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VARIATIONS

Motivations for the U.S. CLIVAR's Phenomena, Observations and Synthesis Panel (POS)

by David M. Legler, Director

Observations of the coupled climate system are critical cornerstones of scientific research, predictions, as well as monitoring. New observations lead to new discoveries, insights, knowledge, and capabilities. U.S. CLIVAR strives to motivate, encourage, and coordinate the development and continuation of a climate observing system, especially, but not exclusively, components for the ocean. The ocean observing system has seen remarkable growth (e.g. Argo, drifting buoys, tropical moored array) over the past five years, and critical ocean-observing satellite missions (Jason-1, Quikscat) have been extended. To fully realize the value of these observing capabilities, we also must develop and improve monitoring tools and products as well as syntheses that assimilate available observations within dynamical mod-

Continued on Page Two

IN THIS ISSUE

Underwater Gliders for Ocean Climate Observations

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Long range underwater gliders have recently made the transition from fantasy to reality, generating considerable community enthusiasm to apply them to a wide range of problems. As with any observational technique, gliders have both promise and limitations. Their most promising role for ocean climate observations is to make high spatial resolution sections repeatedly, autonomously, and at very low cost compared to conventional methods involving ships or moorings. While they provide profiles, as ARGO floats do, the time and location of glider observations is remotely controllable. Gliders can collect repeat observations on a prescribed spatial grid tailored to provide a description of how the ocean evolves in space and time on relevant scales. They provide a means for monitoring boundary currents, of particular importance to ocean climate.

The seminal attribute of existing gliders is that they are inexpensive tools with which to sample the upper ocean. They cost the equivalent of a few days of ship time to purchase plus only a couple more to operate for several-month missions. They relay data ashore within hours of collection and can be controlled globally via the internet.

Three models of underwater gliders currently have been developed and tested for purchase: Spray, Slocum, and Seaglider, developed by Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution, Webb Research Corporation, and the University of Washington, respectively. All three are roughly the same size (mass ~ 50 kg), hence easily handled manually by two people(Figure 1). Descriptions and further references can be found in Rudnick et. al. (2004).

Underwater gliders are buoyancy-powered devices that glide slowly (~0.5 kt) along saw-tooth path trajectories through the ocean. They trade speed for range and endurance: halving speed doubles range and quadruples endurance, a result of the quadratic drag law. They lose their ability to navigate when they travel at speeds near or below the speed of currents through which they travel. Their wings provide propulsion by converting buoyancy generated by vehicle displacement volume variations to forward motion. In contrast to typical aeronautical gliders, ocean gliders were designed to fly along paths steeply sloped compared to environmental property surfaces.

Gliders have held the record for autonomous underwater vehicle (AUV) mission endurance and range throughout the current millennium. The longest mission to date lasted over 7 months and covered 3750 km, accomplished by a Seaglider in the Labrador Sea. Longer range missions are planned for gliders with improved endurance due to more

Continued from Page One

eling frameworks in order to provide global gridded products (a table of links to U.S.-lead ocean synthesis products is now available on the U.S. CLIVAR web page).

Observations and synthesis are two of the areas of focus for the US CLIVAR Phenomena, Observations, and Synthesis Panel (POS). U.S. CLIVAR has been working closely with the observational community through the POSP and the International CLIVAR Global Synthesis and Observations Panel (GSOP) to coordinate activities and continue motivation for the climate observing system.

In this issue we highlight the successful introduction of new autonomous vehicle technology for ocean profiling. Additionally, we report on the development of a new generation of high-resolution SST products, NASA's new atmospheric reanalysis project, and receive an update on the status of the deep-ocean measurement program initiated by the U.S. CLIVAR and Carbon communities.

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and better batteries. Primary lithium cells provide the longest range and endurance. One year glider missions will soon be possible. Current developments include thermally powered, under-ice, and full-ocean depth models.

Gliders are versatile. They can be commanded to visit a sequence of way-points, stay in one location, or steer a constant heading, interchangeably on the same mission. Where, when, and how they sample can be adjusted each time they communicate at the sea surface. They can 'hold station' as well as a moored surface buoy in deep water. They measure temperature, conductivity, dissolved oxygen, several bio-optical parameters, and currents. Sensor payload requirements are small size, low power, and low hydrodynamic drag.

They typically collect profiles with depth resolution comparable to shipboard CTD casts, but with much higher horizontal resolution. Gliders are thrifty enough to be able to repeat a survey line several times in a mission. Persistence is one their most endearing and rewarding qualities.

Gliders have operated through the most severe seas and across the mightiest currents the ocean has to offer. They have worked through Labrador Sea winters and a western Pacific typhoon. They have crossed the Gulf Stream and Kuroshio, and crossed the Alaska Stream, the California Current system, the Labrador Current, and several other boundary currents many times. They have worked in deep water and over the continental shelf and from the tropics to the Arctic Circle. Glider tracks executed between July 2003 and February 2006 are drawn in Figure 2.

As the tracks in Figure 2 attest, glider speeds limit how well they can be controlled in regions of strong current. Since currents are typically surface intensified, deep dives tend to mitigate this limitation. Other constraints faced by gliders are sensor suites limited by power, size, and hydrodynamic smoothness. Their lithium batteries pose special challenges for air transport. Along with other self-navigating AUVs, export of gliders from the U.S. is regulated for national security and anti-terrorism reasons.

An example of how gliders can be used to observe both the spatial structure of oceanic features and the temporal structure of their variability on seasonal

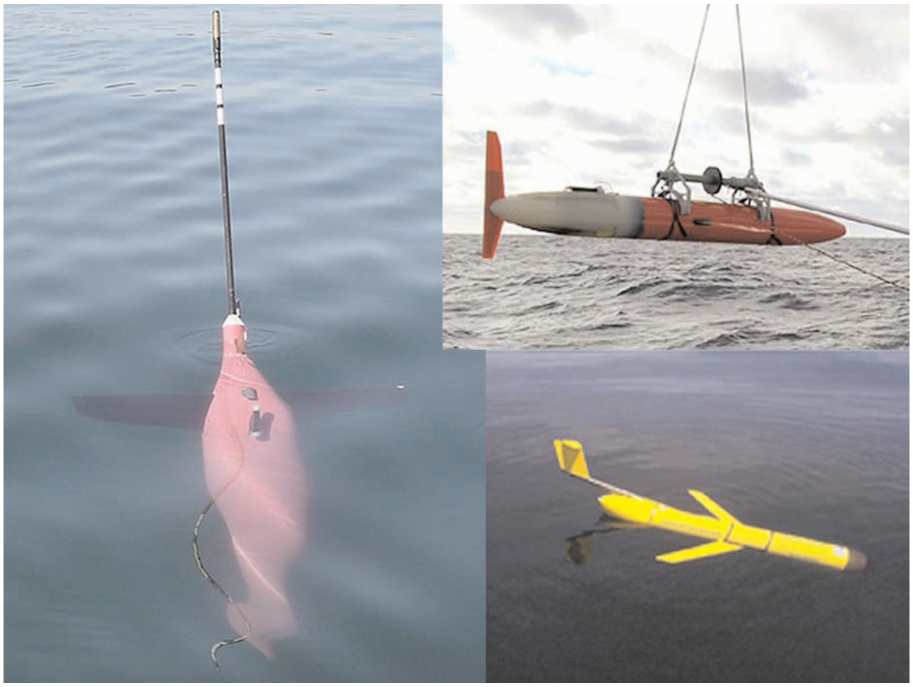


Figure 1. Seaglider, Spray, and Slocum underwater gliders (clockwise from left). The vehicles are of similar size and weight (~2m long, ~50kg) and can be launched and recovered manually by two people.

