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THE GODAE HIGH-RESOLUTION SEA SURFACE TEMPERATURE PILOT PROJECT

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ABSTRACT. Sea surface temperature (SST) measurements are required by operational ocean and atmospheric forecasting systems to constrain modeled upper ocean circulation and thermal structure. The Global Ocean Data Assimilation Experiment (GODAE) High Resolution SST Pilot Project (GHRSS-PP) was initiated to address these needs by coordinating the provision of accurate, high-resolution, SST products for the global domain. The pilot project is now complete, but activities continue within the Group for High Resolution SST (GHRSS). The pilot project focused on harmonizing diverse satellite and in situ data streams that were indexed, processed, quality controlled, analyzed, and documented within a Regional/Global Task Sharing (R/GTS) framework implemented in an internationally distributed manner. Data with meaningful error estimates developed within GHRSS are provided by services within R/GTS. Currently, several terabytes of data are processed at international centers daily, creating more than 25 gigabytes of product. Ensemble SST analyses together with anomaly SST outputs are generated each day, providing confidence in SST analyses via diagnostic outputs. Diagnostic data sets are generated and Web interfaces are provided to monitor the quality of observation and analysis products. GHRSS research and development projects continue to tackle problems of instrument calibration, algorithm development, diurnal variability, skin temperature deviation, and validation/verification of GHRSS products. GHRSS also works closely with applications and users, providing a forum for discussion and feedback between SST users and producers on a regular basis. All data within the GHRSS R/GTS framework are freely available. This paper reviews the progress of GHRSS-PP, highlighting achievements that have been fundamental to the success of the pilot project.

INTRODUCTION

Accurate knowledge of sea surface temperature (SST) distribution and how it changes over time is of importance to many government agencies worldwide. Satellites and in situ sensors readily measure SST. It is needed as a key input to forecasting and prediction systems to constrain modeled upper-ocean circulation and thermal structure at daily, seasonal, decadal, and climate time scales and to constrain the exchange of energy between the ocean and atmosphere in coupled ocean-atmosphere models. SST is long established as a key climate variable and is a Global Climate Observing System (GCOS) Essential Climate Variable (ECV; GCOS, 2004). In 2000, the Global Ocean Data

Assimilation Experiment (GODAE) recognized that the diverse SST products then available could not meet the stringent availability, accuracy, coverage, and timeliness criteria required for operational ocean or meteorology prediction and ECV production. GODAE thus initiated the GODAE High-Resolution SST Pilot Project (GHRSS-PP) to address these issues through the production of a common format data set that includes all satellite SST data together with uncertainty estimates.

The primary aim of GHRSS-PP was to develop and demonstrate a system that could deliver high-resolution, global-coverage SST data products operationally in near-real time according to GODAE specifications. Although an operational

network of SST measurements from ships and buoys was available, the only way to meet GODAE requirements was to use measurements from Earth observation satellites. The Pilot Project worked to establish an internationally distributed system that acquired existing SST data products, enhanced them by adding additional information, and made them available in a common format so that they could be combined to produce a new generation of products. This project required international collaboration among organizations that produce satellite SST data products from different complementary sensor types. GHRSS-PP developed a system that exploited the unique contributions of each sensor type and institutional partner (Donlon et al., 2007). Success was achieved not just by solving scientific, operational, and technical problems, but also by cooperation at an international level to agree on data product definitions and standards acceptable to users, producers, and data managers.

GHRSS-PP participants established international consensus definitions for SST that are now part of the network Common Data Format (netCDF) Climate Forecast (CF) convention. They conducted detailed research on the impact and mitigation of diurnal SST variability in SST measurements and analyses, developed satellite pixel and grid-point time varying uncertainty estimates, coordinated international data management systems, established procedures and protocols, tested and implemented archives to manage the extensive GHRSS-PP data sets (currently ~ 25 Gb per day), provided near-real-time data access portals and user services, implemented near-

real-time quality control monitoring services, and developed a framework of international collaboration, support, and resource sharing that was actively nurtured by an international science team, an international project office, and dedicated technical advisory groups. Based on these useful activities, the Pilot Project leveraged national and regional agencies and offices to fund its activities. For a full review of GHRSSST SST definitions, impacts, and importance of diurnal variability, technology, and standards used, the reader is referred to Donlon et al. (2007). For a full review of future GHRSSST activities, the reader is referred to a white paper submitted

for the September 2009 OceanObs 09 decadal conference by author Donlon and colleagues (available at <http://www.oceanobs09.net/>).

GHRSSST-PP was successful in revolutionizing the way satellite SST data sets were developed, shared, and applied in modern oceanography, meteorology, and climate centers. Coincident with the formal closing of GODAE in 2008, the Pilot Project became the Group for High-Resolution SST (GHRSSST), which continues to build on the firm foundations laid by the Pilot Project in supporting improvement of the quality of the satellite-derived SST fields and the timely provision of data to the

operational community. This paper provides a summary of GHRSSST-PP, beginning with a review of user requirements and challenges.

REQUIREMENTS FOR GHRSSST-PP

GODAE defined the minimum data specification required for use in operational ocean models, stating that SST measurements with global coverage, a spatial resolution of 10 km, and an accuracy of 0.5°C need to be updated every six hours (Smith and Koblinsky, 2001). GHRSSST-PP data products should include uncertainty estimates to facilitate their use by data assimilation systems and should properly address the difficult issues of SST at the sea ice edge and diurnal variability. A series of international workshops during 2000–2003 (Smith, 2000; Donlon et al., 2002, 2003) established a wider set of user requirements for the GHRSSST-PP. The following key requirements emerged from these workshops.

