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Predicting Earth orientation changes from global forecasts of atmosphere-hydrosphere dynamics

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Abstract

Effective Angular Momentum (EAM) functions obtained from global numerical simulations of atmosphere, ocean, and land surface dynamics are routinely processed by the Earth System Modelling group at Deutsches GeoForschungsZentrum. EAM functions are available since January 1976 with up to 3 h temporal resolution. Additionally, 6 days-long EAM forecasts are routinely published every day. Based on hindcast experiments with 305 individual predictions distributed over 15 months, we demonstrate that EAM forecasts improve the prediction accuracy of the Earth Orientation Parameters at all forecast horizons between 1 and 6 days. At day 6, prediction accuracy improves down to 1.76 mas for the terrestrial pole offset, and 2.6 mas for ΔUT1, which correspond to an accuracy increase of about 41% over predictions published in Bulletin A by the International Earth Rotation and Reference System Service.

Keywords: Earth rotation excitation; Earth orientation prediction; Global geophysical fluids

1. Introduction

The orientation of the solid Earth with respect to inertial space is conventionally described by five Earth Orientation Parameters (EOP) comprising the celestial pole position (nutation), the terrestial pole coordinates (polar motion), and the non-uniform part of the angular spin velocity (ΔUT1). Daily EOP estimates are routinely provided by the International Earth Rotation and Reference Systems Service (IERS; Bizouard and Gambis, 2009), the most recent EOP 14 C04 series (abbreviated as C04 in the following) is usually available with 30 days latency. Earth orientation parameters are determined from a realization of the International Terrestrial Reference System through instruments and observatories attached to the crust that provide various space geodetic observations. The latest realization, the International Terrestrial Reference Frame 2014 (ITRF2014; Altamimi et al., 2016) is consistent with C04. The IERS also disseminates rapid EOP estimates and EOP predictions for up to 90 days into the future (Bulletin A), which are in particular important for real-time spacecraft navigation and the tracking of deep-space objects with terrestrial radio telescopes. A thorough evaluation of numerous alternative EOP prediction algorithms has been recently performed within the Earth Orientation Prediction Comparison Campaign (EOP-PCC; Kalarus et al., 2010).

Dynamic causes for Earth orientation changes are conveniently studied by applying the principle of conservation of angular momentum in the system Earth including effects of external torques, internal mass-redistribution, and exchange of angular momentum of the solid Earth with atmosphere, oceans, and the terrestrial hydrosphere (Gross, 2007). Estimates of angular momentum changes due to mass transport in the geophysical fluid layers are available from atmospheric reanalyses (Chen, 2005), ocean

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state estimates (Gross et al., 2003), and land data assimilation systems (Nastula et al., 2007) as collected by the Global Geophysical Fluid Centre (GGFC) of the IERS. Even though mass transport on Earth has a small but non-negligible impact on nutation via tidal terms of nearly diurnal retrograde frequencies (see, e.g., Schindelegger et al., 2016), it is in particular polar motion (PM) and ΔUT1 that are dominated by Earth system dynamics.

For some time already, atmospheric angular momentum estimates derived from operational numerical weather forecasts contribute to the prediction of ΔUT1 (Freedman et al., 1994; Gross et al., 1998; Gambis et al., 2011), which is largely dominated by the effects of zonal tropospheric winds. For PM prediction, however, solely forecasted AAM do not yield noteable improvements since contributions from ocean dynamics and terrestrial water storage are also relevant (Dill and Dobslaw, 2010; Dill et al., 2013). The Earth System Modelling group at Deutsches GeoForschungsZentrum (ESMGFZ) provides so-called Effective Angular Momentum (EAM $\chi_{1,2,3}$; Brzeziński, 1992) functions representing the effects of mass distribution and transport on the orientation of the Earth based on data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and corresponding numerical simulations describing ocean and land surface dynamics (Dobslaw et al., 2010). In addition, 6 days-long EAM forecasts for atmosphere, oceans, and the terrestrial hydrosphere are now routinely provided so that EAM-based predictions of PM and ΔUT1 become possible by considering all three geophysical fluid layers consecutively.

