infrared and microwave sensors. NESDIS's satellite oceanography accomplishments include a long history of extracting SSTs from multi-channel infrared data. Current science efforts focus on improving the retrieval of SST values by correcting for atmospheric attenuation and accommodating sensor design changes. In-situ SSTs, from drifting and moored buoys, are used to remove biases and for compiling statistics to assess and maintain operational accuracy. Current efforts include developing a physical retrieval algorithm to replace the current empirically-derived regression-based operational algorithm and investigating the influences of aerosols on SST retrieval values. A significant additional task is deriving a modified retrieval algorithm to compensate for the design change that eliminated the 12-micron split-window channel on the GOES-12 series satellites. Near-term product efforts are focused on transitioning available Geostationary Operational Environmental Satellite (GOES) SSTs to operational status and fusing GOES and Polar-orbiting Operational Environmental Satellite (POES) observations into a blended satellite SST product (Maturi and Harris, 2002). The division has developed an initial microwave SST retrieval algorithm for the Tropical Rainfall Measuring Mission (TRIMM) Microwave Imager (TMI). The methodology developed for TMI will be used for the WindSAT and the Conical Microwave Imager/Sounder (CMIS) proposed to fly on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) when that data becomes available. The objective is to eventually create a blended GOES/POES/microwave SST product with known and characterized errors.

In support of numerical weather prediction, the division provides SST data for assimilation into the National Weather Service models. Routine high-resolution (temporal and spatial) infrared imagery from GOES and POES satellites is also provided to the National Weather Service for validation of ocean modeling results, in particular for comparing SST signatures of ocean dynamics with the modeled location of currents, fronts, and eddies.

In conjunction with support for the National Weather Service and operational oceanography users, the SST science team is developing a "best-value" SST product that blends GOES and POES observations. This new product is currently undergoing validation. Work has also begun to extend this product to incorporate microwave SST observations.

Using a satellite-only climatology [1984-1993], SST anomalies are now being generated from the 50-km daily field produced from operational multi-channel SST data. These anomalies are somewhat less reliable at high latitude where, due to more persistent clouds and ice, limited satellite data was available for the computation of monthly climatologies. The SST Anomaly charts and their time series are useful in assessing El Niño-Southern Oscillation (ENSO) development, monitoring hurricane "wake" cooling, assessing major shifts in coastal upwelling, and evaluating recent climate changes (Strong et al., 2000).

The 50-km climatology was primarily developed in conjunction with producing new Coral Reef HotSpot Charts. Work on coral reef bleaching is a significant focus area. The Division has developed initial algorithms using satellite sea-surface temperature imagery to identify regions of concern for coral bleaching events. New Coral Reef Watch (CRW) products provide early warnings of when sea-surface temperatures reach higher than 1° C above expected maximum summertime levels (Wellington et al., 2001). This threshold appears to be the level above which corals accumulate dangerous heat stress. Excessively-warm events appear to closely correlate with the onset of bleaching of healthy corals and, with subsequent continued exposure, the eventual death of the coral and possible severe damage to the reefs. Consequently, CRW also recently developed a product to track degree-heating weeks (DHWs) to measure the accumulated thermal stress experienced by the corals. The HotSpot product, together with the DHW Product, are now provided on an operational basis. CRW is a broader initiative that is both domestic (US Coral Reef Task Force) and international (World Bank Targeted Research, and The Nature Conservancy).

Another application recently developed combines satellite SST observations with a model of salinity to analyze/forecast probable locations of sea nettles, a stinging jelly, within the Chesapeake Bay. This work has now been extended to an experimental system for nowcasting harmful algal blooms of the toxic dinoflagellate *Karlodinium micrum* in the Chesapeake Bay. It is anticipated that this will evolve to combining SST observations with satellite sea-surface salinity measurements when available (Brown et al., 2002).

3.2 *Sea-surface Height*

Sea-surface height (SSH) efforts within the division are centered in the Laboratory for Satellite Altimetry (LSA). Historically, LSA has been involved in every U.S. and foreign satellite-based radar altimeter mission since Geos-3 in 1975. The science expertise spans the areas of physical oceanography, geophysics, and geodesy (Cheney, 2001). Significant research areas include: improving sea-surface height retrievals through re-tracking the altimeter observations; applying altimeter data to the issue of global sea-level rise to assess the contributions of thermal expansion and mass addition; evaluating and maximizing the value of gravity observations from the GRACE mission; and pursuing the development of satellite bathymetry.

