Development of Enhanced Ocean Climate Products

David W. Behringer and Hendrik Tolman
NOAA National Centers for Environmental Prediction, Camp Springs MD

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1. Abstract

The Global Ocean Data Assimilation System (GODAS) combines global ocean observations with a numerical ocean model to produce an estimate of the ocean state. The new second-generation operational coupled Climate Forecast System (CFSv2) has a fully incorporated version of the GODAS that serves to initialize the ocean component for seasonal to interannual prediction at NCEP. The GODAS analysis also provides a means for monitoring the state of the ocean climate and is used for this purpose by the NCEP Climate Prediction Center. In FY2010 the new coupled CFS Reanalysis (CFSR) was completed as part of the preparation for implementing the new CFSv2 in production. In FY2011 the hindcasts for calibrating the CFSv2 were finished and the CFSv2 was successfully implemented in operations on March 30, 2011. The current version of the GODAS is based on GFDL's Modular Ocean Model, version 4p0 (MOM4p0) and uses a 3DVAR method for data assimilation. Looking toward the future NCEP established a new collaboration with the University of Maryland with the goal of developing a new advanced method for ocean data assimilation. Through this agreement we have made a strong start in FY2011 on the development of an ensemble Kalman filter for MOM4p1.

2. Project Summary

The Global Ocean Data Assimilation System (GODAS) at the National Centers for Environmental Prediction (NCEP) uses a statistics based algorithm to combine a numerical ocean model with ocean observations to provide a global estimate of the ocean state (fully three dimensional fields of temperature, salinity, velocity, and sea surface height). In effect, Ocean Data Assimilation (ODA) systems use model ocean dynamics to interpolate in time and space between the locations of individual observations and to compute those parts of the ocean state that may not be directly observed. For example, there are currently many more observations of temperature and salinity in the ocean than there are of velocity. Assimilation of these data adjusts the model temperature and salinity fields to be in accord with the observations (within

specified statistical bounds) and the model then computes a velocity field in balance with the distribution of mass established by the temperature and salinity. The GODAS assimilates temperature profile observations from eXpendable BathyThermographs (XBTs), fixed moorings, and autonomous Argo floats, salinity from Argo floats and synthetic salinity from temperature observations and the observed correlation between temperature and salinity, and sea surface altimetry observations from TOPEX/Poseidon, Jason-1 and Jason-2 satellite missions. Tide gauge and velocity observations are reserved for validation.

The work covered by this project is the construction, maintenance and development of ODA at NCEP. The GODAS uses the Modular Ocean Model (MOM) developed over the last several decades at NOAA's Geophysical Fluid Dynamic Laboratory (GFDL). The current uncoupled operational GODAS uses the MOM3, while the new version of the GODAS incorporated in thecoupled operational CFSv2 uses the MOM4p0. The assimilation algorithm in both cases is a sequential 3-Dimensional Variational (3DVAR) method that estimates the ocean state through minimization of a cost function that balances statistically weighted contributions from the model and from the observations. The original purpose of the GODAS was to provide initial conditions for the ocean component of the coupled Climate Forecast System (CFS) used for operational seasonal to interannual (S-I) prediction At NCEP. S-I prediction has a well established social benefit and it remains the primary rationale for the maintenance and further development of the GODAS. The GODAS has a second important use as a means for monitoring the changing ocean state, which derives from its operational, near real-time, 3D synthesis of global ocean observations. The Climate Prediction Center (CPC) of NCEP maintains an interactive web site (http://www.cpc.ncep.noaa.gov/products/GODAS/) that allows the visitor to view GODAS output in a variety of ways. The same site provides links for acquiring the GODAS output data.

NCEP is committed to developing advanced techniques for ocean ODA. For this reason, we have undertaken in 2011 a new collaboration with the University of Maryland to develop an ensemble Kalman filter based on MOM4p1. We anticipate eventually combining this new method with our existing 3DVAR ODA to create a hybrid variational-ensemble ODA. We further expect that the experience gained in developing this system for MOM will provide the starting point for a similar development with NCEP's Real-Time Ocean Forecasting System (RTOFS) based on HYCOM. The first steps in this project are included as item 4 in the Work Plan.

