Enhanced Ocean Climate Products from NCEP

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1. 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 (the three dimensional fields of temperature, salinity, velocity, plus sea surface height). In effect, the GODAS uses the 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 profiles from Argo floats and synthetic salinity profiles 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. NASA's Aquarius instrument was successfully launched in June, 2011, and a "first look" image of the global sea surface salinity has been released. These data look very promising and we expect to begin experimenting with them as well as the SMOS data soon. Tide gauge and velocity observations are reserved for validation.

The work covered by this project is the construction, maintenance and development of the NCEP GODAS. 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 MOM version 3 (GODAS/MOM3), while the new version of the GODAS incorporated into version 2 of the operational coupled Climate Forecast System (CFSv2) uses the MOM version 4 (GODAS/MOM4). The assimilation algorithm 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 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. Within NCEP the CFSv2 and the GODAS are fundamental tools used by the Climate Prediction Center (CPC) to prepare the official seasonal outlooks disseminated by the National Weather Service. Internationally the GODAS is an established member of an ensemble of ocean analyses produced by governmental and academic institutions worldwide that provides researchers with the means to study the evolution of the ocean state over past decades, including a measure of the uncertainty associated with the observed evolution.

NCEP/CFC 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.

2. Scientific and Observing System Accomplishments

As stated above ocean state estimation is fundamental to forecasting and monitoring climate variability. Maintaining and improving GODAS at NCEP is a top priority.

We have completed the basic development necessary to implement an uncoupled version of GODAS/MOM4 in operations, intended to replace the current operational version based on MOM3. We have run the new GODAS/MOM4 offline in parallel with the operational version. The two versions use identical data sets for assimilation (temperature and salinity profiles and Jason-2 altimetry). The new MOM4 version uses Reynolds 1/4° daily SST analysis to constrain the surface temperature, while the operational version uses the older 1° weekly SST analysis. Figure 1 shows a comparison of the average temperature in the upper 300 meters in the two versions for the period of July through September of 2012. The largest differences in both the mean and standard deviations occur where the gradients in ocean currents are greatest (western boundary currents, Southern Ocean, etc.). This is an expected result because of the higher resolution of the GODAS/MOM4 (1/2° x 1/2°; 1/4° in the equatorial zone) is approximately twice that of the GODAS/MOM3 (1° x 1°; 1/3°).The 3DVAR assimilation scheme in the GODAS/MOM4 has also been modified to

