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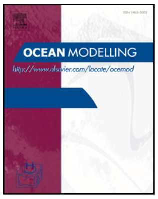

Impact of uncertainties in atmospheric boundary conditions on ocean model solutions

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ABSTRACT

We quantify differences in ocean model simulations derived solely from atmospheric uncertainties and investigate how they relate to overall model errors as inferred from comparisons with data. For this purpose, we use a global configuration of the MITgcm to simulate 4 ocean solutions for 2000–2009 using 4 reanalysis products (JRA-25, MERRA, CFSR and ERA-Interim) as atmospheric forcing. The simulations are compared against observations and against each other for selected variables (temperature, sea-level, sea-ice, streamfunctions, meridional heat and freshwater transports). Forcing-induced differences are comparable in magnitude to model-observation misfits for most near-surface variables in the tropics and sub-tropics, but typically smaller at higher latitudes and polar regions. Forcing-derived differences are expectedly largest near the surface and mostly limited to the upper 1000 m but can also be seen as deep as 4000 m, especially in regions of deep water formation. Errors are not necessarily local in nature and can be advected to different basins. Results indicate that while forcing adjustments might suffice in optimization procedures of near-surface fields and at low-to-mid latitudes, other control parameters are likely needed elsewhere. Forcing-induced differences can be dominated by large spatial scales and specific time scales (e.g. annual), and thus appropriate error covariances in space and time need to be considered in optimization methodologies.

1. Introduction

Ocean general circulation models (OGCMs) aid in interpreting observations, assessing dynamics and simulating past and future conditions of the ocean on a variety of space and time scales. Uncertainties in the information derived from OGCMs can arise from deficiencies in the model numerics and physical parameterizations, as well as from inaccurate initial and boundary conditions (e.g., surface forcing fields). Quantifying and understanding these different sources of ocean state uncertainty is important to improve data analysis and climate forecasting capabilities.

The availability of globally gridded multi-decadal atmospheric reanalyses (Kistler et al., 2001; Uppala et al., 2005; Onogi et al., 2005; Saha et al., 2010; Rienecker et al., 2011; Dee et al., 2011) has stimulated many studies of the global ocean circulation on climate time scales. Atmospheric fields from these reanalyses are commonly applied as a surface forcing of OGCMs. Uncertainties in these forcing fields (e.g. Chaudhuri et al., 2013) arise from many factors such as differences in model set-up, assimilation schemes, data streams and cloud parameterization schemes amongst others (Milliff et al., 1999; Sun et al., 2003; Drobot et al., 2006; Brunke et al., 2003; Smith et al., 2001; Nicolas and Bromwich, 2011; Wang and McPhaden, 2001; Zhang et al., 1995). Comparisons of surface reanalysis fields against each other and against observations have been conducted on global (Wang et al., 2011; Xue et al., 2011) to regional scales (Bromwich et al., 2011; Jakobson et al., 2012; Naud and Booth, 2014). For example, zonal mean of 4 reanalyzes for zonal wind stress (Fig. 1) suggests that they are quite similar. However the standard deviations show that there is large variability at higher latitudes, with CFSR wind stress being the largest. The CFSR wind stress product is in better agreement in terms of mean biases with the QuickSCAT climatology as reported by Xue et al. (2011). The spreads become larger for both mean and standard deviation in the case of precipitation flux (Fig. 1), especially in the equatorial regions. The general conclusion from all the above studies is that no single reanalysis does better than others for all the different variables.

Our approach is complementary to studies that have compared and contrasted the responses of different ocean models to a given set of forcing fields. For example, Griffies et al. (2014) forced 13 ocean models with the same forcing fields and reported that the models responded in a consistent manner.

