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Consideration of ocean tides in an OGCM and impacts on subseasonal to decadal polar motion excitation

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Abstract. Ocean induced changes of Earth's rotation are attributed either to tides or to variations of the general circulation. Analogously, numerical world ocean models can still be divided into Ocean General Circulation and tidal models, although a neglect of nonlinear interactions in favor of a linear superimposition of both components of motion is questionable. By means of a simultaneous simulation of the ocean's circulation and tides we estimate the importance of two oceanic effects with respect to excitation of polar motion: nonlinearities between circulation and long-period tides and the circulation induced potential due to loading and self-attraction of a baroclinic ocean. Comparing the linear superimposition of separate model simulations with the simultaneous calculation of circulation and tides it turns out that these second-order effects contribute about 8% to ocean induced changes in Earth's orientation.

Introduction

In general, large scale dynamics of the world ocean are separated into the contributions of the tidal field and that of the general, i.e., thermohaline, wind- and pressure-driven circulation. Existing numerical global ocean models reflect this separation. While the circulation is simulated by baroclinic Ocean General Circulation Models (OGCM), tidal dynamics are approximated by means of a linear superimposition of partial tides reproduced by barotropic models. In numerous investigations both kinds of numerical models have been used to estimate changes of circulation induced oceanic angular momentum (OAM) as well as oceanic tidal angular momentum (OTAM) and corresponding rotational variations. Recently, *Ponte et al.* [1998], *Ponte and Stammer* [1999], as well as *Johnson et al.* [1999] showed by means of OGCMs that the ocean plays an important role in exciting movements of the Earth's pole of rotation for annual to submonthly timescales. *Gross* [1993], e.g., used results from an unconstrained model [*Seiler*, 1991] to calculate the influence of numerous partial tides on Earth's rotation. Improved OTAM estimates based on TOPEX/POSEIDON data were reported by *Chao et al.* [1996]. In all studies it is implicitly assumed that the total contribution of the oceans to angular momentum changes of the Earth can be approximated by means of a linear superimposition of OAM and OTAM. In this approximation nonlinear interactions between circulation and tides as well as interactions between partial tides are ignored. Further, secondary effects arising from loading and self-attraction (LSA) of water masses are usually taken into account when tidal dynamics are simulated, but OGCMs exclude these effects so far.

This study is concerned with the impact of both secondary contributions, i.e., nonlinear interactions and LSA in OGCMs, to the equatorial components of angular momentum variability on timescales from one month to decades. With a numerical global ocean model for circulation and tides three long-term runs have been performed: two separate and one simultaneous calculation of circulation and tides. Comparison of the resulting equatorial effective angular momentum functions (EAM) reveals the contributions of both secondary oceanic effects in excitation of polar motion.

The numerical model

The numerical model used here is the Hamburg Ocean Primitive Equation model (HOPE) [*Wolff et al.*, 1996]. It is based on nonlinear balance equations for momentum, the continuity equation, and conservation equations for heat and salt. The hydrostatic and Boussinesq approximations are applied. Water elevation, three-dimensional horizontal velocities, potential temperature as well as salinity are calculated prognostically; vertical velocities are determined diagnostically from the incompressibility condition. Implemented is a sea ice model [*Hibler*, 1979], which allows a prognostic calculation of sea ice thickness, compactness, and velocities. The temporal resolution of the originally climatological model [*Drijfhout et al.*, 1996; *Wolff et al.*, 1996] is now one hour. Thirteen layers exist in the vertical, the horizontal resolution is a constant 1.875° in longitude and latitude on a C grid [*Arakawa and Lamb*, 1977].

Three model runs from 1949 to 1993 have been performed: To simulate the ocean's circulation, the model

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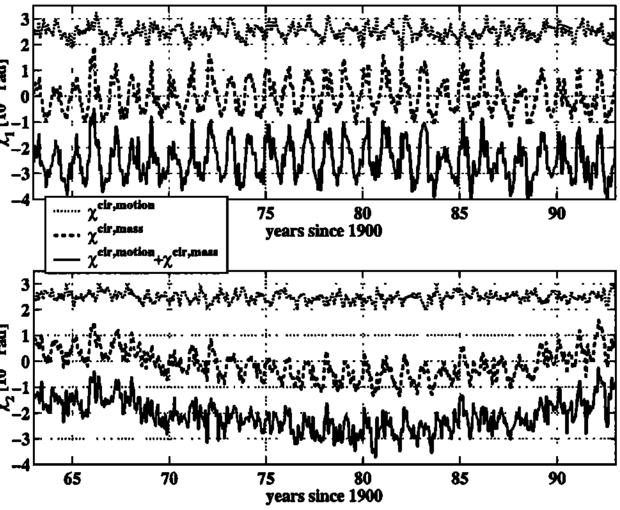