In the following, we will outline the characteristics of the current set of EAM functions provided by ESMGFZ (Section 2), highlight the importance of atmospheric tides (Section 3) and discuss the quality of the routinely issued EAM forecasts for up to 6 days into the future (Section 4). Based on hindcast experiments (i.e., experimental forecasts starting at some time in the past so that those can be readily verified against already available final EOP estimates) extending over a period of 15 months, we finally demonstrate that the incorporation of forecasted EAM functions substantially improves predictions of ΔUT1 and PM over the current quality level of Bulletin A.

2. Effective angular momentum functions from ESMGFZ

The atmospheric EAM functions (AAM) from ESMGFZ are based on analysis and forecast data out of global numerical weather prediction (NWP) models from the ECMWF. We use ERA-40 (Uppala et al., 2005) for 1976–1978, ERA-Interim (Dee et al., 2011) for 1979–2006, and operational NWP data from 2007 onwards. The different ECMWF data-sets are harmonized by mapping surface pressure to a common reference orography as outlined in Dobslaw (2016). A combination of 6-hourly analyses and 3-hourly forecasts is performed as suggested by Dobslaw and Thomas (2005). The inverse-barometric (IB) correction is applied over the ocean regions. AAM forecasts for up to 6 days into the future are calculated every day from the ECMWF high-resolution deterministic forecast initialized at 0 h UTC. The temporal resolution of those forecasts is 3 h as well.

Ocean bottom pressure and baroclinic currents from an unconstrained simulation with the Max-Planck-Institute for Meteorology Ocean Model (MPIOM; Jungclaus et al., 2013) are used for the calculation of ocean angular momentum functions (OAM). MPIOM is an ocean general circulation model discretized globally on an Arakawa-C grid in the horizontal and a z-grid in the vertical. We utilize a medium-resolution model configuration with a 1° tripolar grid and 40 vertical layers. The model is forced with atmospheric surface pressure, wind stress, temperature, incoming solar radiation, and precipitation taken from the ECMWF data-sets introduced above. The additive-inverse IB correction is applied over the ocean regions for sake of consistency with the AAM. OAM forecasts for up to 6 days into the future are calculated once per day from a dedicated MPIOM model run that is forced with atmospheric conditions from the latest ECMWF high-resolution deterministic forecast.

Terrestrial water storage is simulated with the global Land Surface Discharge Model (LSDM; Dill, 2008). Physics are based on Hagemann and Dümenil (2003) and represent the dynamics of soil moisture, snow storage, as well as water stored in wetlands, rivers, and lakes. The model is discretized on a 0.5° equiangular grid and provides water storage and transport estimates at daily time intervals. Forecasts of hydrospheric angular momentum functions (HAM) for up to 6 days into the future are calculated once per day from a specific LSDM integration that is forced with atmospheric conditions obtained from the corresponding ECMWF forecast.

Further technical documentation and routinely updated plots of the most recent EAM time-steps are available from http://www.gfz-potsdam.de/en/esmdata. This web-site also provides access to the GRACE Atmosphere and Ocean De-Aliasing Level-1B Product (Dobslaw et al., 2017) and to globally gridded elastic deformations of the Earth's crust caused by geophysical fluid loading (Dill and Dobslaw, 2013) that are based on identical mass distributions as the EAM functions discussed here. The final EAM series for atmosphere, oceans, and the terrestrial hydrosphere start in January 1976 and are routinely updated at about 10 h UTC with all 8 time-steps of the previous day. The associated 6 days-long EAM forecasts are typically available one hour later.

3. Separation of tidal signals

Daily estimates of polar motion and ΔUT1 as provided by C04 are considered to be free of diurnal and semi-diurnal tidal effects which were reduced during the processing of the space geodetic data, and we consequently attempt to exclude periodic signals at similar frequencies

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