Atlantic MOC Observing System Studies Using Adjoint Models

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Award Number: *NNX08AV89G*
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LONG-TERM GOALS

To understand, with a comprehensive data set and a state-of-the-art ocean model, the nature of the North Atlantic Ocean circulation, with a particular emphasis on its long term variability and climate consequences.

OBJECTIVES

The so-called meridional overturning circulation (MOC) is a simplified schematic of the complex North Atlantic Ocean circulation that is believed important to the climate system. As such, it is a useful shorthand for the description of circulation changes (past, ongoing, and possibly in the future) that can have serious climate implications and consequences for society in general.

APPROACH AND WORK PLAN

Adjoint models are used to study the MOC in three distinct, but nonetheless, overlapping ways. In one approach, the adjoint is used as a numerical tool for fitting a general circulation model to a great variety of oceanic observations. Approach 2 exploits explicitly the mathematical result that the adjoint solution (the Lagrange multipliers) are the sensitivity of an arbitrarily chosen scalar-function, for example, climate metrics that capture Atlantic transport and heat content variability, to almost any perturbation in the model or its external constraints (initial and boundary conditions). Approach 3 extends the adjoint application through formulating an optimality problem in which initial conditions are sought which lead to maximum transient amplification of climate-related norms, such as the MOC. From approach 1, we obtain estimates of the North Atlantic time-varying three-dimensional ocean state as a subcomponent consistent with the global-scale ocean. That estimate can be used to study the behavior of the MOC directly.

WORK COMPLETED

In previously published work, Wunsch and Heimbach (2009) discuss trends in the global (not just the North Atlantic) meridional overturning circulation, and showed that whatever changes were taking place were largely confined to low latitudes and the deep Southern Ocean. Beyond a general tendency for the upper ocean to be warming, no large scale trends were apparent.

Extensions of the study of the North Atlantic circulation and its variability were described in Heimbach et al. (2011). In addition, a major effort went toward producing results and recommendations for the OceanObs2009 Conference (Heimbach et al., 2010; Wunsch, 2010). A review of major issues associated with measurements and analyses of oceanic temperature and heat content was also provided by Ponte (2011a).

In related work, now being prepared for publication, the sensitivity of major elements of the ocean circulation in the North Atlantic has been undertaken. These particularly focus on the socially important meridional heat transport and sea level changes. One important aspect is how the heat content variability in the North Atlantic relates to the meriodional overturning circulation, as well as to other circulations and to direct exchanges with the atmosphere, The results described in detail in Piecuch and Ponte (2011) indicate a complex, regionally-dependent behavior, with several factors contributing to heat content variability at seasonal and interannual timescales. For example, shallow overturning circulations dominate at low latitudes but zonally-asymmetric (gyre) components become important at higher latitudes. Oceanic advection is generally important, but temperature variability (not just velocity variability) can contribute to variable heat transports at high latitudes.

In two related studies (Wunsch, 2011a,b), the North Atlantic circulation state estimate was analyzed for the degree to which it appears to be in equilibrium with the wind field and the extent to which it can be regarded as a linear system. In turn, linear prediction theory was applied to study the extent to which the MOC is predictable. It was found that there is predictive skill in some parts of the system out to about 5 years.

Related to the problem of linear predictability is the inference of time scales and associated patterns (singular vectors) over which climate metrics such as the MOC or near-surface heat content can undergo transient amplification due to non-normal growth of associated modes. Zanna et al. (2011a, b) showed that compared to surface-ocean perturbations (e.g., from atmospheric forcing) deep oceanic perturbations (e.g., from interior eddy variability) can drastically reduce the time-horizon over which such amplifications occur, with important consequences for predictability. This in turn relates to optimal observing design to reduce uncertainties related to transient amplifications.

