Observing System Simulation Experiments for the Atlantic Meridional Overturning Circulation

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LONG-TERM GOALS

The long-term goals of this project are to (1) develop the necessary software to conduct Observing System Simulation Experiments (OSSEs) and Observing System Experiments (OSEs) as tools to design ocean observing strategies and (2) perform OSSEs and OSEs to design observational strategies for monitoring changes in the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is one component of a global overturning circulation. It plays an important role in climate variability because it transports a large amount of heat northward in the Atlantic basin which in turn influences sea surface temperature (SST) and atmospheric circulation, particularly over middle and high northern latitudes. This flow is difficult to monitor because it has complicated three-dimensional pathways and interacts with wind-driven ocean current systems that are not directly related to the overturning. Furthermore, observing systems are costly to design, deploy, and maintain. To design an efficient and cost-effective system to monitor the AMOC, it is necessary to identify the critical variables to be monitored, the required spatial configuration of sensors, and the necessary frequency of measurements. To achieve these goals, OSEs will be performed to evaluate the impact of the existing ocean observing system while OSSEs will be performed to evaluate the impact of potential new observing systems.

OBJECTIVES

The initial objectives of this project during the first two years involved (1) building the hardware and software systems required to conduct OSSEs and OSEs at NOAA/AOML, (2) evaluating the suitability of different ocean models for performing these experiments, and (3) estimating the errors in ocean variables produced by present-day numerical models, These initial objectives have been satisfied and we are now performing sensitivity tests on the data assimilation system and OSE/OSSE software with the objective of performing initial OSEs and OSSEs to test AMOC monitoring strategies during year 3. As stated in out initial proposal, these initial experiments will not produce a final state-of-the-art OSE/OSSE system for ocean climate research. Development of such a system will occur over several stages where ocean models of increasing complexity and resolution plus data assimilation techniques of increasing realism are used for OSEs and OSSEs. Results from each stage, including the first stage supported by this project, will be used to guide the design and execution of subsequent stages of OSE/OSSE development.

APPROACH AND WORK PLAN

The primary tool for conducting OSEs and OSSEs is an ocean data assimilation system, which is often referred to as an ocean "nowcast-forecast" system (e.g. Chassignet *et al*., 2007). This system is analogous to numerical weather forecast models which are typically run for a week or two into the future to provide guidance to weather forecasters. Both oceanic and atmospheric model forecasts must be started from the most accurate possible representation of the state of the ocean and atmosphere, respectively. Without observations of the ocean, however, the evolution of state variables such as temperature, salinity, and current velocity in ocean models gradually drifts away from reality. Data assimilation employs mathematical and statistical methodologies to blend observations with modelf fields to both produce optimal initial states of the ocean and correct model drift.

Ocean OSEs are conducted as follows. First, an ocean data assimilation system is run for a long period of time assimilating all available observations to produce the most accurate possible time series of modeled ocean variability in temperature, salinity, and currents. To test the impact of one particular subset of the observations that have been assimilated, the system is re-run with these particular observations withheld from the analysis. If the withheld observations are important for monitoring a particular ocean phenomenon such as the AMOC, then the representation of this phenomenon in the second run will be significantly degraded as will forecasts initialized by the second run. If these observations are unimportant, the representation will not be significantly degraded. OSEs are limited to testing the impact of existing ocean observations. The only way to test a new observing system through OSEs is to undergo the expense of actually designing and deploying the new system.

Ocean OSSEs provide a method to test new observing systems before deployment, thus realizing potentially large cost savings. The trick is that instead of using actual observations of the real ocean to perform an OSE, synthetic observations sampled from a long ocean simulation performed using a second ocean model are used. The model run that is sampled is referred to as the "nature run". For OSSEs to work properly, certain thresholds must be achieved by the nature run. First, the nature run must represent the structure and variability of the oceanic phenomena of interest with good statistical realism. Second, properties of the nature run model must differ significantly from properties of the ocean model used in the data assimilation system. Ideally, statistical differences in the representation of phenomena of interest between the two models must approximate the errors and biases that exist in present-day ocean models with respect to the actual ocean. One important method of validating OSSEs is to perform two OSEs, one a true OSE using actual observations of the ocean and the other using identical synthetic observations with the same error characteristics extracted from the nature run. Results from these two OSEs will not differ significantly if the OSSE system is viable.