Figure 1. Low-pass filtered effective angular momentum functions $\chi_{1,2}^{cir}$ resulting from the general circulation alone. Dotted lines represent the effect of currents, dashed lines of mass distributions, and solid lines the sum of motion and mass term. Note that all time series have been arbitrarily shifted.

was driven with twice-daily atmospheric forcing fields from the Deutsches Klimarechenzentrum (Hamburg, Germany) that include wind stresses, surface temperatures, and freshwater fluxes [*Roeckner et al.*, 1992]. The transient dynamical state of the atmosphere is the result of simulations with the ECHAM3 AGCM [*DKRZ*, 1992] that was forced with monthly means of observed sea surface temperatures and global ice covering according to the GISST2.2 data set provided by the Hadley Center for Climate Prediction and Research (Bracknell) [*Parker et al.*, 1994]. In the second case, the model was driven exclusively with the complete lunisolar tidal potential without decomposition into Fourier components. Applying the algorithms described by *Van Flanders and Plukkinen* [1998], at each time-step distances, right ascensions, and declinations of the Moon and Sun are calculated to determine the instantaneous tidal potential. In contrast to the first case, this run allows for the secondary potential, Φ_{LSA}, that arises from LSA of the water column. Here, LSA is parameterized by a modified formulation of *Accad and Pekeris* [1978]. In the barotropic case, *Accad and Pekeris* [1978] concluded that LSA is proportional to the local (tidal) elevation. In the baroclinic case, local water elevations and vertical density distributions tend to compensate each other. Thus, LSA is taken into account by a term proportional to the density, ρ, of the local water column:

$$\Phi_{LSA} = g\varepsilon \int \frac{\rho}{\rho_0} dz \ , \qquad (1)$$

where g is the mean gravitational acceleration, ε a proportionality factor, ρ_0 a reference density, and the integral is taken over the actual height of the water column. Sensitivity studies led to $\varepsilon = 0.085$, which is consistent with *Accad and Pekeris* [1978], who used a similar grid resolution. The third run refers to a simultaneous calculation of circulation and tides and includes LSA and nonlinear interactions of both components of motion.

Polar motion excitation

Using the formulation of *Barnes et al.* [1983] instantaneous values of relative angular momentum and relevant components of the tensor of inertia are expressed in terms of EAM functions, $\chi_{1,2}$, where χ_1 points to the Greenwich, χ_2 points to the 90°E meridian. Interactions between circulation and tides are expected to become most important at timescales where both tidal and circulation induced variations are significant. Since the time resolution of ECHAM3 forcing fields is only 12 hours, the diurnal cycle of the atmosphere cannot be accounted for in this study. Another prominent candidate for interactions are annual and semiannual variations that are manifested on the one hand in the seasonal cycle, on the other hand in long-period tides like *Sa* and *Ssa*. Therefore, only variations with periods longer than a month are considered here, although short-period tides have been modelled, too. Since the latter mask the long-term variations, EAM functions are low-pass-filtered with a cutoff period of 30 days.

To inspect the impact of circulation (*cir*) and tides (*tid*) alone with respect to polar motion, firstly, in Figure 1 low-pass filtered time series $\chi_{1,2}^{cir}$ resulting from the ocean's general circulation are given for the period 1963-1993. Although the motion term (*motion*) reaches half of the mass term (*mass*), main characteristics of total OAM are dominated by mass induced variations. According to Figure 2, the influence of OTAM is more

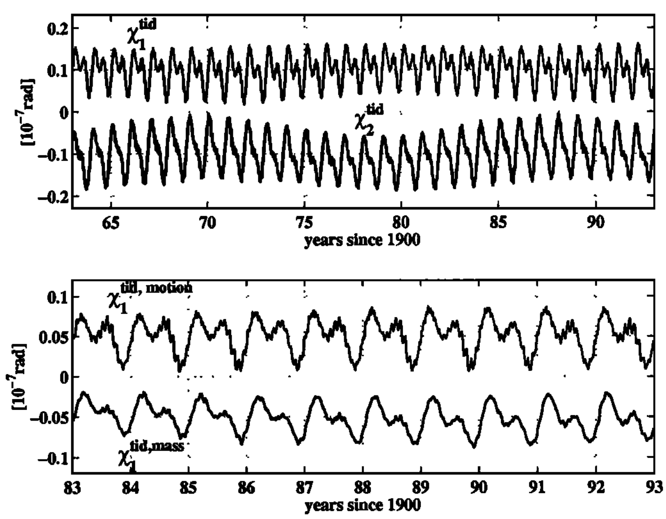

Figure 2. Effective angular momentum functions $\chi_{1,2}^{tid}$ resulting from ocean tides (upper panel). In the lower panel contributions of tidal currents, $\chi_1^{tid,motion}$, and mass distributions, $\chi_1^{tid,mass}$, are given for the last decade of the simulation.