Scientific Research and Development Requirements

- Provide tools to convert between radiometric “skin” SST and SST at depths measured by ships and buoys.
- Ensure that SST diurnal variability (DV) is properly flagged within observational data and provide tools to isolate the DV signal from measurements prior to their use in data assimilation and analysis procedures.
- Develop new methods to merge in situ data with complementary microwave and infrared satellite data.
- Develop methods to correct for bias in different satellite data sets.
- Develop methods and tools that

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provide SST uncertainty estimates with every observation or analysis grid point.

- Develop methods to merge long-term SST data sets in a reanalysis program that considers SST data for the entire satellite era.
- Develop high-resolution sea ice data sets and accurate SST products in the marginal ice zone.
- Promote the project at scientific meetings and symposia.

Operational Requirements

- The user community should be involved at all stages of GHRSSST-PP service and product development and evolution.
- Products should be delivered in near-real time and in an operational-like manner.
- Diverse SST data product formats and content should be homogenized so that users need only develop one software reader.
- Data management should enable interoperability, and good data stewardship should follow internationally agreed standards, leverage existing data distribution protocols, and provide tools and services.
- Delivery and timeliness of products should be monitored and users informed of problems when they occur at the earliest possible time.
- Language barriers should be overcome using an agreed vocabulary.
- Quality-control procedures should be developed and installed within a common framework for all data providers and users.
- Tools for real-time intercomparisons and validation/verification of GHRSSST-PP products

should be established.

- A set of user-focused services should be provided in a common framework for seamless data access.
- Long-term stewardship of GHRSSST-PP output, user support, and help services should be developed and operated within a common framework.
- Updated product and service documentation are required.
- Outreach and training activities should be initiated to include the end user community via a dedicated Internet portal.

Product Requirements

- GHRSSST-PP should provide both SST measurement products (Level-2 [L2]) and multi-sensor merged Level-4 (L4) analysis products, including uncertainty estimates for each derived SST value.
- L2 products should be provided as native grid (i.e., swath projection), and analysis products should be developed at resolutions of 10 km or better for the global ocean and regions of interest.
- Both L2 and L4 products should include supporting auxiliary data sets to aid interpretation of SST by users.
- An accurate, historical time series of L4 analysis products and input measurements should be developed for use in seasonal forecasting and climate monitoring.

Programmatic Requirements

The project should:

- Directly address international organizational challenges, including diverse user requirements
- Recognize the implementing

institutional capacities, capabilities, and funding prospects

- Develop international recognition and standing as the international authority for SST activities
- Ensure that data providers and users are included in all GHRSSST-PP activities and are consulted on a regular basis

These requirements were critical to establishing a framework and a work plan, and they formed an essential part of GHRSSST-PP evolution. By establishing and documenting clear requirements in a consultative manner at the start of the project and through all stages of its development, GHRSSST-PP was able to develop confidently and purposefully to address the needs of the international SST user community.

INTERNATIONAL ORGANIZATION AND PARTNERSHIP

As GHRSSST-PP evolved, it was clear that formal organization was required to foster international relationships and coordinate ever-increasing activities within the pilot project. An international team of 24 scientists was formed to oversee the implementation of GHRSSST-PP. Within this team, several technical advisory groups and dedicated working groups were convened to address specific details. An international project office was established, funded by the European Space Agency and the UK Met Office, and a full-time project director was appointed. An advisory council of major stakeholders was established to provide direct advice and guidance to the Project Office, which reported annually to the International

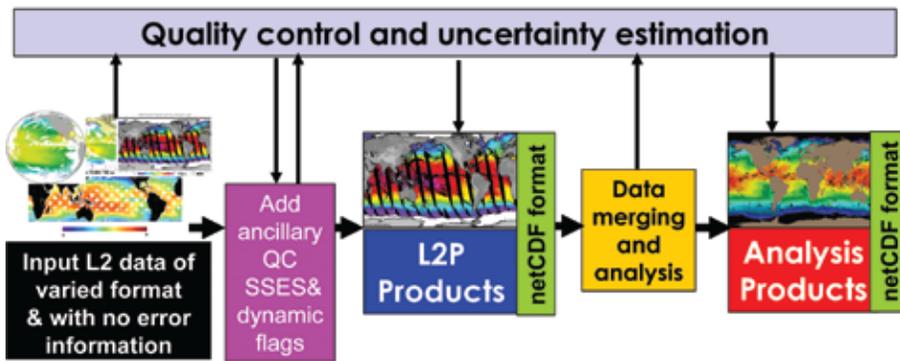


Figure 1. The strategy adopted by the GHRSSST-PP for near-real-time data product development.

GODAE Steering Team. The Project Office was a key driver for GHRSSST development, taking responsibility for coordinating activities on a day-to-day basis, managing the GHRSSST-PP user requirements, providing advocacy for the project, managing GHRSSST-PP documentation and project reporting, and coordinating outreach activities. The Project Office provided a focal point for the teams and individuals contributing to GHRSSST-PP; the directors and managers responsible for national contributions to GHRSSST-PP; satellite and in situ SST data providers; GHRSSST-PP users, sponsors, and funding agencies; and the national projects that were actually implementing GHRSSST-PP. The Project Office remains an essential component of the GHRSSST Regional/Global Task Sharing (R/GTS) framework that underpins GHRSSST operations.

GHRSSST-PP DATA PRODUCTS AND SERVICES

GHRSSST-PP provided two major types of near-real-time SST products (L2 pre-processing and L4 analysis products) supplemented by user support, data delivery, data management, and quality-control services, as illustrated

schematically in Figure 1. Together, these products and services provide a consistent system through which any satellite SST measurement can be channelled, conditioned, and evaluated against in situ measurements and other satellite data, and thus can be easily used by operational forecasting systems to construct real-time SST analyses and contribute to the long-term climate data record of global SST.

