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Effect of global warming on the length-of-day

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[1] The anthropogenic increase in greenhouse gas concentrations in the Earth atmosphere will probably induce important modifications of the global circulation in the atmosphere and ocean. Due to the angular momentum conservation of the Earth-atmosphere-ocean system, variation of the length-of-day (LOD) can be expected. By using the outputs of the models participating to the Coupled Model Intercomparison Project (CMIP-2), we reach the following conclusions: (1) the models globally agree to an increase of the LOD of the order of 1 μs/year, (2) the effect is mostly associated with an increase of the mean zonal wind, of which about one third is compensated by a change in mass repartition. *INDEX TERMS:* 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1645 Global Change: Solid Earth; 1699 Global Change: General or miscellaneous

1. Introduction

[2] Earth rotation rate fluctuations and the associated length-of-day (LOD) variations are mainly due to interaction between the solid Earth and the geophysical fluids (atmosphere, ocean, and core). The increase of the greenhouse gas content in the atmosphere is already observed and will continue in the future. This increase is expected to affect the global circulation of the atmosphere and of the ocean. The effect of a doubling CO_2 on the zonal wind and the associated relative atmospheric angular momentum (AAM) has been already studied from three atmospheric general circulation models by [*Rosen and Gutowski*, 1992], who found a decrease of the relative AAM (associated with an decrease of the LOD). More comprehensive coupled ocean-atmosphere models have also been used to predict the impact of CO_2 increase. Several of these simulations, based on a standardized scenario (see [*Meehl et al.*, 2000]), have been gathered in the Coupled Model Intercomparison Project (CMIP-2). The purpose of the present paper is to evaluate the effect of those climate changes on the LOD. To this end, we analyzed the axial angular momentum (AM) of the fluid layers as simulated by the models involved in CMIP-2, based on the hypothesis of an exponential CO_2 increase of 1% per year.

2. CMIP-2 Project Model and Hypotheses

[3] The CMIP-2 project collects the output of state-of-the-art coupled ocean/atmosphere models. We restricted our study to the 14 models (out of 18) that have all the data needed, i.e., the models of: the Bureau of Meteorology Research Centre, (BMRC) [*Power et al.*, 1993], the Center for Climate Modeling and Analysis (CCCma) [*Flato et al.*, 2000], the Center for Climate System Research (CCSR) [*Emori et al.*, 1999], the Commonwealth Scientific and Industrial Research Organization (CSIRO) [*Gordon and O'Farrell*, 1997], the Center for Research and Advanced Training in Scientific computation (CERFACS) [*Barthelet et al.*, 1998], the Max Plank Institute (ECHAM3) [*Voss et al.*, 1998], the Geophysical Fluid Dynamics Laboratory (GFDL) [*Delworth and Knutson*, 2000], the Institute of Atmospheric Physics (IAP) [*Wu et al.*, 1997], the Laboratoire de Météorologie Dynamique (LMD) [*Leclainche et al.*, 2000], the Meteorological Research Institute (MRI) [*Tokioka et al.*, 1996], the National Center for Atmospheric Research (NCAR CSM) [*Boville and Gent*, 1998], the Naval Research Laboratory (NRL) [*Li and Hogan*, 1999], the Hadley Centre for climate prediction and research (HadCM2, [*Johns et al.*, 1997] and HadCM3 [*Gordon et al.*, 2000]). The information about the models can be found in the above references and from the CMIP2 web page [http://www-pcmdi.llnl.gov/cmip/]. All these models have been forced by a 1% of CO_2 increase per year, for 70 years, the total increase being equivalent to a doubling of the CO_2, while the concentrations in other greenhouse gases are maintained constant during the simulation. The data have been archived as 4 mean states of the atmosphere, once every 20 years. The goal of CMIP-2 is to compare the response of various climate models to a radiative perturbation caused by an increase in greenhouse gases with the time-scale and magnitude of this perturbation in the range of the one expected during the 21st century. The great advantage of CMIP-2 is that exactly the same scenario drives all the models, which allows an intercomparison that is particularly valuable for the present study.

3. Angular Momentum of the Fluid Layer

[4] The total AM of an isolated system is conserved. If the system considered is composed of the solid Earth, the ocean and the atmosphere (with other components such as the core neglected), the knowledge of the evolution of the AM of the fluid layers give all the information about the changes of the AM of the (rigid) solid Earth and, as a consequence, of the LOD.