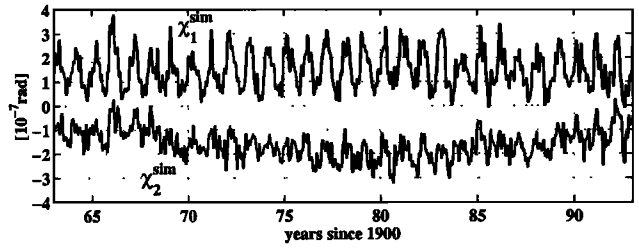

Figure 3. Effective angular momentum functions χ_1^{sim} (upper curve) and χ_2^{sim} (lower curve) resulting from the simultaneous calculation of circulation and tides.

than one order of magnitude less than that of OAM at these timescales. Apart from the most pronounced annual tide, *Sa*, modulated by the 18.6-year zonal tide, the effect of the semiannual tide, *Ssa*, is evident, especially in χ_1^{tid}. In contrast to $\chi_{1,2}^{cir}$, here the contribution of the motion term prevails and becomes even more important at shorter periods (cf. lower panel of Fig. 2).

Figure 3 shows the time series $\chi_{1,2}^{sim}$ resulting from the simultaneous (*sim*) model run that, not surprisingly, resemble the χ_i^{cir} curves strongly. Again, variations are dominated by the annual period accompanied with interannual as well as subseasonal signals. The differences between the simultaneous calculation and the linear superimposition of the separate simulations of circulation and tides, i.e., $\chi_i^{\Delta} = \chi_i^{sim} - (\chi_i^{cir} + \chi_i^{tid})$, $i = 1, 2$, are represented by the solid curves of Figure 4. These differences reflect the combined contributions of circulation induced LSA and nonlinear interactions between circulation and tides. Evidently, these second-order effects, that are responsible for about 8-10% of total ocean induced angular momentum changes, have a stronger influence on Earth orientation than (primary) long-period tides (Fig. 2). Main characteristics of χ_i^{sim} and χ_i^{Δ}, like

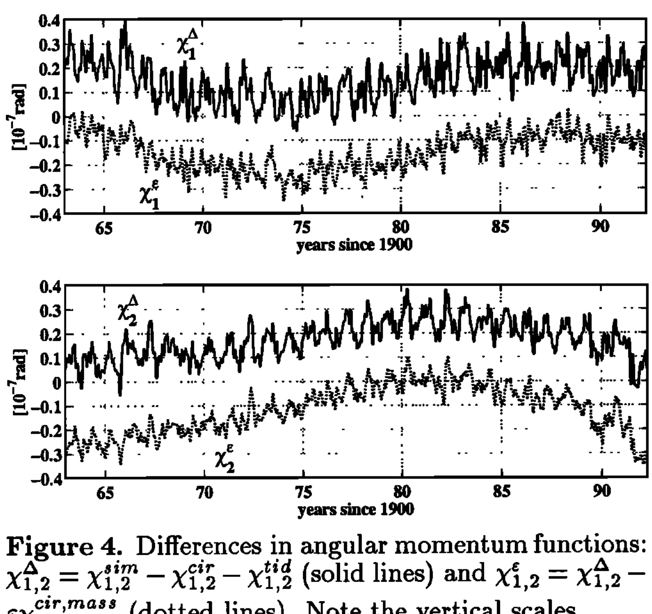

Figure 4. Differences in angular momentum functions: $\chi_{1,2}^{\Delta} = \chi_{1,2}^{sim} - \chi_{1,2}^{cir} - \chi_{1,2}^{tid}$ (solid lines) and $\chi_{1,2}^{\varepsilon} = \chi_{1,2}^{\Delta} - \varepsilon\chi_{1,2}^{cir,mass}$ (dotted lines). Note the vertical scales.

