OBSERVING SYSTEM SIMULATION EXPERIMENTS FOR THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

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ABSTRACT

We report on initial efforts associated with a new project supported by NOAA and the National Oceanographic Partnership Program to quantitatively evaluate observing system strategies for the purpose of monitoring the Atlantic Meridional Overturning Circulation. The primary strategy is to use Observing System Simulation Experiments (OSSEs) to evaluate the impact of new and planned observing systems, and also to use Observing System Experiments (OSEs) to evaluate the impact of existing observing systems. We summarize our plans for developing and validating an ocean OSSE capability at NOAA/AOML and the University of Miami over the next 1-2 years. During this development period, our initial effort toward monitoring the AMOC is focused on evaluation of a multi-model ensemble to quantify the significant errors in the representation of the AMOC that exist in present-day ocean models, and also on identifying the best choice for use as a nature run. Nature run identification will be difficult given the large differences in AMOC transport and associated meridional heat flux produced by ocean models in conjunction with the lack of long-term observations. Despite these large uncertainties, this ongoing effort will contribute to evaluating the strengths and weaknesses of the ocean models and the data assimilation procedures that are used. This will provide important guidance for improving these systems.

1. INTRODUCTION

The Atlantic Meridional Overturning Circulation (AMOC) is one limb of the global overturning circulation and plays an important role in climate variability due to the associated large northward heat flux in the Atlantic basin and its impact on SST. Unfortunately, this flow is difficult to monitor because it has complicated three-dimensional flow pathways and the northward upper ocean limb must transit through wind-driven gyres that have large annual cycles at low latitudes. One potential approach for designing new observing strategies to monitor the AMOC involves Observing System Simulation Experiments (OSSEs) for evaluating the impact of new observing systems and Observing System Experiments (OSEs) for evaluating the impact of existing observing systems.

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 [1]. 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, particular in regards to ocean climate variability. Nevertheless, by attempting OSSEs for AMOC monitoring at this stage, we will learn more about the strengths and weaknesses of present-day ocean models, and also about the methodologies used to assimilate ocean observations. Because data assimilation demands quantitative estimates of model uncertainties, it forces us to confront model errors and their correlations. In this paper, we discuss the limitations of ocean models with respect to performing ocean OSSEs and OSEs to design AMOC monitoring strategies.

2. OSSE PROCEDURES

- Using a state-of-the-art OGCM (the “nature run” model), generate a long non-assimilative ocean simulation that realistically represents phenomena of interest. Assume that this model output represents the “true” ocean.
- Using a second OGCM (the “operational” model), perform a non-assimilative ocean simulation spanning the same time interval as the nature run. Statistically analyze the differences between this run and the nature run. These differences represent the “errors” in the operational model with respect to the nature run. Ideally the magnitude of these errors should be the same as the expected errors in state-of-the-art OGCMs with respect to the real ocean.
- Sample this nature run output with the observing system to be evaluated and add both

the random and correlated errors expected for the actual instruments.

- Assimilate the "observations" sampled from the nature run into the operational model over the time interval of the nature run.

- Evaluate the impact of the planned observing system by quantifying the reduction in operational model errors with respect to the nature run. This is accomplished by either (a) directly comparing ocean analyses from the data-assimilative operational model to the nature run; or (b) generating a set of ocean forecasts starting at different times during the nature run that are initialized by fields from the operational model run, and then evaluate the quality of these forecasts against the nature run.

In contrast, OSEs use an existing data assimilation system to evaluate the impact of components of the present-day ocean observing system. By withholding one component of the existing observing system (e.g., ARGO profiles), the impact of these observations can by assessed.