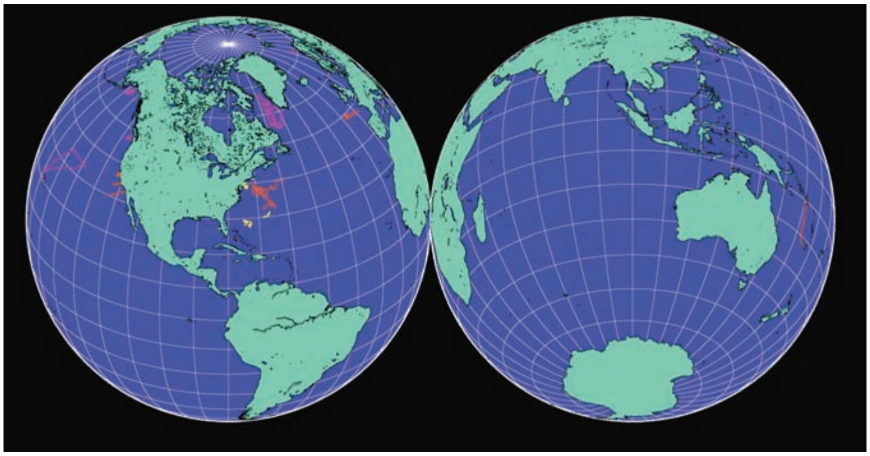
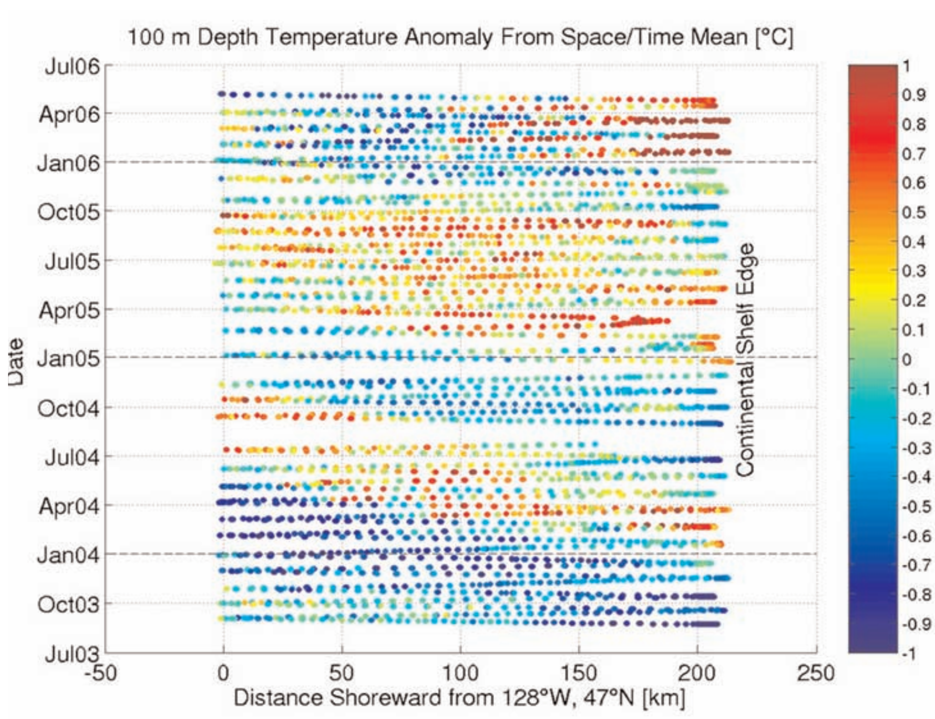


Figure 2. Tracks of Seaglider (pink), Spray (orange), and Slocum (yellow) missions from July 2003 to February 2006 carried out by the University of Washington, Scripps Institution of Oceanography, the Woods Hole Oceanographic Institution, and Rutgers University. Note there are missions of limited spatial extent in the East China Sea, Irish Sea, Norweigan Sea and the west coastal waters of Australia.

and longer scales is given in Figure 3. It shows the temperature anomaly at 100 m depth from the space-time mean on a pair of transects normal to the coast, extending seaward 220-240 km from the continental shelf edge. The continuing repeat survey, started in August 2003, is indicated by the V-shaped pink curves with an apex at 47°N, 128°W offshore western North America in Figure 1. Each leg of the V-shaped pattern across the NE Pacific boundary current system takes about 2 weeks to complete, with dives every 8 hr to 1 km depth along glide slopes of about 1:3 (vertical to horizontal). Individual missions last as long as 5 months with vehicles being launched and recovered from small boats on day trips from shore. Both a prominent annual signal that propagates offshore with a wavelength near 350 km and an interannual warming trend are evident over the 32 month sequence of sections to date. These signals are evident despite the presence of eddies and internal waves in the anomaly field plot-

Figure 3. Temperature anomaly [°C in color] over 32 months from the space-time mean at 100 m depth plotted against date and distance shoreward from 47°N, 128°W over the continental slope offshore of Washington. These data were collected from a sequence of single Seaglider missions following the V-shaped pink track shown in the northeast Pacific in Figure 2. A symbol is drawn for each Seaglider crossing of the chosen depth horizon. Anomalies were calculated from depth interpolation along slanting glide paths without any spatial or temporal filtering to remove eddy or internal wave noise.



ted, showing how sampling by a comparatively slow moving vehicle can be effective in resolving spatial structure associated with seasonal and lower frequency oceanic variability

The cost of collecting the data shown in Figure 2 is comparable to about 10 days of ship time, or about what it would cost a ship to occupy the pattern twice including transit to and from port.

Gliders feature prominently in plans for the NSF Ocean Research Interactive Observatory Network (ORION) program's Ocean Observatories Initiative (OOI) coastal and global components. While they comprise at most a few percent of the infrastructure costs anticipated by the OOI, they are expected to provide most of the spatial context of ocean circulation observations currently planned in ORION. Multiple continuous repeat transects in the coastal regions of the U.S., particularly off its west coast, are projected for the next 30 years. Continuous glider repeat surveys around OOI global component moorings is expected to provide estimates of advective contributions to observed temporal changes.

Glider observations are also planned for key elements of the ocean's general circulation. Gliders have been used to collect sections across the Gulf Stream and Kuroshio and regular observing programs for such boundary currents are an active subject of discussion. Glider transects along the Iceland-Scotland Ridge to simultaneously observe Atlantic inflow to and deep overflow from the Nordic Seas are scheduled to begin in June 2006. With glider endurance expected soon to exceed one year, missions in remote subpolar regions can be undertaken without the need for field operations in severe sea and weather conditions. An under-ice glider that navigates acoustically via moored RAFOS sound sources is to be deployed in September 2006 to monitor heat and fresh water exchange between Baffin Bay and the Labrador Sea through Davis Strait. The prospect of a full ocean depth glider makes feasible repeat transects across the Antarctic Circumpolar Current on year-long missions. The prospect of a glider that draws power from the ocean's thermal stratification makes feasible multi-year missions in tropical and subtropical regions.

In recent years, the ARGO program has established a network for monitoring large scale climate signals of the ocean interior. Glider technology is poised to make a complementary contribution to knowledge and understanding by resolving the many smaller scale features of which ocean circulation is comprised.

Acknowledgements

The contributions of C. Lee, D.Rudnick, and O. Schofield to the tracks drawn in Figure 1 are gratefully acknowledged. Data in Figure 2 is from a project of the author with C. Lee at the University of Washington.

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U.S. CLIVAR Madden-Julian Oscillation Working Group

In spring 2006, U.S. CLIVAR established the Madden-Julian Oscillation (MJO) Working Group (MJOWG). The formation of this 2-year limited lifetime WG was motivated by: 1) the wide range of weather and climate phenomena that the MJO interacts with and influences, 2) the fact that the MJO represents an important, and as yet unexploited, source of predictability at the subseasonal time scale, 3) the considerable shortcomings in our global climate and forecast models in representing the MJO, and 4) the need for coordinating the multiple threads of programmatic and investigator level research on the MJO. Near-term tasks involve the development of metrics for assessing model performance in both climate simulation and extended-range/subseasonal forecast settings, as well as designing and coordinating multi-model experimentation and analysis to diagnose and improve model shortcomings and assess MJO predictability characteristics and present-day prediction skill. In addition, the WG will help to coordinate MJO-related activities across other programmatic bodies (e.g., GEWEX, International CLIVAR, Thorpex) and will explore the applications and potential user base for subseasonal predictions based on the MJO. Workshops that address these issues are being planned, with results being communicated in summary reports and peer-reviews articles. For additional information on the working group, see

www.usclivar.org/Organization/MJO_WG.html

NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA)

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Atmospheric retrospective analyses (or reanalyses) synthesize temporally and spatially irregular observations to provide a spatially complete gridded meteorological database spanning the historical data record. The first and second rounds of reanalyses (Kalnay et al., 1996; Uppala et al., 2005) facilitated tremendous research in weather and climate in the community. These research efforts feed back into the reanalysis system by identifying future development pathways. This leads to improvements in our models, data assimilation techniques and the quality of the observations, which should then result in improvements in subsequent retrospective analysis.

