Multi-sensor Improved Sea Surface Temperature (MISST) for GODAE

Lead PI : Chelle L. Gentemann
438 First St, Suite 200; Santa Rosa, CA 95401-5288
Phone: (707) 545-2904x14 FAX: (707) 545-2906 E-mail: gentemann@remss.com

CO-PI: Gary A. Wick
NOAA/ETL R/ET6, 325 Broadway, Boulder, CO 80305
Phone: (303) 497-6322 FAX: (303) 497-6181 E-mail: gary.a.wick@noaa.gov

CO-PI: James Cummings
Oceanography Division, Code 7320, Naval Research Laboratory, Monterey, CA 93943
Phone: (831) 656-5021 FAX: (831) 656-4769 E-mail: cummings@nrlmry.navy.mil

CO-PI: Eric Bayler
NOAA/NESDIS/ORA/ORAD, Room 601, 5200 Auth Road, Camp Springs, MD 20746
Phone: (301) 763-8102x102 FAX: (301) 763-8572 E-mail: Eric.Bayler@noaa.gov

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LONG-TERM GOALS

The Multi-sensor Improved Sea Surface Temperatures (MISST) for the Global Ocean Data Assimilation Experiment (GODAE) project intends to produce an improved, high-resolution, global, near-real-time (NRT), sea surface temperature analysis through the combination of satellite observations from complementary infrared (IR) and microwave (MW) sensors and to then demonstrate the impact of these improved sea surface temperatures (SSTs) on operational ocean models, numerical weather prediction, and tropical cyclone intensity forecasting.

SST is one of the most important variables related to the global ocean-atmosphere system. It is a key indicator for climate change and is widely applied to studies of upper ocean processes, to air-sea heat exchange, and as a boundary condition for numerical weather prediction. The importance of SST to accurate weather forecasting of both severe events and daily weather has been increasingly recognized over the past several years. Despite the importance and wide usage of operational SST analyses, significant weaknesses remain in the existing operational products.

The improved sensors on the Terra, Aqua, and EnviSAT-1 satellites, in conjunction with previously existing sensors on several other US Navy, NASA, and NOAA satellites, provide the opportunity for notable advances in SST measurement. In addition to more frequent coverage for increased temporal resolution, these sensors permit the combination of highly complementary IR and MW retrievals. While clouds, aerosols, and atmospheric water vapor affect IR retrievals, these phenomena have little impact on MW retrievals. Characteristically, IR SST provides high spatial resolution (~1 km at nadir) but poorer coverage with the presence of clouds. Although having a reduced resolution (~25 km grid), MW SST provide >90% coverage of the global ocean each day. These factors have motivated interest in the development of merged IR and MW SST products to leverage the positive characteristics of each

sensor type. Merging multiple SST sensors into a single analysis will result in enhanced reliability, availability, and accuracy.

This project has two distinct goals: (1) producing an improved sea surface temperature (SST) product through the combination of observations from complementary infrared (IR) and microwave (MW) sensors, and (2) demonstrating the impact of improved multi-sensor SST products on operational ocean models, numerical weather prediction, and tropical cyclone intensity forecasting. Close collaboration and the international coordinated exchange of SST products with error statistics with operational agencies will optimize utility of these new data streams by US and international operational agencies. Innovative techniques to blend these complementary data will be applied in operational frameworks at NOAA and Navy. This project will make a direct US contribution to the Global Ocean Data Assimilation Experiment (GODAE) by working within the GODAE High-Resolution SST Pilot Project (GHRSST-PP), initiated by the international GODAE steering team, to coordinate the production of a new generation high-resolution SST. By contributing to the GHRSST-PP this team will minimize duplication of efforts, harmonize research and development activities, and maximize data access.

This effort will ensure that US scientists and operational activities remain at the forefront of the international ocean and weather forecasting activities and are provided with state-of-the-art SST data products and analyses.