GHRSSST-L2P Products

These products are baseline measurement data sets. SST data generated from different sensors are made available to users in a common format together with ancillary information to assist with their interpretation. For every L2 file (defined as geo-referenced SST products) of input data, GHRSSST produces a matching L2P (L2 pre-processed) product that contains identical SST values in the same geographical layout (swath or latitude/longitude coordinates) as those in the source L2 product. On a pixel-by-pixel basis, each SST retrieval is augmented with estimates of the bias error and standard deviation error typically derived from statistical databases of in situ and satellite data on a sensor-by-

sensor basis. These single sensor error statistics (SSES), along with ancillary data for surface wind speed, aerosol optical depth, sea ice concentration, time of measurement, and a set of quality control flags, are integrated with the original L2 SST data to form the core content of an L2P product. The ancillary fields in the data record are provided as “dynamic flags” that can be employed by different user communities to evaluate the usefulness and applicability of any individual SST observation for their specific applications. Use of these dynamic fields rather than binary mask flags provides more flexibility for users in deciding whether a given SST observation is fit for a particular purpose. For example, wind speed can be used to determine the likelihood of significant skin-temperature deviations and/or diurnal warming in each pixel.

Figure 2 shows an example of the content of an L2P data set. The L2P data format is netCDF following the CF v1.3 convention, thus producing data sets with an extensible common interface format that is Internet “aware”—appropriate for the Open-source Project for a Network Data Access Protocol (OPeNDAP; see Blower et al., 2009) and the Open Geospatial Consortium-based interoperable data discovery and access applications. All GHRSSST products can be read and manipulated directly within common Geographic Information Systems (GIS), MATLAB, IDL, and custom applications in C, Fortran, and other programming languages using freely available netCDF libraries. A unique metadata record is also produced for each L2P product that is used for data discovery, real-time data tracking within the GHRSSST-PP distributed processing system, and

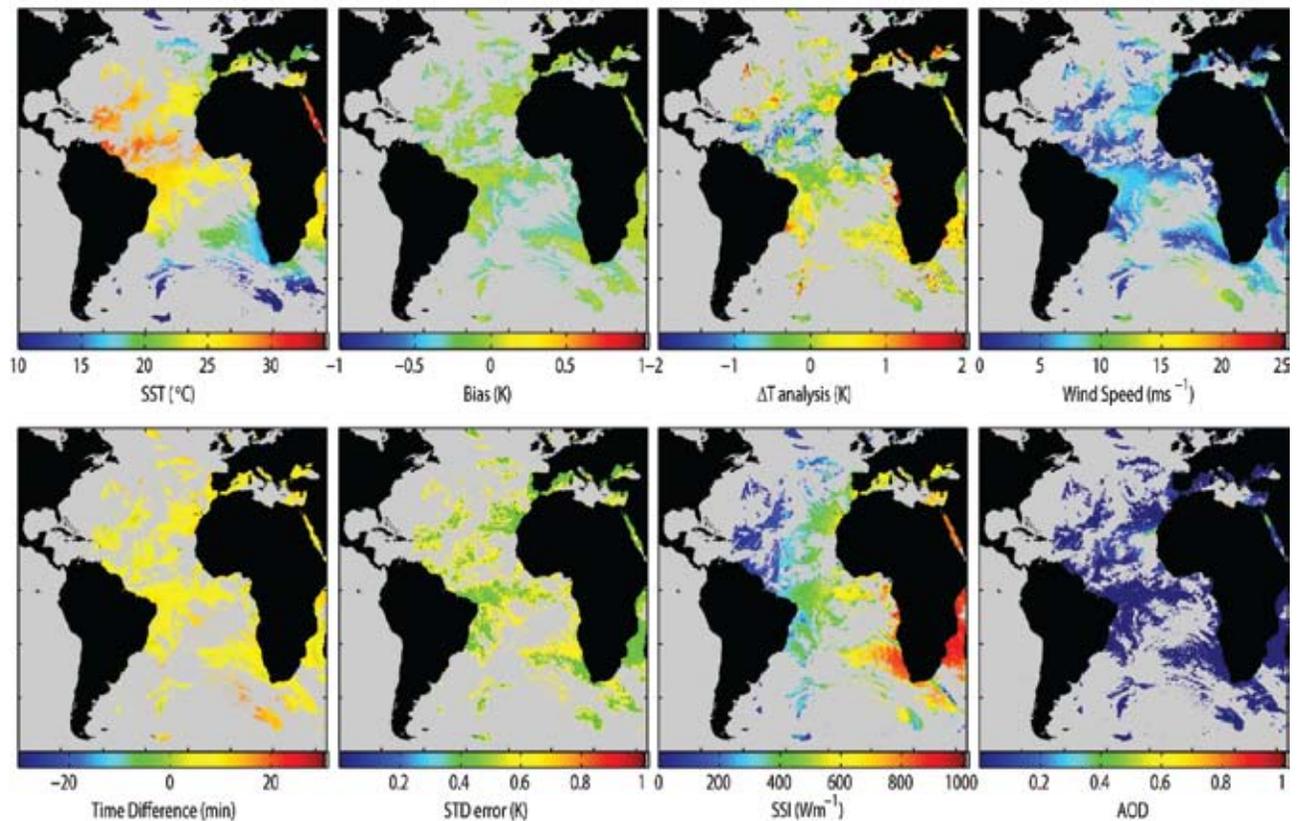


Figure 2. Example GHRSSST-PP Level-2 pre-processed data set derived using Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) sea surface temperature (SST) data collected over a three-hour period. (From top left to bottom right, the figure shows SST, estimated SST bias error, difference from previous reference SST analysis field, European Centre for Medium-Range Weather Forecasts (ECMWF) surface wind speed, time of observation within a three-hour window (SEVIRI makes measurements every 15 minutes), estimated standard deviation of SST error, surface solar irradiance (from SEVIRI visible channels), and aerosol optical depth from NOAA's National Environmental Satellite, Data, and Information Service (NESDIS).

long-term preservation of information. L2P files are the basic building blocks from which all other GHRSSST-PP SST data products are derived.