[5] The AM of the fluid parts is computed using the formula (see [*Munk and MacDonald*, 1960]):

$$H = \frac{a^3}{g} \int \int \left(\int v \sin^2 \theta \, dp + a \, \Omega \, P \sin^3 \theta \right) \; d\theta \; d\lambda, \qquad (1)$$

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Table 1. Trend in the LOD (in μs/year)

Model	Pressure	Wind	Current	Total
BMRC	−1.0	1.4	0.0	0.4
CCCma	−1.0	2.6	0.1	1.6
CCSR	−0.1	4.4	0.1	4.4
CERFACS	−0.2	2.0	0.3	2.2
CSIRO	−0.8	0.7	0.1	0.0
ECHAM3	−0.9	0.7	0.1	−0.1
GFDL	−1.0	0.7	−0.1	−0.4
TAP	−0.6	−1.7	0.1	−2.2
EMD	−0.8	3.7	0.1	2.9
MRI	−0.6	1.3	0.0	0.7
NCAR CSM	−0.1	0.9	0.1	0.9
NRL	−0.1	1.2	0.0	1.1
HadCM2	−1.6	5.3	0.0	3.7
HadCM3	−1.5	2.0	0.0	0.5
Mean	−0.75	1.81	0.06	1.13
σ	0.49	1.77	0.09	1.74

Table 2. Source of the Variation in the LOD at Low Frequency

Source	Data	ΔLOD
Core motion	observ.	1–2 *ms*[a]
Tidal friction	observ.	20μs/year
Contin. water res.	observ.	−6μs/year
Post glacial rebound	observ.	−5 μs/year
Wind AAM	CMIP	1.81μs/year
Mass term	CMIP	−0.75 μs/year
Sea level	observ.	0.5 μs/year
Glacier	observ.	0.4 μs/year
Earthquake	observ.	−0.1 μs/year
Ocean current	CMIP	0.1 μs/year

[a] Not a trend but a decadal variation.

where H is the axial component of AM of the fluid part, a is the Earth mean radius, g is the mean gravity acceleration, v is the zonal wind velocity, p is the atmospheric pressure, θ is the colatitude, λ is the longitude, P is the surface pressure and Ω is the Earth mean rotation rate. The first term in (1) is usually called the motion term, and the second term is called the mass term.

[6] From [*Munk and MacDonald*, 1960], it can be easily deduced that, if the effects of the core-mantle coupling are neglected, the variations of the LOD are related to the variations of the AM of the fluid layer by: $\Delta LOD = 1.68 \times 10^{-29} (\Delta H_{\mathrm{atmos}} + \Delta H_{\mathrm{ocean}})$, where the LOD and AM are given in SI units.

[7] At periods larger than 20 days, the ocean is supposed to respond to atmospheric pressure change as an inverted barometer. In that hypothesis, the change of ocean and atmosphere AM mass term is given by the mass term of the atmosphere integrated over the continent plus the mass term associated with the mean atmospheric pressure over the whole ocean acting on each grid point of the ocean surface. The total change of LOD due to the atmosphere and the ocean will thus arise from AM changes associated with changes in the surface pressure over the continent, mean surface pressure over the ocean, zonal winds and zonal currents.

4. Results

[8] We evaluated the axial AM due to the mass term, the motion term and the oceanic current term for the present time and at +20, +40 and +60 years. The trend of each series from each model is given in Table 1, with the global mean and standard deviation (σ). Some remarks can be made: (1) the major effect is associated with the motion term and tends to increase the LOD for all but one (IAP) model, but the magnitude differs significantly from one model to another; (2) the pressure effect is about one third of the wind effect and tends to decrease the LOD for all