WORK COMPLETED

Out of necessity, the first two years of this project has emphasized (1) the developmental work required to build ocean OSE/OSSE capabilities at NOAA/AOML, and (2) generation and evaluation of suitable nature runs. Traditionally, OSSEs have been performed by meteorologists using numerical weather prediction models to assess the capability of a new observing system to reduce weather forecast errors (e.g. Atlas, 1997). In contrast, ocean OSSEs are in a relative state of infancy. Present-day ocean models are not as mature as numerical weather prediction models and have significant errors and systematic biases that make it difficult to execute viable OSSEs, particularly in regards to monitoring long-period variability in ocean climate. Using an ensemble of existing model runs, a postdoctoral researcher (Haoping Yang) has documented the error statistics of ocean models required to perform data assimilation runs. The software required to perform observing system design experiments is now in place at AOML and we are now in the process of setting up and running initial OSE and OSSE experiments.

The OSE/OSSE system now being tested at NOAA/AOML will initially use the same model code base (the “fraternal twin” approach) to represent the nature run and the data assimilative model. The HYbrid Coordinate Ocean Model *HYCOM) is suitable for this purpose because it is highly flexible in terms of vertical coordinate discretization, and also offers multiple choices of numerical algorithms and subgrid-scale parameterizations. These choices allow HYCOM to be configured to substantially mimic the behavior of other types of ocean models. The feasibility of this approach has been demonstrated in a low-resolution Atlantic model. Figure 1 illustrates that the representation of the AMOC streamfunction differs significantly between the two HYCOM configurations as required to perform OSSEs. We have also designed and tested the software required to extract the synthetic observations from the Nature Run model. This has not been a trivial task because it is necessary to add errors to these extracted observations that have the same statistical error properties as the actual observing systems. For the data assimilation system, HYCOM has been configured to use the Singular Evolutive Extended Kalman (SEEK) filter (Pham *et al.*, 1998) to perform the required data assimilation. Other assimilation methods are also now being tested to determine the impact of data assimilation method on our ability to perform observing system design studies using OSSEs.