3. INITIAL OSSE STRATEGY FOR THE AMOC

For simplicity, our initial OSSE strategy will use the same model code base (the "fraternal twin" approach), specifically the HYbrid Coordinate Ocean Model (HYCOM). This code is highly flexible in terms of choosing the vertical coordinate discretization, and also offers multiple choices of numerical algorithms and subgrid-scale parameterizations. Three realizations of HYCOM are being evaluated for this purpose, from which we will select both the nature run and operational models. The first realization is the standard hybrid configuration of HYCOM that maximizes the use of isopycnic coordinates in the ocean interior while transitioning to fixed pressure coordinates near the surface and to fixed pressure or sigma coordinates over shallow water regions. This realization uses KPP vertical mixing, the Montgomery potential pressure gradient force, and second-order flux corrected transport scalar advection. The second realization mimics the hybrid sigma-z version of the Princeton Ocean Model (POM) by using fixed sigma-pressure vertical coordinates while also using a fourth-order pressure gradient scheme [2], the Mellor-Yamada level 2.5 turbulence closure for vertical mixing, and MPDATA scalar advection. The third configuration is achieved by running the Miami Isopycnic-Coordinate Ocean Model (MICOM) option of HYCOM. This configuration consists of a single slab Kraus-Turner type slab mixed layer on top of the isopycnic layers that represent the ocean interior, and uses the Montgomery potential pressure gradient force and MPDATA scalar advection. These three configurations were spun up for 30 years using climatological NCEP reanalysis surface forcing, and then run from 1948-2003 forced by monthly NCEP reanalysis forcing fields.

4. REPRESENTATION OF THE AMOC BY PRESENT-DAY OCEAN MODELS

Before performing a viable OSSE, it is necessary to identify a suitable nature run that accurately represents the structure and variability of the AMOC. To pursue this question, we obtained fields from eight publically-available ocean hindcasts and the ocean component of coupled model runs designed to reproduce ocean-atmosphere variability over the last several decades. Time series of the AMOC transport (maximum value of the AMOC streamfunction) and the associated meridional heat flux at 26.5°N (Fig. 1) demonstrates that there are considerable differences in both the mean values and fluctuations of these variables among the models over the last several decades. Although their decadal fluctuations are very similar, the three HYCOM/MICOM simulations display differences in mean overturning transport consistent with the large differences that exist among the other models. Specifically, the two runs that used predominantly isopycnic coordinates (the standard hybrid case plus MICOM) produce overturning transports that are several Sverdrups larger than the sigma-p fixed coordinate case. These differences in the overturning are illustrated in Fig. 2.

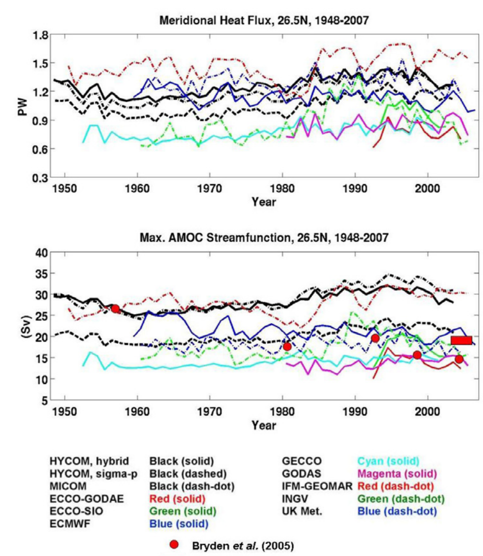

Figure 1. Meridional heat flux (top) and maximum AMOC streamfunction at 26.5°N (bottom) from the three NYCOM/MICOM runs along with eight other publicly available ocean models. The observed estimates of transport from [3] are shown along with the mean transport obtained by RAPID/MOCHA.

The models in Fig. 1 do not provide a consistent representation of the AMOC even though several of them assimilated observations. Although low model resolution is an issue, identification of the reasons behind the inability of these models to provide a consistent representation is beyond the scope of this paper. The important implication here is that it will be very difficult to identify a suitable nature run that not only provides reasonable values for the mean and variability of the transport, but also accurately reproduce the flow pathways. Unfortunately, nature run evaluation is difficult because few observational estimates of these properties of the AMOC exist over preceding decades. Although the accumulation of RAPID/MOCHA observations will soon improve this situation, considerable effort will need to be expended toward evaluating and improving ocean climate models for the purpose of generating nature runs for the AMOC.

