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 limb of the global overturning circulation and 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 climate, particularly over middle and high northern latitudes. This flow is difficult to monitor because it has complicated three-dimensional pathways and interacts with other strong 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, particularly during the first two years, are focused on (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, (3) estimating the errors in ocean variables produced by present-day numerical models, and (4) performing a preliminary assessment of AMOC monitoring strategies using “virtual” OSSEs. Once these initial objectives have been satisfied, we plan to conduct OSEs and OSSEs to test AMOC monitoring strategies, which is expected to occur primarily during year 3.

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 guide weather forecasts. Both oceanic and atmospheric model forecasts must be started from the most accurate available 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 gradually drifts away from reality. Data assimilation is the technique used to produce optimal initial states by using observations to correct this model drift. Data assimilation employs mathematical-statistical methodologies to blend model output with observations to product the most optimal representation of the present state of the ocean.

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 ocean variability in temperature, salinity, and currents. To test the impact of one particular subset of the observations that are assimilated, the assimilation system is run again 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 sampling the real ocean to perform an OSE, the “observations” required to perform the OSE are sampled from a long ocean simulation that is performed using a second ocean model. 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 and the model that generated it. 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 real ocean. One OSSE validation method is to perform two OSEs, one using actual observations of the ocean and the other using identical “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.

Out of necessity, the first two years of this project emphasizes the developmental work required to build ocean OSE/OSSE capabilities at NOAA/AOML and also to generate and evaluate 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. The initial work described below emphasizes progress made on these issues. 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. Zulema Garraffo is now running global, intermediate-resolution ocean model simulations over a several-decade time interval that will be evaluated as potential nature runs. Over the next several months, Carlisle Thacker and George Halliwell will perform “demonstration” OSEs and OSSEs to test our software systems. Carlisle Thacker and Haoping Yang will also perform “virtual OSSEs”, a technique to perform a preliminary estimate of error reduction that will be achieved by a new set of ocean observations without actually having to run the ocean data assimilation system. Collectively, this work will move us toward our eventual goal of performing the most realistic possible OSEs and OSSEs during year 3 of the project for the purpose of evaluating AMOC monitoring strategies.