There are substantial differences between the existing reanalyses. In part, these differences are an important measure of the uncertainty in any reanalysis product, due to deficiencies and differences in the assimilating models and how the models interact with the assimilated data. Such differences can be exacerbated by observing system changes that are often manifest in reanalysis time series by abrupt variations or discontinuities. These impacts from observing system changes must be distinguished from real climate variations. As an example, consider the 25 year Japanese Reanalysis (JRA25, http://www.jreap.org/) in which total column water vapor from Special Sensor Microwave/Imager (SSM/I) are assimilated, beginning in June 1987. While there is some evidence that the SSM/I assimilation has improved the quality of the reanalysis precipitation, a discontinuity is apparent in the time series (Figure 1). On the other hand, in 1995 there is a shift in the precipitation anomalies that grows in time. This change also appears in the NCEP/NCAR reanalysis, NCEP-2 reanalysis and ERA-40 reanalysis (not shown) and may be related to a possible phase change in the Pan Pacific Decadal variability (Chen, 2005).

The Global Modeling and Assimilation Office (GMAO) at the NASA Goddard Space Flight Center is developing a new data assimilation system to synthesize the large volume of the Earth Observing System (EOS) era satellite and other observations (e.g. Bosilovich et al., 2007), with the goal of improving our understanding and predictions of the Earth's environment and climate. Using this system for reanalysis allows us to better address such questions as: What is the impact of new data on the climate time series? How do we place new satellite observations into the context of the long-term climate record?

To this end NASA is producing the Modern Era Retrospective-analysis for Research and Applications (MERRA). The MERRA project supports NASA's Earth science interests by:

1) utilizing the NASA global data assimilation system to produce long-term (1979-present) synthesis that places the current suite of research satellite observations in a climate data context;

2) providing the science and applications communities with state-of-the-art global analyses, with emphasis on improved estimates of the hydrological cycle on a broad range of weather and climate time scales.

In this brief article, we will summarize our plans for MERRA.

Model and Data Assimilation

The data assimilation system (DAS) for MERRA consists of the Goddard Earth Observing System version 5 (GEOS-5) atmospheric model coupled to the Grid-point Statistical Interpolation (GSI) analysis scheme being developed by the Environmental Modeling Center of the National Centers for Environmental Prediction (NCEP/EMC) and GMAO.

The GSI analysis solver was developed at NCEP to support inhomogeneous and anisotropic 3D background error covariances (e.g., Wu et al., 2002; Derber et al. 2003; Purser et al. 2003). The data streams currently assimilated by the DAS are shown in Table 1. Jack Woolen (NCEP) has provided an updated conventional observation data set for reanalyses.

The GEOS-5 atmospheric model is a weather-and-climate capable model using the finite-volume dynamical core (Lin, 2004). In developing GEOS-5, attention has focused on the representation of moist processes (see gmao.gsfc.nasa.gov/systems/geos5/). The tropical precipitation morphology has been analyzed in Bacmeister et al. (2006). The moist physics package uses a single phase prognostic condensate and a prognostic cloud fraction. Two separate cloud types are distinguished by their source: anvil cloud originates in detraining convection, and large-scale cloud originates in a PDF-based condensation calculation. Ice and liquid phases for each cloud type are considered. Once created, condensate and fraction from the anvil and statistical cloud types experience the same loss processes: evaporation of condensate and

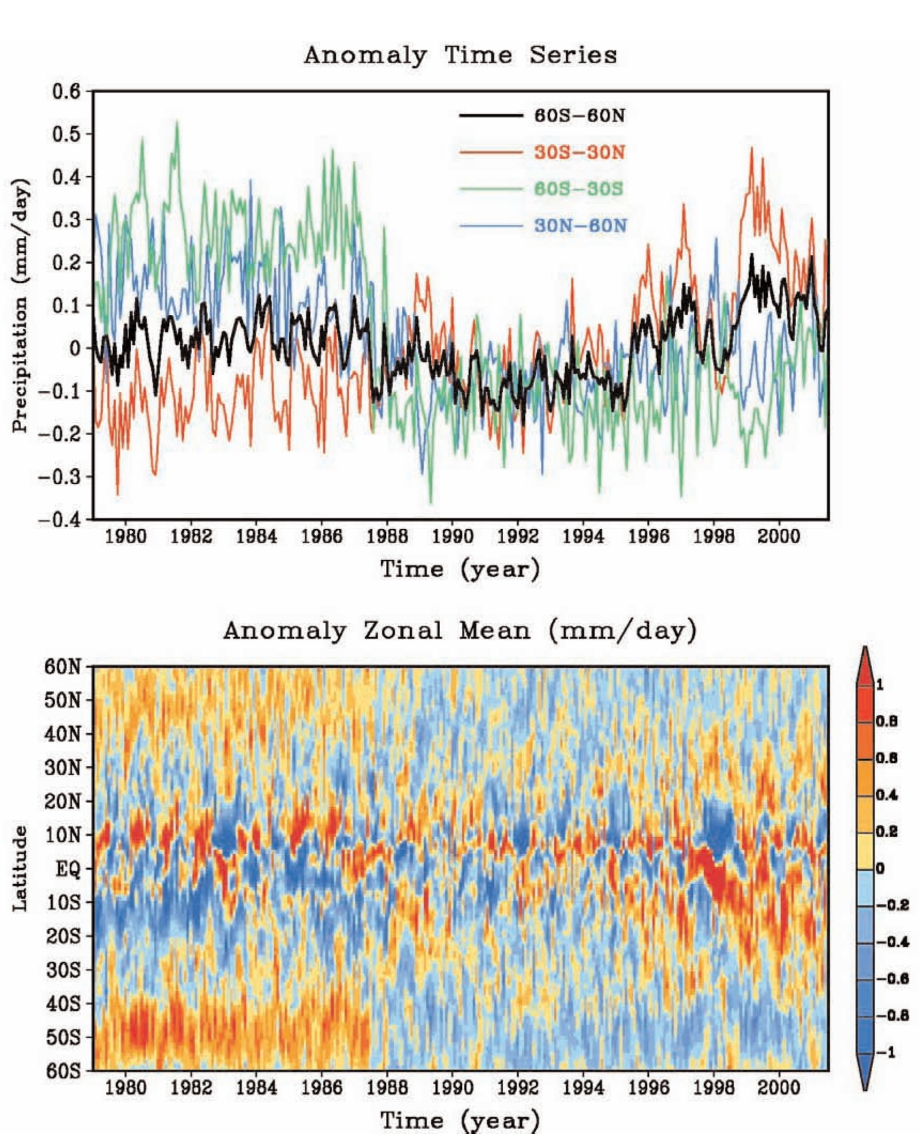

Figure 1.The time variation of monthly precipitation in JRA-25 reanalysis. Upper plot: the regional mean of the time series of anomalies, which defined as the deviation from the mean annual cycle. Black: 60S-60N; red: 30S-30N; green: 60S-30S; blue: 30N-60N. Lower plot: the latitude-time distribution of the zonal mean of the precipitation anomalies.

fraction, autoconversion of liquid or mixed phase condensate, sedimentation of frozen condensate, and accretion of condensate by falling precipitation.

Developments of GEOS-5 were guided by a realistic representation of tracer transports and stratospheric dynamics. The ozone analysis of the DAS is input to the radiation package along with an aerosol climatology. GEOS-5 is coupled to a catchment-based hydrologic model (Koster et al., 2000) and a sophisticated multi-layer snow model (Stieglitz et al., 2001). MERRA will not include a coupled ocean component.