3. Scientific Accomplishments

In FY2011 the CFSv2 become operational on March 30, 2011. The components of the new system are the Global Forecast System (GFS) atmospheric model and the Gridpoint Statistical Interpolation (GSI) scheme for atmospheric assimilation and on the ocean side MOM4p0 and GODAS which are supported by this project.

In last year's work plan we anticipated implementing a new uncoupled version of GODAS based on MOM4p0. The new version with a ½^{o} x ½^{o} grid would double the resolution of the existing operational GODAS, based on MOM3, and would be a true global model, incorporating the Arctic for the first time. The implementation has been delayed until 2012 and in the meantime the MOM3 GODAS remains in operations. We have continued work on the MOM4 GODAS

aimed at improving its performance as climate modeling tool. For example, we have extended the depth of the assimilation to 2000 meters (from 750 meters) to take full advantage of the Argo data. We've also improved our automatic quality control code which now handles salinity profiles as well as temperature profiles. The new code also integrates observed with synthetic salinity profiles, which is an important capability for a retrospective analysis that must transition from the pre-Argo period to current mature Argo era. Figure 1 illustrates this system's ability to track observations of the Atlantic Meridional Overturning Circulation (AMOC) made by the MOCHA array of the University of Miami. The MOCHA array is at about 26.5^{o}N (bottom panel) and the GODAS at 30°N (top panel) captures the observed signal very well in its amplitude range, seasonal cycle and interannual variability.

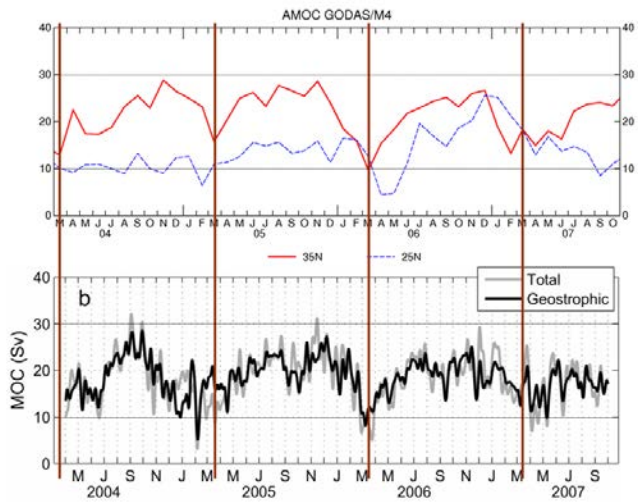

Figure 1. AMOC transport from GODAS at 35N and 25N (top) and from the MOCHA array (bottom, adapted from the U. of Miami website).

We've also undertaken an experiment to better control model bias. This was prompted by variations in the GODAS upper ocean heat content that did not match with estimates based solely on the observations. We traced these variations to regions of the model domain where data for assimilation are scarce. We've developed a method to assimilate climatological profiles derived from the WOA09. These are assimilated only in places and times where observations are absent for at least a year. The method has shown good results in a test run and we will test it further in a longer multi-decade analysis.

The second task for 2011 was to participate in the so-called CFSR Lite (CFSRL) which is to repeat the CFSR at reduced atmospheric resolution and in a single continuous thread. The idea is to avoid discontinuities caused by the necessity to multi-thread the original CFSR. Much of the effort so far has been focused on reducing an excessive cold drift in the upper ocean heat content at the start of the analysis in the early 1980s and on improving the tuning of the coupled model based on the experience with the CFSR and the CFS hindcasts. This has led to improvements in the analysis and the 30 year retrospective analysis is ready to go forward.