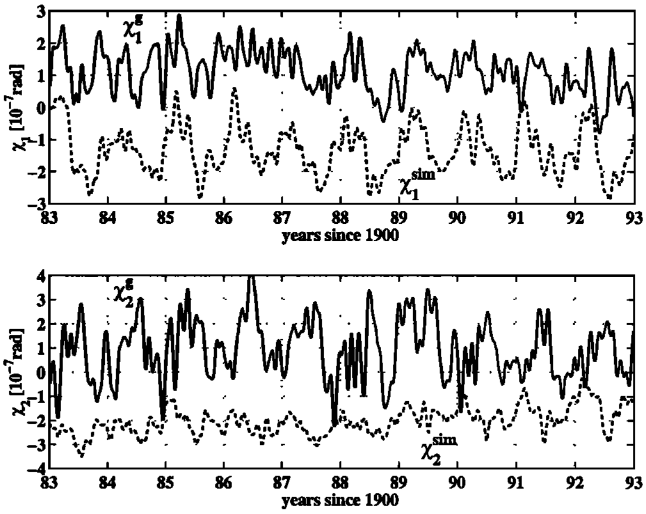

Figure 5. Comparison of geodetic excitation functions $\chi_{1,2}^{g}$ according to the EOP C 04 data of the IERS (solid lines) with time series $\chi_{1,2}^{sim}$ from the simultaneous calculation of circulation and tides (dashed lines).

seasonal variations and local extremes, are qualitatively quite similar, since magnitudes of OAM and OTAM as well as of nonlinear interactions and LSA are controlled by variations of currents and mass distributions.

One might expect a linear relation between the above stated magnitude of χ_i^{Δ} and the choice of the factor ε in eq. (1). LSA, as parameterized here, is assumed to counteract the pressure gradient, analogous to reduced gravity. If differences χ_i^{Δ} arise from a linear impact of ε on circulation induced pressure gradients which control the magnitude of $\chi_i^{cir,mass}$, i.e., the amount of χ_i^{cir} due to mass redistributions, the difference $\chi_i^{\Delta} - \varepsilon\chi_i^{cir,mass}$ should vanish. According to the dotted lines in Figure 4, this is not the case. Differences χ_i^{Δ} cannot be explained by means of a linear dependence upon the parameterization of LSA. Thus, second-order contributions cannot be properly modelled subsequently to separate calculations by means of a manipulation of $\chi_i^{cir,mass}$

To estimate the relative importance of simulated oceanic excitation of polar motion with respect to observed integral measures, polar motion data made available by the International Earth Rotation Service [*IERS*, 1997] (EOP C 04 data set) were converted to corresponding geodetic excitation functions, $\chi_{1,2}^{g}$, by applying the deconvolution method of *Wilson* [1985]. According to *Wilson and Vicente* [1980] a Chandler period of 433.45 sideral days and a dissipation factor $Q = 175$ were assumed. Exemplarily, for the period 1983-1993 in Figure 5 the time series χ_i^{g} are contrasted with the simulated χ_i^{sim}, which contain the combined variations of OAM and OTAM including nonlinear interactions and effects arising from LSA. Since the contribution of the atmosphere has not been removed, one cannot expect good agreement between χ_i^{g} and χ_i^{sim}. However, qualitatively there are quite similar characteristics of χ_i^{g} and χ_i^{sim} curves, especially with respect to χ_1. In contrast to the components of the geodetic excitation functions, χ_1^{sim} exhibits larger variations than χ_2^{sim}, presumably because of the continent–ocean geography. The relation of χ_1^{sim} and χ_2^{sim} identifies those ocean sectors with most important current and mass variations.

Conclusions

The comparison of a linear superimposition and a simultaneous simulation of the world ocean's general circulation and tides indicates that on timescales longer than one month secondary effects arising from LSA and nonlinearities can be larger than primary influences of long-period tides themselves. The simulations suggest that such second-order effects are responsible for about 8% of total oceanic excitation of polar motion. Hence, according to our simulation results a linear superimposition of OAM and OTAM neglects a significant part of ocean induced variations of Earth's orientation.

Recent findings emphasize the important role of the oceans in excitation of polar motion [*Ponte et al.*, 1998; *Gross*, 2000]. In order to allow an assessment of the compatibility of oceanic simulations presented here with reported polar motion excitation, the effects of the atmosphere, hydrology and pressure-driven ocean mass transports have to be considered, too. For reasons of consistency the atmospheric contribution should be calculated from that transient dynamical state of the atmosphere that has been used to force the ocean model. This topic will be considered in a forthcoming study.

The simultaneous calculation of thermohaline, wind-driven, and tidal ocean dynamics can be considered as a step towards an operational modelling of the instantaneous state of the oceans, something so far has been possible for the atmosphere, but not for the ocean on the global scale. This will become important especially with respect to the gravity missions GRACE and GOCE in the near future where the ocean's contributions to the gravity change have to be identified in terms of three-dimensional mass transports.

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