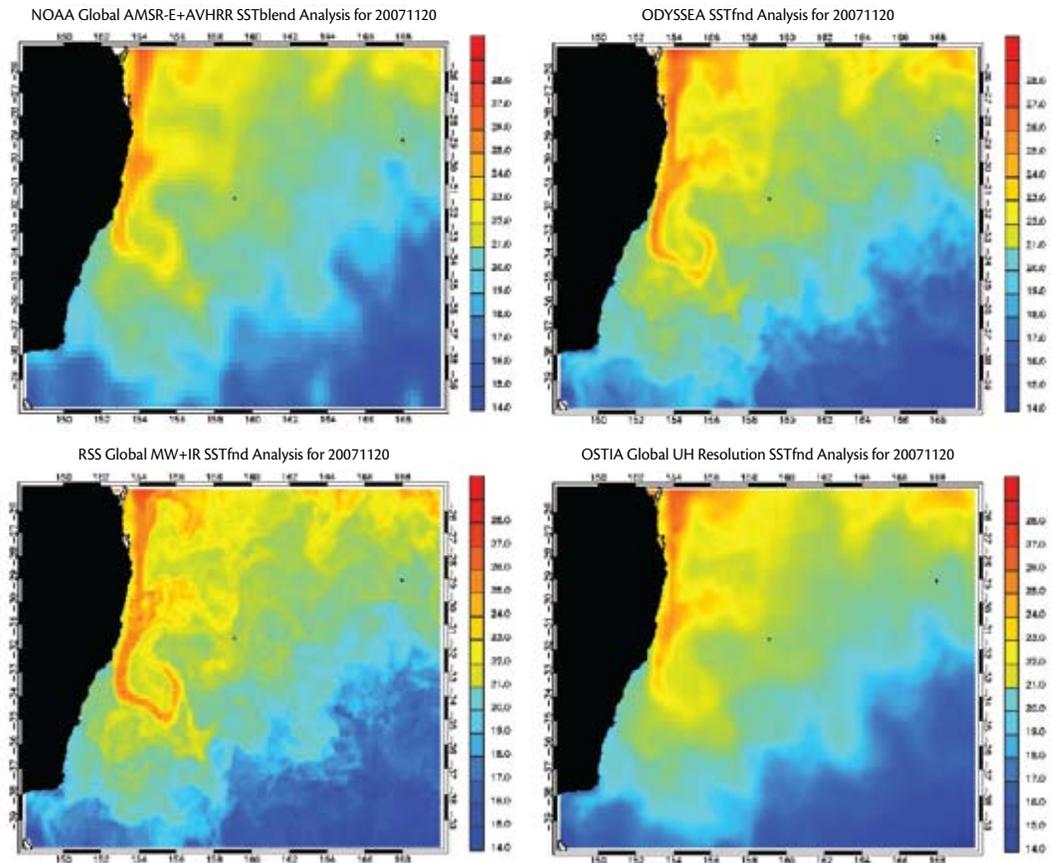
GHRSSST L4 Analysis Products

GHRSSST L4 analysis products provide merged, gridded, and gap-free SST data sets produced by analysis of several complementary SST inputs. The primary objective in generating L4 products is to provide the best available estimate of SST from a combined analysis of all available L2P (and other) SST data. L4 products exploit the synergy among data from in situ, satellite microwave, and

satellite infrared sensors and typically use all available data in a 24-hour period prior to the analysis. As for L2P data streams, the GHRSSST-PP L4 data format specification is a netCDF file following the CF v1.3 convention. Several L4 production systems with global and regional coverage are currently operational using different analysis methods (e.g., Reynolds and Smith, 1994). In situ data form an important component of the L4 process as these data can be used to correct for biases among the satellite data sets. Bias correction of all input data used in the analysis procedure is critical to obtaining a valid output (for

example, see Reynolds et al., 2007). Bias due to diurnal stratification and cool skin effects must also be accounted for using auxiliary data and/or parameterization schemes prior to performing the analysis, in order to adjust observed SST to an estimate of subsurface SST at a specific depth. Although SST analysis methods predate the initiation of GHRSSST-PP, the availability of L2P data has greatly facilitated their operation and allowed them to exploit more sources of SST than was previously possible. Figure 3 shows an intercomparison among several GHRSSST L4 SST analysis products.

Figure 3. An example of some of the Level-4 SST global daily analyses available from the GHRSSST Global Data Assembly Center (GDAC) for November 20, 2007, displaying a region southeast of Australia (148°E–170°E, 25°S–40°S), showing the East Australian Current. (Top left) NOAA Reynolds AMSR-E (Advanced Microwave Scanning Radiometer-Earth Observing System) + AVHRR (Advanced Very High Resolution Radiometer) 1/4° resolution analysis. (Top right) ODYSSEA (Ocean Data Analysis System for MERSEA) 1/10° resolution analysis. (Bottom left) USA Remote Sensing Systems microwave and infrared ~ 1/11° resolution analysis. (Bottom right) Met Office OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis) 1/20° resolution analysis.



The Reanalysis Program

GHRSSST has a reanalysis (RAN) activity that is developing long-term, satellite-derived SST data sets at high resolution with higher accuracy and consistency with quantified uncertainties and diurnal variability estimates. Experience with the generation and application of real-time satellite SST data sets indicates a clear need for sustained, long-term reprocessing efforts that optimize product accuracy and temporal stability. RAN builds on operational data streams and offline, delayed-mode SST data sets not available to the real-time system. By applying extensive quality-control procedures, using new technological developments, and conducting routine reprocessing of the entire time series

from different sensors using a consistent set of techniques, the RAN system facilitates a wide range of additional GHRSSST-PP product applications. For example, reprocessed RAN products will be suitable for use in climate studies as “climate data records” (CDRs), an important concept in environmental data stewardship that requires long-term consistency and sound error estimates. The RAN effort must also assure that biases between the long-term climate record and the modern, satellite-derived SST record are properly documented. The GHRSSST-RAN global product is expected to have a spatial resolution of 5–10 km, will conform to GHRSSST L4 data and metadata format specifications, and will strive to achieve the

ambitious temporal stability requirement of ~ 0.1 K per decade. GHRSSST reanalysis products are expected to extend back to the beginning of the satellite SST period with the start of the five-channel Advanced Very High Resolution Radiometer (AVHRR) series in late 1981. The first formal GHRSSST reanalysis products are expected to begin production in 2010, but the critical individual satellite reprocessing activities have already begun through GHRSSST-RAN program coordination. In addition, L4 intercomparison activities, including data from before the satellite era in collaboration with GCOS, are well underway (see <http://ghrsst.nodc.noaa.gov>).