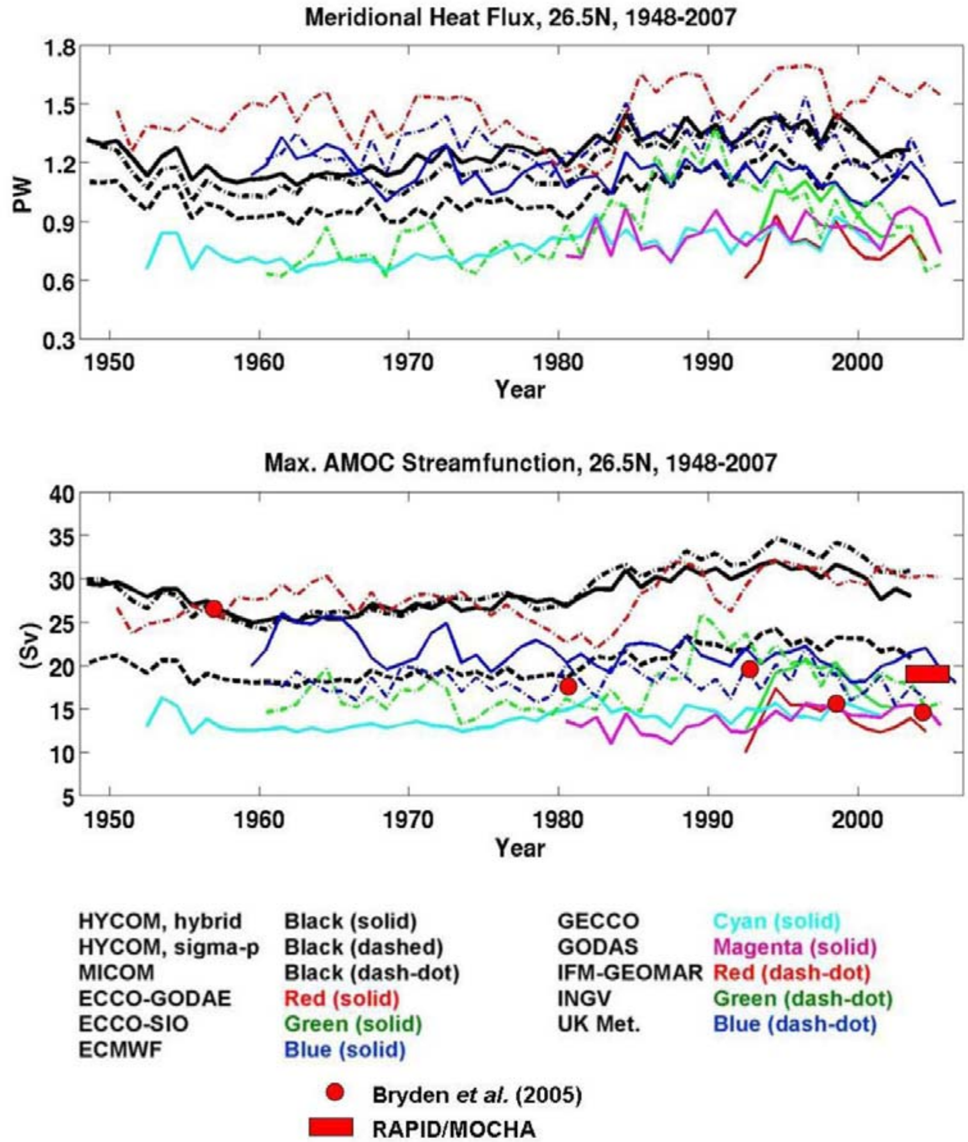

Figure 1. Meridional heat flux in Petawatts carried by the AMOC at 26.5°N (top) and maximum AMOC streamfunction (volume transport in Sverdrups, with 1 Sv = 10^6 cubic meters of water per second) at 26.5°N (bottom) from eleven available model runs. The observational estimates of the AMOC volume transport from Bryden et al. (2005) are shown along with the values obtained from the RAPID/MOCHA project.

WORK COMPLETED

Progress has been made on three fronts: (1) estimating error statistics of ocean models; (2) generating and evaluating a suitable nature run; and (3) building the OSE/OSSE software systems at NOAA/AOML. To determine error statistics of ocean models, we obtained fields from eight publicly-available ocean model runs designed to reproduce ocean-atmosphere variability over the last several decades, and also performed three multi-decadal Atlantic Ocean simulations at AOML using the HYbrid Coordinate Ocean Model (HYCOM) run in three different configurations to mimic differences expected when using other types of ocean models. Using two indices of the AMOC determined from the set of eleven ocean models, specifically the volume transport of water carried by this flow near

26.5°N and the associated meridional (northward) transport of heat at that latitude (Figure 1), it is evident that present-day ocean models display large differences in both of these indices. These large uncertainties and errors present in ocean models will make it difficult to generate a suitable nature run for AMOC OSSEs. This problem is further exacerbated by the lack of observations of these AMOC indices over recent decades (Figure 1) to determine which models are most correct. We are now performing global ocean simulations using HYCOM, which will then be evaluated for potential use as a nature run. The OSE/OSSE system under construction at NOAA/AOML will initially use the same model code base (the “fraternal twin” approach). 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. 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. This version has just been installed at NOAA/AOML and is now undergoing tests. Tests of the AMOC OSE/OSSE system will begin shortly.