RESULTS

The results discussed at length in the above papers are too many to describe here. Among other inferences, a major effort has gone towards using the adjoint model (Lagrange multipliers) of the ECCO-GODAE effort, to understand the factors controlling the North Atlantic circulation, and in particular, the controls on sea level change. As one example, Fig. 1 shows response magnitudes of sea level anomalies near the US East Coast to temperature perturbations of sizes comparable to local variability estimates at 222 m depth, 15 years back in time. A positive value at a specific location implies US East coast sea level increases 15 years after a unit temperature increase at that location. The results were obtained for an optimized ECCO-GODAE solution, so-called version 3, iteration 73. The influence of remote regions is clearly visible.

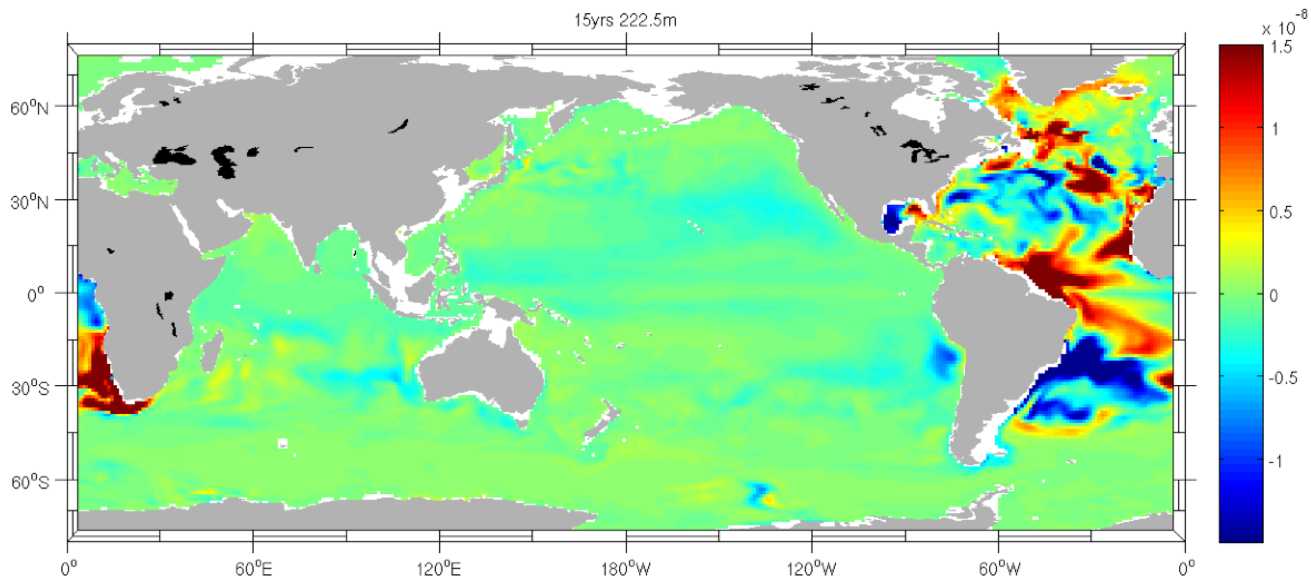

Figure 1 Estimate of the sensitivity of the sea level change along the US east coast to temperature anomalies 15 years prior, at a depth of 222 m. Maps such as these show the challenge of designing observing systems for understanding and prediction

Another area of focus has been the assessment of temperature and salinity variability in ocean layers below approximately 2000 m, which are not now sampled by the Argo observing system. Analyses of adjoint-based state estimates that dynamically interpolate the very sparse hydrographic data available at depth show substantial temporal variability in deep steric height fields (see example in Figure 2). These results, including the implications for future observing system design, are summarized in Ponte (2011b),