The GHRSSST-PP High-Resolution Diagnostic Data Set

The GHRSSST-PP High-Resolution Diagnostic Data Set (HR-DDS; see <http://www.hrdds.net>) is a component service conceived within GHRSSST-PP that allows users to interactively view, compare, and analyze L2 and L4 SST data products, ocean model data sets, and auxiliary data sets from the various data streams within GHRSSST. The HR-DDS system consists of regularly gridded subsets of all available GHRSSST SST within predefined small sites (typically 2° x 2° in size). Approximately 250 of these sites were chosen to provide evenly distributed global coverage and allow detailed examination of the effects of specific atmospheric or oceanic conditions. Sites are included to represent regions affected by Saharan dust aerosol, or areas of high spatial and temporal SST variability such as western boundary currents. HR-DDS ensures that operational users and scientists have ready access to information in a well-defined format tuned to specific areas and issues that can be used to diagnose faults and data problems immediately. Model SST outputs are also included in HR-DDS to enable direct comparison between model and measurement data. Figure 4 provides example outputs of the HR-DDS Web site.

HR-DDS files contain all ancillary data available at the time of observation; these data are resampled onto the same grid and are immediately available at the HR-DDS Web site via both File Transfer Protocol (FTP) and OPeNDAP. Work is underway to link HR-DDS with the GHRSSST Match-up Database (MDB) system (described below) to create a complete set of Web-based interactive

diagnostic tools that better characterize both the magnitude and sources of errors not only in satellite-derived SST fields but also in model and analysis system outputs. Tools are provided with the HR-DDS portal, which permits download of comma separated value (CSV) files or Unix TAR archives containing only information chosen by the user.

The GHRSSST Match-up Database
An MDB of collocated satellite and in situ SST is required by GHRSSST for quality control of satellite SST data sets, in particular, for deriving or verifying SSES using in situ SST measurements from ships, buoys, and profiling floats. Such measurements provide a reliable, independent reference data set that

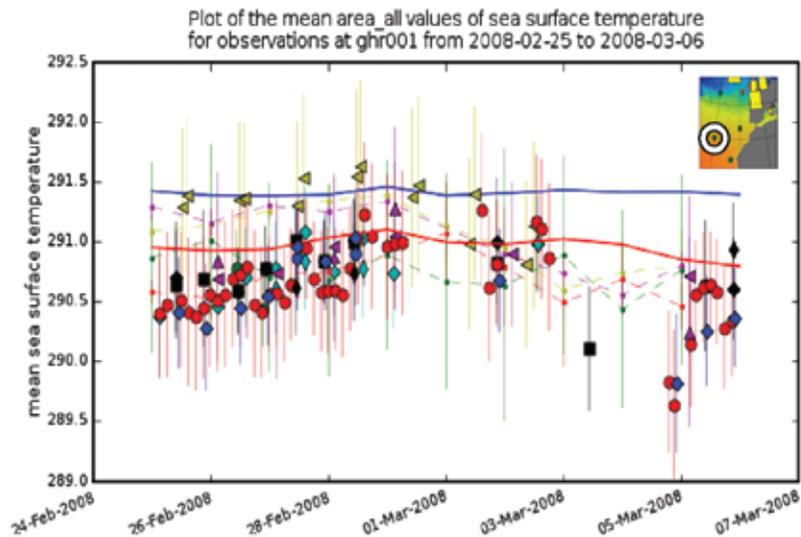
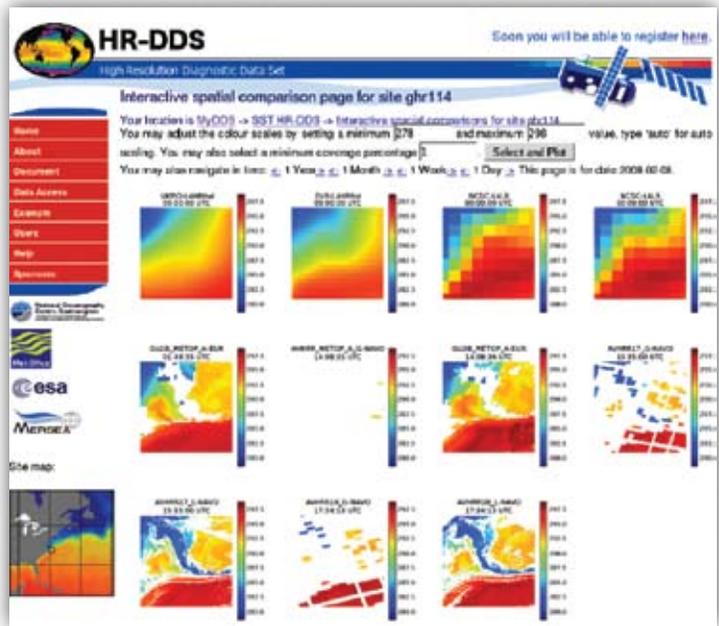


Figure 4. Examples of diagnostic data set (DDS) images (top) and time series of observational data for a variety of satellites and model SST outputs (bottom). The high-resolution DDS (HR-DDS) provides updates to all data sets in near-real time. Solid lines indicate model outputs, dotted lines analysis data sets, and large symbols measurements. SST units are degrees Kelvin (K).

