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. 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 performance of the simulated Argo array, but emphasize the need for additional, dense spatial sampling in the Antarctic Circumpolar Current and the high-latitude North Atlantic, as well as in the regions characterized by 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.

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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 2009, the analysis of the expected performance of the Argo observing system in a suite of observation system simulation experiments (OSSE) **coarse-resolution OGCM** has been completed (in collaboration with Drs. Wei Cheng, E.S. Sarachik and D.E. Harrison, University of Washington). Our activities during this year were focused on the benefits of sustained observations and effects of float divergence and random instrumental errors. The manuscript describing these findings is published in the *Journal of Geophysical Research.*

The next important step of this project is to extend these analyses to **high-resolution, eddy-permitting simulations** of the oceanic state. These analyses are currently in progress and have already led to interesting results. 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. Such effects are demonstrated in a high-resolution idealized simulation of the North Atlantic (manuscript in preparation). In collaboration with Drs. Z. Garraffo and C. Schmidt, we have also begun numerical simulations of the Argo array in a state-of-the-art high-resolution global OGCM (HYCOM).

Coarse-resolution studies

The global ocean model used in this study has 2° resolution in both latitude and longitude. The simulated ocean state is as realistic as can be expected in a coarse-resolution model. However, because of the coarse resolution, the intensity of the boundary currents is underestimated and the mesoscale eddies are not resolved. The effects of the oceanic velocities on the Argo array in reality are expected to be even stronger than in this model.

In these OSSE, 3,000 Argo floats are advected with the GCM-simulated velocities at 1500m depth during most of the time. Every 10th day, a simulated float surfaces, while taking the temperature and salinity (T/S) profile; it then spends 8 hours at the surface, where the float is advected by the surface currents. Random instrumental errors are added to the data. Resulting data are used to reconstruct temperature and salinity of the ocean, using objective analysis. The simulations are carried for ten years.

We have analyzed the expected accuracy of the Argo system in reconstructing such important oceanographic variables as temperature, salinity, upper ocean heat content (UOHC, calculated over the top 800 m) and mixed layer depth (MLD). For each of the variables, the analysis is carried for:

(i) annual-mean values;
(ii) amplitude of the annual cycle: the absolute value of the difference between the September and March values;
(iii) amplitude of the interannual difference: the absolute value of the difference between the annual means for year 10 and year 1.

The first two or these variables characterize the climatology averaged over 10 years of GCM data. The second and third variables quantify the amplitude of the variability on annual and interannual time scales.

We analyze the **reconstruction errors**, the difference between the actual GCM-simulated and reconstructed fields. Results are described in *Kamenkovich et al.* (2009) and are briefly summarized below:

1) Overall performance of the simulated Argo array is good, and the reconstructed climatological means of such key quantities as the temperature, salinity, UOHC, and mixed layer depth are very close to the actual OGCM-simulated values in most of the global ocean. In particular:
    - The errors in temperature exhibit a maximum at approximately 100-150m, where the average errors in the annual mean reach 0.6 degrees in ACC and 0.3 degrees elsewhere. Average errors below 1000m are very small, less than 0.1 degrees.
    - The reconstructed climatology of UOHC is close to the actual GCM-simulated values over most of the ocean. The errors are particularly small for the annual-mean values and the magnitude of the annual cycle. However, the reconstruction errors are more significant in the regions of high gradients and intense currents, particularly in the Antarctic Circumpolar Current (ACC) and high-latitude North Atlantic.
    - The largest errors in these regions are found in the magnitude of the interannual difference (Figure 1), which suggests that the detection of interannual trends from the Argo data alone can be problematic.
    - Similar to UOHC, the reconstruction errors in MLD are significant in ACC and the high-latitude North Atlantic. Errors in the magnitude of the annual cycle are particularly large.
    - Random errors in temperature and salinity do not affect the overall performance.
    - Extended observations (from 5 to 10 years) significantly improve reconstruction of the interannual difference and linear trend.
2) Advection of the Argo floats has an overall adverse effect on the reconstruction of the oceanic state. In particular,

- Gradual loss of spatial sampling coverage, caused by divergent oceanic currents, additionally results in large errors in the subpolar region of the North Atlantic, parts of the ACC and some coastal areas (Figure 2).
- Sensitivity experiment, in which the simulated floats do not move, exhibits a substantial reduction in the reconstruction errors. The largest difference is found in ACC, where the float advection is demonstrated to be the main cause of reconstruction errors in the standard case.

3) The reduction in the number of floats (from 3000 to 1500) leads to a substantial (30-40 per cent) increase in the reconstruction errors, demonstrating the potential decrease in the reconstruction skill due to the floats gradually reaching the end of their lifetime.

