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Improved geophysical excitation of length-of-day constrained by Earth orientation parameters and satellite gravimetry products

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SUMMARY

At timescales shorter than about 2 yr, non-tidal length-of-day (LOD) variations are mainly excited by angular momentum exchanges between the atmospheric, oceanic and continental hydrological fluid envelopes and the underlying solid Earth. But, neither agreement among different geophysical models for the fluid dynamics nor consistency with geodetic observations of LOD has reached satisfactory levels. This is mainly ascribed to significant discrepancies and uncertainties in the theories and assumptions adopted by different modelling groups, in their numerical methods, and in the accuracy and coverage of global input data fields. Based on careful comparisons with more accurate geodetic measurements and satellite gravimetry products (from satellite laser ranging, SLR), observed LOD and C_{20} geopotential time-series can provide strong constraints to evaluate or form combined geophysical models. In this study, wavelet decomposition is used to extract several narrow-band components to compare in addition to considering the total signals. We then make refinements to the least difference combination (LDC) method proposed by Chen *et al.*, to form multimodel geophysical excitations. Two combination variants, called the weighted mean combination (WMC2 and WMC4), are also evaluated. All the multimodel methods attempt to extract the best-modelled frequency components from each geophysical model by relying on geodetic excitation and the C_{20} series as references. The comparative performances of the three combinations LDC, WMC2 and WMC4 and the original single models are determined. We find that (1) Estimating the Circulation and Climate of the Ocean and Max-Planck-Institute for Meteorology Ocean Model give a more reliable view of the ocean redistributions than the Ocean Model for Circulation and Tides used by European Centre for Medium-Range Weather Forecasts, especially for the annual component; (2) C_{20} series from SLR can provide a rigorous constraint for the total matter excitation of the geophysical fluids, especially for broad-band parts; (3) the Sea-Level Angular Momentum functions term, correcting for sea-level effects (global mass balance) put forward by the Earth System Modelling group at GFZ German Research Centre for Geosciences, can significantly improve the Hydrospheric Effective Angular Momentum functions matter terms; (4) the LDC/WMC combinations are much better than the original individual geophysical model excitations, reducing the magnitude of unexplained LOD excitations to roughly the $10 \mu\text{s}$ level; (5) the level of residual LOD variations after removing models or model combinations is remarkably invariant with respect to LOD periods between ~ 2 months and ~ 3 yr, being $12\text{--}14 \mu\text{s}$ for the best original models and $7\text{--}12 \mu\text{s}$ for our combinations; (6) while differences between the IERS 14C04 and the JPL SPACE2015 geodetic LOD time-series are not negligible, errors in both series are still not large compared to the geophysical models (for periods > 2 months) so the impact on excitation studies is minimal except at semiannual periods and usually 14C04 compares better with excitation models. The improved geophysical models are recommended to replace the original ones as they present overwhelming advantages.

Key words: Earth rotation variations; Satellite gravity; Time variable gravity.

1 INTRODUCTION

Changes in the excess length-of-day (LOD), compared to 86 400 SI s, reflect variations of the speed of the Earth's axial rotation. The portion caused by zonal tides of the solid Earth and oceans, which can exceed 1 ms peak-to-peak, is accurately known from geophysical models (e.g. Petit & Luzum 2010). The remaining non-tidal LOD variations, over timescales shorter than about 2 yr, reach a similar magnitude and are mainly seasonal and caused by the dynamic interaction of the solid Earth with its fluid envelopes (atmosphere, oceans and continental hydrology; e.g. Barnes *et al.* 1983; Höpfner 1998; Brzeziński *et al.* 2002; Gross 2015). The dominant part of subbiennial LOD variations is attributable to the angular momentum carried by the zonal winds, but the effects of ocean current momentum and incremental moment of inertia of mass redistribution in the geophysical fluids are not negligible (e.g. Aoyama & Naito 2000; Gross *et al.* 2004; Yan *et al.* 2006). LOD changes over longer spans are ultimately largest but involve unrelated processes in the deep Earth (e.g. Bloxham 1998; Kuang & Chao 2003; Jault 2004; Roberts & Aurnou 2012; Silva *et al.* 2012; Holme & de Viron 2013; Davies *et al.* 2014) that are outside the scope of this paper. This basic consensus view has been achieved over many years, while precise quantification of the residual contributions from oceans and continental hydrology remains controversial (e.g. Kouba & Vondrák 2005; Chao & Yan 2010). The outstanding questions mainly concern the significant discrepancies between and associated uncertainties of geophysical fluid models built by different institutes. The aim of this study is to address these questions by constructing combinations of geophysical models that extract the best components of each original model. The results will provide a new, more robust basis to investigate observed LOD variations.