The third task was to support data denial experiments with GODAS by the Climate Prediction Center (CPC). Two experiments have been done, one without TAO data and the second without both TAO and Argo data. Since neither experiment includes TAO, the TAO have been used as independent data for evaluation. The comparisons at 110°W provide a good illustration of the results. The experiments were run by Anna Borovikov of CPC who also provided Figure 2. The plots show the RMS differences between the GODAS and the TAO observations in a sliding 5-month window. The top panel corresponds to GODAS assimilating XBTs and Argo, the middle panel corresponds to GODAS assimilating only XBTs, and the bottom panel represents the middle panel minus the top panel. The first half of the middle panel is omitted since it would be identical with the top panel. The effects of Argo are clear: in the early part of the 2000's the Argo profiles are too sparse to have a real impact at 110°W, but their impact builds rapidly after 2004. It's also worth noting that between 1999 and 2003, before the increase in the number Argo profiles, the decrease in the numbers of XBT's during those years has led to greater RMS differences between GODAS and the TAO observations. Further analysis of these experiments and forecasts initialized these analyses are needed before drawing any conclusions about the relative importance of the XBT, Argo and TAO data sets.

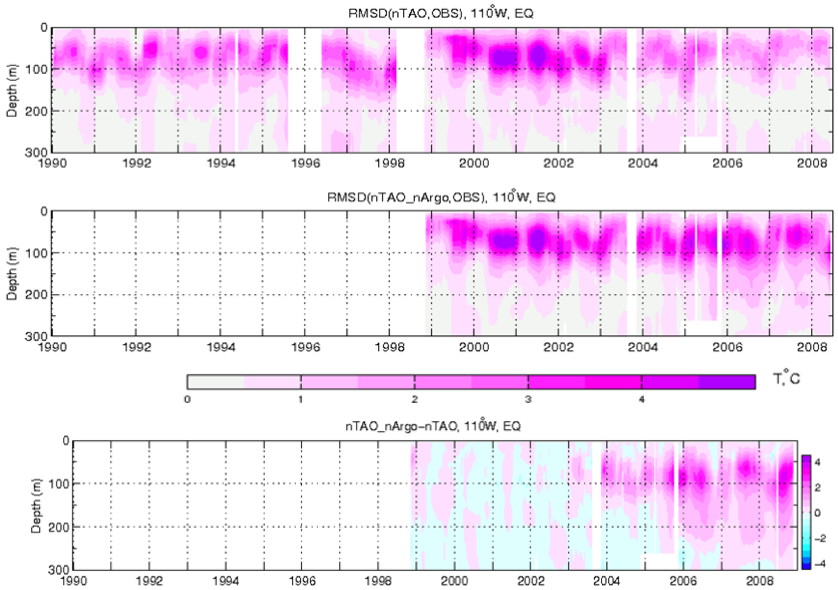

Figure 2. Comparisons of GODAS with TAO observations at 110°W. Top: GODAS assimilating XBTs and Argo; Middle: GODAS assimilating only XBTs; Bottom: Middle minus Top panel. See text for more information.

The fourth task for 2011 was to begin experimenting with the assimilation of sea surface salinity (SSS) as observed from satellite. We have recently acquired monthly averaged global SMOS SSS*