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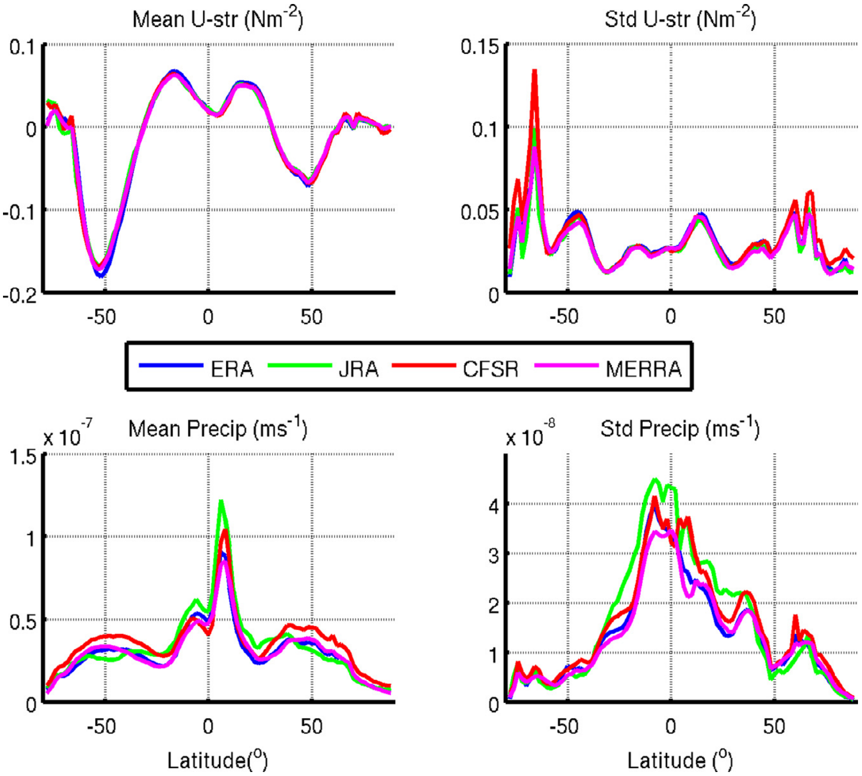

Fig. 1. Top: mean (left panel) and standard deviation (right panel) of zonally averaged zonal wind stress for the 4 reanalysis models. Bottom: as in top panels but for zonally averaged global precipitation flux.

Danabasoglu et al. (2014) however reported significant differences in the Atlantic Meridional Overturning Circulation (AMOC) amongst 18 ocean models forced by Common Reference Ocean Experiment (CORE2) fields from Large and Yeager (2009). They tentatively attributed the large model spread to differences in internal ocean model parameterizations. In such uniform forcing experiments model-model differences can be due to internal model errors whereas model-observation differences can also include atmospheric state errors, experimental design limitations, and/or observational error or limitations (Griffies et al., 2014).

In this study we attempt to quantify oceanic state uncertainties that derive solely from atmospheric forcing uncertainties and assess their relative importance as compared with overall model-observation errors. This work is in part motivated by the “Estimating the Circulation and Climate of the Ocean” (ECCO) effort (Wunsch et al., 2009; Forget et al., 2015a). ECCO aims at achieving a least squares fit of an OGCM to the great majority of meteorological and oceanic observations by adjusting a control vector representing initial conditions for temperature and salinity, the surface atmospheric state, and internal model parameters (e.g., Forget et al., 2015a, 2015b). In this context, the present study aims at addressing several important questions. How much of model-observation errors can be ascribed to errors in forcing fields? To what extent may forcing field adjustments suffice to reduce model-observation misfits to the expected level of data noise? Are differences in model simulations due to uncertainties in atmospheric forcing fields strongly dependent on location, depth, and time scale?

To this end, we employ a global OGCM to simulate the evolving ocean state over 2000–2009 under 4 different sets of atmospheric forcing fields. Comparing these simulations against each other and against observations permits an assessment of forcing-induced uncertainties in the context of overall model-observation errors. Details of the methodology are presented in Section 2. Since the largest impact of atmospheric forcing errors is likely to occur at the surface, we evaluate model-observation differences in variables such as sea surface temperature (SST) and sea-ice cover (SIC) in Section 3. We then analyze how errors propagate to the ocean interior by evaluating diagnostics of sea level anomalies (SLA), full depth temperature and oceanic transports in Section 4. The spatio-temporal structure of the model errors is discussed in Section 5. Our findings are summarized in Section 6.

2. Data and methods

For numerical computations we use the Massachusetts Institute of Technology general circulation model (MITgcm) (Marshall et al., 1997; Adcroft et al., 2004), which is a general purpose hydrodynamic model that solves the Boussinesq and hydrostatic or non-hydrostatic form of the Navier–Stokes equations for an incompressible fluid. The model uses a grid that reduces grid lines convergence and place grid poles on land. The fully global grid has a zonal spacing of 1° longitude. The meridional grid spacing is 0.3° of latitude within ± 10° of the equator and increases to 1° latitude outside the Tropics. The model has 50 vertical levels ranging in thickness from 10 m near the surface to approximately 450 m at a maximum model depth of 6150 m. The partial-cell formulation of Adcroft et al. (1997), which permits accurate representation of the bathymetry, is used. The model is integrated with real fresh water surface fluxes and properly accounts for their effects on global mean sea-level.

The ocean model is coupled to a sea-ice model that computes ice thickness, ice concentration, and snow cover as per Zhang et al. (1998) and that simulates a viscous-plastic rheology based on Hibler (1979). The C-grid sea-ice code allows for no-slip and free-slip lateral boundary conditions. Ice mechanics follow a viscous-plastic rheology and the ice momentum equations are solved numerically using line-successive-over-relaxation (LSOR)