To enhance our study, we consider also the long tracking history for the orbits of Starlette, LAGEOS-1/2 (Laser Geodynamics Satellites) and other geodetic satellites that enable laser ranging (SLR) to provide low-degree geopotential coefficients with high accuracy. These contribute to monitoring geocentre motion (degree-1 terms) and Earth's time-variable figure (e.g. Crétaux *et al.* 2002; Cheng & Tapley 2004; Cheng *et al.* 2011, 2013). In particular, the degree-2 terms C_{20} , C_{21} and S_{21} are closely related to the Earth rotation parameters (C_{20} to LOD variations; C_{21} and S_{21} to polar motion; e.g. Nastula *et al.* 2007; Chen & Wilson 2008; Brzeziński *et al.* 2009; Yan & Chao 2012; Meyrath *et al.* 2013; Gross 2015). Only the C_{20} results from SLR will be considered here for the mass excitations (moment of inertia) of LOD variations. Due to the significant discrepancies among the Gravity Recovery and Climate Experiment (GRACE) data processed by different institutes, the separate C_{20} series from the GRACE mission are not used in this study (e.g. Chen *et al.* 2007, 2013b; Riva *et al.* 2009; Chambers & Willis 2010; Rio *et al.* 2011; Schrama *et al.* 2014; Ries 2015, personal communication). The reliability of SLR-derived C_{20} has been demonstrated by Chen & Wilson (2008, 2010) and by Meyrath *et al.* (2016). The SLR C_{20} time-series solution used here is from M.K. Cheng, Centre for Space Research (CSR) (Cheng *et al.* 2013).

We use the available relevant versions of Atmospheric Effective Angular Momentum (AAM) functions, Oceanic Effective Angular Momentum (OAM) functions, Hydrospheric Effective Angular Momentum (HAM) functions and newly released Sea-Level Angular Momentum (SLAM) functions, derived by Jet Propulsion Laboratory (JPL) and GFZ German Research Centre for Geosciences (GFZ). The atmosphere models are from the U.S. National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR; e.g. Salstein *et al.* 1993; Kalnay *et al.* 1996, and revised by Zhou *et al.* 2006), European Centre for Medium-Range Weather Forecasts (ECMWF; e.g. Dobslaw *et al.* 2010) and the Earth System Modelling group at ESMGFZ (e.g. Dobslaw & Dill 2018). The ocean models consist of estimating the circulation and climate of the ocean (ECCO; e.g. Gross 2003; Gross 2009), Ocean Model for Circulation and Tides (OMCT; e.g. Dobslaw & Thomas 2007) and Max-Planck-Institute for Meteorology Ocean Model (MPIOM; e.g. Jungclaus *et al.* 2013). The Land Surface Discharge Model (LSDM; e.g. Dill 2008) is the only specific measure of continental hydrology used here. The NCEP HAM is ignored due to its very poor accuracy; adding NCEP HAM will only degrade the quality of the NCEP + ECCO data set (e.g. Chen *et al.* 2013b). NCEP, ECMWF and ESMGFZ are the atmospheric forcing data sets for their associated ocean and hydrology models and so are regarded as the collective names for their respective multifluid model combinations (see Table 1). The adopted theories, numerical methods, input observations and underlying assumptions of different geophysical models are distinct. Their total excitations have so far failed to account fully for the observed LOD variations (e.g. Yan & Chao 2012). Compared with the geodetic LOD excitation, NCEP + ECCO may be significantly underestimated, while ECMWF + OMCT may be overestimated across certain frequency bands (e.g. Chao & Yan 2010).

