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The effect of ocean tides on a climate model simulation

M. Müller [a,b,*], H. Haak [a], J.H. Jungclaus [a], J. Sündermann [c], M. Thomas [d]

[a] *Max Planck Institute for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany*
[b] *University of Victoria, School of Earth and Ocean Sciences, P.O. Box 1700 Stn Csc, Victoria, Canada V8W2Y2*
[c] *University Hamburg, Institute of Oceanography, Bundesstr. 53, 20146 Hamburg, Germany*
[d] *German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany*

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ABSTRACT

We implemented an explicit forcing of the complete lunisolar tides into an ocean model which is part of a coupled atmosphere–hydrology–ocean–sea ice model. An ensemble of experiments with this climate model shows that the model is significantly affected by the induced tidal mixing and nonlinear interactions of tides with low frequency motion. The largest changes occur in the North Atlantic where the ocean current system gets changed on large scales. In particular, the pathway of the North Atlantic Current is modified resulting in improved sea surface temperature fields compared to the non-tidal run. These modifications are accompanied by a more realistic simulation of the convection in the Labrador Sea. The modification of sea surface temperature in the North Atlantic region leads to heat flux changes of up to 50 W/m^2. The climate simulations indicate that an improvement of the North Atlantic Current has implications for the simulation of the Western European Climate, with amplified temperature trends between 1950 and 2000, which are closer to the observed trends.

1. Introduction

In the last decade ocean tides have returned into the focus of attention in oceanographic research. Theoretical and observational estimates support the hypothesis that a considerable amount of energy is transferred from tidal currents into mixing processes of the oceans (Munk and Wunsch, 1998; Egbert and Ray, 2000). These findings suggested that it is necessary to allow for an interactive approach of ocean tides and ocean circulation.

In climate modelling the consideration of ocean tides failed to appear due to considerably different time scales of climate and tidal models, numerical stability problems, and due to the “rigid lid” condition often used in the ocean component of climate models (see Schiller (2004) for more details). So far, three global Ocean General Circulation Models (OGCMs) are existing, which explicitly include ocean tides: (1) Thomas et al. (2001) extended an OGCM by implementing the complete lunisolar tidal forcing. (2) Schiller and Fiedler (2007) described the implementation of the forcing of eight tidal constituents in an OGCM and their influence on transport and mixing processes in the Indonesian Seas and off the Australian Northwest Shelf. Finally, (3) a recent study by Arbic et al. (2010) included a forcing of the major tidal constituents in a high-resolution eddy resolving ocean model. The processes of tidal mixing are unresolved in OGCMs and must be parameterized, even when tides are forced explicitly. In shelf regions, where strong tidal currents occur, mixing is generated by enhanced vertical velocity in the bottom boundary layer. In the deep ocean tidal mixing is caused by the generation and breaking of internal waves over rough topography (Garrett, 2003). Tidal mixing in the deep ocean is usually considered by a parameterization depending on roughness of the ocean topography, on vertical stratification and on the magnitude of tidal currents (Simmons et al., 2004; Montenegro et al., 2007). To allow for tidal mixing in shelf regions Lee et al. (2006) included tidal currents of an external ocean tide model into their Richardson number dependent vertical mixing scheme. In another approach Bessières et al. (2008) included the ocean tidal residual mean circulation, obtained from an tide-only model, into a global climate model. Detailed studies of locally enhanced mixing on the general ocean circulation can be find in Saenko (2006) and Jayne (2009).

In the present study we implemented the tidal module developed by Thomas et al. (2001) in a climate model which was used for the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report simulations. Thus, tides are forced explicitly and tidal mixing is realized in the ocean model by tidal currents inducing vertical shear of velocity through bottom friction, which in turn acts on the vertical mixing scheme. This approach generates tidal mixing mainly on the continental shelf and not in the deep ocean. The next step will be to implement an additional parameterization of tidal mixing generated by internal wave breaking (St.-Laurent et al., 2002) and will be subject to future research. In addition to mixing the tidal currents interact with low frequency

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* Corresponding author at: University of Victoria, School of Earth and Ocean Sciences, P.O. Box 1700 Stn Csc, Victoria, Canada V8W2Y2. Tel.: +1 250 472 4008.
E-mail address: mmueller@uvic.ca (M. Müller).

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motions through nonlinear bottom friction and act on the vertical viscosity parameterization scheme of the model.

The goal of the present study is to present an ensemble of climate model experiments with an explicit lunisolar tidal forcing. The results show that the effect of tides through mixing and nonlinear interactions have a significant influence on the climate model simulations. Further, this study demonstrates that it is possible to obtain global tidal patterns in an OGCM with an accuracy comparable with classic barotropic non-constrained tidal models. In Section 2 we give a brief description of the model and the setup of the experiments. Section 3 describes the tidal patterns and their accuracy and in Section 4 we show how physical quantities are modified by tides in the model. In Section 5 we describe the impact of tides on current and water mass properties in the North Atlantic. Since the sea surface temperature and ocean–atmosphere heat flux in the North Atlantic is changed on large scales, a significant secondary effect occurs in the atmospheric component of the climate model (Section 6).

