Simulation of the Argo Observing System

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1. Abstract

The main goal of this study is to examine how well the Argo observing system determines the state of the global upper ocean. For this purpose, this study employs a suite of observation system simulation experiments (OSSE) in ocean general circulation models (OGCMs). Oceanic fields in these experiments are sub-sampled in ways similar to how the Argo float array samples the ocean, reconstructed and compared with the direct model fields. This procedure leads to quantification of errors in reconstructions of the oceanic state by the actual Argo array and understanding of factors that control these errors, and is expected to assist interpretation of Argo data. The results of these studies demonstrate a very good overall quality of the Argo-based reconstructions, but emphasize the need for additional, dense spatial sampling in the regions characterized by strong oceanic advection and intense mesoscale variability.

2. Project Summary

The Argo array currently consists of approximately 3000 instruments that make vertical profiles of temperature and salinity every 10 days over the upper 1500-2000 meters. The array has been brought to full strength, and a comprehensive assessment of the limitations of the Argo observing system is urgently needed.

The main goal of this study is to examine how well the Argo observing system determines the state of the global upper ocean. For this purpose, this study employs a suite of observation system simulation experiments (OSSE) in ocean general circulation models. Oceanic fields in these experiments are sub-sampled in ways similar to how the Argo float array samples the ocean, reconstructed and compared with the direct model fields. This procedure leads to quantification of errors in reconstructions of the oceanic state by the actual Argo array and understanding of factors that control these errors, and is expected to assist interpretation of Argo data. The project directly addresses the second mission goal of the NOAA Strategic Plan: to *Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond*, in the area of *Climate Observations and Analysis*.

The research is being carried as a part of the Cooperative Institute for Marine and Atmospheric Studies (CIMAS) program. The relevant CIMAS theme is *Integrated Ocean Observations*, which has the objectives "to improve the integration of modeling and physical measurements in the ocean and the atmosphere so as to achieve optimal designs of observing systems; to develop the criteria for the acquisition of oceanic data needed to determine and document the role of the ocean in long-term climate change and to monitor these changes". The work on this project began at the University of Washington (Seattle, Washington) and is now continued at the Rosenstiel School of Marine and Atmospheric Science (Miami, Florida).

3. Scientific Accomplishments

During FY 2011, the analysis was carried in **high-resolution, eddy-permitting simulations of the oceanic state.** The presence of mesoscale variability introduces a wealth of important effects on the accuracy of the Argo system, which have not been addressed before in scientific literature. The analysis have been completed first in an **idealized eddy-permitting model** of the North Atlantic, where a suite of carefully designed sensitivity studies was carried out in order to illuminate the most important effects of the mesoscale variability (*Kamenkovich et al.* 2011). Currently, our group (Kamenkovich, Haza, Garraffo and Schmid) is carrying out and analyzing the most realistic simulations of the Argo array in a **state-of-the-art high-resolution global ocean model**. Accomplishments from both projects are summarized below.

3.1 Eddy-resolving simulations of the North Atlantic

These idealized simulations of Argo measurements are carried out in a high-resolution ocean model of the North Atlantic, set up in a way to produce the annual mean hydrography and circulation. High horizontal resolution of these OSSEs ($1/8^o$ resolution in latitude/longitude) permits simulation of mesoscale eddies. Initially, 250 Argo floats are evenly distributed in the model domain; the floats are then *advected* by simulated currents for nine model years. Idealized, but relevant to the real ocean, setting permits a comprehensive and transparent analysis of the important properties of mesoscale variability. In particular, a suite of sensitivity experiments allows to accurately separate the most important effects of mesoscale eddies: eddy advection and high-frequency variability in temperature and salinity. During FY 2011, this analysis was completed, following the suggestions of the anonymous reviewers, and the manuscript describing the findings was published in its final form. The main findings in the final version are:

- In the most of the domain, the eddies help to achieve more uniform spatial coverage, acting to reduce gaps in the spatial coverage (Fig.1). Identification of regions corresponding to strong eddy dispersion, based on Argo float trajectories, is particularly important, since these regions will require continuing redeployment of the floats.
- In many parts of the domain, improved coverage in the presence of eddies corresponds to smaller ***reconstruction errors*** – the difference between the reconstructed and actual (GCM-simulated) temperatures and salinities (Fig.2a,b). Gaps in the sampling coverage do not always correspond to elevated reconstruction errors, as demonstrated by the analysis (Fig.2b).