MERRA Validation and Production

MERRA will use a 1/2 degree resolution model and analysis, with 72 levels to 0.01 hPa. A 2-degree resolution version of the MERRA system (called Sweeper) is being prepared and is planned to run for the period 1972 through 2005. From the software engineering point of view, the Sweeper will progress quickly through the input data, identifying problems that would otherwise slow the MERRA production. The Sweeper will be spilt into 4 streams, 3 of which will provide 5 years of analysis spin up to the land surface states.

Full resolution validation experiments will be run for 2001 and 2004, prior to initiating MERRA production. The water cycle, specifically global precipitation and evaporation, as well as the dynamical circulation and radiative processes are being evaluated. An interdisciplinary user group, external to the GMAO, will have access to the validation data and review the validation results. MERRA production will be accomplished through three streams (Figure 2). The streams will be initialized by the Sweeper run, and then spun up one more year to address the downscaling of the coarse grid data. When one stream catches another, there will be some overlap in the processed data. We intend to continue some of this overlap to evaluate the uncertainty and sensitivity of the analysis system to initial conditions.

In 1987, SSM/I becomes available and will strongly affect the water cycle. Subsequent advanced data products from EOS-era satellites, such as AIRS, TMI and QuikSCAT, likewise contribute to the analysis data and impact the climate record. To help assess the effect of new data on the reanalysis, an additional analysis will continue with the Reduced Observing System Baseline (ROSB) data stream. The ROSB will use only the non-satellite conventional data and the TOVS data for the entire period. With the ROSB we will assess the impact of the modern observing system on forecasts and analyses (e.g. water and energy budgets) and begin to understand how to incorporate new instruments and data into the long term climate time series.

Data Products and Portals

While disk technology and internet bandwidth still limit data distribution, they are improving rapidly with time. So, our product distribution plans are ambitious. The three dimensional data will be available at the analysis time, every six hours. Two dimensional and vertically

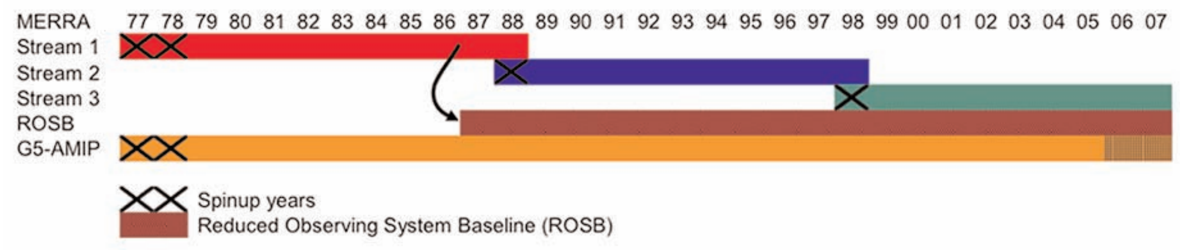

Figure 2. Configuration of MERRA production computing streams. The highest priority streams (1-3) include the full resolution output and complete input data. The Reduced Observing System Baseline (ROSB) will continue from Stream 1 but withhold new and advanced observing systems. G5-AMIP is a model-only integration to define the model's climate.

integrated fields will be available at hourly intervals. This will allow for detailed analysis into the variations of the diurnal temperature range and precipitation frequency statistics. Full budget information will be available in these data products, including the analysis increment. In addition, post processing of the data products to monthly means and monthly mean diurnal cycle (for the surface data) will be done. A reduced spatial resolution (2.5 degrees) data set will also be prepared at 6-hourly and monthly intervals.

Current estimates indicate that 100 TB of data will be available from online drives. We plan to use the Nomads system (Rutledge et al., 2006; http://nomad3.ncep.noaa.gov/), a flexible system that includes a quick look viewer, ftp, http and OpenDAP access to the data. The form of the eventual system is still being finalized but will include several additional portals into the online data holdings.

Summary

The GMAO is producing the Modern Era Retrospective-analysis for Research and Applications (MERRA) to support NASA's Earth science interests by placing the current suite of research satellite observations in a climate context, and by providing the science and applications communities with state-of-the-art global analyses.

The MERRA system is currently in the last stages of assembly and is entering final validation before production. The latest information and updates on MERRA can be found at http://gmao.gsfc.nasa.gov/merra/. Production should begin in the summer of 2006. It is anticipated that it will take 1.5 years to complete the time series. The terminus of the time series will likely be dictated by the lifetime of the computing platform; however, we expect that the time series will eventually include at least all of 2007. We expect to start making data available to the community prior to completion of the full time series.

Acknowledgements.

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Table 1. Input observation data sources and parameters.

Conventional Data	
	Radiosondes
	Pibal Winds
	Wind profiles
	Conventional aircrafft reports, ASDAR, MDCARS
	NEXRAD radar winds
	Dropsondes
	Surface land observations
	Surface ship and buoy observations
Satellite Retrievals	
	GMS, METEOSAL, cloud drift IR and visible winds
	MODIS clear sky and water vapor winds
	GOES cloud drift IR winds
	GOES water vapor cloud top winds
	SSM/I rain rate and wind speed
	TMI rain rate
	QuikSCAT wind speed and direction
	SBUV2 ozone (Version 8 retrievals)
Satellite Radiances	
	TOVS 1b Radiances
	DMSP SSM/I radiances
	GOES sounder TB
	Aqua/AIRS radiances (150 channels)
	Aqua/AMSU-A radiances

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The U.S. CLIVAR/CO2 Repeat Hydrography Program

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Scientists and measurement teams in the U.S. have for four years been carrying out a systematic, global re-occupation of select hydrographic sections called the US CLIVAR/CO2 Repeat Hydrography program. Jointly sponsored by the U.S. National Science Foundation's Physical and Chemical Oceanography programs and NOAA's Office of Climate Observation, with contributions from NASA and the U.S. Department of Energy, this work provides data aimed to quantify changes in storage and transport of heat, fresh water, carbon dioxide, and related parameters. The program integrates scientific needs and measurement strategies of the carbon and hydrography/tracer communities. In addition to efficiency, this coordinated approach is meant to facilitate scientific advances that exceed those of having individual programs. Scientific objectives include contributing to model calibration and validation, carbon system studies, heat and freshwater storage and flux studies, deep and shallow water mass and ventilation studies, and calibration of autonomous sensors.

Those scientific objectives are important both for operational activities and for research programs, such as CLIVAR (Climate Variability and Prediction) and global carbon programs. The CLIVAR/CO2 Repeat Hydrography program is an outgrowth of earlier programs with global scope, principally the World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Study (JGOFS) during the 1990s. These provided a full depth baseline data set that is used for detection of changes, and show where atmospheric constituents are entering the oceans. The new measurements are revealing information about the stability of internal pathways and changing patterns in ocean properties. They help to assess changes in the ocean's biogeochemical cycle in response to natural and/or anthropogenic activity. Global warming-induced changes in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning, can be followed through long-term measurements. Below the level of the Argo array (approximately 2000 m), repeat hydrography is the only global method capable of observing these long-term trends in the ocean. The program also provides data for sensor calibration (e.g., www.argo.ucsd.edu), and to support continuing model development that will lead to improved forecasting skill for oceans and global climate. The impact of the measurements is enhanced by broad and near immediate dissemination of data, use of the data to assess climate change, and a resource for model calibration of the climate system. The program also explicitly promotes training and learning for graduate students, postdoctoral scientists, and new scien-