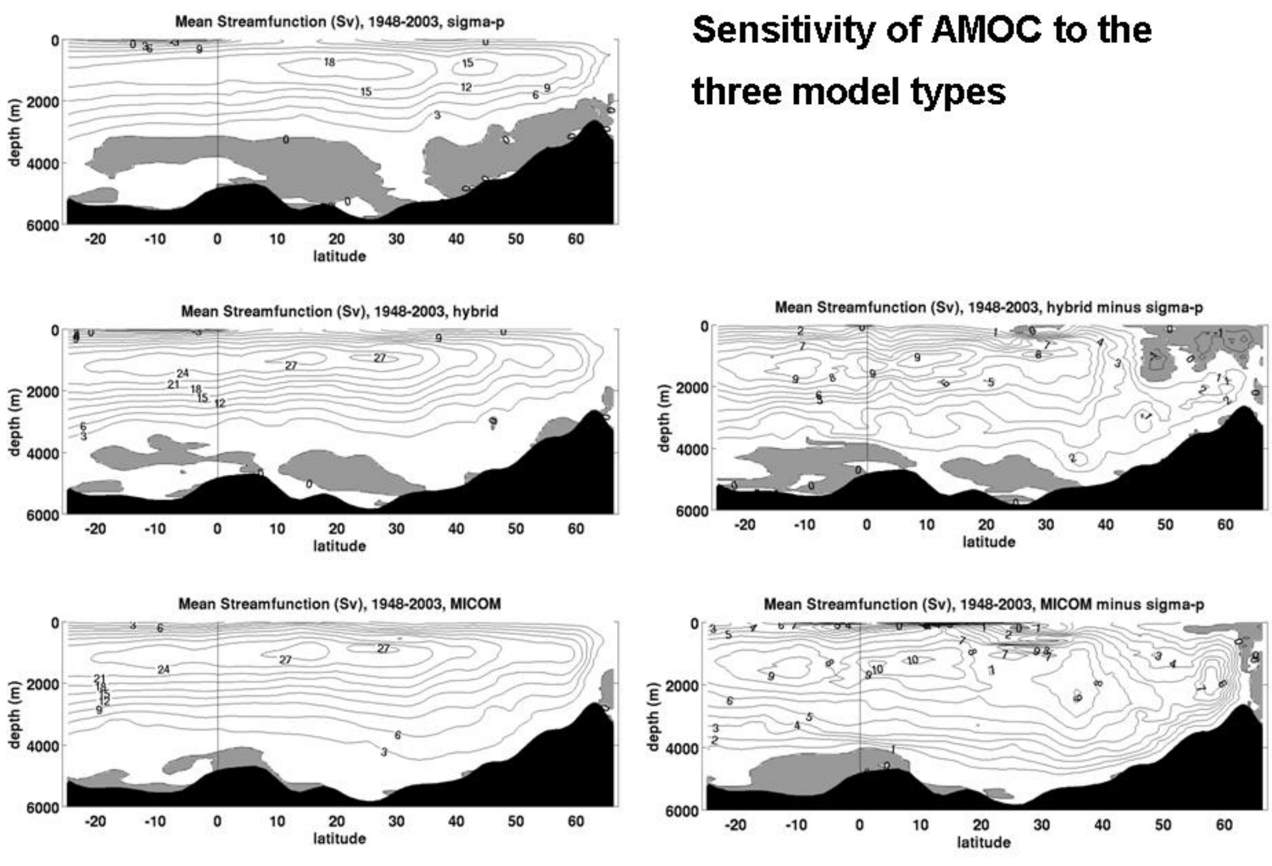

Figure 1. AMOC streamfunction as a function of latitude and depth from the three HYCOM simulations (left panels). The maximum value of this streamfunction at a given latitude equals the water volume transport in Sverdrups (1 Sv = 10^6 cubic meters of water per second). The flow in the

Atlantic basin is along streamfunction contours with increasing streamfunction to the right so that flow above (below) about 1200 m depth is northward (southward). The large streamfunction differences between pairs of simulations are shown in the right panels.