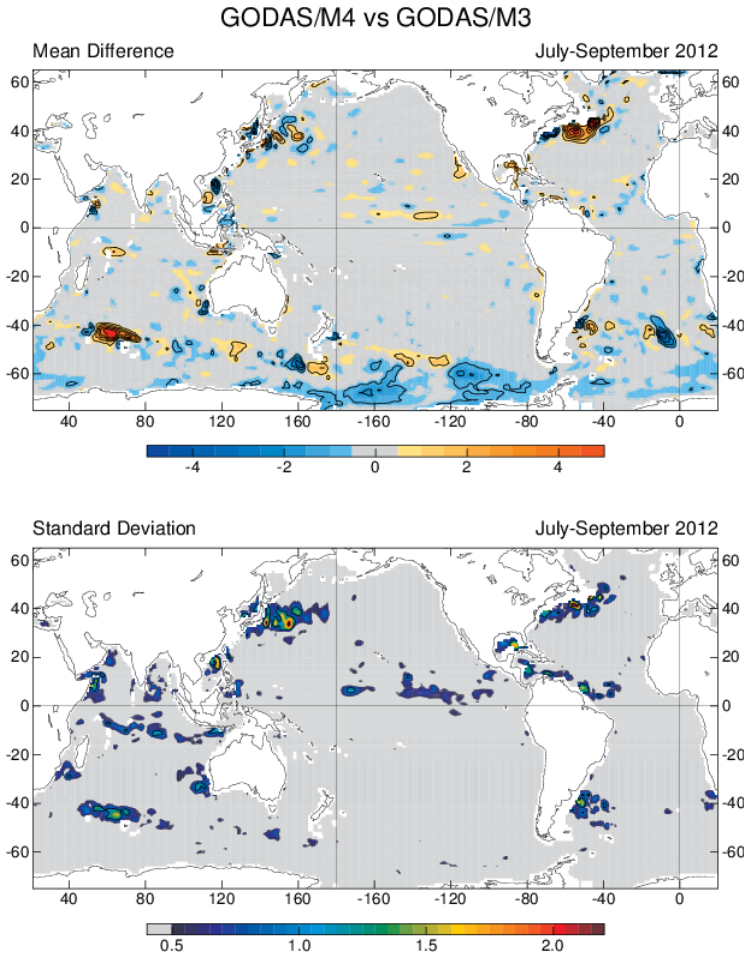

Fig. 1. The mean (top) and standard deviation (bottom) of the difference in the average temperature of the upper 300m in GODAS/MOM4 and GODAS/MOM3 between July and September, 2012.

assimilate climatological data in the deep ocean below 2000m, with the goal of controlling deep model bias in the absence of sufficient real-time data. A benefit of this approach will discussed below in the context of a data denial experiment.

NCEP is currently in the process of upgrading its operational computers and the implementation of GODAS/MOM4 is on hold. The current operational suite, including GODAS/MOM3, will be ported to the new computers over the course of the coming year. Once that process is completed, the operational GODAS will be upgraded to MOM4. In the meantime, the GODAS/MOM4 will be used in developmental experiments. The delay also opens the possibility of bypassing the MOM4 upgrade and jumping to a MOM5 upgrade. GFDL released MOM 5.0 on October 12, 2012, and we have acquired a copy.

Data denial experiments serve two related purposes, both of which are specific to the ocean model at the heart of the assimilation system. The first of these provides information about the importance of a particular data set to that model. The second illuminates weaknesses in the model itself. The importance of a global data set like Argo is undeniable, so that the described here experiment fits essentially into this second category.

We have done a preliminary data denial experiment using the GODAS/MOM4 system to look at the impact of the Argo profile data. The expectation was that the impact would be large, but we were specifically interested in the effect on the Atlantic Meridional Overturning Circulation (AMOC). Figure 2 shows the growing dominance of Argo profiles from the year 2000 onward. One experiment (EA) uses all of the profiles from 2000 through 2011 and climatology below 2000 meters, a second experiment (ExA) uses only the XBT, CTD and mooring profiles, highlighted by boxes in the figure.

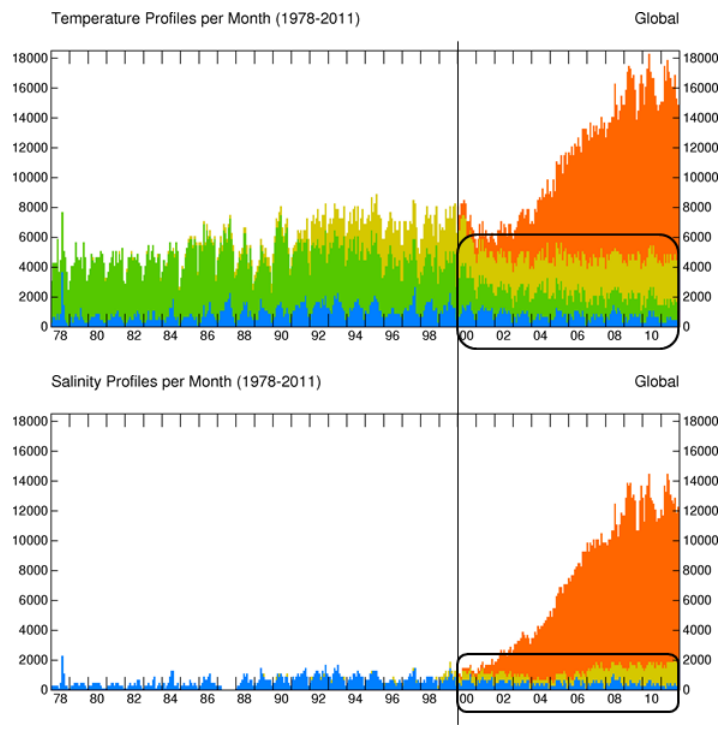

Fig. 2. The number of profiles per month from CTDs (blue), XBTs (green), tropical moorings (yellow) and Argo (orange). Temperature profiles are in the upper panel; salinity profiles are in the lower panel.