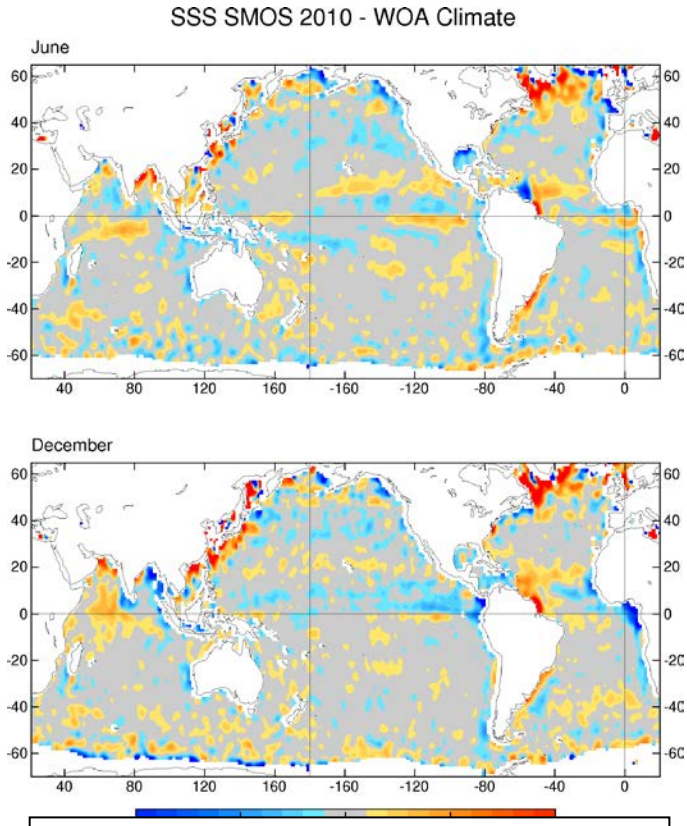

Figure 3. Differences between monthly fields from 2010 SMOS and WOA climatology.

fields for 2010. Figure 3 shows the differences between the SMOS product and a surface climatology based on the WOA for the months of June and December. There are a number of interesting features: saltier Labrador and Greenland Seas, variability in the vicinity of river outflows, and variability in the ITCZ. At the same time there are bands of color along land boundaries that may be the result of contamination caused by the proximity of the land. It is important to remember that the satellite SSS fields are a research product that will be evolving. For this reason our focus for some time will be on developing the best method for assimilating the data. Additional data will be available soon. The NASA Aquarius mission was successfully launched in June 2011, and a "first look" global SSS field has recently become available. We will include the Aquarius data in our experiments as soon as monthly fields become available.

The work plan for 2011 did not include new developments in ODA, but because of a new collaboration with the University of Maryland we have made some significant progress in that area. Steve Penny, a post doc at the university, but working at NCEP in the NCEP computing environment, has ported the Local Ensemble Transform Kalman Filter (LETKF) to MOM4p1. The LETKF was originally developed by Brian Hunt and others at Maryland as an atmospheric application. Steve Penny ported it POP for his dissertation and has now done the same for MOM4p1. A 1-year test reanalysis was successfully performed using a coarse-resolution 'Solo ocean' version of MOM4p1 and observed vertical profiles of temperature and salinity from the Argo data. A 2-week test reanalysis has recently been performed using a 1-degree tripolar-grid 'Coupled ocean/ice' version of MOM4p1 using observed

