

U.S. Operational Applications of Argo Data Report to the 8th Argo Steering Team Meeting

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The purpose of this report is to provide a description of the use of Argo at the various ocean data assimilation centers in the United States. The centers that provided input into the report include: (1) U.S. Navy - Fleet Numerical Meteorology and Oceanography Center (FNMOC) and Naval Oceanographic Office (NAVOCEANO), (2) NASA/GSFC Global Modeling and Assimilation Office (GMAO), (3) NOAA National Center Environmental Prediction, Environmental Modeling Center (NCEP/EMC), and (4) the Estimating the Circulation and Climate of the Ocean (ECCO) consortium at JPL and at Scripps/MIT.

Argo is more than just an observing system. Argo also contains a full data management function that provides temperature and salinity profile observations in both real-time and in delayed mode. The real-time data undergo relatively simple, fully-automated gross error checks, and are required to be available on GTS within 24-hours of observation. The delayed-mode data are made available at the Argo Global Data Assembly Centers (GDAC) after processing through rigorous, scientific quality control procedures. As such, it was decided to obtain information on the use of both the Argo observing system and the Argo data management system by the assimilation groups. To help guide the responses, the groups were asked a series of five questions in regards to their assimilation systems and products: (1) describe how Argo data are used, (2) list the source (GTS, GDAC) and type (real-time, delayed mode) of Argo data, (3) indicate any timeliness issues of Argo data, (4) assess the quality of Argo data and use of Argo real-time or delayed mode QC flags, and (5) describe the impact of Argo data on forecast or other measure of system/application skill. The responses to the questions are listed below by assimilation group. Assimilation group points of contact are provided if further information on a particular system is needed.

NCEP: Environmental Modeling Center – D. Behringer, NOAA/NWS/NCEP/EMC.

The NCEP global ocean data assimilation system (GODAS) is described in:

Behringer, D.W., M. Ji, and A. Leetmaa (1998). An improved coupled model for ENSO prediction and implications for ocean initialization. Part I: The ocean data assimilation system. *Mon. Wea. Rev.*, 126:1013-1021.

Behringer, D.W., and Y. Xue (2004). Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. *Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, AMS 84th Annual Meeting, Washington State Convention and Trade Center, Seattle, Washington, 11-15.*

Behringer, D.W. (2007). The Global Ocean Data Assimilation System (GODAS) at NCEP. *Eleventh Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, AMS 87th Annual Meeting, H. B. Gonzalez Convention Center, San Antonio, Texas, 12pp.* <http://ams.confex.com/ams/pdfpapers/119541.pdf>

1. *Describe use of Argo data.* The Argo profile data, both temperature and salinity, are used in the ocean data assimilation component of an operational seasonal-interannual (S-I) climate forecast system at NCEP. Only Argo temperature profiles are used in the operational version of

GODAS, but temperature and salinity Argo profiles are used in developmental versions of GODAS. The use of Argo has had two immediate benefits to GODAS: (1) the deep sampling of the Argo floats allows GODAS vertical depths to be extended to 2200 m versus the old assimilation limit of 750 m, and (2) Argo salinity observations have reduced the dependence on synthetic salinity profiles computed from local T-S relationships in the assimilation.

2. *Source (GTS, GDAC) and type (real-time, delayed mode) of Argo data.* The operational GODAS uses real-time Argo acquired via GTS. Argo data used in GODAS developmental work are acquired in delayed mode from the Argo GDAC on the GODAE server in Monterey.

3. *Timeliness of Argo data.* The timeliness of the Argo data is entirely adequate for GODAS operational use. GODAS runs in 2 modes in operations: one with a 2-week delay and the other with a one-week delay.

4. *Quality of Argo data and use of Argo real-time or delayed mode QC flags.* Overall, Argo data quality is excellent. Argo delayed-mode QC flags are found to be extremely reliable. In the follow-up QC that is performed at NCEP, very few additional Argo profiles are rejected.