- Mesoscale variability in temperature/salinity has an almost uniformly adverse effect on the reconstruction errors. The importance of the mesoscale variability increases for lower data coverage and shorter averaging period.
- The reconstruction errors are gradually reduced, when longer periods and larger number of samples are used; the reduction is, however, significantly slower than that for the standard error in a sample average of a random variable.
- Velocity estimates from the simulated Argo float trajectories at 1x1 degree grid are accurate enough for detection of concentrated oceanic currents like the multiple zonal jets with characteristic widths of 1.5-2 degrees (Fig.3). The ability of the Argo-based velocity estimates to reconstruct the shape and positions of the zonal jets is encouraging and can be used for the jet detection with the real Argo trajectories in the World Ocean (*van Sebille et al.* 2011).

3.2 Global high-resolution HYCOM simulations

Simulation of the Argo observing system is continued in one of the most comprehensive numerical models of the World Ocean: a high-resolution ($1/12^o$) global Hybrid-Coordinate Ocean Model (HYCOM). These simulations exhibit both realistic mean state of the ocean and its mesoscale variability. HYCOM model has been used extensively at National Research Laboratory (NRL). A list of publications, and on-line presentations, are available at http://www.hycom.org. For this study, a global $1/12^o$ climatological simulation with 32 vertical layers is used. The model is forced with monthly climatological ECMWF (ERA40) forcing fields plus 6-hourly anomalies and includes an "energy loan" ice model. HYCOM $1/12^o$ global simulations without Argo floats have already been carried out with simulated daily velocity and temperature/salinity fields archived. The simulated stratification closely resembles observations and the eddy field is sufficiently realistic.

During FY2011, our activities focused on finishing the development and testing of: (i) the profiling float advection algorithms; and (ii) software for reading and storing massive HYCOM archives needed for simulation of the Argo float trajectories. These tasks have been completed. Simulated Argo floats are now advected at the depth of 1000 meters for nine days, followed by a 6-hour ascent (during which a profile is taken), 12 hours of surface advection, and a 6-hour descent to the 1000-m depth; the floats continue being advected during their ascent/descent. At this stage, the differences in float design are not addressed. The deployment sites and times closely match those for the actual Argo.

The simulations are competed for years 2004-2006 and are continued for later periods with new synthetic floats added (and removed) in agreement with the actual Argo floats. The float trajectories exhibit strong signature of the mesoscale variability (Fig.4), particularly in such eddy-rich regions as the vicinity of the western boundary currents and the Southern Ocean. The resulting spatial sampling coverage is uneven (Fig.5); the analysis of the importance of eddy advection for the coverage distribution is under way. The analysis of the reconstruction of temperature, salinity and density has also begun (Fig.6); the gaps in coverage are expected to correspond to significant reconstruction errors in regions of high spatial and temporal variability, which can negatively impact the ability to detect ongoing changes in the oceanic state.

Work on the internet data portal, which will contain simulated float trajectories and temperature/salinity profiles, has begun. The site will also contain links to existing HYCOM data portals, as well as instructions on how to download these data. This site is expected to be very useful for researchers who need to carry out their own OSSEs designed to assess various applications of Argo data and to help to design new analysis techniques.

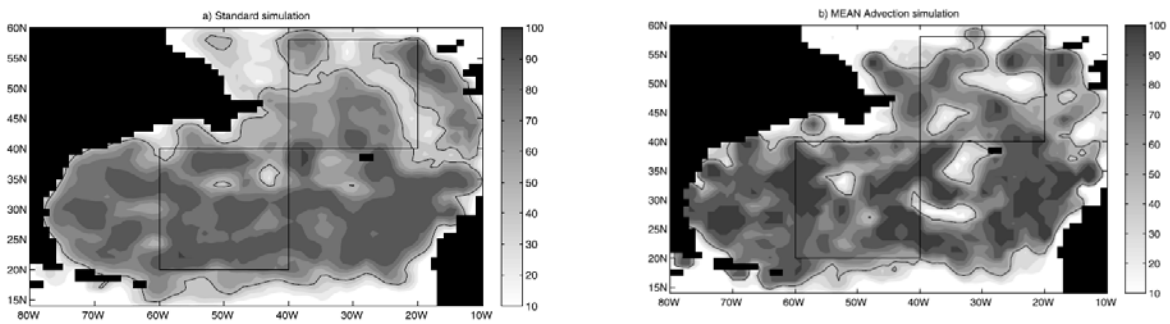

Figure 1: Effects of eddies on the sampling coverage by the simulated Argo array in the North Atlantic. Shown is the percentage of valid reconstructed values at each grid point at 1000-meter depth during the 9-year lifespan of the simulated Argo system for (a) the standard simulation; b) the simulation with the mean advection only. The contour on each plot represents 50% value. Areas where the water depth is less than 1000 meters are shaded black. Eddies help to achieve a generally more uniform spatial coverage. From *Kamenkovich et al.* (2011).