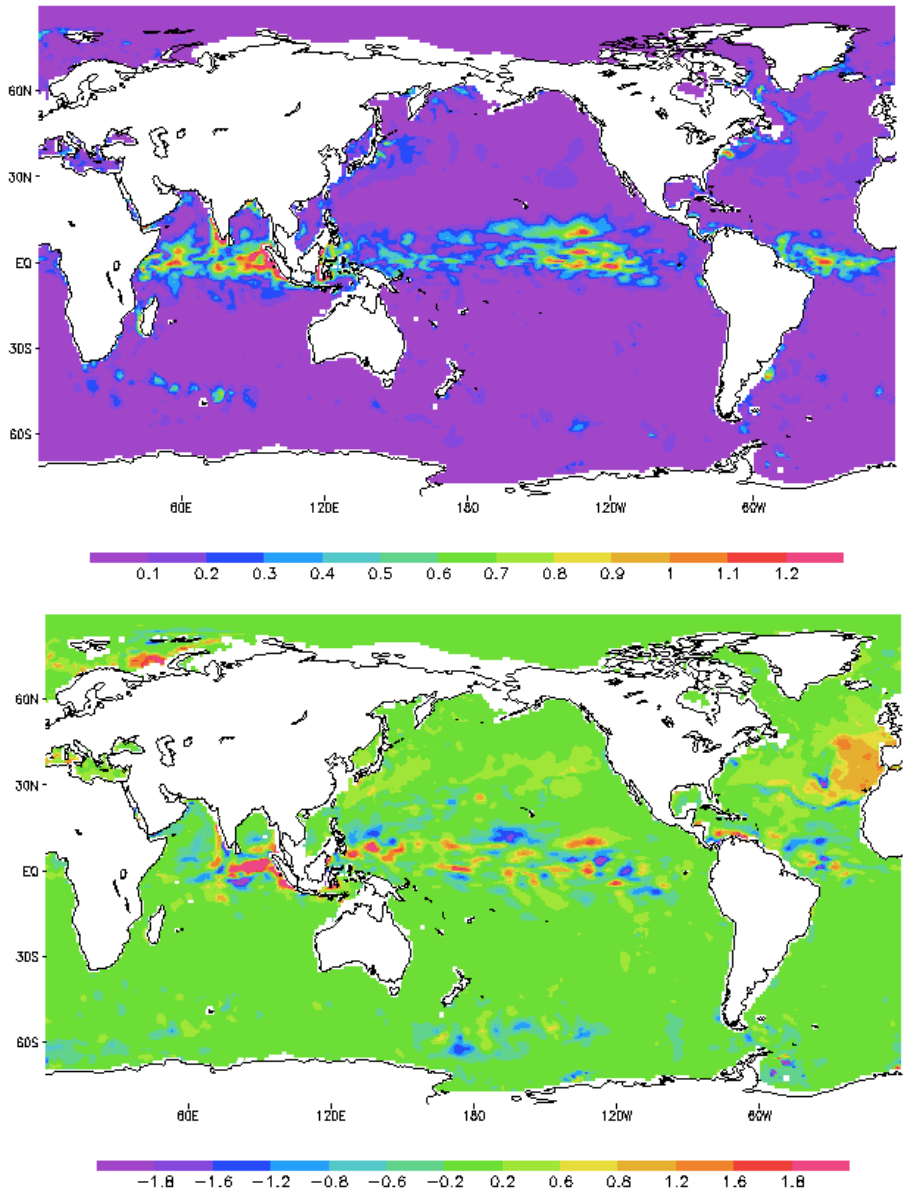

Figure 4. Temperature analysis at 100 meters. Top: ensemble spread at two weeks. Bottom: analysis increment at two weeks.

vertical profiles, satellite surface temperature and altimetry data. Figure 4 shows some sample output. The top panel shows the ensemble spread (i.e. model error) after two weeks for temperature at 100 meters. The bottom panel shows the analysis increment after two weeks for temperature at 100 meters.

* These data were obtained from the "Centre Aval de Traitement des Données SMOS" (CATDS), operated for the "Centre National d'Etudes Spatiales" (CNES, France) by IFREMER (Brest, France)

4. Education and Outreach

The outreach associated with the GODAS takes the form of an interactive, public web page (http://www.cpc.ncep.noaa.gov/products/GODAS/) developed and maintained by NCEP's Climate Prediction Center. Users can select views of the GODAS analyses with interactive tools available on the site. The site also provides links for downloading the data.

Data from the CFSR is available at http://nomads.ncdc.noaa.gov/

5. Publications and Reports

Publications by Principal Investigators

Huang, B., Y. Xue, A. Kumar, and D. W. Behringer (2011) AMOC variations in 1979–2008 simulated by NCEP operational ocean data assimilation system. *Clim. Dyn.*, doi: 10.1007/s00382-011-1035-z

Xue, Y., B. Huang, Z.Z. Hu, A. Kumar, C. Wen, D. Behringer, (2011) An Assessment of Oceanic Variability in the NCEP Climate Forecast System Reanalysis. *Clim Dyn.*, doi: 10.1007/s00382-011-0954-4