5. FUTURE PLANS

We will use the HYCOM data assimilation system to test and debug our OSSE system based on the fraternal twin approach. Due to the problems enumerated here, we anticipate that the fraternal twin OSSE system will initially be used for other oceanographic problems where ocean models display more realistic performance; e.g. forecasting synoptic ocean weather systems. The ongoing AMOC effort in the near future will of necessity focus on model evaluation and improvement with the goal of generating at least one viable nature run. The next step will be to evaluate high-resolution Atlantic Ocean simulations nested within intermediate resolution global simulations for nature run suitability. However, it will be possible to make progress with imperfect nature runs that reproduce some, but not all, aspects of the AMOC. Such ongoing efforts will contribute to evaluating strengths and weaknesses of the ocean models and the data assimilation procedures that are used and provide important guidance for improving these systems.

6. REFERENCES

1. Atlas, R. (1997). Atmospheric observations and experiments to assess their usefulness in data assimilation. *J. Meteor. Soc. Japan*, **75**, 111-130.

2. Shchepetkin, A.F. & McWilliams, J.C. (2003) A method for computing horizontal pressure-gradient force in an ocean model with a non-aligned vertical coordinate. *J. Geophys. Res*., **108**, 35.1-35.34.

3. Bryden, H.L., Longworth, H.R., & Cunningham, S.A. (2005). Slowing of the Atlantic meridional overturning circulation at 25°N. *Nature* **438**(7068), 655–657.

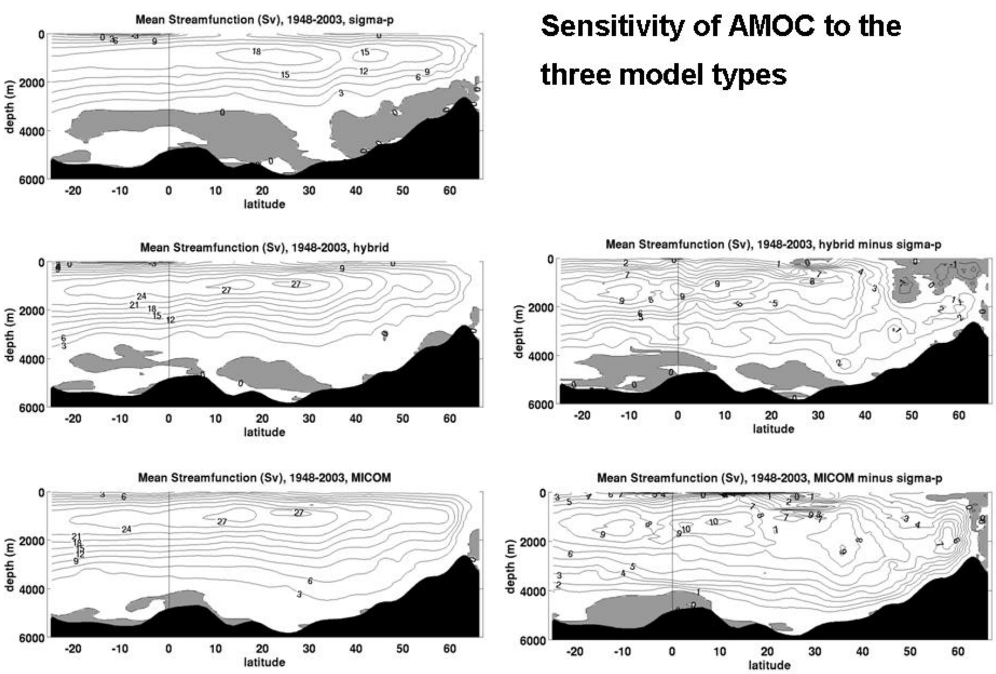

Figure 2. AMOC streamfunction as a function of latitude and depth from the three HYCOM/MICOM simulations (left panels). Difference streamfunctions between pairs of these simulations are shown in the right panels.