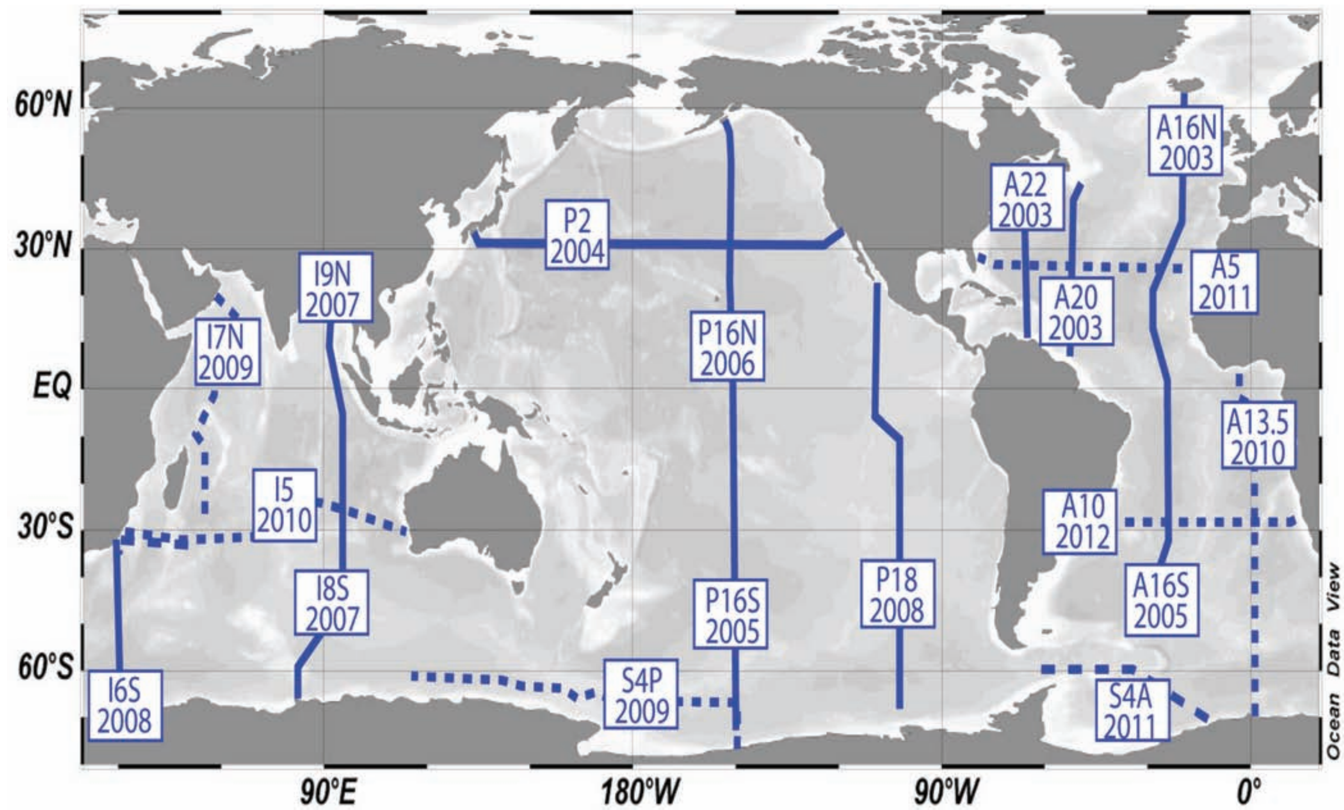

Figure 1. U.S. Repeat Hydrography Cruises

tists.

The field work consists of a timed sequence of basin-spanning transects which make up the primary data gathering effort. The pace and choice of transects reflects the program objectives, other international contributions, and the resources available to do the work. The transects are selected so that there is roughly one decade between these new occupations and the WOCE/JGOFS occupation. Basic global coverage includes a zonal cruise in each subtropical basin and sufficient meridional cruises to calculate inventories of carbon and tracers.

The work is primarily supported via a partnership between NSF and NOAA. Using an approach which was novel when the program began - but which has proved quite successful - the agencies provided support to collect the data and efficiently perform the quality control measures routinely carried out by providers of reference-quality data, and then the data are made public, typically within one month of the sea work. A key aspect of the program is that recognized data centers are involved in handling nearly every data stream from the sea program, hence data users can quickly find the data, and there is a recognized path to handle post-cruise data tasks. For example, the CTD and bottle data are handled post-cruise by the CLIVAR and Carbon Hydrographic Data Office (CCHDO), which continues key tasks of the WOCE Hydrographic Program Office. The CCHDO gathers together the CTD and water sample data, improves the adherence of the data to standard community format and content specifications, and assembles and provides relevant documentation. With the data from these cruises in such immediate use, but considering that as typical with early data, updates are required as the data are exercised and issues are identified. Utilizing the CCHDO provides a single source for data updates, merger, distribution, and availability to the archive at NODC.

The list of parameters measured (Table 1) on these cruises is aimed to be comprehensive within the scientific requirements, but feasible in terms of resources.

The other side of data numbers is data documentation, and in this regard the US program has standards equal to the reference quality of its numbers. Each data provider sends the documentation necessary to understand the origin and quality of the data, and the CCHDO assembles these plus adds all data comments received post-cruise plus records of action, the idea being to greatly enhance the long-term use of the data. This is truly meant to be a reference data set.

The program is based on the fundamental concept that data collected belong to the community, and are available to the community at large rather than being proprietary for the investigators involved in the project. The stringent data policy provides rapid and open dissemination, and the means for all data to undergo thorough quality control. The data files contain reference to the data originators and appropriate citation information.

A U.S. Oversight Committee makes

Table 1.

Level I Measurements (mandatory on all cruises; measured at highest spatial resolution)	**Level II Measurements (recommended measurements, coarser station spacing; coordinated with the core effort but funded by separate proposals).**	**Level III Measurements (ancillary measurements, may be regional or specific to individual cruise; extramural funding)**
DIC (Dissolved Inorganic Carbon)	Discrete pCO2	Chlorophyll
Total Alkalinity	14C by AMS	Primary Production
CTD pressure, temperature, conductivity	CCl4 and SF6	HPLC pigments
CTD oxygen	d13C of DIC	PIC
Nutrients (NO3/NO2, PO4, SiO3)	Fe/trace metals	HCFC
Dissolved oxygen	CTD transmissometer	d15N NO3
Bottle salinity	More complete underway system: nutrients, O2, Chl, DIC	32Si
Chlorofluro carbon tracers (CFC-11, -12, -113		18O of H2O
Tritium-3He		NH4
Total organic carbon (TOC, DOC and/or POC)		Low level nutrients
Total organic nitrogen		Total organic phosphorus
Surface underway system: T, S, pCO2		Upper ocean optical profile
ADCP shipboard		d17O of O2
ADCP lowered		Methyl halides

recommendations on changes in lines, sequencing, measurement teams, Chief, and co-Chief scientists, and other matters as required. They make recommendations on Level III measurements as they contribute to program objectives, and ship time, berths, and seawater sample volume available for analysis. They ensure smooth interactions with funding agencies and individual investigators, and that adequate support is provided for the data management structures. They serve as contact for coordinating with other national and international efforts, and coordinate with CLIVAR and Carbon program steering committees.

Each cruise leg is overseen by a Chief Scientist's team consisting of chief and co-chief scientists, and two graduate or post-doctoral assistants. The team is assembled by the oversight committee and participants are supported by the program, without need to propose separate fiscal support. This greatly helps the program aim to serve as a community resource for training and entraining new scientists. Efforts are made to broaden participation. For example, on some program cruises experience at sea has been provided to science teachers or undergraduates. Usually every berth available to the science party is filled.

The cruise plans are examined closely well ahead of time for any fine tuning due to scientific or logical considerations. Once commitments of the science parties is made the oversight committee hands off the detailed planning and execution of the work to the designated science party, meanwhile providing financial support, foreign observer travel, and so forth as required.

The sea work itself follows the approach proven successful during the 1990's WHP/JGOFS surveys: CTD/rosette stations at 55 km spacing (closer over boundaries, steep bathymetry, and across the equator; separately-proposed shallow trace metal casts at 110 km spacing are accommodated), use of a 36-place rosette with 10- or 12-liter bottles proven excellent for dissolved gas sampling (there is room for a lowered-ADCP), latest-generation hardware and procedures (overseen by consortia and working groups), extensive examination and processing of data at sea (including merging disparate bottle sample data), full support of quality coding, standard community data formats, and so forth. Some have observed that one of the legacies of the recent CO2 surveys and WOCE Hydrographic Program work was that we would know how to do it by the time we were done with it, and the success of this sea program confirms the point.