OBJECTIVES

To produce multi-sensor improved SSTs and successfully assess the impact of these products, five clear project objectives have been identified:
1) Computation of sensor-specific observational error characteristics is required for optimal application and data fusion techniques.
2) Parameterization of IR and MW retrieval differences, with consideration of diurnal warming of the ocean surface and cool-skin effects at the air-sea interface is required for multi-sensor blending and production of both skin and bulk analyses.
3) Production and dissemination of Level 2 Processed (L2P) sensor-specific SST products with associated retrieval bias error, standard deviation (STD), and diurnal warming estimates to the application user community.
4) Production and dissemination of improved multi-sensor high-resolution skin and bulk SST analyses to demonstrate and optimize utility in operational applications.
5) Targeted impact assessment of the SST analyses on hurricane intensity forecasting, numerical data assimilation by ocean models (both national and within GODAE), numerical weather prediction, and operational ocean forecast models.

APPROACH AND WORK PLAN

Production of a multi-sensor, improved SST product requires detailed, consistent processing of all input data and characterization of retrieval errors and differences in addition to development of fusion techniques. Much of the methodology to be applied is selected for consistency with the GHRSST-PP Data processing Specifications (GDS), which is being designed to produce SST data products that satisfy the requirements of existing operational ocean forecast and prediction systems.

This project will also provide an assessment of the operational impact of improvements by the enhanced sampling and error characterization of the IR and MW sensors in the areas of NWP and ocean modeling. Targeted applications include Navy fleet operations, naval and civilian NWP, operational oceanography, and climate monitoring and forecasting. Each of these areas is of national importance and has corresponding national programs. For each of these applications, it is anticipated that this project will provide significant enhancements to the quality and availability of data. Through affiliation with the GHRSST-PP, the products will also be directly utilized by the international GODAE modeling communities. This product sharing will be achieved through the partnerships and close connections between the data provider and user communities.

The MISST project has a broad partnership of scientists from academia, government, and private industry, including **Remote Sensing Systems** (C. Gentemann), **NOAA** (G. Wick, J. Cione, K. Casey, E. Bayler, M. DeMaria, R. Reynolds), **NRL** (J. Cummings, C. Barron, N. Baker, J. Goerss), NAVOCEANO (D. May), **NASA JPL PODAAC** (J. Vasquez), **U. Maryland** (A. Harris), **U. Edinburgh** (C. Merchant), **U. Miami** (P. Minnett, B. Evans, E. Chassignet), **U. Colorado** (B. Emery, S. Castro, **WHOI** (B. Ward), and the **International GHRSST-PP Project Office** (C. Donlon). The project has identified specific tasks: data provision (C. Gentemann, B. Evans, D. May, E. Bayler), determining sensor errors (G. Wick, C. Gentemann, A. Harris, P. Minnett, B. Evans, S. Castro, B. Emery, D. May), modeling diurnal warming and skin layer effects (G. Wick, C. Gentemann, S. Castro, B. Emery, B. Ward), production and distribution of data analyses (J. Cummings, E. Bayler, J. Vasquez), and performing impact studies (E. Bayler, J. Cione, J. Goerss, N. Baker, E. Chassignet, C. Barron).

Additionally, this NOPP project is closely partnered with two other NOPP projects: "U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)" and "POSITIV: Prototype Operational System – ISAR – Temperature Instrumentation for the VOS fleet". The HYCOM Consortium will evaluate the impact of the improved SSTs on its ocean forecast system and the POSITIV ocean temperatures will be utilized in NRT for error characterization of satellite SST retrievals.

During the second year of the project (June 2005 – June 2006) we plan to (1) continue the NRT *in situ* satellite database, (2) continue development of error characteristics for MODIS, AVHRR, GOES, TMI, and AMSR-E SSTs (3) produce L2P for AVHRR, TMI, and AMSR-E, (4) update the diurnal and skin layer modules, (5) produce blended IR/MW SST, (6) begin validation of blended SSTs, (7) begin impact studies.