must be matched in space and time to satellite measurements. Although several independent MDB systems have previously been created by agencies responsible for particular SST products, their formats are diverse, their in situ data sources may be different, and they do not share uniform quality control and spatial/temporal match-up criteria. These important differences make it difficult to compare MDB analyses and SSES of different SST products with each other, and the GHRSSST MDB is intended to address these issues. In situ and satellite data are collocated on a daily basis within ± 25 km and six hours of the satellite overpass as a “worst-case” scenario, and the match-up criteria can be spatially and temporally constrained further as required. In situ temperature data sources include all near-surface measurements (thermosalinographs on ships and thermometers on drifting and moored buoys) and data from profiling sensors such as Argo floats, ship-deployed expendable

bathythermographs (XBTs), and conductivity, temperature, depth (CTD) sensors. Between 100,000 and 150,000 match-ups are registered each month within MDB. All the ancillary data attached to L2P and L4 products are available for each satellite match-up in MDB. By adopting a single source of independent, quality-controlled, in situ data and automating the match-up procedure for all satellite data sets, GHRSSST MDB ensures that all match-ups are computed with the same in situ data and with the same level of quality; this procedure removes any ambiguity introduced by different groups producing their own independent uncertainty. Furthermore, it provides a resource that can be used to investigate the definition of SSES, test different SSES approaches, and verify other uncertainty estimation schemes. It furnishes a mechanism for incorporating new satellite-derived SST fields, such as from recently launched instruments, in an effective and efficient manner to ensure continuity in a quantitative sense across many spacecraft

missions (access to the GHRSSST-PP MDB can be gained at <http://www.medspiration.org/tools/mdb/>).

The GHRSSST-PP Multi-Product Ensemble (GMPE)

This system uses ensemble techniques to investigate SST analysis differences using both analyses and observational products. GMPE allows operational agencies to assess the relative performance of an L4 product against a “consensus” standard L4 SST product. Each day, a median average SST map from 10 international operational global coverage SST analysis products is calculated after their differing analysis grids have been homogenized by area averaging onto a standard 0.5° latitude/longitude grid. The GMPE ensemble is updated each day and output data sets are available together with a variety of diagnostic and anomaly plots on a daily basis (see <http://www.ghrsst-pp.org/Todays-global-SST.html>). Figure 5 is an example of GMPE output.

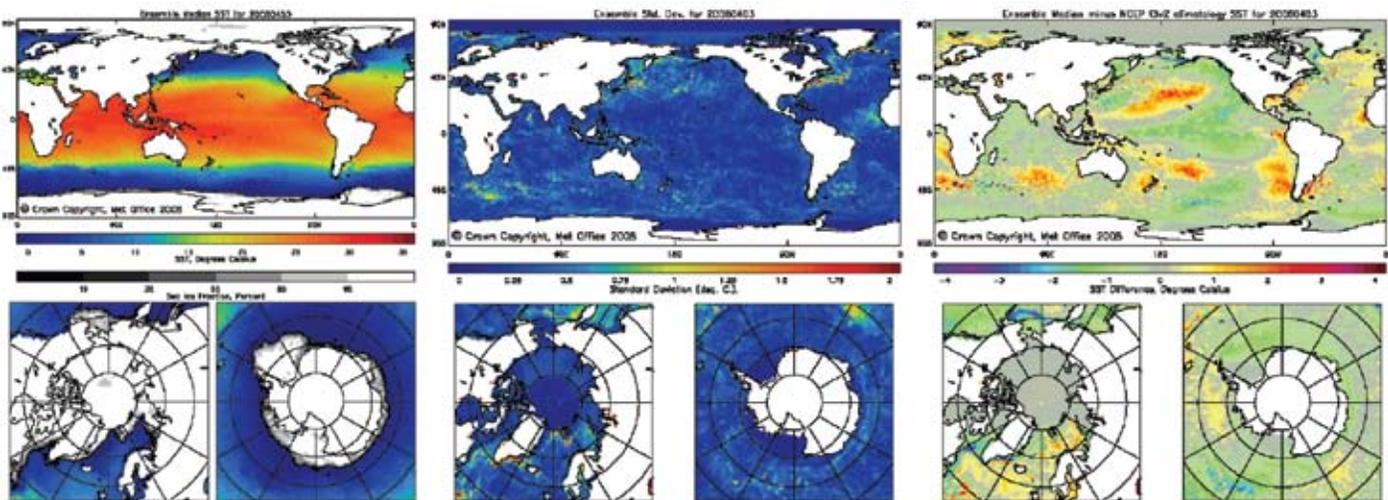


Figure 5. The GHRSSST-PP Multi-Product Ensemble (GMPE). (left) Median SST ensemble. (center) Median ensemble standard deviation. (right) Ensemble median minus US National Weather Service National Centers for Environmental Prediction Olv2.0 climatology for April 3, 2008.