Thinking of the example of the parable of the six blind sages and the elephant, one suspects that the many contributors and beneficiaries of the U.S. Global Ocean Carbon and Repeat Hydrography program have rather different views of what this large, long program attempts and offers. Regardless, the fact is that this program of systematic, very carefully done, repeat basin-crossing hydrographic/carbon/tracer transects would never have got off the ground this decade were it not for the shared efforts and support from modelers, mappers, and other data users who needed to know just how, where, and at what rate key aspects of the World Ocean water column were varying on the ca. decadal to centennial time scales of interest to ocean climate studies.

Calendar of CLIVAR and CLIVAR-related meetings

Further details are available on the U.S. CLIVAR and International CLIVAR web sites: www.usclivar.org and www.clivar.org

Understanding Sea-level Rise and Variability
6-9 June 2006
Paris, France
Attendance: Invited
http://copes.ipsl.jussieu.fr/Workshops/SeaLevel/index.html

Holivar 2006 Open Science Meeting on Natural Climate Variability and Global Warming
12-16 June 2006
London, England
Attendance: Open
http://www.holivar2006.org

ECMWF Reanalysis Workshop
19-22 June 2006
Reading, England
Attendance: Open
http://www.ecmwf.int/newsevents/meetings

CCSM Meeting
20-24 June 2006
Breckenridge, Colorado
Attendance: Limited
http://www.ccsm.ucar.edu/

Arctic/Subarctice Ocean Fluxes (ASOF) Science Conference
28 June – 1 July 2006
Faroe Islands
Attendance: Open
http://asof.npolar.no/

VACS workshop on Predictability and Prediction of southern African climate variability and impacts of the neighboring oceans
10-13 July 2006
Tanzania
Attendance: Limited
http://www.clivar.org/organization/vacs/VACS_workshop.php

Ocean Carbon Cycle Science Workshop
10-13 July 2006
Woods Hole, Massachusettss
Attendance: Open
http://www.whoi.edu/sbl/liteSite.do?litesiteid=8453

Workshop on Climate Variability and Extremes during the past 100 Years
24-26 July 2006
Gwatt near Thun, Switzerland
Attendance: Open
http://www.iac.ethz.ch/people/stefanbr/workshop2006

U.S. CLIVAR Summit
26-28 July 2006
Breckenridge, Colorado
Attendance: Invited
Contact: http://www.usclivar.org

CLIVAR WGCM / AIMES Workshop: Next generation Earth System Models and emissions scenario requirements
31 July – 4 August 2006
Aspen, Colorado
Attendance: Invited
Contact: www.clivar.org

Climate Prediction Program for the Americas (CPPA) PI Meeting
14-18 August 2006
Tucson, Arizona
Attendance: Limited
http://www.climate.noaa.gov/cpo_pa/cppa/

NAME Science Working Group Meeting
17-18 August 2006
Tucson, Arizona
Attendance: Invited
http://www.joss.ucar.edu/name/

WCRP Observation and Assimilation Panel – 2nd meeting
28-30 August 2006
Ispra, Italy
Attendance: Invited
http://www.wmo.ch/web/wcrp/meetings.htm

NOAA Climate Diagnostics and Prediction Workshop
23-27 October 2006
Boulder, Colorado
Attendance: Open
http://www.cpc.noaa.gov/products/outreach/CDPW31.shtml

RAPID Climate Change Workshop
24-27 October 2006
Birmingham, England
Attendance: Open
http://www.noc.soton.ac.uk/rapid//rapid2006/index.php

Earth System Science Partnership Oppen Science Conference
9-12 November 2006
Beijing, China
Attendance: Open
http://www.essp.org/essp/ESSP2006/

Multidecadal to centennial global climate variability
15-17 November 2006
Honolulu, Hawaii
Attendance: Open
http://www.phys.uu.nl/~dijkstra/AMO/index.html

AGU Fall Meeting
11-15 December 2006
San Francisco, California
Attendance: Open
www.agu.org

3rd WGNE Workshop on Systematic Errors in Climate and NWP Models
February 12-16, 2007
San Francisco, California
Attendance: Open
http://www-pcmdi.llnl.gov/wgne2007

The measurement teams, each with direct scientific participation, provide the data, and the data management structure works to see that the data can be put to use nearly immediately.

If the program continues to proceed as intended - and as it has for its first four years - the integrated, carefully overseen approach should provide a near-ideal data set to help quantify long-term ocean changes on inter-basin to global spatial scales, thus moving beyond disparate measurements of local changes and providing the measurements which will underlie a developing global-scale appreciation of the changes and large-scale feedbacks between the ocean carbon cycle and climate.

The U.S. program completed three meridional North Atlantic transects (Figure 1) in 2003, a zonal North Pacific transect in 2004, meridional South Atlantic and South Pacific transects in 2005, and with the Pacific transect extended north to the Aleutians in 2006. Next up is a meridional Indian Ocean transect in 2007. Programs of other nations have been providing many of the zonal transects, such as the globe-circling Japanese BEAGLE expedition along 30 degrees south in 2003.

The unique data policy permits broad analyses of the data. Presentations at meetings and a growing suite of manuscripts show that U.S. and international investigators are collaborating on combining and analyzing data sets, typically with an eye on long-term changes water properties, with implications regarding changes in circulation and ventilation processes. For example sampling in the Pacific Ocean from the southern to northern hemispheres confirms that the oceans are becoming more acidic from the uptake of carbon dioxide released as a result of fossil fuel burning, consistent with data from previous field studies conducted in other oceans. These highly resolved data sets are already changing the understanding of carbon cycle processes and their affects on climate and the biosphere.

The Global Ocean Data Assimilation Experiment High Resolution Sea Surface Temperature (GHRSST) Pilot Project

Kenneth S. Casey, NOAA National Oceanographic Data Center, US
Craig Donlon, National Centre for Ocean Forecasting, Hadley Centre, Met Office, UK

The Global Ocean Data Assimilation Experiment (GODAE) High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP) is an operational demonstration system for delivering a new generation of multi-sensor, high-resolution sea surface temperature (SST) products in real time and delayed mode. It was formed in 2000 by the International GODAE Steering Team to meet the diverse needs of the GODAE community by bringing international SST research and operational efforts into a cooperative framework, but has since grown to serve a much broader range of users and applications. The project is managed by an international Science Team and a Project Office sponsored by the European Space Agency and the Met Office, in the United Kingdom. In the future, the GHRSST system will deliver a rigorous SST climate data record (CDR), particularly suited to the needs of the CLIVAR and more general climate research community.

The GHRSST-PP (www.ghrsst-pp.org) relies on a regional/global task-sharing (R/GTS) framework to achieve its goals of generating and delivering an optimized set of both individual-sensor and merged, multi-sensor SST products. This system (Figure 1), establishes an international set of Regional Data Assembly Centers (RDACs), each of which delivers data to a Global Data Assembly Center (GDAC, http://ghrsst.jpl.nasa.gov) at the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC). The data are served from the GDAC to near real time users and applications for 30 days before the data are sent to the GHRSST Long Term Stewardship and Reanalysis Facility (LTSRF, http://ghrsst.nodc.noaa.gov) at the NOAA National Oceanographic Data Center (NODC) for long-term archive, stewardship, provision to delayed mode users, and future CDR production.