We use wavelet decomposition to obtain both filtered geodetic and geophysical model excitations over several discrete frequency bands where significant signals are expected. In this way the effects of lower-amplitude background noise, from both geodesy and the models, can be minimized. The observed geodetic LOD excitations and total matter excitations derived from SLR C_{20} (denoted SLR excitations for short) have been high-pass filtered to remove broad-band components with periods near 5–6 yr, decadal and other longer-period signals. Adding the C_{20} series from SLR can provide a powerful constraint for the total geophysical matter excitation, which is needed because the geophysical fluid models do not rigorously conserve mass. Therefore, the observed LOD series and C_{20} series can be adopted as reliable references to form geophysical model combinations by selective component agreement (observed LOD for the total of motion and matter excitations, and C_{20} only for the total of matter excitations). Chen *et al.* (2013b) demonstrated that the least difference combination (LDC) method is able to improve the ability of geophysical models to quantify excitation of polar motion variations. The core idea of LDC is to extract the best modelled frequency components from each geophysical model according to agreement with geodetic excitation on the basis that the polar motion observations are far more accurate than any of the geophysical models. In this study, we make refinements to the LDC method and apply it to LOD excitations. We compare the geophysical excitations with geodetic and SLR excitations after wavelet decomposition to extract the leading subcomponents. In other words, we compare the filtered components in addition to the total signals. We also propose a modified

* Retired.

Table 1. Angular momentum products provided by different geophysical models.

Model	NCEP/NCAR AAM mat- ter + motion	ECCO ^b OAM mat- ter + motion	ECMWFop ^c AAM mat- ter + motion	OMCT OAM mat- ter + motion	LSDM HAM matter only	ESMGFZ ^d AAM mat- ter + motion	MPIOM OAM mat- ter + motion	SLAM ^e matter only
Product(s)								
Availability ^a and version	since 1948	January 1993 through September 2016, driven by NCEP/NCAR	since 2001	driven by ECMWFop	driven by ECMWFop and ESGFZ	since 1976	driven by ESMGFZ	corresponds to ESMGFZ
Combinations	NCEP ^f			ECMWF			ESMGFZ	

^aAccording to the websites of the IERS Special Bureaus for Atmosphere, Ocean and Hydrology.

^bThe ECCO version used in this study is kf080g; the original anomalous trend in the kf80 run since 2012 has been corrected in this version.

^cECMWFop is not updated after December 2016.

^dAll the data used by new version ESGFZ are processed consistently to the GRACE de-aliasing products AOD1B Release 06.

^eSLAM series is the total mass correction according to the global mass balance, which gives the excitation due to global sea-level change. For more information, please refer to GFZ website, <ftp://ig2-dmz.gfz-potsdam.de/EAM/>.

^fThe NCEP HAM is not used due to its very poor accuracy. Adding NCEP HAM will only degrade the quality of the NCEP data set (e.g. Chen *et al.* 2013b).

combination called the weighted mean combination (WMC) method that tests differential weighting schemes. Here, we shall examine the standard derivations of the excess excitations (those residuals unexplained by geophysical excitations) from the original geophysical models and the improved combined geophysical models, and demonstrate quantitatively significant improvements of the latter.

2 FORMULATION AND DATA

Conventionally, variations of the Earth orientation parameters (EOP) are expressed by five parameters: polar motion (x, y), precession/nutation and universal time (UT1). Precession-nutation and polar motion describe motions of the same pole but in the inertial and terrestrial cartesian reference systems, respectively, separated spectrally by convention so that the former includes only periods greater than 2 d viewed in the celestial frame. For details about the background, observing methods and the international services, please refer to www.iers.org. LOD denotes the excess of UT1 during each solar day compared to uniform atomic time. It is mathematically equivalent to the negative change of UT1 over intervals of 86 400 SI s.