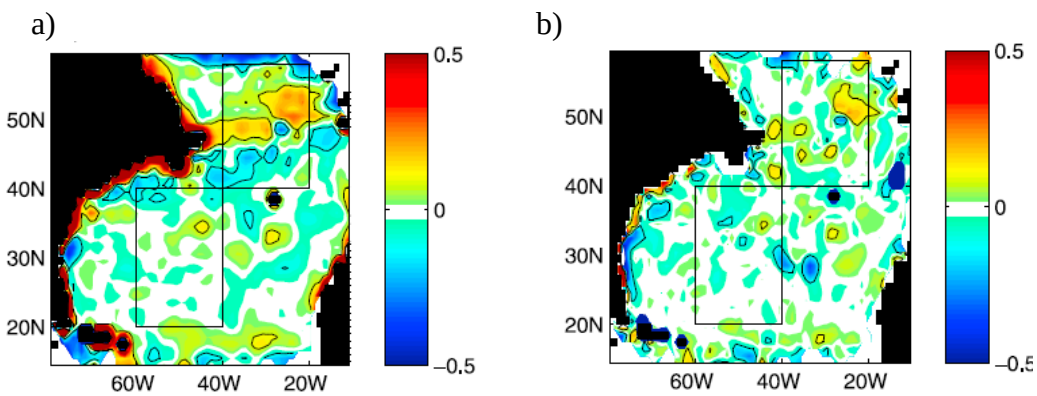

Figure 2: Effects of eddies on reconstruction of temperature in the North Atlantic. Shown are: (a) Reconstruction errors for the depth-averaged (over 1000m) temperature averaged in the standard simulation. (b) Difference in the magnitude of the reconstruction errors between the standard and the simulation with the mean advection only – positive values indicate the increase in errors due to the presence of the eddy advection. The contour interval for temperature is 0.05K; the contour lines show the +/-0.1K line. From *Kamenkovich et al.* (2011).

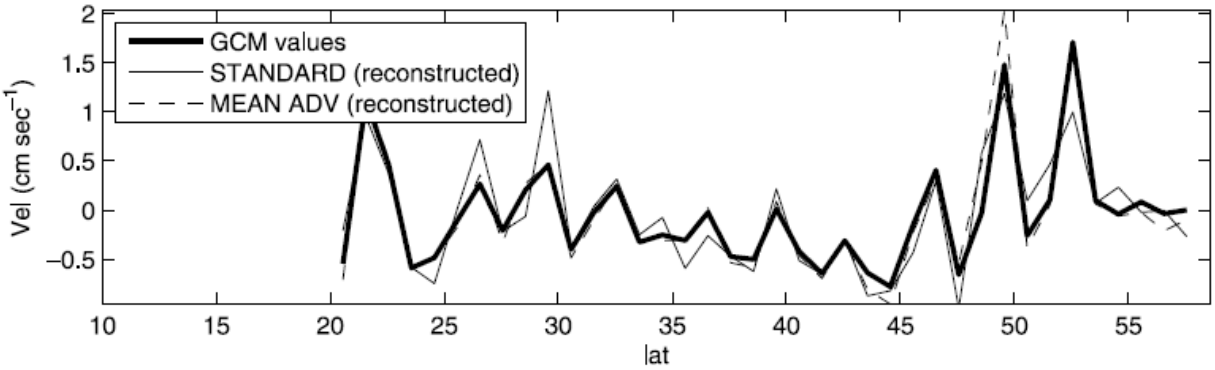

Figure 3: Effects of eddies on reconstruction of horizontal velocities in the North Atlantic. Shown are the zonally averaged zonal velocities at 1500 meter depth, averaged within 1x1-degree bins: actual GCM-simulated values (thick solid) and reconstructed from the simulated Argo trajectories (thin solid and dashed). Units are cm sec^{-1}. Multiple zonal jets are seen as local maxima in velocity magnitude; they are successfully detected by the reconstruction. From *Kamenkovich et al.* (2011).