Building on past experience, the LSA prepares altimeter data sets and is responsible for the production and documentation of data for the Geosat Follow-On (GFO) altimeter mission launched in 1998 and expected to operate until 2006. LSA investigators also serve as principle investigators on the science teams for Jason-1 and Envisat altimeters. NOAA's initial experience with operating its own altimeter will come with the Jason-2 altimeter, when NOAA and European counterpart, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), join the National Aeronautics and Space Administration (NASA) and the Centre National d'Etudes Spatiales (CNES) in making Jason-2 a 4-party project. NOAA will provide two Earth stations, satellite command and control, and operational data processing. NOAA altimetry will continue with the NPOESS constellation.

Products and services provided by LSA include routinely delivering SSH data to the National Weather Service for assimilation into their ocean model and verification of the NWS wave forecast model. A newly developed product depicts the evolution of the total surface current in tropical Pacific, fusing the geostrophic component derived from SSH measurements made by the Jason-1 altimeter with the wind-driven component from surface winds observed by the QuikSCAT radar scatterometer. Both of these measurements are processed at NOAA in near real-time, enabling operational monitoring of open ocean circulation. Another new data fusion effort combines SSH and SST to assess upper ocean heat content, especially as related to ocean forcing of tropical cyclones. The incorporation of this ocean surface heat content product into tropical cyclone intensity forecasting has contributed to a statistically significant improvement.

The LSA is also a leader in altimetry as applied to marine geophysics. To first order, the profiles of sea surface topography produced by orbiting altimeters provide information on the Earth's gravity field over the oceans. This can be combined with models of the solid Earth and depth measurements from ships to generate detailed maps of the ocean floor (Sandwell and Smith, 2001). Building on previous work, the LSA is involved in planning future missions for more advanced altimeters that would further improve knowledge of open ocean bathymetry (http://fermi.jhuapl.edu/abyss).

3.3 *Ocean Color*

Ocean color investigations focus on converting sensor-level measurements into instrument-specific geophysical products by exploring and defining the underlying physics. This work involves developing and validating model functions used to retrieve the geophysical parameters and understanding the uncertainties associated with the various components and parameterizations invoked. Significant time is spent providing continuous near-real-time radiometric observations from the Marine Optical Buoy System (MOBY) located off the coast of Lanai, Hawai'i in open-ocean (Case 1) water.

A major element of the MOBY program is providing results that have been calibrated to National Institute of Science and Technology (NIST) radiometric standards. Shipboard experiments are routinely conducted to: collect data for product algorithm development; provide in-situ observations for initializing newly-launched ocean color sensors; validating radiometric retrievals and derived products; and developing new in-situ instrumentation and measurement protocols (Clark et al., 2002). The present focus is on the validation of bio-optical products and radiometric calibration of the Moderate Resolution Imaging Spectrometer (MODIS). In conjunction with this MODIS effort, the division's research centers on measuring upwelling radiances and the spectral absorption coefficients of suspended particles for bio-optical algorithm development. A set of field experiments in the Chesapeake Bay during 2002 and 2003 has begun to test preliminary instrument designs for a coastal MOBY for research on the optical properties of coastal (Case 2) waters.

In addition to calibrated observations, the division develops ocean color applications. Recent improvements in ocean color instrumentation have allowed tracking of regional and local events such as red tides for coastal health mitigation. Active projects include routinely generating and validating the accuracy of NOAA/NESDIS operational products derived from satellite ocean color data, and developing algorithms for the production of beneficial ocean color products. An operational product resulting from this effort is the identification and location of Harmful Algal Blooms (HAB), such as red tides.

3.4 *Ocean Vector Winds*

Ocean vector winds investigations and products have been principally based on scatterometry, currently with QuikSCAT data. In conjunction with NPOESS risk reduction, passive polarimetry retrievals are also being pursued. Additionally, Synthetic Aperture Radar high-resolution retrievals and products are being developed. Current scatterometry efforts include: QuikSCAT high wind retrievals, characterization of scatterometer measurements in high winds and with/without precipitation (aircraft-based experiments); high-resolution (12.5 km) wind product validation and improvement through ambiguity removal and rain flagging; generation of standard 25km products, normalized radar cross section, and ambiguity plots; and science support for operational forecasting users.