The EOP 14C04 (IAU2000A version) series from the International Earth Rotation and Reference Systems Service (IERS) provides internationally recognized EOP, recently updated to be consistent with the new ITRF2014 terrestrial reference frame (see hpiers.obspm.fr/eop-pc for details). Past versions of this series, which is based on a non-rigorous combination of raw measurements made by independent space geodetic observing systems, have been most widely used for excitation studies (e.g. Altamimi *et al.* 2016; Bizouard *et al.* 2017).

The combined JPL Earth orientation series, SPACE2015, consists of values and 1σ standard errors for polar motion, UT1, and their rates from 1976 September 28 to 2016 June 1 at daily intervals; it is available in versions with epochs at either midnight or noon. Unlike the IERS 14C04 series, JPL uses a Kalman filter for their combination, which permits the known stochastic character of EOP variations to be modelled as part of the data assimilation. The effects of the solid Earth and ocean tides have been added back to the UT1/LOD values using the same models for these effects that were originally used to remove them from the raw series before combining: namely, the Yoder *et al.* (1981) model for the solid Earth tides, the inelastic body tide of Wahr & Bergen (1986) and the Kantha *et al.* (1998) model for the ocean tides. However, consistent with IERS standards, semidiurnal and diurnal ocean tidal terms have not been added to and are therefore not included in the SPACE2015 UT1/LOD values (Gross 1996, 2000; Gross *et al.* 1998; Ratcliff & Gross 2016) nor for 14C04 either.

The excitation of LOD is governed by the linearized Liouville equation (e.g. Eubanks 1993). The relationship between the geodetic excitations and the LOD observations is defined simply by

$$\chi_{\text{obs}}(t) = \frac{\Delta \text{LOD}}{\text{LOD}}, \quad (1)$$

where the LOD here is the nominal length of one solar day of 86 400 s. Fig. 1 shows the time-series of daily geodetic excitation of LOD variations from 1962 to 2016 (from 14C04), with and without the zonal tides. In Fig. 1, the tidal variations are removed with the routine RGZONT2.F from R. Gross (JPL), provided by the IERS 2010 Conventions (e.g. Petit & Luzum 2010).

Fig. 2 compares the 14C04 and SPACE2015 observed non-tidal LOD excitations for the most recent period from 2002 to 2016. The dominant seasonal variation of LOD is apparent (top panel), modulated by a slower deep-Earth component that is not of interest here. The overall RMS of the differences over this span is 0.0154 ms (or 0.231 mas, which equals 7.1 mm of east–west rotation of the Earth’s equator). But notably larger variations are visible from 2006 to 2007 as well as at a few other epochs. Considering that the LDC combination method is sensitive to some extent to the chosen reference series, which should be much more accurate than the geophysical model excitations being combined, we conclude that it is prudent to select both 14C04 and SPACE2015 as observed LOD references. Thus, we will evaluate the quality of original geophysical fluid models while at the same time testing the quality of observed LOD combination series, at least for periods between about 2 months and 3 yr.

Figure 1. Green curve is the original geodetic excitations from the 14C04 LOD time-series, and red curve is the same but with zonal tides removed. In this study, we use the latter tidally corrected geodetic LOD excitations.

The excitation of LOD also can be studied by applying the principle of angular momentum conservation to the entire Earth system (e.g. Wahr 1982, 1983; Barnes *et al.* 1983; Eubanks 1993; Dickman 2003). The Effective Angular Momentum Functions (EAMF) consist of two terms, usually referred to as the matter (or mass) and the motion terms (e.g. Munk & MacDonald 1960; Lambeck 1980; Wahr 1982). The matter term describes the influence of mass redistribution on the Earth's inertia tensor, whereas the motion term corresponds to the relative angular momentum change with respect to the mean rotating reference system (e.g. Gross 2015).