Eddy-resolving simulations of the North Atlantic

To investigate the effects of mesoscale variability on the accuracy of the Argo system, we continued our last-year analysis of the OSSE in a high-resolution regional model of the North Atlantic. High horizontal resolution of these OSSE ($1/8^{o}$ 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 GCM-simulated currents for nine model years. Four experiments are being analyzed and described in a manuscript (in preparation):

1) In the *control* simulation, the Argo floats are advected by the full velocities. In agreement with the coarse-resolution experiments, the regions of the fast advection correspond to the largest systematic biases in the reconstructed fields and loss of spatial sampling coverage. The reconstruction errors in UOHC are substantial in most of the subpolar gyre (Figure 3a).
2) The effects of mesoscale variability on the expected accuracy of the Argo system are studied in the second experiment ("*time-mean*" case), in which the mesoscale variability is removed from both the velocities and temperature/salinity fields. As Figure 3b demonstrates, the mesoscale variability explains a substantial part of the reconstruction errors in the control experiment, particularly in the subpolar gyre.
3) If the mesoscale variability is removed from the velocities and not from the temperature and salinity, the errors are very similar to those in the time-mean case. The high-frequency variability in velocities (and float movements) is, therefore, the main cause of the increase in reconstruction errors due to eddies.
4) To further quantify effects of advection, we conduct the fourth experiment, in which the magnitude of mesoscale variability is amplified by a factor of 2.5. This amplification factor was chosen to bring the variance in the simulated sea-surface height closer to the observed one. As a result of the amplification, the biases in the simulated fields increase everywhere in the domain, with the largest change within the Labrador Current, and near the Cape Hatteras.

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 realistic mean state of the ocean and its mesoscale variability. Float locations and sampling methods will most closely match the ones in the real Argo array.

HYCOM model was 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, we will use a HYCOM global $1/12^o$ climatological simulation with 32 vertical layers. The model is forced with monthly climatological ECMWF (ERA40) forcing fields plus 6-hourly anomalies obtained from NOGAPS winds (corresponding to Jan 2003-2004). A simple "energy loan" ice model is included, without advection or dynamics.

HYCOM $1/12^o$ global simulations without Argo floats have already been carried. The simulated stratification closely resembles observations. The eddy field is well-developed, as manifested by the standard deviations of the sea-surface height anomalies, which are in good overall agreement with the satellite-based estimates from the TOPEX-Poseidon data.

Simulated Argo floats are advected at the depth 1000 meters for nine days, followed by a 6-hour ascent, 12 hours of surface advection, and a 6-hour descent to the 1000-m depth. The deployment sites will closely match actual Argo float locations. In a preparatory experiment, the described simulations of Argo float trajectories were carried in the South Atlantic region. Results show substantial effects of eddy advection on the float trajectories and spatial sampling coverage in the vicinity of South America (Figure 4).

Significance of results

These studies help to identify the regions, in which the reconstruction of oceanic variables from the Argo data set can be less reliable than in the rest of the World Ocean. The results also demonstrate several important effects of oceanic advection on the accuracy of the reconstruction. As shown by our coarse-resolution global simulations, float movements represent a major source of reconstruction errors in ACC and the high-latitude North Atlantic, particularly in inter-annual variability. The eddy-resolving simulations further suggest that the mesoscale variability in velocities and float movements act to increase reconstruction errors in the North Atlantic.

The results emphasize the need for additional, dense spatial sampling in ACC and the high-latitude North Atlantic, as well as in the regions characterized by intense mesoscale variability. Combining Argo data with other measurements less affected by oceanic currents, such as satellite, XBTs and mooring data, will also help to improve accuracy of the reconstruction of oceanic variables.

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, E.S. Sarachik, and D.E. Harrison: Effects of mesoscale variability on the accuracy of the Argo observing system, in preparation