WORK COMPLETED

(1) Collocated satellite *in situ* database are established and continually updated for AVHRR, MODIS, AMSR-E, and TMI, available in NRT from NAVOCEANO, U. Miami, and RSS. (2) Updated reports on the error characteristics for MODIS, AVHRR, GOES, TMI, and AMSR-E SSTs. (3) Orbital L2P and associated support files are available in NRT for AVHRR, TMI, and AMSR-E. (4) Completed initial diurnal warming model evaluations and sensitivity studies, updates to the diurnal and skin layer modules are expected by June 2006. (5) Blended IR/MW SST products are under development at RSS (MODIS, TMI, and AMSR-E) and NRL (AVHRR and AMSR-E). A blended IR SST product is under development at NOAA. Production of a blended global MW SSTs is on-going. (6) Validation of blended SSTs is underway, (7) Impact studies are expected to begin by June 2006.

RESULTS

SST error estimates

Significant progress has been made towards a better understanding of the errors in MW and IR SST retrievals and methods to estimate these errors in NRT. Better estimates of sensor errors are necessary for multi-sensor data fusion because the accuracy of the commonly used statistical method depends on the accuracy of our understanding and modeling of biases between sensors.

NAVOCEANO has developed a methodology to add information on retrieval error to the US NAVY operational data stream. This method adds quantitative estimates of reliability to every MCSST sample operationally generated at NAVOCEANO. The current scheme appears to be robust and low-maintenance, both attributes being major requirements in an operational environment. Retrieval errors are calculated for N-16, N-17, and N-18 AVHRR GAC and LAC data.

RSMAS has developed error arrays, analogous to those previously produced for AVHRR, for MODIS AQUA and TERRA. These are based on MAERI radiometric and buoy in situ observations coupled to the complete mission lifetime for the two MODIS sensors. Error statistics computed from these error 'hypercubes' will be used to compute expected bias and standard deviation needed for MODIS AQUA and TERRA SST L2P datasets.

Estimation of the bias caused by aerosols in infrared SST retrievals can most optimally be calculated using a fast-forward radiative transfer model (RTM) and inclusion of the full aerosol field in the state vector. This work is on-going.

Multiple initial proposed methodologies for the computation of error estimates for the AVHRR were inter-compared using extended collocations with drifting and moored buoys. The effectiveness of the formulations was objectively assessed through application to direct differencing of IR and MW data. The work yielded a multi-tiered look-up table for the errors where different optimal combinations of inputs are used depending on data availability. Different methodologies are recommended based on whether the application is to real-time processing or reanalysis.

TMI and AMSR-E error statistics were computed using both *in situ* data and the Reynolds optimum interpolated analysis. The errors are calculated based on NRT buoy collocations and look-up tables with error determined as a function of SST, wind speed, and distance to land.

Evaluation of the error estimates from the MISST data providers is being performed at FNMOC. Results showed that the AVHRR GAC error estimates are consistent with the innovations, but that the AMSR-E error estimates from the data provider are too low. A representation error computed from the gradient of the background field times the ratio of the spatial averaging properties of the SST retrieval to the grid resolution was added to the error estimates for both the AVHRR GAC and AMSR-E MW retrievals. The diagnostic for this run was consistent with the innovation time series. Further work on the sensitivity of the J_{min} diagnostic to the MISST error estimates from the data providers is on going.

Datasets

Several new SST datasets, in a common format, are available through this project. NAVOCEANO is producing N-18 AVHRR GAC and LAC L2P files. RSS is producing orbital TMI and AMSR-E L2P files. NOAA is currently developing L2P for GOES SSTs.

Diurnal Warming and Skin Models
Comparisons of simulations from full diurnal warming models with detailed temperature profile measurements from the SkinDeEP instrument identified the best combination of model physics for use in evaluation of simplified parameterizations and quantified expected errors in estimates of diurnal warming. Sensitivity studies revealed optimal sources of wind speed and insolation data for diurnal warming calculations based on non-continuous satellite data. Instantaneous winds provide the best results for modeled skin temperatures while averaged winds result in reduced error in predicted subsurface temperature. The impact of short term insolation variations was found to be significant only in morning hours.

Global SST publicly distributed
Global blended MW SSTs are available from RSS in NRT. Three blended products are available at daily 25-km resolution. All three analyses are continually reprocessed as new data becomes available.