In particular, the division has been trying to characterize scatterometer measurements of the ocean surface in high wind speed conditions and in the presence of varying amounts of precipitation. The approach has been to fly two scatterometers (C and Ku-band) on the NOAA P-3 aircraft in various experiments over the past several years (Donnely et al., 1999), including, most recently, a mission on Hurricane Isabel to collect data in Category 5 conditions. This work is being done in collaboration with the Microwave Remote Sensing Laboratory at the University of Massachusetts (UMASS) and the NOAA Hurricane Research Division at the Atlantic Oceanographic and Meteorological Laboratory (AOML). UMASS recently modified the scatterometers to have the capability of measuring reflectivity profiles through a precipitating atmosphere in addition to the Doppler velocity of the rain, permitting the measurement of wind profiles to the surface. Another new capability will be dual-polarized antennas that will collect horizontal and vertical polarized backscatter for the first time in these limiting conditions. These modifications, coupled with data being measured from other sensors, should allow full exploration of the ocean surface backscatter response in these limiting conditions. Working with the JPL scatterometer project, an experimental 12.5 km-resolution product has been implemented in the NESDIS near-real-time processing stream, but it has restricted distribution while the division works on validation and improvement (Jelenak et al., 2002). NWS marine forecasters are permitted access for evaluation and the overall feedback is that the higher detail is very useful at times, even though the current product still requires refinement.

The division's work with passive polarimetry focuses on the development of initial retrieval algorithms for WindSat and assessing the WindSat data. Specifically, the division is investigating the wind retrieval and ambiguity removal algorithms; participating on the WindSat calibration/validation team; addressing data distribution issues; and developing an operational demonstration project for all environmental data records (EDR). A relevant website is at http://manati.wwb.noaa.gov/doc/oceanwinds1.html. The division has been working closely with the Naval Research Laboratory (NRL) to develop the atmospheric portion of the physics-based wind vector retrieval algorithm for the WindSat project. In FY01, funding was received for a joint proposal with NRL to establish an operational demonstration project around WindSat as risk reduction for CMIS. A near real-time processing system has been established for WindSat that will allow processing and distribution of the full range of EDRs in addition to the wind vector.

3.5 *Sea-surface Roughness*

Sea-surface roughness investigations seek to exploit satellite synthetic aperture radar (SAR) data for a multitude of oceanographic applications. The range of applications being investigated within the division includes: mapping and analyzing detailed ocean surface dynamic features and underlying topographic features, identifying oil spills, mapping sea ice, locating algal blooms, and determining high-resolution vector winds (Pichel and Clemente-Colon, 2000) (http://orbit-net.nesdis.noaa.gov/orad/sar/). A goal of the sea-surface roughness team is establishing operational synthetic aperture radar data and products.

A demonstration of near real-time SAR applications (AlasKa SAR DEMOnstration Project - AKDEMO) began in the fall of 1999, employing data from RadarSat-1. The areas of interest are coastal Alaska waters of the Bering Sea, Beaufort Sea, Chukchi Sea, and Northern Gulf of Alaska. Goals for the demonstration include: 1) testing and validating prototype SAR products that respond to critical needs not satisfied with observational data in the Alaska region; 2) providing SAR imagery and derived products in near-real-time via the Internet for trial use by operational agencies; and 3) familiarizing operational agencies with SAR image data and products.

Recently, the division has been focusing on the development of SAR applications. The division continues to participate in the GHOSTNET project, providing SAR and additional data to help NMFS locate regions of ocean convergence in the North Pacific where lost and discarded fishing nets may congregate. The objective of this effort is to protect marine habitats, coral reefs in particular, from damage and entanglement of protected species. Additionally, the division is sponsoring SAR research projects that exploit the SAR's ability to image coastal ocean features. One project aims at using images of an estuarine plume, adjacent coastal water circulation, and oil slick signatures to validate a local circulation model. Another project seeks to relate similar SAR observations and *in-situ* data to the life cycle of salmonid species.

3.6 *Sea Ice*

Sea ice is addressed predominately from an operational perspective. The advent of satellite ocean remote sensing has allowed increased knowledge of the features of the polar ocean that would ordinarily be inaccessible during many months of the year and prohibitively expensive to survey using ground- based methods. Recent satellite research has demonstrated the efficacy of satellite data in improving sea-ice forecasts in the polar and surrounding regions. Ongoing efforts include close collaboration with the National Ice Center (NIC) via the Satellite Oceanography Division's sea-ice science team and by providing the NIC's Chief Scientist. The NIC science branch has the mission to maintain a strategic vision for NIC operations and recommend appropriate operational and scientific investments and improved concepts for operational processes. The Satellite Oceanography Division's sea-ice team helps NIC science branch's development of ice analyses and forecast products by improving infrared, scatterometer, and SAR satellite products used to validate the NIC ice model. QuikSCAT daily ice maps are routinely provided to the NIC. Sea-ice products are also provided to the NWS National Center for Environmental Prediction. Recently the division's sea-ice science team has been pursuing the use of satellite altimetry to measure sea-ice thickness.