5. *Impact of Argo data on forecast or other measure of system/application skill.* The Argo data have not been around long enough for a proper statistical evaluation of its impact on S-I forecasting. The impact of Argo on GODAS itself, however, shows two strong results: (1) the assimilation of deep Argo profiles corrects a persistent deep model temperature bias in all of the ocean basins (Fig. 1), and (2) the assimilation of salinity profiles corrects the model equatorial currents in the Pacific (Fig. 2). Correction of model velocity in the tropical Pacific has been a stubborn problem for a long time, and the fact that the solution is the result of assimilating observed salinities is considered remarkable. In the western tropical Pacific, assimilating Argo salinity corrects the model current speed bias at the surface and the depth of the undercurrent core, in addition to reproducing better the complex vertical structure of the current at 165°E. In the eastern tropical Pacific, assimilating Argo salinity reduces the model current speed bias at the surface and sharpens the velocity profile below the thermocline at 110°W.

Navy: FNMOC and NAVOCEANO – J. Cummings, Naval Research Laboratory

The Navy assimilation and quality control systems are described in:

Cummings, J.A. (2005). Operational Multivariate Ocean Data Assimilation. *Q. Journal Royal Met. Society* 131:3583-3604.

Cummings, J.A. (2006). Description of the NRL Real-Time Ocean Data Quality Control System. NRL Technical Note (*in press*).

Fox, D.N., W.J. Teague, C.N. Barron, M.R. Carnes, and C.M. Lee (2002). The Modular Ocean Data Assimilation System. *J. Atmos. Ocean. Technol.* 19:240-252.

1. *Describe use of Argo data.* Argo temperature and salinity profiles are routinely assimilated in the Navy Coupled Ocean Data Assimilation (NCODA) system that is in operations at FNMOC and NAVOCEANO. NCODA is a multivariate optimum interpolation (MVOI) system (Cummings, 2005). The system is run in analysis-only mode at FNMOC and in assimilative mode at NAVOCEANO as part of the HYCOM forecast system. The global, 12-km resolution, real-time FNMOC/NCODA analysis that assimilates Argo data is available on the GODAE server at: http://usgodae.fnmoc.navy.mil/ftp/outgoing/fnmoc/models/glb_ocn. The HYCOM forecasting system, with NCODA assimilation, is currently being spun-up to real time at NAVOCEANO. Argo is also being used at NAVOCEANO as a source of observations in the development of statistical databases that relate surface properties, such as SST and SSH, to

density structure at depth. The databases are used to assimilate altimeter SSH anomaly observations using the synthetic BT approach in both MODAS (Fox et al., 2002) and NCODA. Argo provides important new observations in ocean areas, such as the South Pacific and Southern Ocean, that previously were poorly sampled or not sampled at all during winter.

2. *Source (GTS, GDAC) and type (real-time, delayed mode) of Argo data.* Argo data are obtained off GTS in real-time. Argo data from the GDAC are not used yet in operations, although there are plans to switch from GTS to the GDAC to make use of the real-time Argo QC flags.

3. *Timeliness of Argo data.* Navy analysis/forecast systems are run in real-time. The global assimilation systems are typically run 9 hours after real-time. Multiple quality control data cuts are performed each day in order to have the latest and most synoptic data available for the assimilation. The Argo data off GTS are, on average, 12-15 hours old when received at the Navy operational centers. These receipt times are well within Navy operational time constraints for Argo data to be considered synoptic.

4. *Quality of Argo data and use of Argo real-time or delayed mode QC flags.* Argo data off GTS are processed through the Navy real-time, fully automated, ocean data quality control system (Cummings, 2006). The quality of Argo data on GTS is highly variable. We reject approximately 5-7% of Argo GTS profiles in the operational real-time QC system. Note that a profile can be rejected either at the QC stage or at the analysis stage. At the QC stage rejection occurs primarily because the departure of the profile observation from the background field (climate, previous analysis, cross validation) is too large. At the analysis stage rejection occurs if the sampling characteristics of the profile do not match the requirements of the assimilation system (top level too deep, bottom level too shallow, large gaps in vertical depth levels, etc). Note that rejection of an Argo profile in the real-time QC does not necessarily mean that the Argo profile contained erroneous data. The Navy ocean data QC system in operations at FNMOC is contributing to the GODAE QC pilot project. The GODAE QC pilot project compares real-time QC system outcomes from the various GODAE data and product centers around the world (US, Europe, Japan, Australia). One aspect of the QC pilot project involves the use of Argo delayed mode data to see if the decision made to accept/reject an Argo profile in real-time is consistent with the final scientific QC decision made on the profile in delayed-mode by the Argo project.

