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The ability of the adjoint technique to recover decadal variability of the North Atlantic circulation

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ABSTRACT

Different oceanic data assimilation products show rather different decadal-scale variability, in particular for the Atlantic meridional overturning circulation (MOC). In order to understand these differences we evaluate the ability of the adjoint technique to reproduce MOC variability using surface heat flux forcing as the control parameter. We find that in a perfect model framework and for a reasonable weighting the adjoint method is, in principle, successful at reproducing decadal-scale MOC variability if adequate synthetic observations and a priori information of the control parameter are given. Temperature of the upper 1000 m and sea surface height and a priori information about surface heat fluxes contain the most useful information. Using only salinity or only synthetic hydrography below 1000 m, the method fails to converge and to reconstruct MOC variability, given surface heat flux as the only control parameter.

In order to provide error bounds for current assimilation products, prescribed artificial errors for a priori control parameter, synthetic observations and initial conditions are introduced systematically to our setup. We find that errors with reasonable magnitude in synthetic observations as well as a priori information of the surface heat fluxes lead to a reconstructed decadal-scale MOC variability with tolerable errors of less than a few percent. Errors in initial conditions lead to a "cold start" problem and can degrade the quality of the MOC reconstruction, but can be damped by sufficient a priori information about the surface forcing in the subsequent integration, even without including the initial conditions as a control parameter. The impact of a model error is analyzed by assimilating synthetic observations from different model configurations, which resembles most likely an underestimation of the "real" model error. Even with this optimistic estimate, the reconstruction is very sensitive to the model error and leads to a large error in the reconstructed MOC variability. Taking all possible errors together, the error of decadal MOC reconstruction in current data assimilation products appears to be larger than 60% (about 1 Sv) with a correlation with the "real" MOC variability by less than 0.5.

1. Introduction

General ocean model simulations driven by realistic surface forcing over the last decades show large decadal-scale variability of the circulation in the North Atlantic. In particular, the meridional overturning circulation (MOC), i.e. the zonally integrated Eulerian mean volume transport, which flows in the North Atlantic mainly northward in the upper few hundred meters compensated by southward flow at depth, shows variability of several Sverdrups (1 Sv = 10^6 m^3/s) on short time scales up to decades (e.g. Eden and Willebrand, 2001; Beismann et al., 2002). Since the northward heat transport in the North Atlantic is predominantly driven by the meridional overturning (Böning et al., 1996), MOC variability is thought to have an impact on decadal variability of the climate system. Because of the decadal time scales involved, the MOC variability is also thought to contain information which might lead to decadal-scale climate predictions (e.g. Matei et al., 2012).

Ocean models contain errors which might lead to errors in the simulated MOC variability in particular at decadal time scales. An alternative to simply forcing an ocean model with atmospheric state variables and letting the model evolve freely, is given by data assimilation. In data assimilation, available observations in the ocean, the atmospheric forcing and the numerical model are combined in some optimal way to yield the best estimate of the variability of the ocean over the last decades. Three examples of such ways are shown in terms of the MOC variability in Fig. 1. The three products differ in their methods: GECCO (Köhl and Stammer (2008)) uses the adjoint method, SODA (Carton and Giese, 2008) adopts a simple relaxation towards observed values in the local temperature and salinity equations and ORA-S3 (Balmaseda et al., 2007) uses a sequential assimilation method. The products

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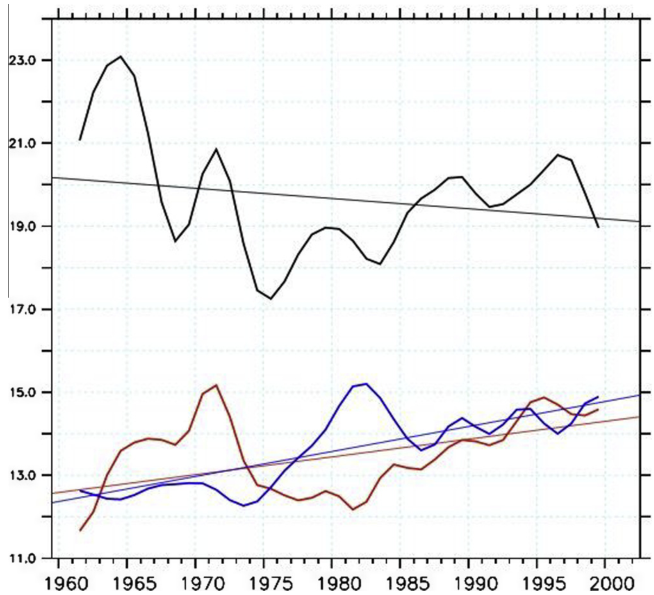

Fig. 1. From Kröger et al. (2012): MOC at 26.5°N in the Atlantic of three different ocean data assimilation products, i.e. GECCO (blue), SODA (red) and ORA-S3 (black). Also shown are linear trends; data have been smoothed with a 5-year running mean. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

also differ in their boundary conditions, model, observational constraints, and error covariances. Although the underlying observational dataset is similar, the decadal-scale MOC variability in the three different ocean state estimates is rather different. In particular for the first two decades, the time series differ considerably, which might be due to unknown initial condition of the ocean state or poor data coverage during the first decades. On the other hand, the decadal MOC variability in the three different ocean state estimates differs also greatly in the following decades, where the impact of the unknown initial condition should be smaller and where the data coverage is much improved. Similar large differences between the simulated decadal-scale changes of large-scale transports of different data assimilation products are also reported by e.g. Keenlyside and Ba (2010) and Munoz et al. (2011).