4. OPERATIONAL OCEANOGRAPHY

In conjunction with other NOAA Offices, the Satellite Oceanography Division's NOAA CoastWatch Program operationally provides near-real-time environmental satellite data products to federal, state, and local coastal resource managers, marine scientists/educators, public, and commercial value-added users. Since the beginning of the Program in 1987, sea surface temperature (SST) from the Advanced Very High Resolution Radiometers (AVHRR) on NOAA's polar orbiting spacecraft has comprised the core data stream of NOAA CoastWatch. Within the last five years, however, data from several other ocean sensing satellite systems have proven increasingly important to coastal and ocean resource managers and scientists so their data and products are also now provided.

Most near real-time CoastWatch products are available without restriction at http://coastwatch.noaa.gov. Retrospective CoastWatch satellite-derived data products are provided through the Satellite Active Archive (http://www.saa.noaa.gov). Presently, the most popular CoastWatch products come from NOAA's geostationary satellites. These data are collected and processed into three-hour composite GOES SST products for all US coastal areas. NOAA CoastWatch currently purchases from the commercial sector U.S. East and West Coast site licenses for unlimited Orbview-2 (SeaWiFS) ocean color scenes to support US coastal resource managers. This arrangement is in the process of transitioning to the EOS (MODIS) ocean color data stream. Sea-surface temperature and ocean color products are routinely available for both EOS Terra and Aqua for U.S. coastal regions and selected additional areas. From images in October 2000, CoastWatch and the National Ocean Service issued the first known nowcast of a harmful algal bloom (HAB) for the west coast of Florida. Ocean surface wind products from scatterometers, QuickSat on SeaWinds and SSM/I on DMSP, are also popular. These products are valuable in the Hawaiian Islands for clearing marine debris from coral reefs and marine resource management. NOAA CoastWatch has over 12,000 users and they receive approximately 2 GB/month of data, covering all coastal areas of the continental United States, Alaska and Hawai'i.

Historically, CoastWatch has operated in close collaboration with NOAA Laboratories and Offices to form CoastWatch regional Nodes in coastal locations throughout the United States. These CoastWatch Regional Nodes provide satellite data access assistance to users and are available for limited consultation on local scientific and technical issues. Starting in 2003, NOAA CoastWatch is expanding geographic coverage to include NOAA mission requirements in the global ocean. While retaining the mission and responsibilities of NOAA CoastWatch, the program will gradually evolve into NOAA OceanWatch. The scope of responsibilities will begin to broaden in recognition of growing requirements for operational oceanography and the growing role of satellite ocean remote sensing in that endeavor

5. SUMMARY

The Satellite Oceanography Division applies remotely-sensed data received from operational and research satellites, other platforms, and in-situ data to infer the surface thermal distribution, surface winds and associated wave structure, bio-optical properties, marine pollution, dynamical and geophysical properties, and the extent and properties of sea ice. The Satellite Oceanography Division conducts research using satellite and *in-situ* observations to understand various oceanic, coastal, climatic, marine weather, and wetland phenomena and processes. It conducts field experiments to assemble comparative data to validate satellite retrieval algorithms. The Satellite Oceanography Division cooperates with other components of NESDIS, NOAA, other U.S. Government agencies, and international groups to develop applications of satellite-derived coastal and ocean properties relating to the physical, dynamical, and biological understanding and modeling of coastal ocean circulation and fisheries resources. To extend and leverage its efforts, the Satellite Oceanography Division has recently formed the Cooperative Institute for Oceanographic Satellite Studies (CIOSS) at Oregon State University.

The Satellite Oceanography Division is the NESDIS focus for defining, developing, and supporting operational satellite ocean remote sensing functions in NOAA. The main implementation pathway for this operational oceanography effort consists primarily of the NOAA CoastWatch/OceanWatch program. The Satellite Oceanography Division does not normally undertake operational activities itself, but rather works in conjunction with NOAA, other Government agencies, and international agencies.

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