5. *Impact of Argo data on forecast or other measure of system/application skill.* A simple, data denial study is planned with the global HYCOM system to assess the impact of Argo data on HYCOM forecast skill. HYCOM is executed on a global, 9-km resolution grid. It is not possible, with existing computer resources, to perform the spin-up run and data denial experiments simultaneously. However, a HPC challenge account on the IBM power-5 computer at NAVOCEANO will be available to the HYCOM consortium beginning in March, 2007. The Argo impact study will be performed using computer time from this new challenge account.

NASA/GSFC/GMAO – M. Rienecker, Global Modeling and Assimilation Office

The GMAO assimilation system is described in:

Keppenne, C.L., M.M. Rienecker, N.P. Kurkowski and D.D. Adamec (2005). Ensemble Kalman Filter Assimilation of Temperature and Altimeter Data with Bias Correction and Application to Seasonal Prediction, *Nonlin. Proc. Geophys.*, 12:491-503.

Sun, C., M.M. Rienecker, A. Rosati, M. Harrison, A. Wittenberg, C.L. Keppenne, J.P. Jacob, R.M. Kovach (2007). Comparison and sensitivity of ODASI ocean analyses in the tropical Pacific. *Mon. Wea. Rev.* (in press)

1. *Describe use of Argo data.* Argo temperature and salinity profiles are assimilated into the two GMAO ocean data assimilation systems: an Optimal Interpolation (OI) implementation (Sun et al., 2007), and an Ensemble Kalman Filter (EnKF) (Keppenne et al., 2005).

2. *Source (GTS, GDAC) and type (real-time, delayed mode) of Argo data.* Argo data are downloaded from the Argo GDAC on a weekly basis.

3. *Timeliness of Argo data.* We undertake near-real time assimilation to generate ocean state estimates for initialization of coupled seasonal forecasts at the beginning of each month. The near-real-time assimilation is conducted with the OI. We also undertake retrospective analyses with the EnKF. In either case, the timeliness of the Argo for the assimilation runs is excellent.

4. *Quality of Argo data and use of Argo real-time or delayed mode QC flags.* We download the Argo data stream from the USGODAE Argo GDAC geographic directories for each ocean basin (<ftp://usgodae1.fnmoc.navy.mil/pub/outgoing/argo/geo/>). The quality of the Argo data and QC flags has progressed over the time we have been using them (since 2003) and the recent changes have been most useful (*note:* <param> can be TEMP, PSAL, or PRES variables).

- New PROFILE_<param>_QC definition for the overall quality flag of the profile. The new definition indicates a percent of good values in the profile. Previously, this flag had just been the maximum value of the level-by-level QC flags. So, if the profile just had one bad value, the entire profile would have been flagged as bad.
- DATA_MODE definition is very useful in determining which data variable to retrieve. The DATA_MODE can be 'D' for Delayed Mode, 'R' for Real Time, or 'A' for Real Time with Adjustment. If the DATA_MODE is 'A' then we know to retrieve the <parameter>_ADJUSTED value and <parameter>_ADJUSTED_QC instead of the real time values stored in <parameter> and <parameter>_QC.

Through all the changes in the Argo data stream and QC flags, we have been given outstanding help by Mark Ignaszewski at FNMOC. There were a few times that Robin Kovach in GMAO had found some discrepancies in the data and QC and Mark resolved these problems quickly.

5. *Impact of Argo data on forecast or other measure of system/application skill.* The Argo stream is of too short a duration to make a statistical evaluation of the impact on coupled model seasonal forecast skill. However, we have evaluated the salinity analysis itself against independent CTD data (not assimilated) during the TAO servicing cruises. We find that the Argo data improve our salinity analysis in the western equatorial Pacific (NINO-4 region) by reducing the bias by about 50% in the upper ocean salty layer and in the halocline. It also reduces the standard deviation of the error in that region. Improvements in the eastern equatorial Pacific are not as marked. These are preliminary results as we are still tuning the observation error statistics that we use with the Argo data in our system.