THE GHRSSST-PP REGIONAL/ GLOBAL TASK SHARING FRAMEWORK (R/GTS)

At the core of GHRSSST-PP's success was the international collaboration on which it was based. The main agencies responsible for operating satellite SST sensors and for producing the primary SST data sets worked with ocean scientists familiar with the processes affecting remote sensing of SST and with key operational users of SST data to develop a rule base for the sharing, indexing, processing, quality control, archiving, analysis, and documentation of SST data from diverse sources. These rules are specified in the GHRSSST-PP data processing specification document (GDS; Donlon et al., 2006), which defines clearly the input and output data specifications, data processing procedures, algorithms, and data product file formats that are common to each GHRSSST-PP subsystem. The group is currently developing a GDS-v2.0, incorporating lessons learned and preparing for the future. In order for the GHRSSST R/GTS framework, illustrated in Figure 6, to function, all GHRSSST products must strictly follow the common GDS when generating L2P and L4 data. As a result, users with tools to read data from one Regional Data Assembly Center (RDAC) can draw data from any of the others and/or the Global Data Assembly Center (GDAC) with confidence. Agreement and commitment to GDS facilitated each existing agency's contribution of a part of the necessary international effort through the R/GTS system. This system is a distributed modular model with a hierarchical distinction among RDAC, GDAC, and the Long-Term Stewardship and Re-analysis Facility (LTSRF). The

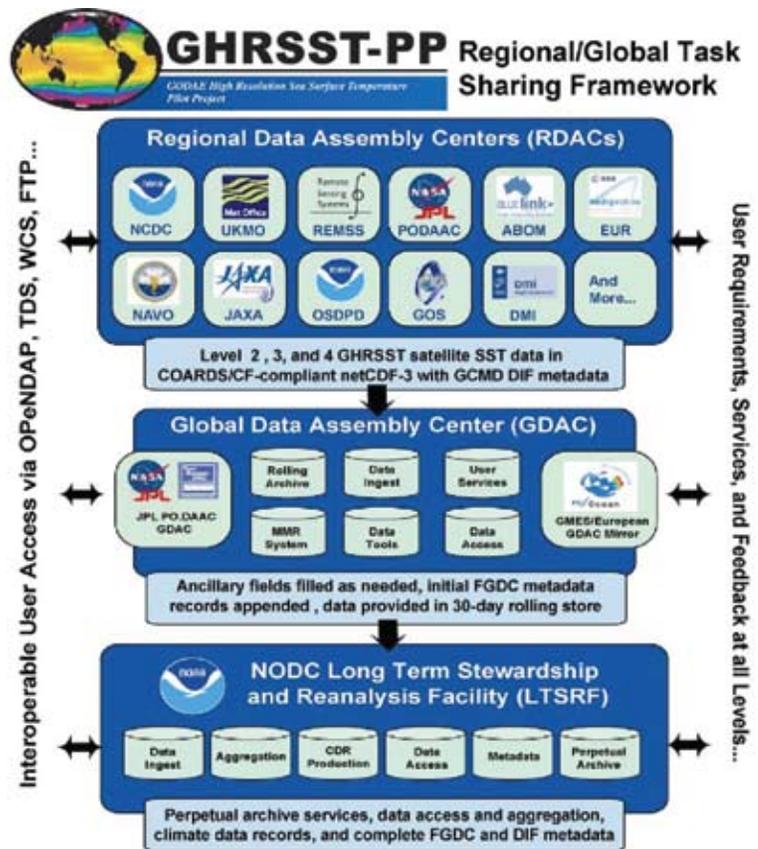


Figure 6. The Regional/Global Task Sharing (R/GTS) framework that established an international set of Regional Data Assembly Centers (RDACs), each of which delivers data to a Global Data Assembly Center (GDAC; see <http://ghrsst.jpl.nasa.gov>) and the regional user community. Data were and continue to be served from GDAC to near-real-time users and applications for 30 days before the data are sent to the Long-Term Stewardship and Reanalysis Facility (LTSRF; at <http://ghrsst.nodc.noaa.gov>) for long-term archive, stewardship, provision to delayed mode users, and future climate data record (CDR) production.

GHRSSST R/GTS, fully described in Donlon et al (2007), has served a significant amount of SST data to the scientific and operational ocean-atmosphere community. The success of R/GTS within GHRSSST-PP may serve as a model for other international projects making a contribution to the Global Earth Observation System of Systems (GEOSS).

APPLICATIONS

The GHRSSST system provides users, for the first time, with standardized, quality-flagged, simultaneous, and timely

access to a wide and near-complete range of global satellite SST measurements. Users have full benefit of the complementary qualities of the individual data sets. For example, by using appropriate analysis schemes, the coverage and cloud penetration afforded by microwave sensors can be combined with the higher spatial resolution offered by infrared sensors and the excellent time resolution of geostationary sensors, as well as the special advantages of other individual sensors, such as the dual-view atmospheric correction provided by

the Advanced Along-Track Scanning Radiometer (AATSR). The GHRSSST system provides most of the data in a common format, and SSES allows users, automatically if they wish, to screen, select, and weight the SST values they use in a scientifically valid way. The GHRSSST system provides an excellent and unprecedented opportunity for operational users to gain access to a wider range of SST data and, also, to interesting opportunities for scientific users studying mesoscale or larger-scale oceanic processes. For these reasons, the successful application of GHRSSST data products and services within operational, scientific, and commercial sectors was at the center of GHRSSST-PP and remains so in the subsequent GHRSSST activities. An important goal of GHRSSST-PP R/GTS was the operational uptake of products, which would happen only if numerical weather prediction (NWP) systems were able to demonstrate useful improvement in their forecast skill. This test is one of the ways by which the success of GHRSSST-PP will be judged. Primary applications include NWP, ocean forecasting, and climate and seasonal forecasting.

GHRSSST-PP worked together with several national meteorological services (including the Japan Meteorological Agency, UK Met Office, Norwegian Meteorological Institute, Australian Bureau of Meteorology, Danish Meteorological Institute, and US Fleet Numerical Meteorological and Oceanographic Center) to ensure that high-quality, readily accessible SST data products, tailored to their requirements, were delivered on an operational basis. For example, the Met Office has recently developed a system called the

Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), which is based on all available GHRSSST-PP data together with in situ observations to provide a $1/20^\circ$ global coverage resolution SST product on a daily basis (see http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html). OSTIA data are now used by all operational NWP applications at the Met Office and at the European Centre for Medium Range Weather Forecasting (ECMWF). Application development at the Physical Oceanography Distributed Active Archive Center (PO.DAAC) is currently focused on integrating GHRSSST products into coastal decision-support systems and marine resource management (e.g., US Integrated Ocean Observing System, IOOS). Making satellite SST data sets accessible in this way releases both operational and scientific users' time to concentrate on applying the data rather than gaining access to them. The number of users as of September 2008 totals 25,544 from 48 countries, and data volumes served by the GDAC and LTSRF systems are ~ 150 gigabytes per month. Finally, it is worth noting that TV5 Monde, the world's second largest television network, has used GHRSSST data products in the Mediterranean Sea (from the ESA Medspiration project) as part of its Internet-based international meteorological service, highlighting the interest in the provision of SST maps to the general public.