$$\chi_{\text{geophysical}}(t) = \frac{0.997}{C_m \cdot \Omega} [\text{motion} + 0.750 \cdot \text{matter}], \quad (2)$$

$$\chi_{\text{motion}}(t) = \frac{0.997}{C_m \cdot \Omega} \cdot \text{motion}, \quad (3)$$

$$\chi_{\text{matter}}(t) = \frac{0.997}{C_m \cdot \Omega} \cdot 0.750 \cdot \text{matter}, \quad (4)$$

where C_m is the principal moment of inertia of the Earth's crust and mantle (taking the Earth's core to be fully decoupled rotationally from the outer planet), Ω is Earth's mean angular velocity. The factors 0.997 and 0.750 account for the yielding of the solid Earth to surface mass loading and core decoupling. Numerical values for these factors are taken from Dickman (2003) and Gross (2015). In fact, the rotational transfer functions are unlikely to be strictly constant but probably possess some frequency dependence as proposed by Dickman (1993) and Chen *et al.* (2013a). However, frequency-dependent transfer functions are only available so far for polar motion (see Chen *et al.* 2013a). So we adopt the traditional constant transfer functions for LOD and use the factors 0.997 and 0.750 in this study. We mention that some authors follow slightly different approaches and that values for these factors differ at the level of about 2 per cent among various studies. The terms 'motion' and 'matter' collect globally all the respective motion and matter components of angular momentum variations due to the

Figure 2. The top panel compares geodetic LOD excitations from 14C04 and SPACE2015 over the most recent period from 2002 till 2016, both corrected for zonal tides. The lower panel shows the differences between the two series, which have an RMS of 0.0154 ms over this period.

atmosphere, oceans and continental hydrology (denoted by AAM, OAM and HAM):

$$\text{motion} = \int_{V(t)} \rho(r, t) \cdot r \cos \phi \cdot u(r, t) dV, \quad (5)$$

$$\text{matter} = \Omega \int_{V(t)} \rho(r, t) \cdot r^2 \cos^2 \phi dV, \quad (6)$$

where the integral is taken over, in general, time-dependent volume $V(t)$ of that component of the Earth system under consideration, ϕ is the north latitude and $\mathbf{r}$ is the geocentric position vector of some mass element of density $\rho(r, t)$ that is moving with the Eulerian velocity $u(r, t)$ with respect to a terrestrial reference frame.

The AAM functions of the ECMWF (e.g. Dobsław *et al.* 2010) have been derived individually from the ERA-40 (1958–2001) and ERA-interim (1989–2008) re-analyses, and from operational ECMWF analysis data (2001–2016). The different ECMWF data sets are harmonized by mapping surface pressure to a common reference orography as outlined in Dobsław (2016) and are augmented by corresponding contributions from the OMCT (e.g. Dobsław & Thomas 2007) and the LSDM (e.g. Dill 2008). This data set has been regularly updated until the end of the year 2016 (e.g. Dobsław *et al.* 2010) and was also made available via the Global Geophysical Fluid Center (GGFC) of the International Earth Rotation and Reference System Service (IERS).

In this study we use the operational ECMWF model (ECMWFop), which is subject to ongoing developments intended to continuously improve the weather forecast accuracies. This model runs on a T799 grid (approximately 25 km horizontal resolution) with 91 vertical levels. The data is provided on 25 pressure levels, and a horizontal resolution of 1° is used.

The OMCT (e.g. Thomas 2002) has been developed by adjusting the originally climatological Hamburg ocean primitive equation model (e.g. Wolff *et al.* 1997; Drijfhout *et al.* 1996) to the weather timescale and coupling with an ephemeral tidal model. The ocean model uses a time step of 30 min, a constant horizontal resolution of 1.875° in latitude and longitude and 13 vertical layers. OMCT is forced by 6 hr wind stress, atmospheric surface pressure, 2m-temperature and freshwater flux.

The Earth System Modelling group at ESMGFZ routinely provides EAMF describing the non-tidal geophysical excitations of Earth orientation changes due to mass redistribution in atmosphere, oceans, and the global water cycle. The data are based on re-analysis and operational analysis outputs from ECMWF, ocean bottom pressure and vertically integrated ocean currents obtained from an experiment with the MPIOM (e.g. Jungclauss *et al.* 2013), and terrestrial water storage (TWS) and river flow velocities out of the LSDM (e.g. Dill 2008). Both MPIOM and LSDM are consistently forced with ESMGFZ data.