6. Figures

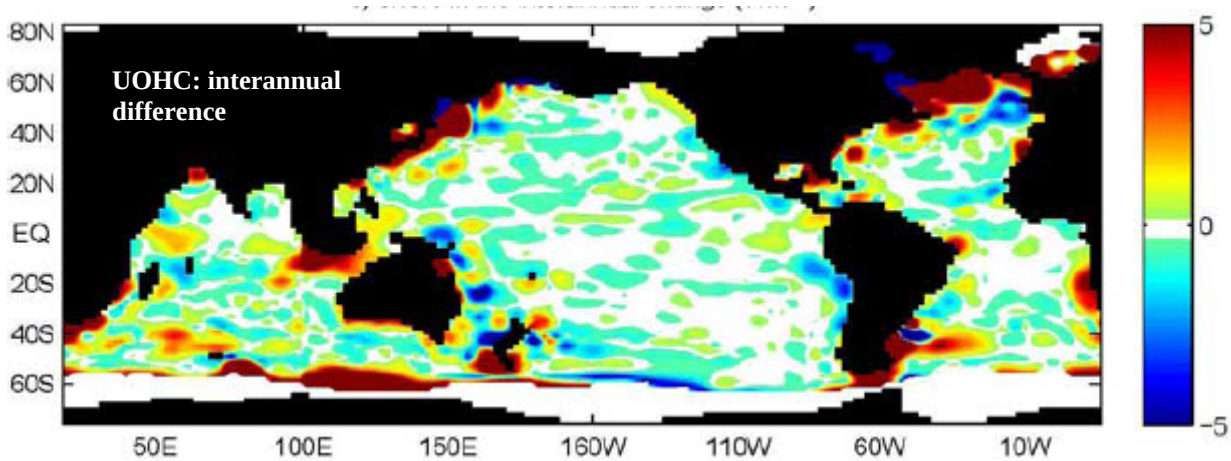

Figure 1 Accuracy of the reconstruction of UOHC in the standard 10-year simulation. Reconstruction errors are shown for the amplitude of the interannual difference (in flux units, contour interval is 0.25Wm^{-2}). Values under ice are not shown.

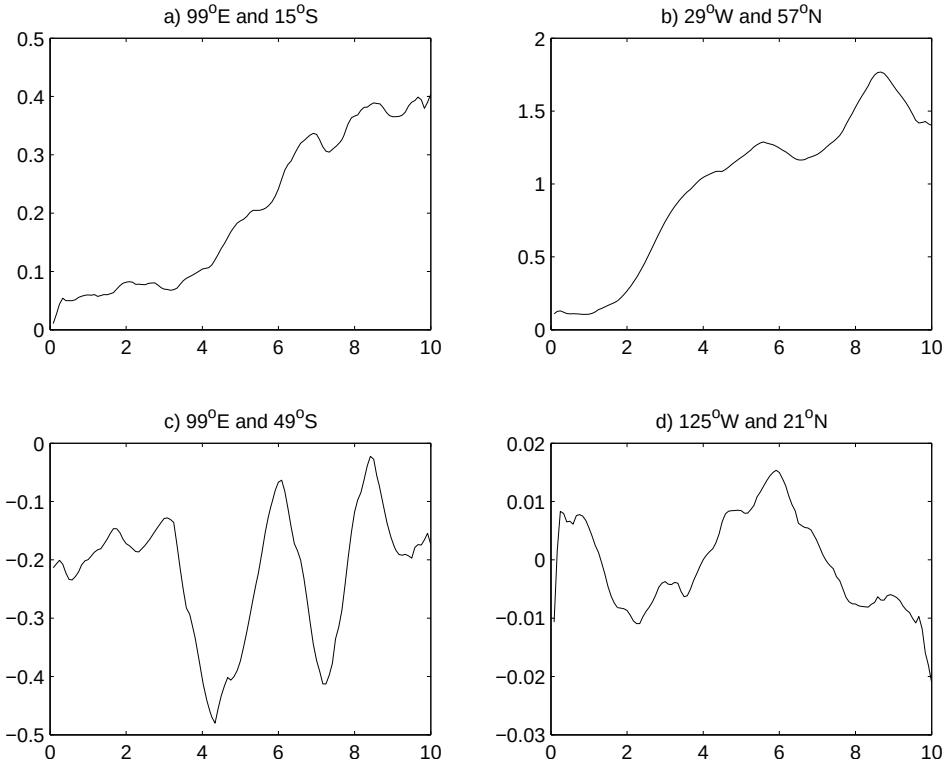

Figure 2 Growth and time dependency in the monthly mean reconstruction errors in UOHC at the following selected locations (in temperature units of K): (a) tropical Indian, (b) high-latitude North Atlantic, (c) Indian sector of the ACC, and (d) midlatitude North Pacific. Time is shown in years.