TRANSITION TO OPERATIONS AND THE FUTURE

As GODAE came to an end, GHRSSST-PP needed to evolve. In terms of the challenges that GHRSSST-PP began

to tackle, particularly in the area of uncertainty estimation for SST retrievals, a considerable amount of work remains. Furthermore, many users now rely upon the R/GTS framework (see Figure 7) that has evolved as a bottom-up development driven by real user needs. At the Ninth GHRSSST-PP Science Team meeting, this pilot project was closed, but the 80 participants, representing many user/producer communities, unanimously agreed that a follow-on activity was required. A new collaboration was developed, called the Group for High-Resolution Sea Surface Temperature (GHRSSST), that will continue to manage R/GTS, GDS-v2.0, and the user/producer need to continually collaborate and learn from each other. GHRSSST will also focus more attention on the production of SST climate data records as part of the reanalysis project in order to satisfy the need for a merged, long-term SST data set through the satellite era. Collaboration with GCOS in this respect has led to exciting new developments such as studying the differences between comparable data sets using dedicated tools (see <http://ghrsst.nodc.noaa.gov/intercomp.html> for more information). Focus will also be placed on the production of higher-resolution (< 5 km) regional and global data sets.

SUMMARY AND CONCLUSIONS

The GODAE High-Resolution SST Pilot Project has harnessed the attention and contribution of many international users and producers of satellite SST. It has successfully built and nurtured a framework in which the exchange of satellite SST data has flourished and given new life to the study of high-resolution SST using satellite and in situ data.

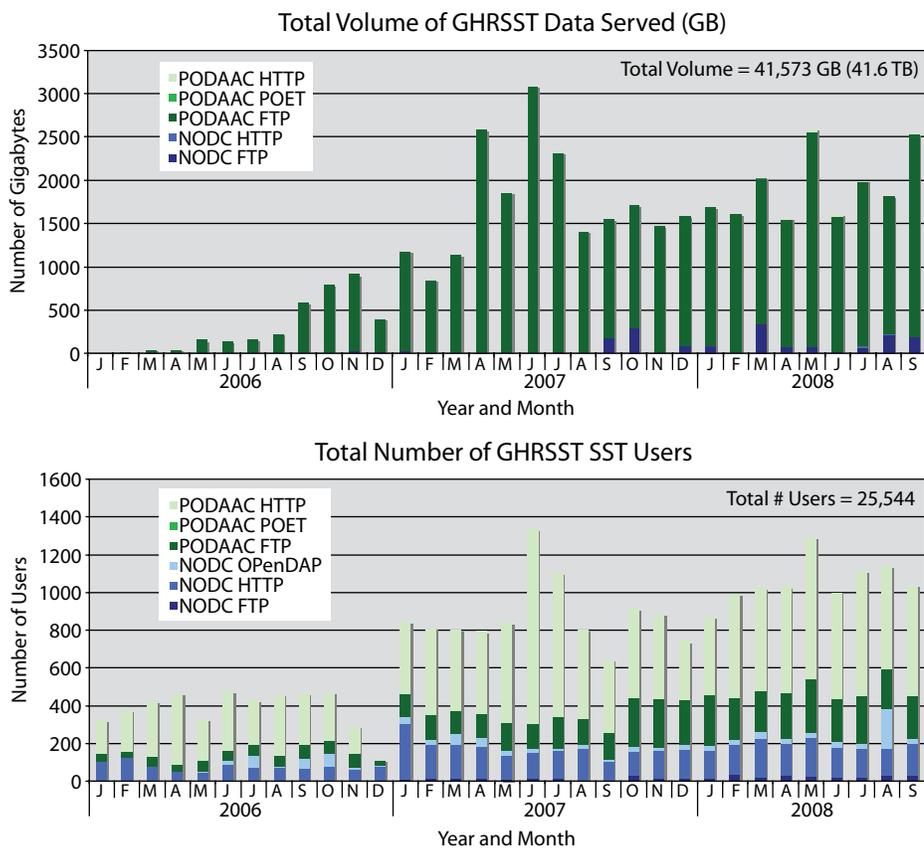


Figure 7. (top) Volume of data acquired by users each month by product access protocol for GHRSSST at GDAC and LTSRF between January 2006 and September 2008. (bottom) Number of users by access protocol at GDAC and LTSRF each month. Users from at least 48 different countries have accessed GHRSSST data.

Applications have demonstrated positive impact in ocean and atmospheric forecasting systems, and a new generation of data products and services to serve these and other users has been built and is operated on a day-to-day basis. GHRSSST-PP successfully demonstrated that GODAE requirements can be met. A new collaboration—the Group for High-Resolution SST—has been initiated to build on the lessons learned during the pilot project. It will continue the evolution of high-resolution SST data sets in near-real time, serve the needs of data assimilation systems, and develop SST climate data records. Full information can be found at <http://www.ghrsst-pp.org>.

Finally, it must be noted that the success of GHRSSST-PP stems from the agencies and offices that have supported its activities over the last eight years, allowing a talented and dedicated group of scientists and operational entities to work together successfully to bridge the gap between operations and science. All good operational systems are underpinned by excellent science, and GHRSSST-PP has endeavored to provide a forum in which operational systems and scientists can meet and discuss problems and solutions to address the real-world challenges associated with the application of high-resolution SST data sets. 

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