Figure 3 shows average Atlantic sections along 30° W for June–December 2006. On the left are sections for temperature and salinity from the experiment with Argo and on the right are sections from the experiment without Argo minus the sections from the experiment with Argo. In mid-basin the Argo experiment is colder by as much as 2° and fresher by as much as 0.4 psu in and just below the Antarctic Intermediate Water. The Antarctic Bottom Water is also 1° colder in the Argo experiment. North of 30°N, the Argo experiment is saltier by as much as 0.3 psu in the North Atlantic Deep Water. This comparison of the two experiments suggests that without the Argo profiles the model is unable to adequately form the Antarctic Intermediate and Bottom Waters. In the North Atlantic it appears the model may need the added saltiness from the Argo profiles to properly form the Deep Water. The impact on the model AMOC is clear: without the Argo profiles the deep convection is weakened and thus the overturning cell is also weakened and largely confined above 2500m (not shown), while with the Argo profiles the model AMOC is 25% stronger and extends as deep as 3500m. Figure 4 compares the maximum transport from the two experiments to the direct observations from the RAPID project[1]. The plots show monthly values of the RAPID observations in blue and the two model experiments in red. Comparing the experiment with Argo in the top panel with the experiment without Argo in the bottom panel, we see that assimilating Argo profiles corrects both phase and amplitude in the model signal, so that not only are the annual and interannual variations well represented, but some of the intra-annual variability as well. Notice also in the top panel that the model to observations agreement improves as time passes and the number of available Argo profiles increases.

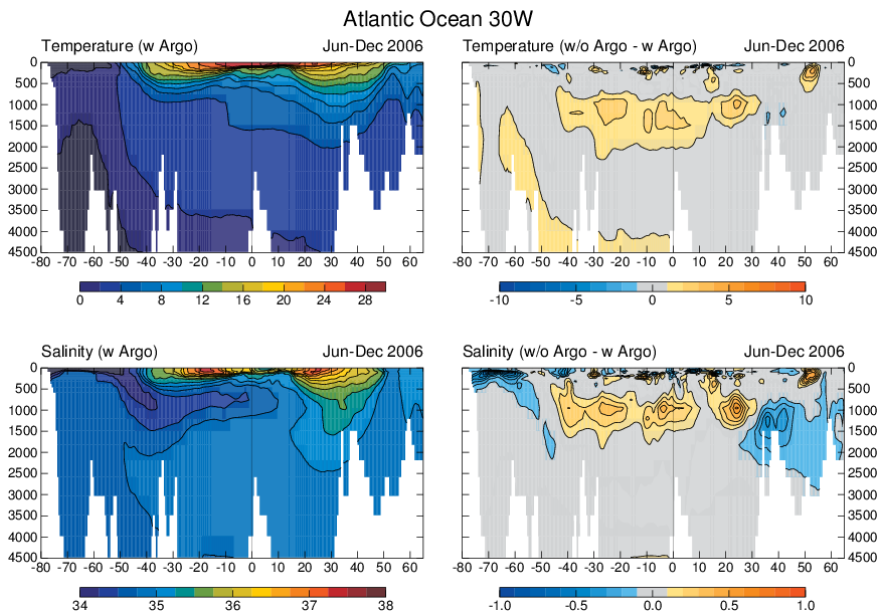

Fig. 3. Sections of temperature (top) and salinity (bottom) at 30°W from EA (left) and the difference, ExA – EA, (right).