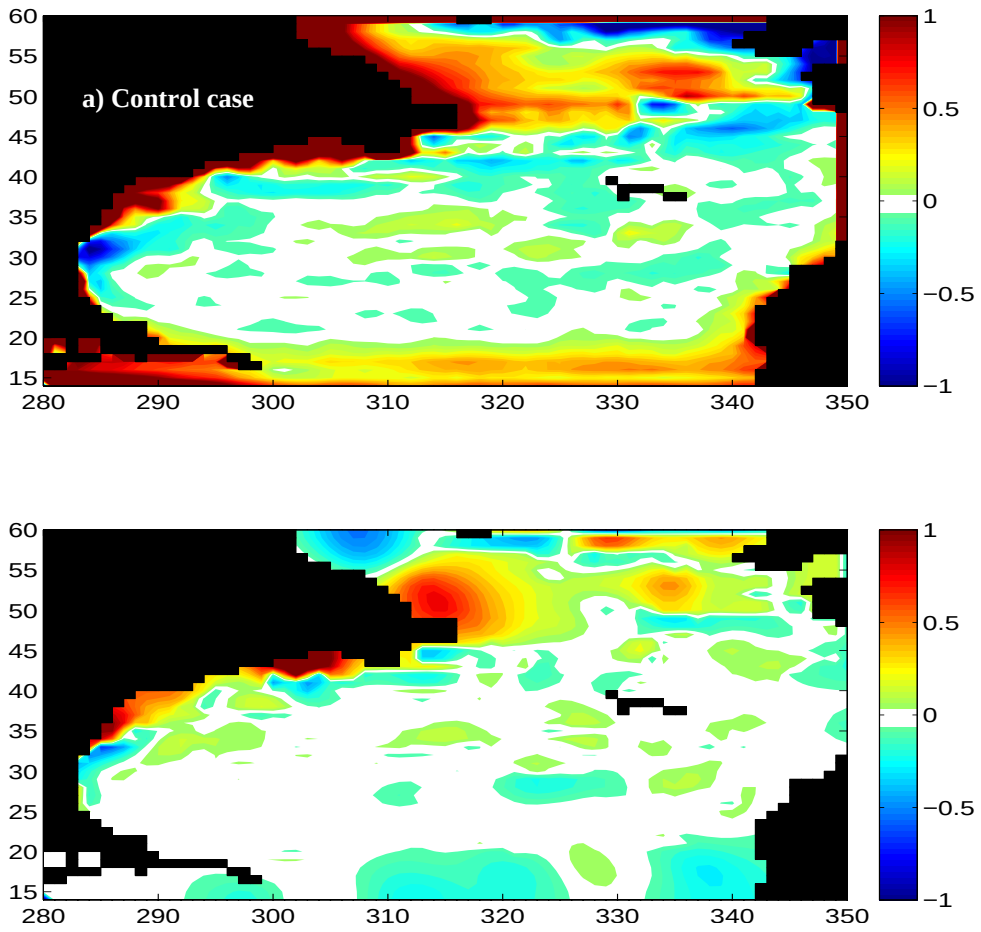

Figure 3 Reconstruction errors and importance of mesoscale eddies for reconstruction of UOHC in the eddy-permitting North Atlantic simulations. Top panel: reconstruction errors in the control case. Bottom panel: the difference in the error magnitudes between the control case and the experiment with the time-mean fields. Units are degrees K (heat content per unit area is divided by 3.4×10^9J)

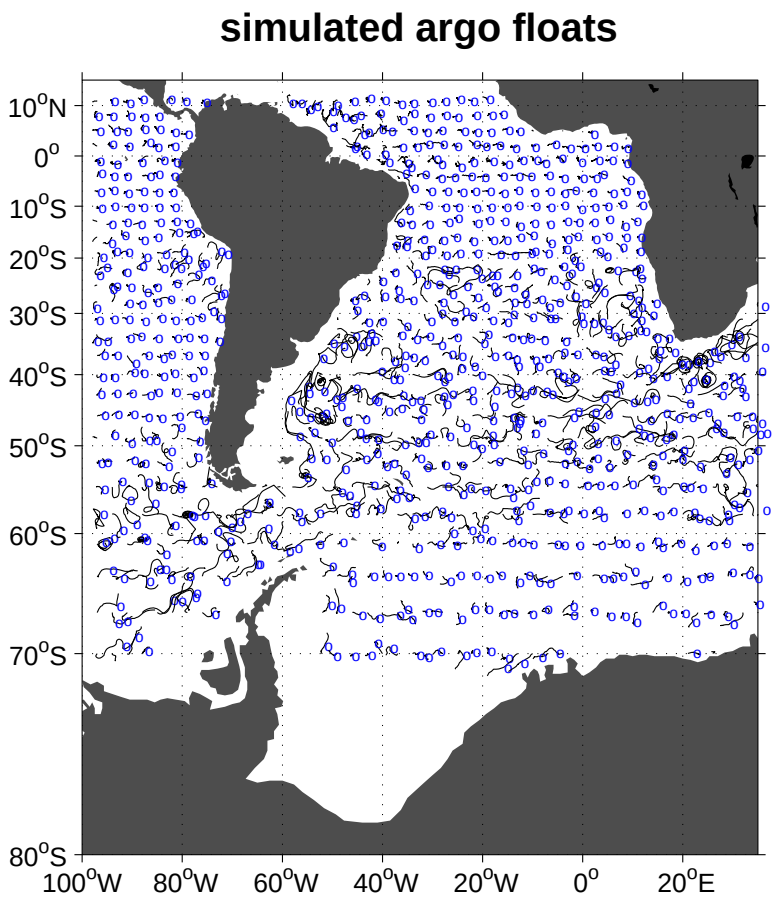

Figure 4 Trajectories and positions of simulated Argo floats in the eddy-permitting (1/12°) global simulation with HYCOM model. The duration of the experiment is two months. Note significant effects of eddies on float trajectories in ACC.