ECCO: JPL and SIO/MIT – T. Lee, JPL

The consortium for Estimating the Circulation and Climate of the Ocean (ECCO) exists in two forms. One ECCO system is at JPL and uses an approximate Kalman filter/smoothen (vertical dynamical modes) in the assimilation. This system is described in:

Fukumori, I. (2006). What is data assimilation really solving, and how is the calculation actually done? In *Ocean Weather Forecasting - An integrated View of Oceanography* (Eds. E.P. Chassignet, and J. Verron), Springer, 317-342pp.

Fukumori, I. (2002). A partitioned Kalman filter and smoother. *Mon. Wea. Rev.*, 130:1370-1383.

The second ECCO system is at Scripps/MIT and uses the adjoint/4DVar assimilation method. This system is described in:

Stammer D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall, Global ocean circulation during 1992–1997, estimated from ocean observations and a general circulation model. *J. Geophys. Res.*, 107 (C9), 3118, doi:10.1029/2001JC000888.

Stammer D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall (2003). Volume, heat, and freshwater transports of the global ocean circulation 1993–2000, estimated from a general circulation model constrained by World Ocean Circulation Experiment (WOCE) data. *J. Geophys. Res.*, 108 (C1), 3007, doi:10.1029/2001JC001115.

1. *Describe use of Argo data.* Argo temperature and salinity profile data are used in the JPL Kalman filter/smoothing assimilation system and the MIT adjoint assimilation system, both geared towards climate diagnostic analysis.

2. *Source (GTS, GDAC) and type (real-time, delayed mode) of Argo data.* The JPL ECCO system obtains Argo data from NOAA/NCEP, which have been quality controlled by Dave Behringer. The Scripps/MIT ECCO system obtains Argo data from IFREMER.

3. *Timeliness of Argo data.* The ECCO consortium has a continuing requirement for Argo data. New Argo data are ingested every month as the assimilation systems go forward in time.

4. *Quality of Argo data and use of Argo real-time or delayed mode QC flags.* ECCO depends on NCEP and IFREMER to provide quality controlled Argo data.

5. *Impact of Argo data on forecast or other measure of system/application skill.* No specific impact studies have been performed for Argo data because the ECCO systems are too computationally expensive. There are no plans at the present time to perform Argo data impact studies with either of the ECCO systems.

