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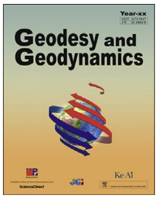

Improved geophysical excitations constrained by polar motion observations and GRACE/SLR time-dependent gravity

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ABSTRACT

At seasonal and intraseasonal time scales, polar motions are mainly excited by angular momentum fluctuations due to mass redistributions and relative motions in the atmosphere, oceans, and continental water, snow, and ice, which are usually provided by various global atmospheric, oceanic, and hydrological models (some with meteorological observations assimilated; e.g., NCEP, ECCO, ECMWF, OMCT and LSDM etc.). Unfortunately, these model outputs are far from perfect and have notable discrepancies with respect to polar motion observations, due to non-uniform distributions of meteorological observatories, as well as theoretical approximations and non-global mass conservation in these models. In this study, the Least Difference Combination (LDC) method is adopted to obtain some improved atmospheric, oceanic, and hydrological/crospheric angular momentum (AAM, OAM and HAM/CAM, respectively) functions and excitation functions (termed as the LDCgsm solutions). Various Gravity Recovery and Climate Experiment (GRACE) and Satellite Laser Ranging (SLR) geopotential data are adopted to correct the non-global mass conservation problem, while polar motion data are used as general constraints. The LDCgsm solutions can reveal not only periodic fluctuations but also secular trends in AAM, OAM and HAM/CAM, and are in better agreement with polar motion observations, reducing the unexplained excitation to the level of about 5.5 mas (standard derivation value; about 1/5–1/4 of those corresponding to the original model outputs).

1. Introduction

Polar motion excitation involves the mass redistributions and motions within the Earth system relative to the mantle, as well as the Earth's responses to these perturbations [1–5]. At seasonal and intra-seasonal time scales, mass redistributions and relative motions are dominated by changes in the Earth's fluid envelopes, namely, the atmosphere, oceans, and continental water, snow and ice [5–13]. These changes cause fluctuations of the atmospheric, oceanic and hydrological angular momenta (AAM, OAM and HAM, respectively), and therefore lead to opposing changes of the angular momentum of the solid Earth, and hence excite polar motions.

Several versions of the AAM, OAM and HAM time series are calculated on the basis of general circulation models (GCMs) for numerical weather prediction developed at various institutes (see Table 1). The theories, numerical methods and assumptions adopted by the different institutes sometimes differ, so their global atmospheric, oceanic and hydrological model outputs are not identical (see Appendix A for some details). In addition, concerning the combined effects of atmospheric, oceanic and hydrological excitations (AE, OE and HE, respectively), we cannot simply add arbitrary versions of OE and HE to a certain AE since consistency

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Key points

1. AAMs, OAMs and HAMs derived from models are not in good agreement with polar motion observations.
2. GRACE/SLR data are assimilated to obtain optimized AAM, OAM and HAM/CAM through an LDC-based method.
3. Optimized AAM, OAM and HAM/CAM can reveal not only periodic fluctuations but also secular trends.

Significant discrepancies between AAMs, OAMs and HAMs derived from models and polar motion observations are found and discussed.

The LDC-based method is used to obtain optimized AAM, OAM and HAM/CAM by assimilating GRACE/SLR data, under the general constraint of polar motion observations.

Improved AAM, OAM and HAM/CAM can provide better understandings in studying global changes in water and ice, and are essential for studying polar motion excited by other causes.

among these atmospheric, oceanic and hydrological models would not be ensured. That is, the models of the ocean and hydrology should be the ones driven by outputs from the same atmosphere model [5]. Artificial signals might be introduced if modeling consistency is not enforced.

In addition, due to non-uniform and sparse distributions of observatories and limitations in those models, the output atmospheric, oceanic and hydrological data still contain large uncertainties. As to the limitations in the GCMs, here we only provide two examples:

1. The hydrostatic equation adopted by the atmosphere models gives the relation between the air density and the decrease of pressure with height. However, it is only an approximation of the real atmosphere, valid for horizontal scales larger than a few tens of kilometers [14].
2. In many cases, the atmosphere, ocean and hydrology models are developed in a somewhat independent manner and thus the global (atmospheric, oceanic and hydrological) mass is not conserved [15].