At the top of this task-sharing structure sit the RDACs, each of which has responsibility for one or a relatively small number of satellite sensors. For example, the US Naval Oceanographic Office RDAC (top left RDAC in Figure 1) produces global Advanced Very High Resolution Radiometer (AVHRR) SSTs from the NOAA-17 and NOAA-18 platforms and a gridded, gap-free analysis product that incorporates in situ data. The European RDAC, a consortium of European agencies and institutions funded by the European Space Agency (the Medspiration project: http://www.medspiration.org), produces real time SST products from the Advanced Along Track Scanning Radiometer (AATSR), AVHRR-High Resolution Picture Transmission (HRPT), and Advanced Microwave Scanning Radiometer-EOS (AMSR-E). In addition, the European RDAC produces a merged, multi-sensor SST analysis product for the Mediterranean Sea. Another RDAC, which focuses on microwave SST products, is functioning at Remote Sensing Systems, Inc. The Japan Aerospace Exploration Agency (JAXA) and the Japan Meteorological Agency (JMA) operate another RDAC. By the end of

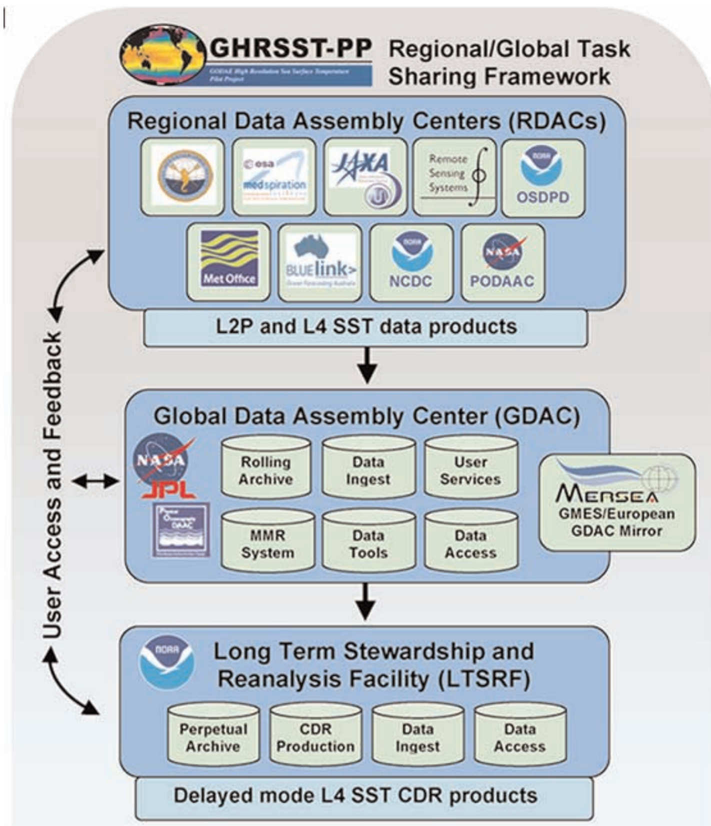

Figure 1. The GHRSST-PP regional/global task-sharing (R/GTS) framework, consisting of RDACs, a GDAC and the LTSRF.

2006, GHRSST will also have RDACs at the Australian Bureau of Meteorology (the BlueLink project: http://www.cmar.csiro.au/bluelink), the NOAA National Climatic Data Center (NCDC), and the NOAA Office of Satellite Data Processing and Distribution (OSDPD). The PO.DAAC, in collaboration with NASA's Ocean Biology Processing Group and the University of Miami will also be serving as the RDAC for MODerate-resolution Imaging Spectroradiometer (MODIS) data.

In the middle of the R/GTS environment sits the GDAC at the NASA PO.DAAC, which conducts an extensive array of data ingest, metadata management, and data distribution functions. The functions include receipt and cataloging of all data produced by the RDACs, generation of a searchable, online GHRSST Master Metadata Repository (MMR), and provision of data over a 30-day rolling store to near real time users through various access mechanisms. In the coming months it is anticipated that a mirror GDAC will be established in Europe as part of the extensive Global Monitoring for Environment and Security (GMES, http://www.gmes.info/) initiative of the European Commission.

At the base of the R/GTS framework is the LTSRF at the NOAA NODC. Thirty days after observation, the GHRSST data are transferred from the GDAC to the LTSRF where stewardship is provided in perpetuity. The GHRSST data streams are cataloged, archived, and made available by the LTSRF to delayed mode users. A capability to reanalyze the GHRSST data to produce longer-term, higher quality, more consistent gap-free analysis products is also under development. A large metadata transformation process, which begins at the GDAC to create Federal Geographic Data Commission-compliant records for every daily collection of GHRSST products, is also completed at the LTSRF.

At all levels of the GHRSST international framework, the user community is fully engaged in the development and specification of services and data products. Products are available at the RDACs, GDAC and at the LTSRF. A key aspect of the R/GTS framework is the ability of science development efforts to feed back into the data management functions and operational production of the data. These science areas focus on error characterization, diurnal variability modeling, and the analysis procedures needed to generate merged, combined SST estimates from the many available satellite inputs. There are communities working in the USA, China, Europe, Japan, and Australia on these topics.

GHRSST Products: L2P and L4 in Near-Real Time

The international GHRSST R/GTS system produces two types of near-real time SST products. The first of these, L2P, is an integrated data product that provides SST data for each of the individual satellite sensor data streams in a common format data structure with supporting dynamic fields to assist interpretation. The second, known as L4, provides merged, gridded, and gap-free

Table 1.

L2P Sensors with approximate spatial resolutions given.
AATSR (1 km)
AMSR-E (25 km swath)
AVHRR (Global Area Coverage 4 km, Local Area Coverage and HRPT 1km)
Spinning Enhanced Visible and Infra-Red Imager (SEVIRI, 10km)
Tropical Rainfall Measurement Mission's Microwave Imager (TMI, 25km)

SST analysis products. In addition, the GHRSST project has developed an extensive high-resolution diagnostic data set system (HR-DDS) for use in detailed SST intercomparison efforts. This article focuses on the L2P and L4 data sets, but for more information on the HR-DDS system see the web site, http://www.hrdds.net.

Near-Real Time L2P

Data for individual satellite sensors is produced in GHRSST L2P format, which contains in addition to the SST a collection of error fields and ancillary data. The L2P specification has been developed over a period of three years by the GHRSST Science Team and represents the output of a comprehensive international review of SST data format and content options. The L2P format is rapidly becoming a recognized standard for satellite SST data sets and is expected to be widely used in the future. For each SST observation, estimated bias and standard deviation errors are provided along with a confidence flag and a series of dynamic ancillary fields including winds, aerosol optical depth, surface solar irradiance, sea ice fraction, the time of observation, satellite zenith angle, and the SST difference from the previous SST analysis. The format also provides for optional experimental ancillary fields that may be attached by the producing RDAC. The data are stored in netCDF with attributes conforming to the Cooperative Ocean/Atmosphere Research Data Service Climate and Forecast (CF-1.0) conventions. Provided along with every data file is a File Record metadata file in eXtensible Markup Language (XML) conforming to the Global Change Master Directory Document Interchange Format specification. International standardization of the data and metadata formats and the establishment of an open data access policy for all GHRSST data are major achievements of the international community embodied within the GHRSST R/GTS framework and have resulted in much broader and easier access to many satellite SST data streams.

The GHRSST L2P data sets are the basic building blocks of the R/GTS framework and enable many regional and global applications in their own right. However, the real power of the L2P data is in their common format and timely delivery in near real time, allowing a broad range of applications to be developed and global coverage high-resolution gap-free L4 analysis products to be generated. See Table 1 for a list of sensors and data available. By the end of 2006, global, 1 km resolution L2P data will be available in real time from the MODIS sensors on board NASA's Terra and Aqua platforms and from the NOAA Geostationary Operational Environmental Satellite system.

Near Real Time L4

GHRSST L4 products are designed to provide the best available estimate of SST from a combined analysis of all available satellite and in situ SST data. Operational analysis and merging procedures generate gridded, gap-free SST products and capitalize on the synergy benefits of using in situ SST, microwave satellite SST, and infrared satellite SST. In situ data form an important component of the L4 process as these data are used to correct for biases between the satellite data sets. To create a useful and accurate L4 analysis product that combines multiple SST inputs, biases between the various measurement platforms must be accounted for, as must differences arising from diurnal stratification and cool skin effects. There are no universally accepted best practices for handling the differences or for combining multiple SST inputs, so several analysis efforts are underway within the GHRSST framework to develop the techniques.

Currently, a 2 km resolution regional L4 product for the Mediterranean is available, and several other regional and global L4 analysis products are being established in the GHRSST framework. These include L4 products being produced in the US, Japan, Australia, and Europe. An example of these is the roughly 5 km resolution global Operational SST and Sea Ice Analysis (OSTIA) product generated daily using GHRSST L2P inputs by the National Centre for Ocean Forecasting in the UK Met Office.