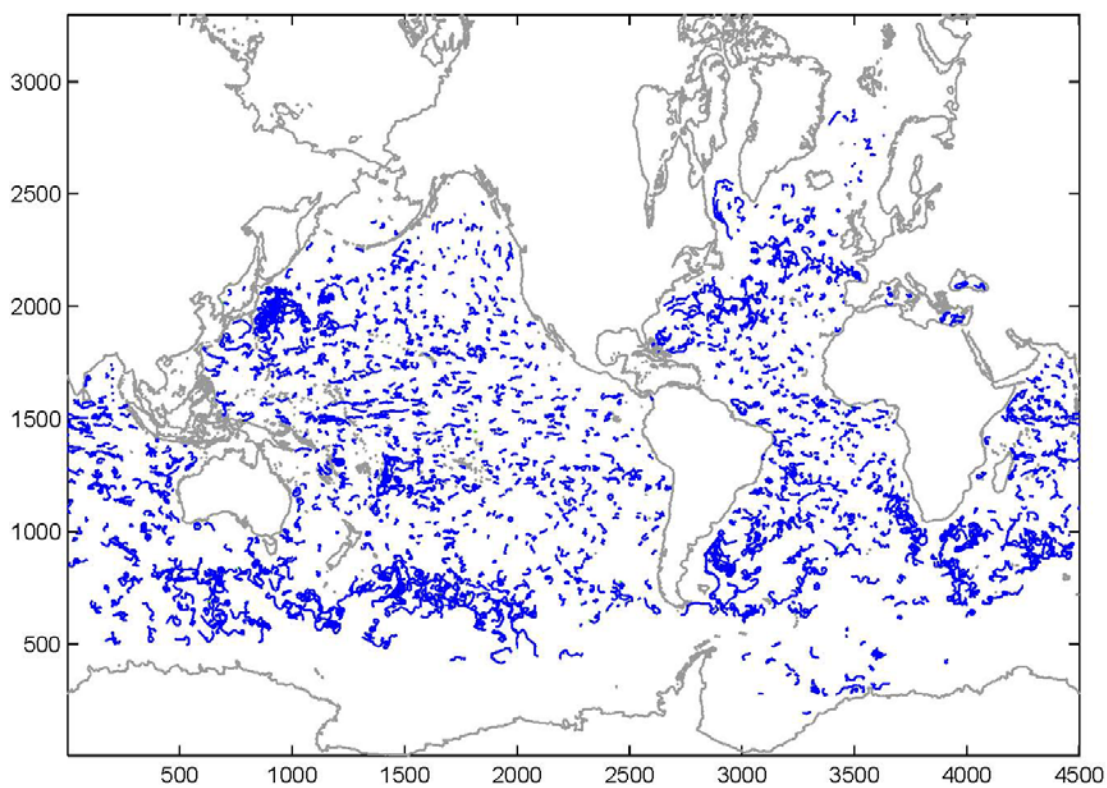

Figure 4: Global high-resolution HYCOM simulations of the Argo array: Float trajectories at 1000m depth during Sep-Oct 2005. Note the signature of mesoscale eddies.