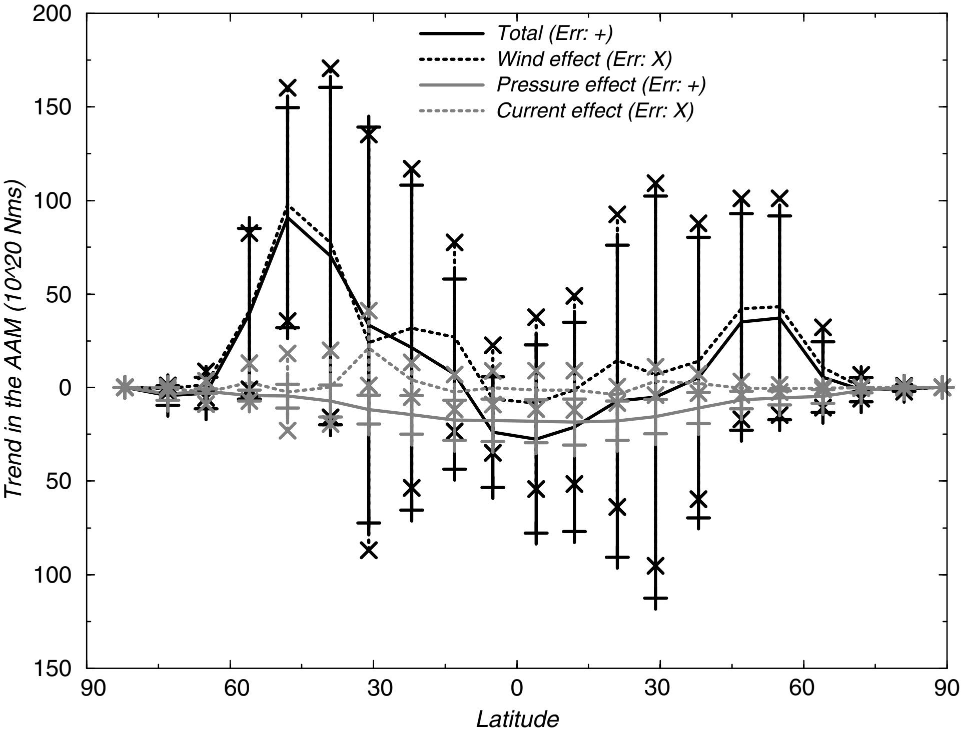

Figure 1. Average (and standard deviation) trend in the LOD as a function of latitude.

models; in some models (CSIRO, ECHAM3, GFDL), the pressure contribution is larger than the wind effect on the LOD; (3) the current effect is about one order of magnitude less than the wind effect and generates an increase of the LOD for all but one model (GFDL); (4) a zero total effect cannot be rejected, as 0 is included in the interval mean value $\pm\sigma$ for the total effect; it is not the case for the pressure nor the wind effect computed separately. The mean trend (averaged on all the model) is 1.1 μs/year, but it could be as large as 4.4 μs/year according to one of the models (CCSR).

[9] Figure 1 shows the mean contribution to the AM change as a function of the latitude (the error bars show the standard deviation at each latitude). From these results, the following conclusions can be drawn:

1. The largest contribution of the wind is mainly associated with an increase in the zonal wind between 10–60 degrees of latitude in both hemispheres. The effect is larger in the Southern Hemisphere than in the Northern Hemisphere, as can be seen in Figure 1. This increase in the zonal wind, by AM conservation, induces an increase in LOD.
2. The effect of the pressure is strongly coherent for nearly all the models. The decrease of the pressure contribution is associated with a decrease of the atmosphere global flattening, i.e. mass displaced from the equator to the pole, inducing a decrease in LOD.
3. The change of the contribution of the oceanic currents is mainly associated with variation in the Southern ocean, a region of strong zonal currents that display a large response to the increase in greenhouse gases, e.g. [*Boer et al.*, 2000].

5. Comparison with Other Effects

[10] The present level of accuracy of LOD observation, using the Very Long Baseline Interferometry, is at about 10 μs. Some other effects can generate observable variations of the LOD at the decadal timescale. An evaluation of such effects was done in [*Chao*, 1994; *Chao and O'Connor*, 1988]. For comparison purpose, we have summarized these effects—including the results of our paper—in Table 2. Note that this comparison has to be taken with caution as the hypothesis in CMIP-2 are not coherent with the ones of [*Chao*, 1994; *Chao and O'Connor*, 1988], based on present day data analysis. The table shows that the trend in the LOD that would be induced in the frame of the CMIP-2 scenario would be of the same order of magnitude as the other low frequency excitations of the LOD. The largest low frequency effect is due to the core-mantle interaction (at the order of magnitude of some *ms* at decadal time scale). This effect is not known with precision because the motions in the core are poorly modeled and not directly observed. The remaining effects are at the some μs/year level. Consequently, they would be observable at the decadal timescale, but their accurate estimations is still difficult. The geophysical interpretation of the LOD trend and long term variations is thus problematic. However, as many core motion models are constrained by LOD data, it would be necessary to estimate as acurately as possible the external source of LOD variation in order to improve the core modeling.

6. Summary and Conclusions

[11] We have estimated the effect of the global warming associated with a common senario of a nominal 1% CO_2 increase per year on AM of ocean and atmosphere and hence on LOD, using the outputs of 14 models from the CMIP-2 data sets. The models show a reasonable agreement: the major effect is associated with the change in the zonal wind, which increases the LOD of some microseconds per year; this effect is compensated of about one third by the mass distribution change. The oceanic current change induces an additional increase of the LOD at the level of some tenths of microsecond per year. Our evaluation of the zonal wind effect agree with the order of magnitude of [*Rosen and Gutowski*, 1992], but differs in sign. This is probably due to the difference in the experimental design (different CO_2 scenario, interaction with the ocean, ...). Considering that the fluid core contributions are poorly determined and have an amplitude at the millisecond level, we do not expect to be able to separate core and global change effects or other long timescale effects, but we have shown here that the effect of global warming should be taken into account when studying the variations of the LOD at decadal and multi-decadal timescales.

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