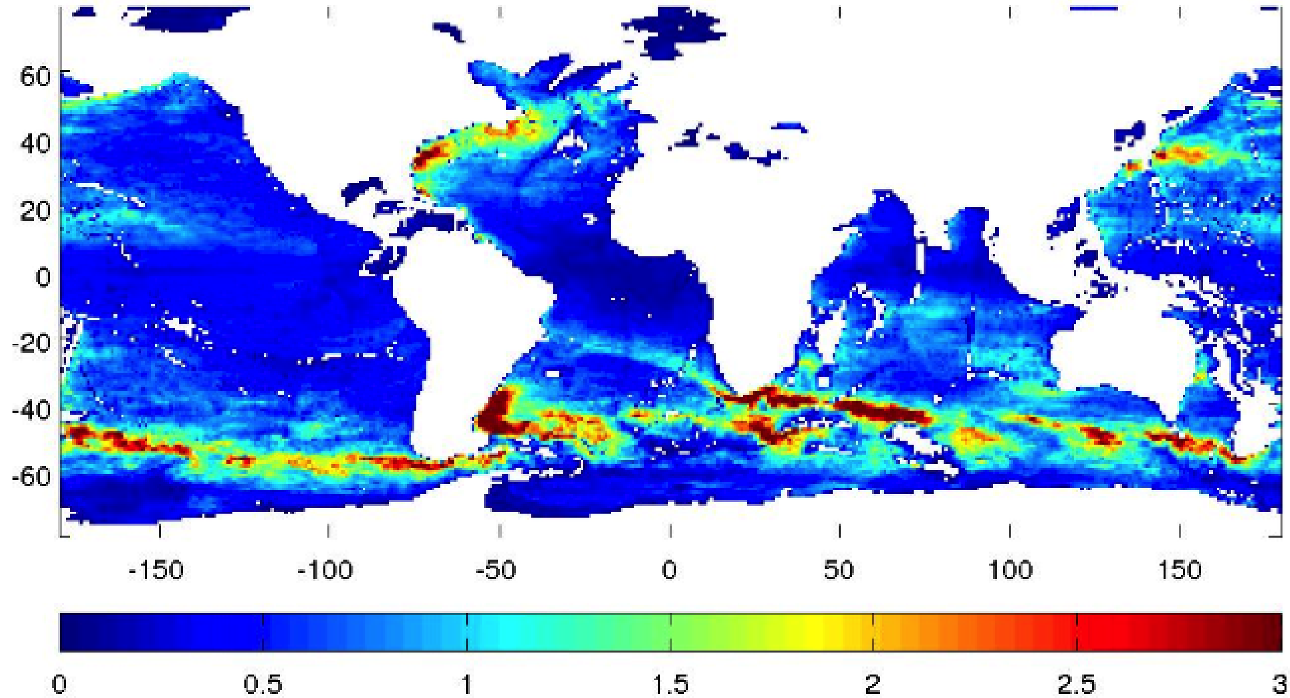

Figure 2 Standard deviation of steric height (cm) integrated over depths below 1700 m and based on 14 years of monthly temperature and salinity fields from an eddy-permitting estimate of the global ocean circulation. A linear trend and mean seasonal cycle are removed from the time series prior to the calculations.

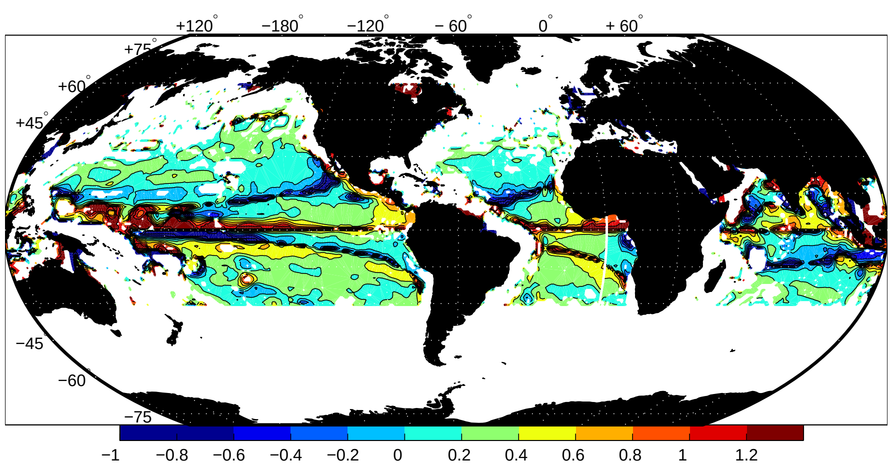

Figure 3 Colored region is where Sverdrup balance can be shown to describe an equilibrium response to the time-average wind field. In the North Atlantic, as elsewhere, the high latitude ocean is not in equilibrium---consistent with simple theory. This lack of equilibrium decouples the prediction problem between high and low latitudes. (from Wunsch, 2011a).