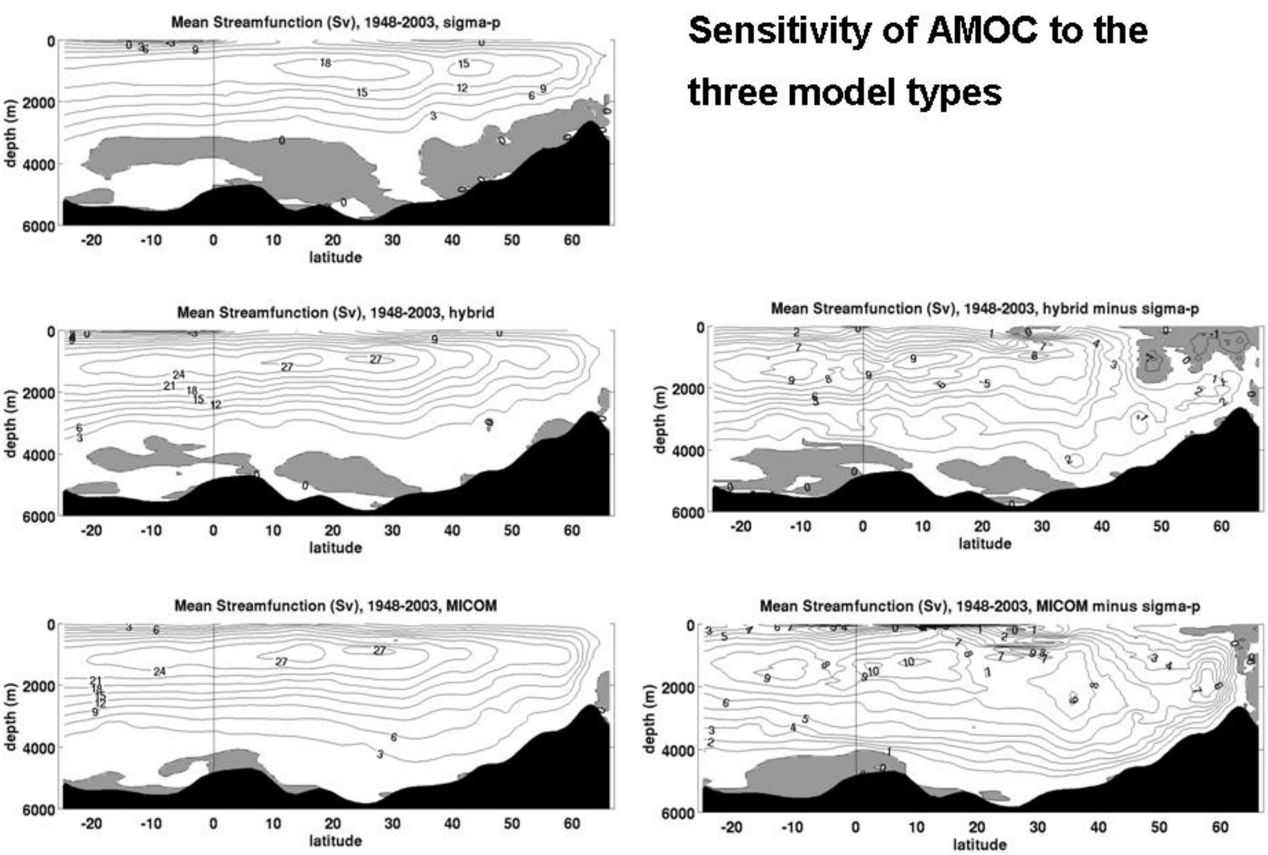

Figure 2. AMOC streamfunction as a function of latitude and depth from the three HYCOM simulations (left panels). The maximum value of this streamfunction at a given latitude equals the water volume transport in Sverdrups (1 Sv = 10^6 cubic meters of water per second). The flow in the Atlantic basin 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.

RESULTS

The only results to date have followed from the initial developmental work required to build a viable ocean OSE/OSSE system at NOAA/AOML, and important aspects of these results are summarized in Figures 1 and 2. The results point to the large difficulties that will have to be overcome to identify a suitable nature run and then perform viable experiments to design observing strategies for the AMOC. We expect to make substantial progress over the next few months in terms of evaluating ongoing HYCOM global ocean simulations conducted at intermediate horizontal resolution as potential nature runs and performing fraternal-twin “demonstration” OSEs and OSSEs to test and evaluate our methodology. These demonstrations will also be used to perform preliminary evaluation of observing system 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 extending ARGO float sampling 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.

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PUBLICATIONS

None