A Global SST and sea ice analysis is available from FNMOC. The analysis is executed on a 9-km mid-latitude (12-km at the equator) resolution grid and is updated every six hours. SST observations used in the analysis include GAC retrievals from AVHRR (NOAA-16, 17, 18) and in situ data from ships and fixed and drifting buoys. The analyzed SST and sea ice fields are available within 6-hours of real time on the US GODAE server (http://www.usgodae.org).

Global SST under-development
A global MW/IR SST and sea ice analysis is under development at FNMOC. The 9-km operational analysis will be used as the baseline Navy system for further development. Initial efforts toward a blended MW/IR SST analysis product indicate that additional quality control is required on the AMSR-E data by comparison against the AVHRR/in situ SST analysis product valid at the time of the microwave SST retrieval. Although the AMSR-E rejection rates were very low (~0.3% over a three month period from July – August, 2005), some rejected retrievals had anomalies greater than 4ºC from the background field. The source of these large AMSR-E anomalies is under investigation.

A global MW/IR SST analysis is under development at RSS. This daily 10-km global SST utilizes observations from TMI, AMSR-E, and MODIS. Extensive cloud contamination in MODIS requires additional quality control. All data are 'corrected' to a daily foundation temperature using the MISST developed diurnal model. Initial validation results show that the cloud contamination in MODIS remains an issue and regional differences between the IR and MW data need to be better parameterized.

A global IR SST is under development at NOAA. This analysis utilizes the AVHRR and GOES SSTS. Internal validation of the product is underway.

IMPACT AND APPLICATIONS

National Security

SST is routinely used both directly in Naval fleet operations and as an input to weather forecast models used to support Naval operations. The improved SST products and better understanding of the associated errors resulting from this project will provide a more accurate description of environmental conditions enabling better planning of operations. A key aspect of this project is directly evaluating the impact of the improved SSTs on Naval applications. SSTs are also a key parameter for identifying

the location and strengths of thermal fronts and eddies, information crucial to assessing the acoustic environment for submarine and antisubmarine operations, as well as for Homeland Security considerations of coastal currents and eddies for public health and safety in the advent of deliberate dumping and dispersion of hazardous material.

Economic Development

SST data is a significant consideration for planning and conducting commercial fishing operations, as well as fisheries management and monitoring efforts. Likewise, SST data is relevant to marine protected species monitoring and de-conflicting protection efforts from commercial fishing.

Quality of Life

The potential for producing more accurate SST products has important application to areas including environmental monitoring and weather forecasting. More accurate knowledge of the SST can lead to improved understanding of coral health, better forecasting of routine and severe weather events, improved recreational fishing, and increased ability to monitor climate change. Improved understanding in these areas will lead to a more informed public and better decision-making. The specific focus on tropical cyclone intensity forecasting will potentially impact warning and evacuation decisions.

TRANSITIONS

National Security

Through direct project partnership with US Navy efforts, the improved SST products and methodologies will be directly integrated into Naval SST products and numerical weather forecasting procedures both in use and under evaluation. As one example, improved error characterization will be incorporated in the NCODA model. To accomplish the goal of determining the impact of the SST improvements in Naval applications, transitioning results to the Naval partners is a central focus of this project.

Economic Development

Satellite IR SST data are already in use by the National Marine Fisheries Service. Improved coverage in persistently cloudy regions will facilitate protected species and fisheries management efforts. The merged IR-MW SST product will be provided when available via the NOAA CoastWatch program.

Quality of Life

Key impact assessments are planned in the areas of numerical weather prediction and tropical cyclone intensity forecasting through the activities of project partners. New SST retrievals and improved error estimates are to be integrated into existing forecast models to determine their impact. Additionally, the merged products will be provided to NOAA's National Weather Service (NWS) National Centers for Environmental Prediction (NCEP)'s Ocean Prediction Center to support ocean forecasting of winds and waves, as well as thermal conditions. Through involvement with the international GHRSST-PP, the resulting products will be further available for incorporation by a diverse, interested user group.

RELATED PROJECTS

"U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM)": http://hycom.rsmas.miami.edu/
"POSITIV: Prototype Operational System – ISAR – Temperature Instrumentation for the VOS fleet"