The data are dimensionless EAMF (e.g. Brzeziński 1992) of the matter and motion terms for atmosphere, oceans and water storage, respectively. The temporal resolution ranges from 3 hr for atmosphere (given at 0.5° equiangular grids) and oceans to 24 hr for the terrestrial hydrosphere and sea-level terms. Tidal variations in atmosphere and oceans for 12 most relevant frequencies are fitted and removed from the data to retain the non-tidal signals only. The non-tidal EAM of ESMGFZ and their associated forecasts are routinely updated every day. Further information on the products is provided via the web-page www.gfz-potsdam.de/en/esmdata.

OAM from ESMGFZ are based on the MPIOM. It is a general ocean circulation code discretized globally on an Arakawa-C grid in the horizontal, and a z-grid in the vertical. MPIOM includes a sea-ice module (e.g. Notz *et al.* 2013) that utilizes the viscous-plastic rheology of Hibler (1979). A medium-resolution configuration of MPIOM is used here that is discretized on a 1.0° tri-polar grid with 40 vertical layers (TP10L40). The internal time-step of the model is 90 min, and ocean state quantities and associated diagnostics as ocean bottom pressure and horizontal currents are stored every 3 hr. The model configuration currently employed for OAM integration does not simulate ocean dynamics underneath the Antarctic ice shelves. Feedbacks on the ocean dynamics from self-attraction effects of the water column and associated deformations of the seafloor (e.g. Ray 1998; Kuhlmann *et al.* 2011) are not considered yet.

HAM functions are calculated from TWS and flows simulated with the LSDM (Dill 2008). Physics and parametrization of LSDM are based on Hagemann & Dümenil (1997), and include the representation of soil moisture, shallow groundwater, snow coverage and surface water stored in rivers and lakes. HAM matter terms are derived from the vertically integrated TWS. The model is discretized on a 0.5° latitude–longitude global grid. Water masses in rivers and lakes are projected from the model grid to a high-resolution 0.125° river and lake network as discussed in Dill & Dobslaw (2013) prior to HAM integration. Globally homogeneous sea-level variations as inferred from integrating masses in LSDM and ECMWF globally are utilized to calculate barystatic SLAM. All three components depend linearly on the sea level depicted and are perfectly correlated.

NCEP/NCAR re-analysis products (e.g. Kalnay *et al.* 1996) span the period from 1948 to the present and were obtained from the IERS Special Bureau for the Atmosphere. The data set contains 6-hr values of AAM driven by changes in atmospheric pressure and atmospheric winds. The gridded variables used here including upper-air temperatures, rotational wind and geopotential height, which are generally strongly influenced by the available observations and are therefore the most reliable method to get AAM matter terms (e.g. Kistler *et al.* 2001). The angular momentum due to winds has been computed as described in Zhou *et al.* (2006), who reprocessed AAM series by integrating zonal and meridional winds from the Earth's surface to 10 hPa, the top of the atmospheric model. The surface topography is taken into account when calculating the atmospheric motion term (e.g. Aoyama & Naito 2000).

ECCO kf080g OAM series is obtained from the IERS Special Bureau for the Oceans. This series contains daily values of OAM due to currents and ocean-bottom pressure from 1993 January to 2016 September. The ECCO kf080g ocean model used to compute this series has 46 levels ranging in thickness from 10 m at surface to 400 m at depth and is forced with data from the NCEP/NCAR re-analysis project, 1/3° at equator to 1° at high latitudes by 1° longitude (see e.g. Gross *et al.* 2005; Gross 2009, for more information on this data set and the kf080g model).

We use the AAM, OAM and HAM time-series from all the relevant geophysical models above, as well as the newly released SLAM model from ESMGFZ (see Table 1).

The ECCO ocean model is driven by the NCEP atmosphere outputs (e.g. Gross 2009), and thus NCEP and ECCO are a consistent set. OMCT and LSDM are both driven by the ECMWF atmosphere outputs, so ECMWFop, OMCT and LSDM are a consistent set (e.g. Dobslaw *et al.* 2010), and similarly, ESMGFZ, MPIOM, LSDM and SLAM are also consistent. Therefore, we have three original self-consistent total excitation data sets – NCEP, ECMWFop (or simply 'ECMWF') and ESMGFZ – where the driving atmospheric model is used to name the data sets.