Data Access

While L2P, L4, and related products can generally be accessed directly from the producing RDACs, the GHRSST system facilitates and simplifies data access through the centralized GDAC and the LTSRF at the NOAA NODC. These two centers are working together to provide seamless access to both the most recent data, which resides physically at the GDAC until 30 days past observation, and the longer-term data sets that reside in perpetuity at the LTSRF. An online interface has been established to provide a mechanism for searching based on geographic and temporal ranges, as well as by L2P or L4 product line and RDAC.

Direct human-to-machine and machine-to-machine access has also been established, using FTP and OPeNDAP protocols. Through both FTP and OPeNDAP at the GDAC and LTSRF sites (listed below in Table 2), the data are organized following the

Table 2. Access to L2P and L4 SST Data Products

Data Access	URL
FTP for data withing the past 30 days	ftp://podaac.jpl.nasa.gov/pub/GHRSST/data
FTP for data older than 30 days	ftp://data.nodc.noaa.gov/pub/data.nodc/ghrsst
OPeNDAP access	http://dods.jpl.nasa.gov/dods-bin/nph-hdf/pub/sea)surface_temperature/GHRSST/data/
OPeNDAP access	http://data.nodc.noaa.gov/cg0-bin/nph-dods/ghrsst

same hierarchy, beginning with SST product type (L2P or L4), then satellite sensor (for L2P) or region (for L4), then producing RDAC, then year and day of year. A variety of tools including example software for working with netCDF files in general and GHRSST data files specifically can be found at

http://ghrsst-pp.metoffice.com/pages/data_tools/index.htm. In addition, comprehensive user services including help desk support, FAQs, and Knowledge Base access are provided at the GDAC.

Future GHRSST Products: L4 Climate Data Records

Of perhaps most interest to the CLIVAR community are the GHRSST efforts to generate a longer-term SST CDR. These efforts, overseen by the international GHRSST-PP Science Team Reanalysis Technical Advisory Group, are based at the LTSRF where all of the individual GHRSST data streams are archived, thereby facilitating future reanalysis efforts. Based on user feedback and consensus of the Science Team, the goals of GHRSST Reanalysis are to produce a daily, global L4 analysis product with quantified uncertainties and diurnal variability estimates. The global product is expected to have a spatial resolution of approximately 5-10 km, will conform to the GHRSST L4 data and metadata format specification, and will strive to achieve the ambitious temporal stability requirement of 0.01 K/decade. These reanalysis products are expected to extend initially back to the start of the microwave SST data in 1997, then back to the beginning of the (A)ATSR series in1992, and eventually back to the beginning of the satellite SST period with the start of the 5-channel AVHRR series in late 1981. Key areas in which the reanalysis system is expected to make improvements over the near real time L4 products include the use of:

•Applying consistent procedures to the entire time series in accordance with the Global Climate Observing System climate monitoring principles.

•L2P products that did not make it into the near real time processes

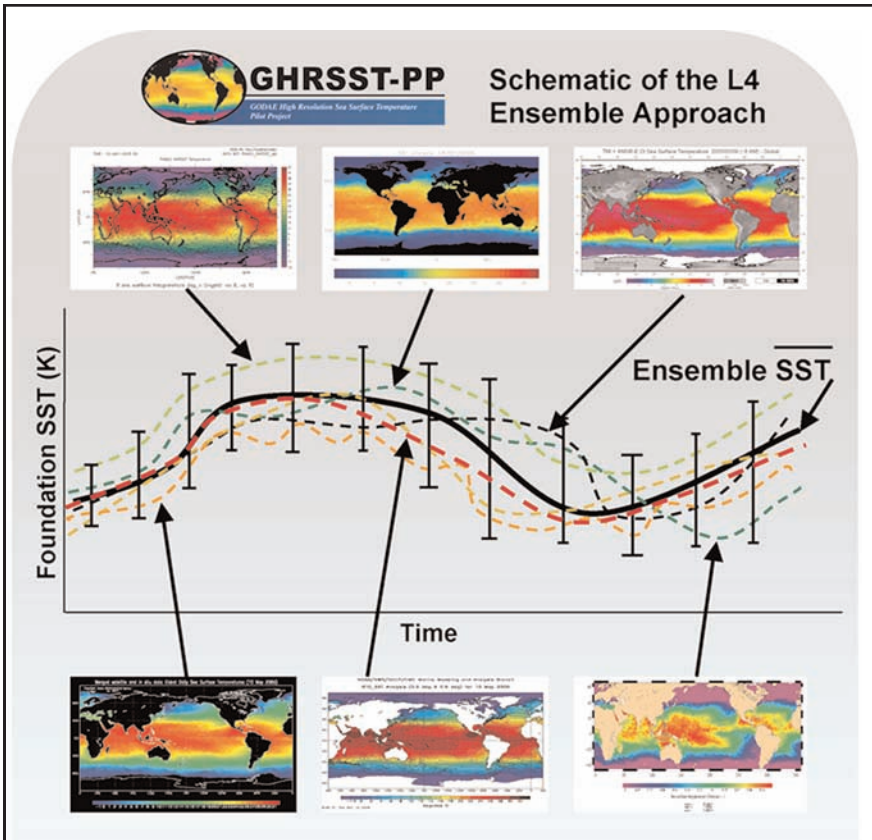

Figure 2. Schematic diagram of the GHRSST-PP ensemble approach for conducting L4 product development, intercomparisons and CDR production. Clockwise from top left (FNMOC GRSST, SST analysis , AMSR, satellite SST, NOAA RTG, and merged satellite and in-situ data).

•Reprocessed L2P data steams provided by RDACs. For example, NODC develops a consistently-reprocessed AVHRR-based Pathfinder SST data set (http://pathfinder.nodc.noaa.gov) that is expected to form a key baseline for GHRSST Reanalysis, since the AVHRR series is the only one available throughout the satellite record. European efforts are also underway to reprocess the (A)ATSR series into a consistent, more accurate data set which will provide a unique reference baseline.

•Improved matchup databases with better quality control and more observations than were available in real-time

•Techniques which utilize data from "future" observations to better account for fluctuating atmospheric effects.

•Improved single sensor error statistics

•New data merging and analysis procedures for creating L4 products, procedures which may be too computationally demanding to be used in near real-time environments.

•Improved diurnal variability and cool skin models and parameterization schemes that can be used to alleviate the impact of diurnal SST variability.

The first formal GHRSST reanalysis products are expected to begin production in late 2007 but L4 intercomparison activities have begun and will include an initial approach based on ensemble averages. This approach, illustrated in Figure 2, is expected to help identify and highlight existing community consensus approaches, strengths and weaknesses of the various L4 analysis techniques, and areas where more intense research activity is required to create optimal long-term CDRs for SST.

U.S. CLIVAR Salinity Workshop Summary

The U.S. CLIVAR Salinity Working Group convened a workshop held at the Woods Hole Oceanographic Institution beginning Monday May 8 and concluding mid-day Wednesday May 10. The meeting which had about 60 attendees, was immediately followed by the Workshop for the upcoming Aquarius satellite mission. Among the topics discussed were the processes and mechanisms linking salinity to the global water cycle, ocean circulation, and climate. The recent discovery of trends and variability in salinity were reviewed. Finally, the type of observations and monitoring requirements needed for future climate studies was discussed. In addition to 19 talks and plenty of time for discussion, the meeting hosted a vibrant set of 23 posters. The presentations will be made available soon through the U.S.CLIVAR website (www.usclivar.org).

One outcome of the meeting will be a whitepaper report to the Phenomena, Observations, and Synthesis Panel of U.S. CLIVAR. This white paper will motivate salinity observations as part of a sustained system; highlight the role of salinity measurements to close the marine branch of the hydrological budget; and describe the potential of sustained salinity observations as ocean tracers. It is hoped that the launch of the Aquarius satellite in 2009, in addition to utilizing current international resources such as the PIRATA and TAO/TRITON arrays, and ARGO will aid in this effort.

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