IMPACT AND APPLICATIONS

National Security

The Defense Department has begun to recognize the threat of climate change to the security of its installations and operations. Atlantic sector changes would influence a number of Naval, Marine and Coastguard bases, and with the potential for human population dislocation in Africa and South America. Limits on predictability mean that very sophisticated planning exercises are required to deal with the unexpected.

Quality of Life

This work is related to the larger problem of understanding ongoing climate change and its implications for human populations.

Science Education and Communication

We teach courses, supervise PhD and master's theses, and support early career scientists, helping to produce the future generations who will have to live with and understand the changing ocean.

TRANSITIONS

National Security

We are estimating the likelihood of significant changes in coastal areas of the North Atlantic Ocean.

RELATED PROJECTS

This project is closely connected to the ECCO project mentioned above. It is also associated with efforts directed primarily at the use of remote sensing data (altimetry and gravity fields in particular) supported mainly through the National Aeronautics and Space Administration. Because the North Atlantic is widely thought to be important to climate change on all time scales, the work on this project has implications for, and is symbiotic with, many other studies. As one example, with partial funding also from the National Science Foundation, graduate student Holly Dail is using the same model to study the circulation during the Last Glacial Maximum (LGM; see Fig.4).

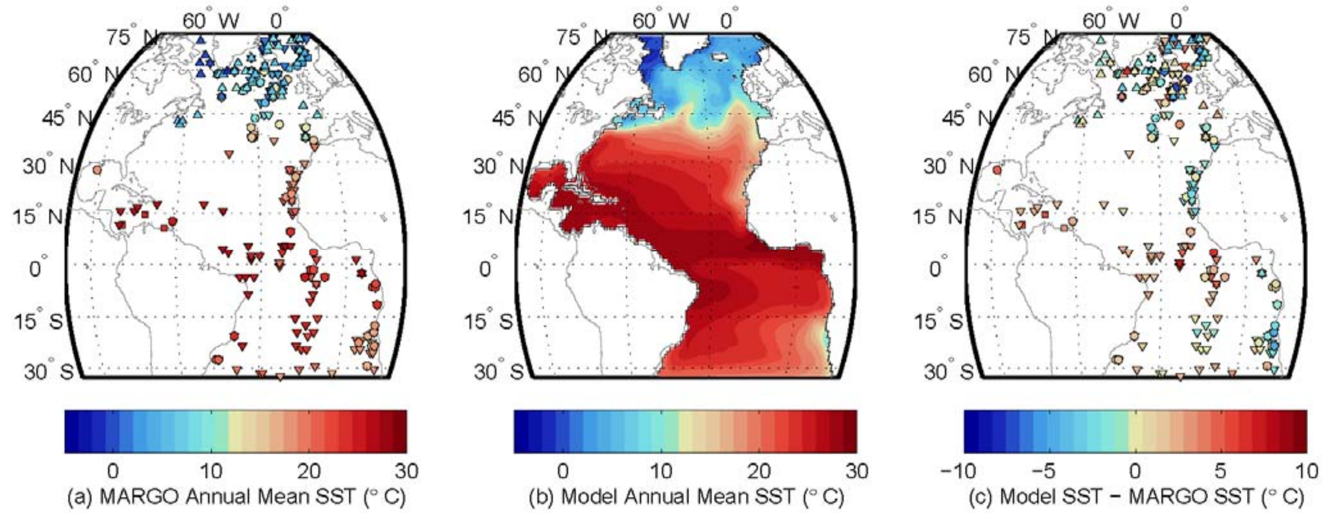

Figure 4 Left panel shows the so-called MARGO estimate of sea surface temperature durnig the LGM. The center panel shows that of the ECCO model optimized (preliminary solution) to those data, and the right panel the difference---showing the remaining misfits. (From PhD thesis, H. Dail, in preparation, 2011.)

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