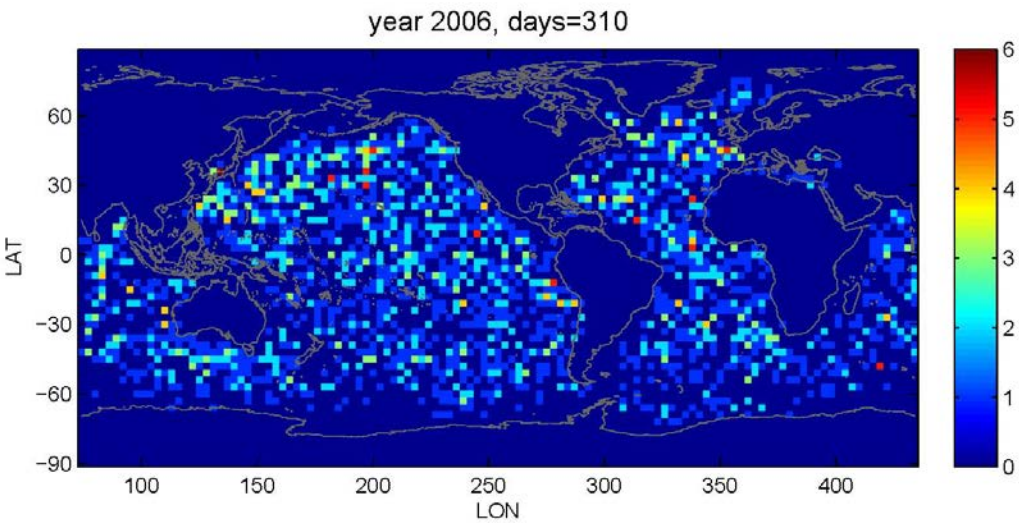

Figure 5: Spatial coverage density by synthetic Argo profiling floats in the global high-resolution HYCOM simulations. The number of available vertical profiles per 3-degree bins and for days 310-320 of year 2006 is shown by colors.

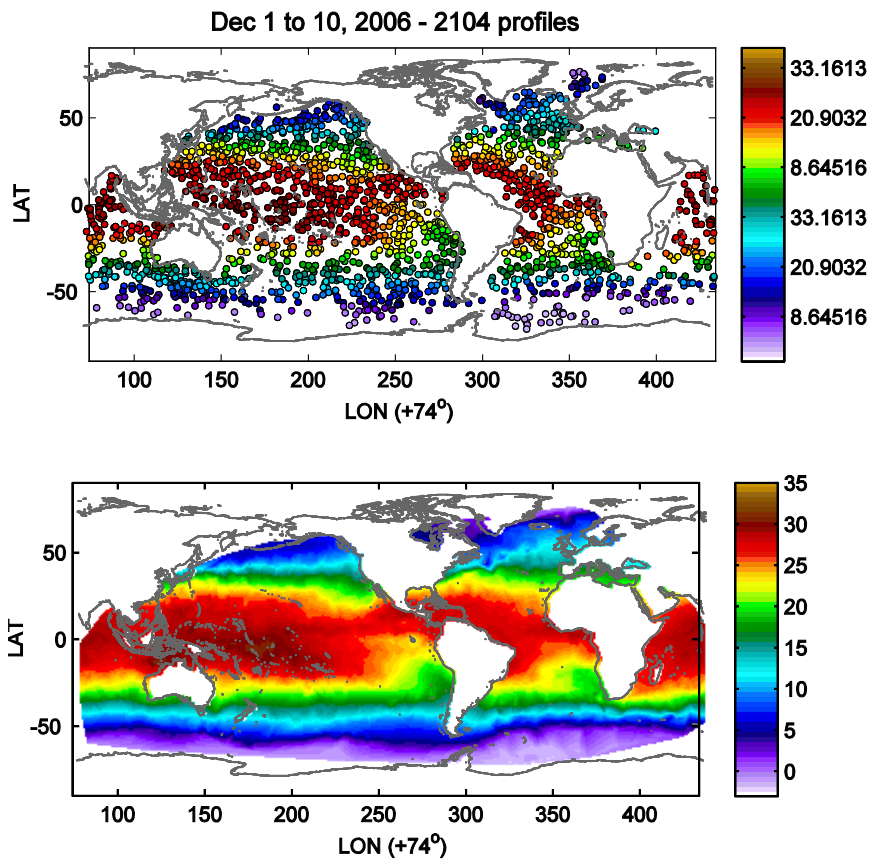

Figure 6: Reconstruction of the sea surface temperature (SST) from the simulated Argo profiles during one 10-day period (Dec.1-10, 2006). Top panel: SST values at the profile locations. Bottom panel: reconstructed SST field.

4. Education and Outreach

5. Publications and Reports

5.1. Publications by Principal Investigators

Kamenkovich, I., W. Cheng, E.S. Sarachik, and D.E. Harrison, 2009: Simulation of the Argo observing system in a global ocean model. *J. Geophys. Res.* **114**, C09021, doi:10.1029/2008JC005184

Kamenkovich, I., W. Cheng, C. Schmid, and D.E. Harrison, 2011: Effects of mesoscale variability on the accuracy of the Argo observing system, *J. Geophys. Res.*, **116**, C06003, doi: 10.1029/2010JC006910.

5.2. Other Relevant Publications

van Sebille, E., I. Kamenkovich, and J. Willis, 2011: Quasi-zonal jets in 3D Argo data of the northeast Atlantic, *Geophys. Res. Lett.*, **38**, L02606, doi:10.1029/2010GL046267.