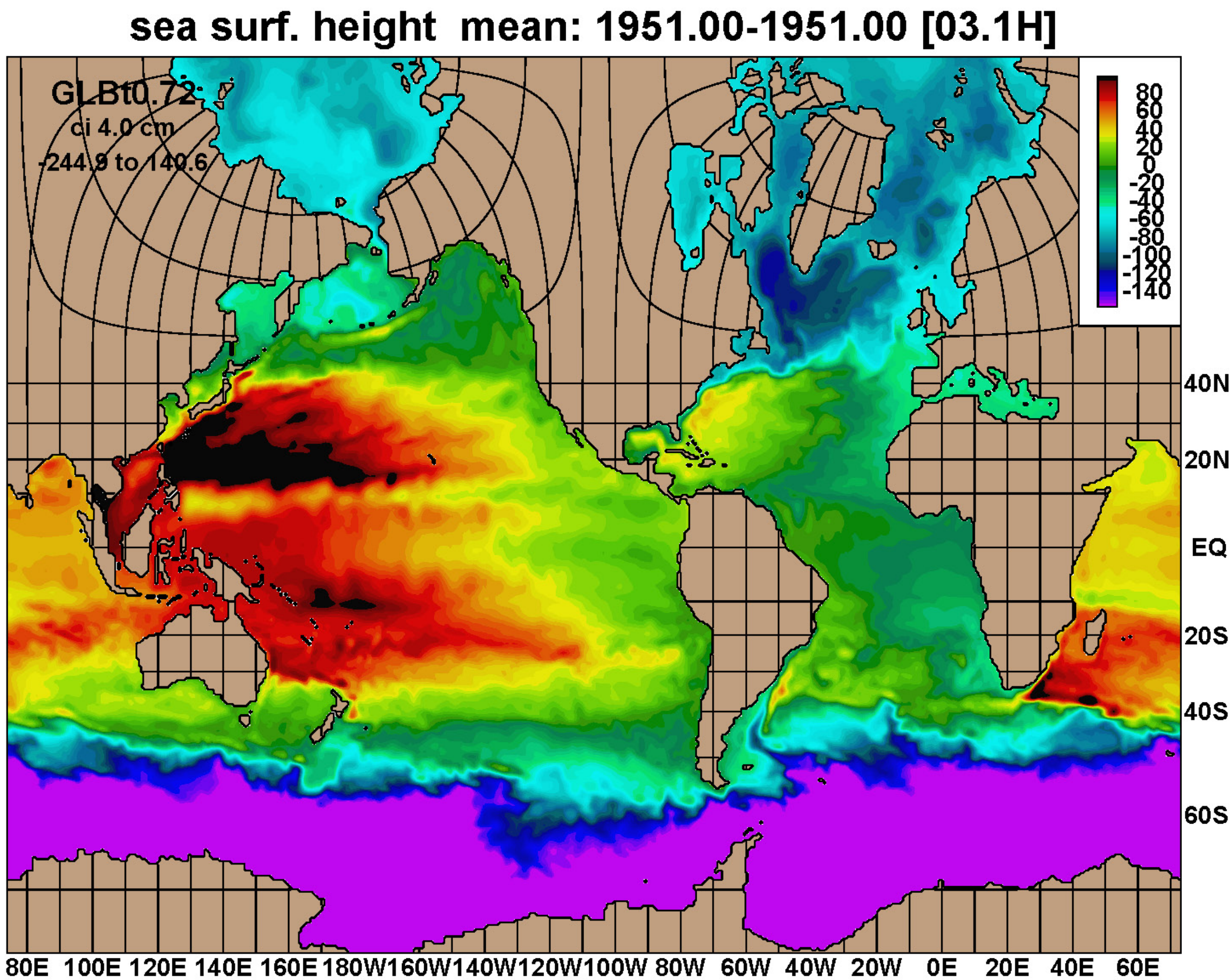

Figure 2. Sea surface height from the global medium-resolution HYCOM multi-decadal ocean simulation for 1 January 1951.

RESULTS

We are now performing calibration studies of the HYCOM data assimilation system using low-resolution Atlantic Ocean HYCOM simulations, the same model used to generate the overturning plots in Figure 1. The initial OSE/OSSE tests to be performed shortly in this domain constitute the first stage of our development effort. At the same time, we have performed multi-decadal ocean simulations using a medium-resolution global version of HYCOM (Figure 2) which will provide a more realistic representation of AMOC properties and more accurately represent the connectivity of the AMOC to the full global overturning circulation. Once the OSE/OSSE system has been thoroughly tested in the low-resolution Atlantic domain, preliminary evaluation of observing system enhancements will be conducted in the medium resolution global domain. These initial experiments will focus on enhancements that have the potential to provide major improvements to monitoring the AMOC; e.g. determine latitudes where cross-basin AMOC monitoring is particularly effective and quantifying the improvement in AMOC representation achieved by extending ARGO float sampling below 2000 m into the deep ocean.

IMPACT/APPLICATIONS

National Security

The ocean model used in this study (HYCOM) is the operational ocean model used by NOAA/EMC and is on the verge of becoming the operational ocean model used by the U. S. Navy. The work performed under this project will help identify improvements that can be made to both the model and the data assimilation methodology, consequently improving the ocean monitoring and forecasting capabilities of these two Federal agencies.

Economic Development

The most obvious potential impact is to design ocean observation strategies that will improve the effectiveness of monitoring the AMOC and other ocean climate processes at reduced cost. There is considerable economic benefit to be realized if the operational ocean monitoring system is capable of early detection of changes in the AMOC.

Quality of Life

Improved early detection of potentially important ocean climate changes will provide lead time to mitigate harmful consequences.

RELATED PROJECTS

G. Halliwell is a member of the AMOC Science Team and maintains interactions with several different AMOC projects. In particular, the U.S./U.K. RAPID/MOCHA project to monitor the AMOC at 26.5°N will benefit from our planned experiments that among other goals will be used to evaluate the impact of monitoring at this latitude along with monitoring at other potential latitudes. G. Halliwell is also involved in efforts to perform observing system design studies with the goal of improving short-term (days to weeks) ocean forecasts.

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PUBLICATIONS

None, but our initial papers are under construction and will be completed once we have completed experiments using the low-resolution Atlantic and medium-resolution global models.