From the SLR degree-2 zonal potential coefficient changes, an independent observed mass redistribution excitation χ_{matter} can be derived by (e.g. Gross 2015)

$$\chi_{\text{matter}} = -\frac{\sqrt{20}MR^2}{1+k'_2+\Delta k'_{\text{an}}} \cdot \frac{1+\alpha_3(k'_2+\Delta k'_{\text{an}})}{3C_m/0.997} \cdot \Delta C_{20}, \quad (7)$$

in which $M = 5.9737 \times 10^{24}$ kg and $R = 6371.0$ km are the mass and mean radius of the Earth, k'_2 is the degree-2 load Love number (-0.305) and $\Delta k'_{\text{an}}$ accounts for the effects of mantle anelasticity on the degree-2 load Love number ($-0.011 + 0.003i$), $\alpha_3 = 1.125$ is a factor to modify the load Love number k'_2 in the axial component because of core decoupling (e.g. Merriam 1980; Wahr 1983; Nam & Dickman 1990; Dickman 2003). We use an SLR solution for C_{20} changes provided by M.K. Cheng, CSR (Cheng *et al.* 2013), which is suitable to constrain the total mass transportations of the Earth system, including atmosphere, oceans and continental hydrology. The SLR data set used in this study is sampled about every 30 d. Though available from 1992, only results from 2002 to 2016 are used here due to the later start of the ECMWFop series.

The observed geodetic LOD excitations from 14C04 and SPACE2015, the ECCO OAM, LSDM HAM and SLAM models are sampled every day, the ESMGFZ AAMs are sampled every 3 hr, the SLR data are sampled approximately monthly and all the other AAMs and OAMs

Figure 3. Time-domain comparisons of the original motion angular momentum variations derived from various geophysical models. The units of angular momentum are $\text{kg m}^2 \text{s}^{-1}$.

are sampled every 6 hr. To match the sampling of ESMGFZ AAMs, all the other data are interpolated with a cubic spline to 3 hr sampling. We remove the components outside of $[1/3, 6]$ cycles yr^{-1} (cpy). Comparisons of original motion and matter angular momenta are shown in Figs 3 and 4.

From Figs 3 and 4 we can see that the AE motions are the largest source of LOD excitation and that the three meteorological models are in generally good agreement with each other. The AE matter excitations from different models are not as large but also agree quite well. On the other hand, the OE motion and matter terms are mostly modest in size, rather noise-like and display poor intermodel agreement. The ECMWFop model ensemble is exceptional because the OMCT ocean matter excitation shows a pronounced annual systematic difference that is not present in the other ocean models. Finally, the two models for HE matter excitation are obviously related but the SLAM corrections applied in ESMGFZ appear to remove artefactual offsets (discussed further below). Therefore, we can conclude that the discrepancies among the ocean and continental hydrology contributions to LOD variation should be the main focus of attention. A specific question is how much independent modelling of the atmosphere, ocean and continental hydrology components, without an overall mass conservation constraint, might contribute to the annual (and longer period) variations of the ECMWFop/OMCT OE matter and HE matter terms. That is why SLAM corrections are introduced in the new ESMGFZ version. But it is not clear whether this correction should be applied to OE matter or HE matter terms. So we consider the comparisons in Fig. 5 between different ensembles of matter-only excitations with SLR-derived excitations.

Comparing the first and second panels of Fig. 5, where SLAM corrections are added to OE matter, the combination of ESMGFZ + MPIOM becomes worse, indicating that SLAM is not suitable for OE matter corrections. From the third panel, neither of the total matter excitations from ECMWF + OMCT + LSDM nor ESMGFZ + MPIOM + LSDM agrees well with SLR results, although the former set performs better, especially compared to excluding the LSDM HE terms as in the top two panels. For the ESMGFZ model set it is evidently necessary to impose a global mass balance constraint by adding the SLAM corrections as well as ESMGFZ HE matter terms, as shown in the fourth panel. The overall best agreement of matter-only model excitations with SLR are achieved by the sets ESMGFZ + MPIOM + LSDM + SLAM, NCEP + ECCO and ESMGFZ + MPIOM. When HAM terms are added to the ESMGFZ ensemble it is essential that the SLAM corrections be applied also.