2. Model description

The climate model is the coupled atmosphere–hydrology–ocean–ice model of the Max Planck Institute for Meteorology (ECHAM5/MPI-OM) (Jungclaus et al., 2006). The Max Planck Institute Ocean Model (MPI-OM) is extended by an explicit forcing of the complete lunisolar tides (Thomas et al., 2001). In this real-time approach the tidal potential is deduced from lunisolar ephemerides according to the instantaneous positions of moon and sun. The loading and self-attraction is not considered in the ocean circulation model. The time resolution of the ocean model is 2160 s. The time-step of the ocean model is reduced compared to the original value used for the IPCC AR4 simulations (4800 s) for the reliable representation of semi-diurnal and diurnal ocean tides. The ocean model utilizes horizontally a bipolar orthogonal grid where the positions of the north and south pole can freely be chosen. In this configuration the grid North Pole is centered on Greenland, which leads to an increased resolution for the North Atlantic region (near Greenland up to 12 km). Vertically the grid has 40 layers. A detailed description of the model is given by Marsland et al. (2003). The atmosphere model is the European Center/Hamburg model version 5 (ECHAM5) and it is run at T63L31 resolution (Roeckner et al., 2003). Atmosphere and ocean are coupled without flux correction by means of the OASIS coupler (Valcke, 2006). Six coupled experiments have been performed, one control run without the tidal potential and an ensemble of five experiments with the consideration of the lunisolar tides. The latter only differ in their initial conditions, which are taken in one hundred year intervals from the 500 year IPCC AR4 pre-industrial control run. The simulations cover the period 1860–2000 and are forced by observed greenhouse gas emissions and pre-calculated sulfate aerosols.

In the following sections we compare the ensemble means of the experiments with tides with the control run without tides. Figures, which show vertically integrated ocean currents are based on one particular ensemble member and are averaged over 10 years. Due to the high temporal variability of the ocean currents the illustration of ensemble mean, or averaged over a longer period, current vectors would blur the pathway of the currents. However, for the scalar variables like sea surface temperature, mixed layer depth and ocean–atmosphere heat flux, we show ensemble mean values averaged over a period of 50 years. Diagnostic quantities, as tidal velocity, bottom friction dissipation, vertical diffusivity and viscosity are based on model output of a particular year and ensemble member.

3. Evaluation of tidal patterns

In this section the main semi-diurnal and diurnal tidal patterns in the climate model are evaluated. It is meaningful to evaluate both, tidal velocities and elevations, since the focus of the present study is on the effect of tides on the ocean circulation model, and this effect is mainly caused by tidal velocities rather than by tidal elevations. The strongest tidal currents occur in shallow waters where current tide models have their largest uncertainties (Shum et al., 1997). Even with modern techniques of assimilating data into tide models the residuals of tidal velocities are still large in shallow waters. Evaluations of tidal currents of barotropic tide models are rare and most of the comparisons with observational data has been done so far in the deep ocean (Ray, 2001). In the following, we compare qualitatively tidal currents with the model of Zahel et al. (2000) (Z2000), which determines tidal velocities by assimilating satellite data in a numerical hydrodynamical model. Tidal elevation fields are compared quantitatively with the observational pelagic ST103 dataset (LeProvost, 1994).

The tidal constituents of the ocean tides, can be obtained from the model output by means of harmonic analyzes (e.g., Emery and Thompson, 1998). The simulated global sea surface elevation and barotropic velocity pattern of every time-step (2160 s) over one arbitrary model year are used for harmonic analyzes. This is a sufficient time resolution and record length to resolve the main semi-diurnal and diurnal tidal constituents. A quantitative comparison of the tidal patterns with the observational pelagic ST103 dataset (LeProvost, 1994) is obtained by computing the RMS errors of the tidal amplitudes:

$$\mathrm{RMS} = \sqrt{\frac{1}{103}\sum_{i=1}^{103}\left(A_i^{Model} - A_i^{\mathrm{ST103}}\right)^2}. \tag{1}$$

Here, A_i^{Model} and A_i^{ST103} are the amplitudes of a tidal constituent at the ith-station in the model and at the tide gauge, respectively. The RMS errors are 12.9 cm for M_2 and 4.8 cm for K_1. These values are, of course, much larger than those of model approaches with assimilation of satellite data which have RMS errors in the range of just a few centimeters, even for the M_2 tide (Shum et al., 1997). Also, a model without assimilation of data (Arbic et al., 2004) shows smaller RMS errors. However, this model has (1) higher horizontal resolution of 0.5°, (2) it considers an internal wave drag (conversion of barotropic tide energy into internal waves) and (3) it has a proper treatment of the loading and self-attraction effect. The accuracy of the tidal patterns simulated by the climate model are comparable with classic barotropic tide model approaches without the consideration of internal wave drag and loading and self-attraction effect.

The amplitudes of the tidal velocities of the M_2 and K_1 constituents of the climate model and of the model of Z2000 are shown in Fig. 1. The main patterns of the velocities are similar. However, in detail there are significant differences between the models, most notably in coastal regions. For example the M_2 tidal currents of Z2000 are larger on the European Shelf, Patagonian Shelf, and in the Bering Sea. Instead K_1 tidal currents of Z2000 are smaller in the Southern Ocean and South China Sea. As already stated in the beginning of this section, there is a large uncertainty of tidal velocities in tide models, especially in shallow waters. As the main tidal patterns of Z2000 and the present ocean circulation model are qualitatively consistent, we conclude that the accuracy is high enough for a further analyzes of the effect of tidal currents on the ocean circulation.

For future studies it will be necessary to include a parameterization of the generation of internal waves and to consider the self-attraction and loading effect, in order to obtain improved tidal patterns. However, the discrepancies between observations and model will have a minor relevance in the following analysis of climate relevant variables.