Given the spread of the different assimilation products, it is the aim of the present study to assess the ability of data assimilation methods to reconstruct MOC variability. This is not clear beforehand since important dynamical ingredients of the MOC, including convection and diapycnal mixing, are not simulated but parameterized in primitive equation ocean models used for data assimilation. Moreover, it is known that large scale meridional transports – an ingredient which ocean models do simulate – are rather sensitive to explicit or implicit mixing in ocean models. It is thus possible that methods based on constraining the temperature and salinity budgets during the model simulation directly (SODA, ORA-S3), and thereby introducing artificial mixing in the budgets, are inferior with respect to decadal MOC reconstructions to methods which only indirectly influence the budgets (ECCO/GECCO).

In this study, we thus focus on the adjoint method as used in ECCO/GECCO (Wunsch et al., 2006; Köhl and Stammer, 2008). We focus further on MOC variability driven by decadal-scale surface heat flux variability in the subpolar North Atlantic, since in particular heat flux variability over the Labrador Sea is known to drive anomalous convection, which is then related to changes in the MOC of the Atlantic Ocean (e.g. (Eden and Willebrand, 2001; Beismann et al., 2002)). Since convection is parameterized by a non-linear function in ocean models for which the adjoint becomes ill-defined, it is necessary to test the principal ability of the adjoint method to reconstruct circulation variability generated by convective activity. Using a method similar to the one used in ECCO/GECCO – with similar standard ocean models using similar standard parameters and grid resolution – we try to reconstruct decadal-scale MOC variability forced by surface heat flux variability. Different to ECCO/GECCO, however, the (synthetic) observations have been generated by the same model beforehand. We stress that this approach, sometimes referred to as "identical twin experiment", differs from a realistic application, since a perfect reconstruction of the synthetic observations is, in principle, possible. Although we demonstrate this principal ability, we also show that under certain circumstances the adjoint method can fail to reconstruct MOC variability.

We then proceed to degrade this setup towards a more realistic situation closer to the case of ECCO/GECCO in order to derive error estimates for the reconstructed decadal-scale MOC variability in the realistic applications. In particular, we test the ability of a model containing errors to reconstruct MOC variability. We find this error source to be the most important and we believe that knowledge about the impact of this error on the reconstructed MOC variability as given here, is necessary to interpret the current data assimilation products in this respect.

The paper is organized as follows. In Section 2, the model configurations and the general procedure of identical twin experiments are explained. The results of the data assimilation experiments with perfect model conditions as well as with introduced errors for observation, control parameter and models are given in Section 3. The conclusions are briefly summarized in Section 4.

2. Models

2.1. Model configuration

The integrations presented here are performed with a non-eddy resolving global ocean model using the MITgcm code (Marshall et al., 1997). The model setup (hereafter named MODEL4) has a horizontal resolution of $4^\circ \times 4^\circ$ and covers a quasi-global domain from 80°S to 76°N with 15 levels in the vertical. The Arctic Seas have been excluded; a sea-ice model is also not included in the configuration (which will add to the unknown model error). We have chosen the rather coarse resolution to discuss a large variety of different optimizations[1] assessing a wide range of issues with the assimilation procedure. Furthermore, selected optimizations are repeated with a regional model with higher, although still non-eddy-resolving resolution.

Rather simple subgrid-scale parametrizations are used in MODEL4, i.e. horizontal and vertical Laplacian diffusivities of $K_h = 1000\ \mathrm{m}^2/\mathrm{s}$ and $K_r = 3 \times 10^{-5}\ \mathrm{m}^2/\mathrm{s}$. In case of a vertical instability in the water column, the vertical diffusivity is increased to $K_r = 100\ \mathrm{m}^2/\mathrm{s}$ to account for convective overturning. No further mixed layer closure is used. Lateral and vertical viscosity are $\nu_h = 5 \times 10^5\ \mathrm{m}^2/\mathrm{s}$ and $\nu_r = 10^{-3}\ \mathrm{m}^2/\mathrm{s}$. A linear 3rd order upwind advection scheme is used to advect temperature and salinity. The reason using such simple parameterizations is to obtain a model setup which is as linear as possible. This allows for assessing the ability of the linear adjoint technique to recover decadal MOC anomalies using surface heat flux as the control parameter. However, the simple parameterizations will also most likely increase the model error. In order to assess the effect of model errors in optimizations with the coarser resolution model, the parameteri-

[1] We refer to optimizations as the entire iterative procedure of minimizing the deviation of a model integration from a certain reference integration, for a specific set of synthetic observations, weighting functions, etc. as discussed below.