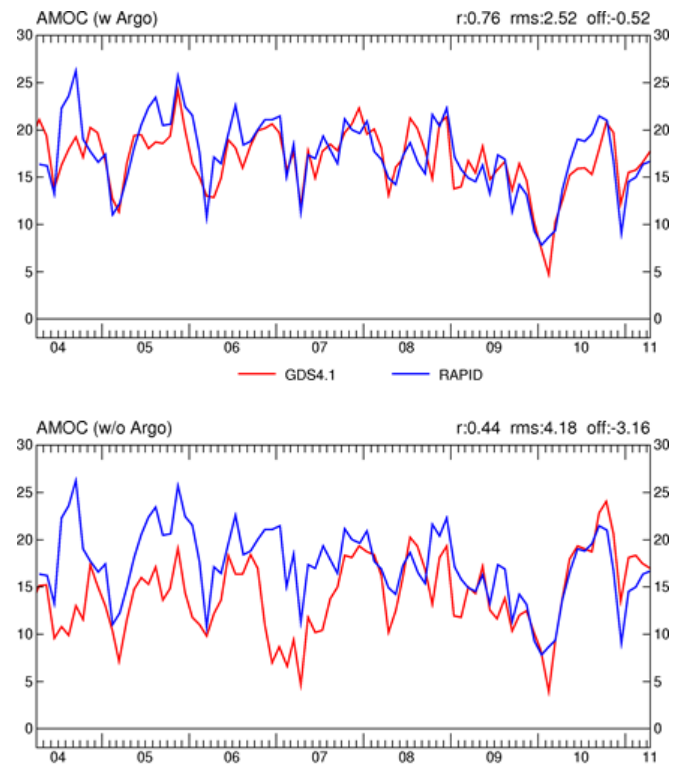

Fig. 4. Monthly values of the maximum AMOC transport (Sv) from RAPID observations (blue) and the assimilation experiments (red), EA (top) and ExA (bottom).

[1] Data from the RAPID-WATCH MOC monitoring project are funded by the Natural Environment Research Council and are freely available from www.noc.soton.ac.uk/rapidmoc.

It is interesting to note that both experiments do a good job of reproducing the rapid collapse and recovery of the overturning transport in 2009-2010. It may be that for this event the atmospheric forcing (NCEP-DOE Reanalysis) and the model response to it was adequate enough to reduce the impact of differences in the assimilation data sets.

We plan to continue with the Argo denial experiments to more clearly separate the effects of Argo assimilation from the effects of climatology assimilation in the deep ocean. We also will do data denial experiments for the tropical moorings, which should provide results more pertinent to seasonal to interannual forecasting. This is discussed further in the workplan.

A basic part of maintaining operational data assimilation systems is incorporating new observations as they become available. Satellite sea surface salinity (SSS) in from SMOS and Aquarius are current examples and we are working on preparations to assimilate them into GODAS. We are currently working with monthly averaged, gridded level 3 (L3) SSS data for 2010 from SMOS[2] and for 2011 and 2012 from Aquarius[3]. These data are research products and at this stage are meant for development purposes only. Before using these data in GODAS it is necessary to understand the differences between them and near surface in situ observations from Argo.

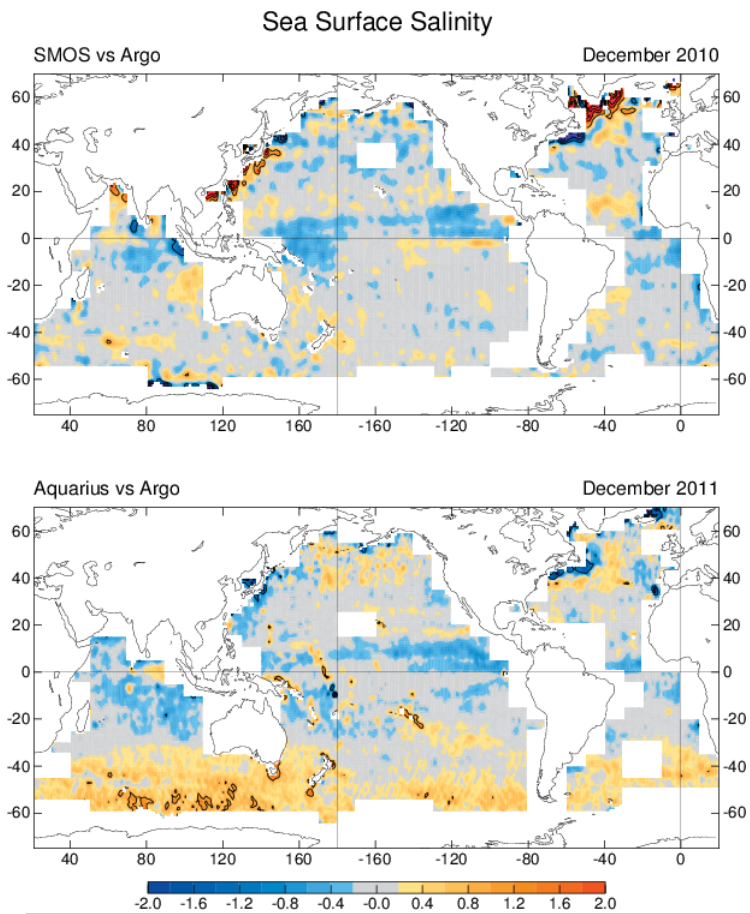

Fig. 5. Satellite SSS minus Argo near-surface salinity. SMOS (top) and Aquarius (bottom). Argo was averaged over the upper 10m and 5°x10° boxes and interpolated to the satellite grids.