Koot et al. [16] estimated the noise levels of various AAMs and constructed a combined AAM series using time-dependent weights chosen so that the noise level of the combined series is minimal. Neef and Matthes [17] compared atmospheric model simulations with and without meteorological data constraints, and identified the potential for the assimilation of Earth Rotation Parameters (ERPs) as an additional constraint on atmospheric models. Gross [3] concluded that a rather large residual remains after the effects of the atmosphere and oceans are removed from the observed seasonal polar motion excitation. Brzeziński et al. [11] and Chen et al. [5] further showed that including hydrological models hardly helps to reduce the residual and the residual is mostly caused by errors in the atmospheric, oceanic and hydrological models, due to the model limitations mentioned above. Chen et al. [5] proposed a Least Difference Combination (LDC) method (also see Section 3 for details), obtained the LDC1 and LDC2 AAMs, OAMs and HAMs by combining various model-based geophysical excitations, and showed that the differences (residuals) between the LDC1 (or LDC2) data set and the geodetic excitation are reduced significantly.

Table 1
Basic information for some model outputs.

Model(s)/Data	Product(s)	Availability[a]
NCEP/NCAR	AAM and HAM (reanalysis)	Available since 1948
ECCO	OAM	Depends on version[b]
ECMWF	AAM (ERA40, ERAinterim, operational)	ERA40: available from 1958 to 2001
OMCT	OAM (ERA40, ERAinterim, operational)	ERAinterim: available since 1989
LSDM	HAM (ERA40, ERAinterim, operational)	operational: available since 2000

[a] According to the websites of the IERS Special Bureaus for Atmosphere, Ocean and Hydrology.

[b] The kf080g run adopted in this study is available since 1993; the original anomalous trend in the kf80 run since 2012 has been corrected in this version.

The time series of degree-2 tesseral geopotential coefficients (C_{21}, S_{21}) are directly linked to Earth's polar motion while the degree-2 zonal one C_{20} is closely related with variations in length of day. Only polar motion and (C_{21}, S_{21}) for an Earth model with frequency-dependent responses are considered in this study, and variations in length of day and C_{20} will be considered in another study with an improved theory for the excitations of length-of-day variations.

The 2002 launch of the GRACE (Gravity Recovery and Climate Experiment) twin satellites has made available several time series of geopotential coefficients. Meanwhile, SLR (Satellite Laser Ranging) also provides time-dependent low-degree geopotential coefficients by tracking the orbits of Starlette, LAGEOS-1/2 (Laser Geodynamics Satellites) and other satellites [18–20]. These GRACE and SLR measurements reflect mass transports in atmosphere, oceans, land water and cryosphere (as well as mostly slow variations within the solid Earth, such as glacial isostatic adjustment) and make it possible to handle the non-conservation problem in atmospheric, oceanic and hydrological models.

Nastula et al. [21] showed that GRACE-based excitations are in good agreement with the geodetic one. Brzeziński et al. [11] found that combination of the GRACE-derived mass term of excitation with the motion terms of atmospheric and oceanic excitations brings the excitation balance considerably closer in case of the retrograde/prograde annual and retrograde semiannual components of polar motion. Göttl et al. [22] developed an adjustment model to combine precise observations from GRACE/SLR and other space geodetic observation systems in order to separate geophysical excitation mechanisms of Earth rotation. However, Göttl et al. mistook the AOD1B GAA and GAB products as observations while they are only model outputs [23,24] (also see Section 3 of this study), which makes their results meaningless. In the present study, we intend to generalize the LDC method by assimilating GRACE/SLR data to obtain better understanding of atmospheric, oceanic and hydrological/cryospheric excitations of polar motion.

This paper is organized as follows: in Sections 2 and 3, we will describe the theoretical relation between geopotential coefficients (C_{21}, S_{21}) and polar motion excitations, as well as the data used, respectively; in Section 4, we will summarize the basic ideas and methods of using polar motion and GRACE/SLR (C_{21}, S_{21}) time-series to improve and correct the meteorological data, and present the main numerical results; finally, Discussions and Conclusions are in Section 5.

2. Theory

2.1. Liouville's equation and geophysical excitations

Theoretically, polar motion excitations are governed by the linearized Liouville's equation [1–4].

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