Standard vs. Deep assimilation

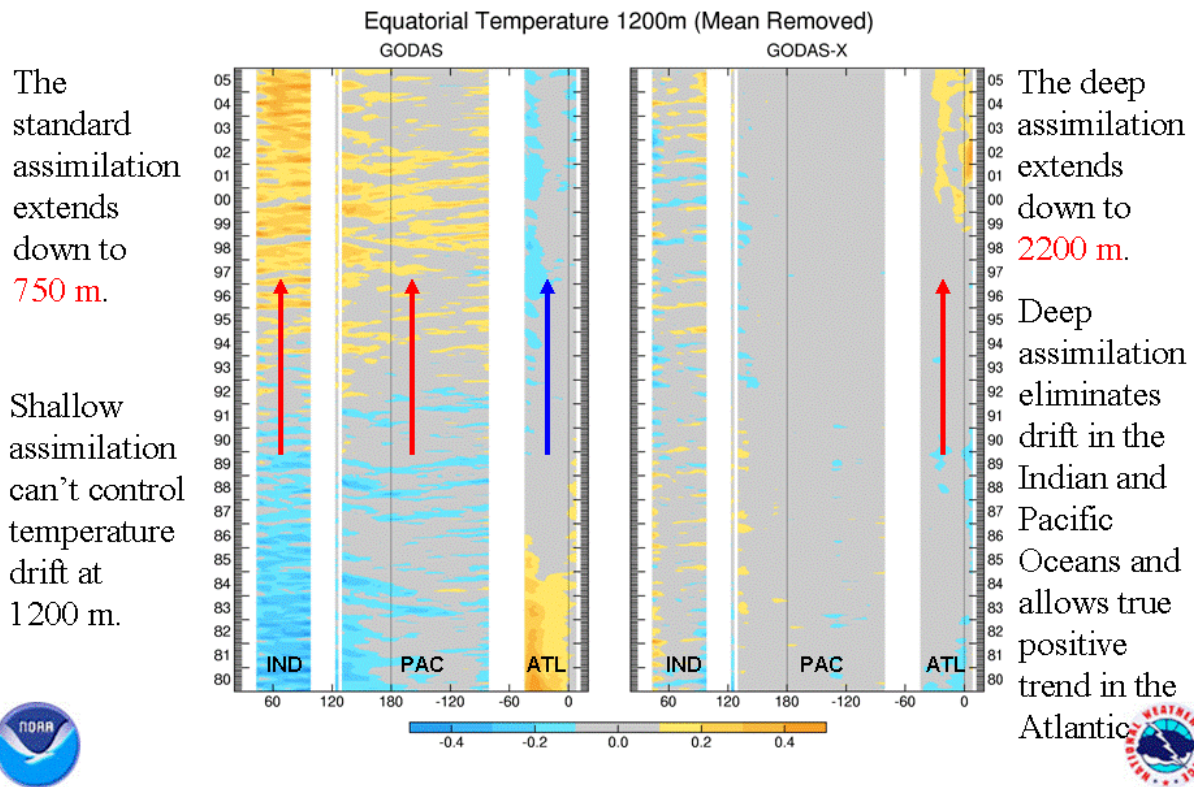


Figure 1. Assimilation of Argo profiles corrects NCEP model drift errors in temperature at depth.

In the west, assimilating Argo salinity corrects the bias at the surface and the depth of the undercurrent core and captures the complex structure at 165°E.

Assimilating Argo Salinity

Comparison with independent ADCP currents.

In the east, assimilating Argo salinity reduces the bias at the surface and sharpens the profile below the thermocline at 110°W.

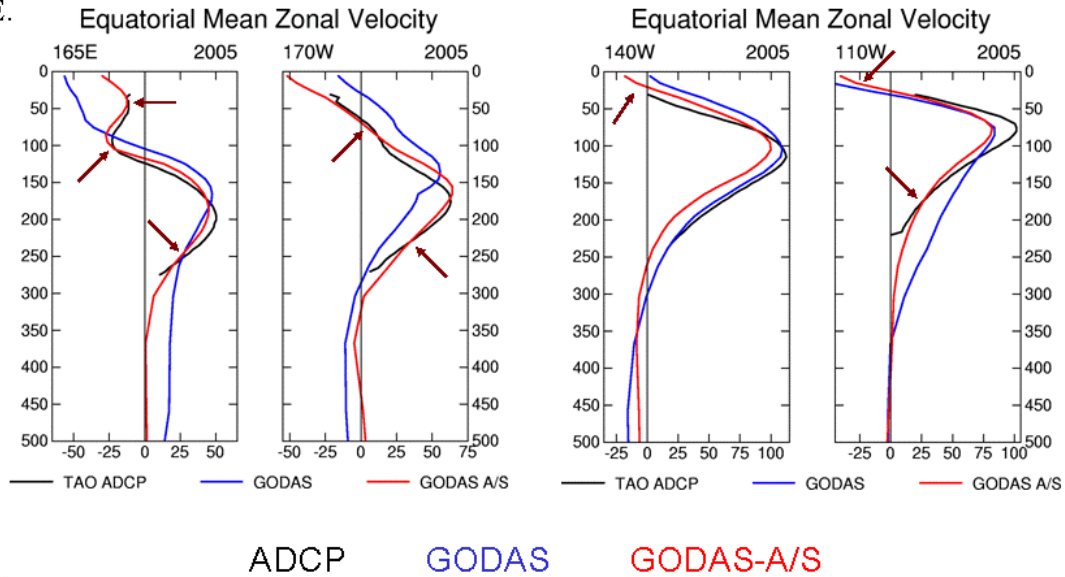


Figure 2. Assimilation of Argo salinity profiles corrects long standing NCEP model velocity errors along the equator in the Pacific.