Figure 5 shows the differences between SMOS SSS and near-surface Argo salinity for December 2010 (top) and between Aquarius SSS and Argo salinity for December 2011 (bottom). The large differences near continental and island boundaries in both panels are associated with the known land contamination of the satellite measurements. In the lower panel the high SSS values south of 30°S are also a known problem that is being worked on by the Aquarius calibration team. In both panels, in the tropical Indian Ocean and the Pacific convergence zones, the satellite SSS is fresher than Argo by 0.4-0.6 psu. These are regions of high precipitation and it is tempting to think that the difference is real.

[2] Data from SMOS were provided by CNES, Toulouse, France
[3] Data from Aquarius were provided by the NASA/JPL PODAAC site

However, for this to be so the fresher water would have to be confined to a thin layer, undetectable by Argo, and able to persist for a month or more. Figure 6 shows year-long scatter diagrams for each satellite versus Argo. In this view the relative freshness of the SSS in the NE Tropical Pacific appears more persistent in the Aquarius comparison with Argo than in the SMOS comparison.

In any case, it is premature to speculate about what the final SSS product details be. We will wait until the satellite teams have finished the calibration of the SSS products and established estimates of the uncertainties before we begin to assimilate the SSS into GODAS.

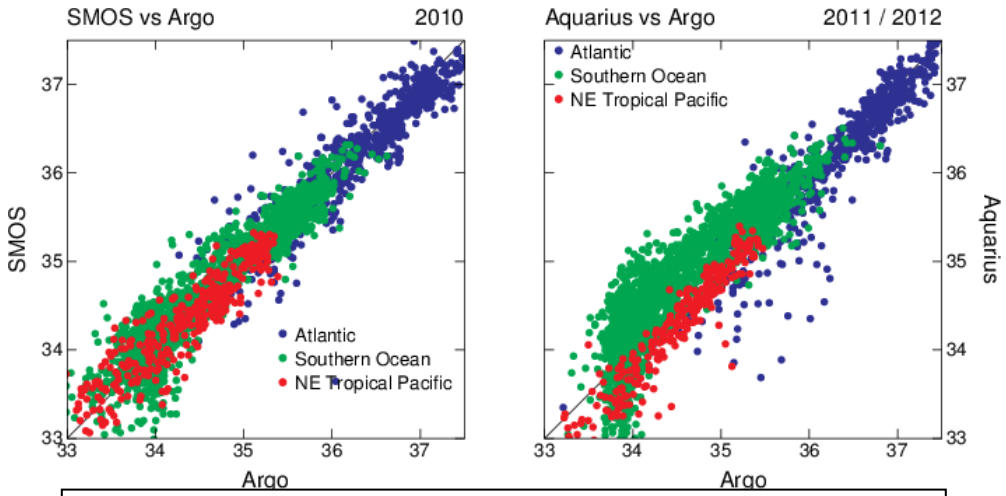

Fig. 6. Year-long scatter diagrams for satellite SSS versus Argo near-surface salinity. SMOS (left) and Aquarius (right). The regions are the Atlantic (30°N-30°S), the Southern Ocean (south of 30°S) and the NE Tropical Pacific (0-14°N, 180°W-80°W).

2.1 Outreach and Education

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/

3. Publications and Reports

3.1. Publications by Principal Investigators

M. Ravichandran, D. Behringer, S. Sivareddy, M. S. Girishkumar, Neethu Chacko, and R. Harikumar (2012) Evaluation of the Global Ocean Data Assimilation System at INCOIS: The Tropical Indian Ocean. *Ocean Modeling*, (in revision)

Robert N. Miller, D. Behringer and L. L. Ehret (2012) Estimates of Representation Error for Ocean Data Assimilation. (in preparation)

M. G. Bosilovich and M. Rixen eds. (2012) Report of the 4th World Climate Research Programme International Conference on Reanalyses. WCRP Report 12/2012, Silver Spring, Maryland, USA, 7-11 May 2012