Figure 4. Time-domain comparisons of the original matter angular momenta derived from various geophysical models. The units of angular momentum are $\text{kg m}^2 \text{s}^{-1}$.

3 METHOD

3.1 The wavelet decomposition of LOD excitation

Several past papers have used wavelet analysis to study the Earth rotation variations, primarily on interannual to decadal timescales (e.g. Gibert *et al.* 1998; Popinski *et al.* 2002). The wavelet spectrum is employed mainly for signal detection and characterization. In this study, we use wavelet decomposition to obtain filtered narrow-band signals of excitations of LOD variations, and to remove the high-frequency (higher than 6 cpy) and broad-band low-frequency components with periods near 5–6 yr and longer at the same time. The latter are thought to be excited mainly by core–mantle coupling; any such signals in the geophysical fluids are tiny.

We focus mostly on these four excitation components of LOD variations: intraseasonal frequencies (>2 cpy and <6 cpy), semiannual, annual and biennial components. These components are related to the mass redistribution and the relative motion in the geophysical fluids.

3.2 The LDC method

Each geophysical model may have better quality than other models within some certain frequency bands but no model is likely to be perfect over the full range, as shown by many studies but especially by Koot *et al.* (2006). The LDC method proposed by Chen *et al.* (2013b, 2017) extracts all the best-modelled components from each geophysical model according to geodetic excitation as the reference. In this study, we make adjustments to the LDC method, that is, comparing each component of geodetic and geophysical excitation based on the wavelet decompositions, rather than the total signals. We use this modified LDC method to combine all the high-quality data of those narrow-band components (intraseasonal frequencies, semiannual, annual and biennial) from each model combination (ECMWFop and ESMGFZ, NCEP in Section 2). The basic idea of the LDC can be stated below (Chen *et al.* 2013b, 2017):

Apply the Fast Fourier Transformation (FFT) to the time-series of the geodetic excitation (as a reference data, REF) and the geophysical excitation combinations (MOD), and get their FFT coefficients $a_{\text{dat}}(f)$ and $b_{\text{dat}}(f)$ corresponding to an arbitrary frequency f , where $\text{dat} = \text{REF}$,

Figure 5. Time-domain LOD comparisons between the different ensembles of matter-only excitations and SLR excitations. The SLR-derived variations (red curves) are the same in all four panels. The NCEP + ECCO matter excitations (lavender curves) are the same in the first, second and fourth panels from the top. The remaining curves illustrate the impacts of adding (or not) the HAM and SLAM terms. From top to bottom: (1) ECMWF + OMCT (turquoise), ESMGFZ + MPIOM (orange); (2) ECMWF + OMCT (turquoise), ESMGFZ + MPIOM + SLAM (orange); (3) ECMWF + OMCT + LSDM (turquoise), ESMGFZ + MPIOM + LSDM (orange); (4) ECMWF + OMCT + LSDM (turquoise), ESMGFZ + MPIOM + LSDM + SLAM (orange).

or MOD- N ($N = 1$ corresponds to ECMWFop; $N = 2$ corresponds to ESMGFZ; $N = 3$ corresponds to NCEP). Those coefficients carry all the information about the amplitude and phase of the data component for the frequency f . In this way, we can build a combined data set by gathering all the frequency components from the MOD set that are closest to the REF in terms of FFT coefficients, namely

$$\begin{aligned}
 a_{\text{LDC}}(f) &= a_{\text{REF}}(f) - \text{Res}a_{\text{LDC}}(f) \\
 b_{\text{LDC}}(f) &= b_{\text{REF}}(f) - \text{Res}b_{\text{LDC}}(f) \\
 |\text{Res}a_{\text{LDC}}(f)| &= \min \{ |\text{Res}a_{\text{MOD}-1}(f)|, |\text{Res}a_{\text{MOD}-2}(f)|, \dots, |\text{Res}a_{\text{MOD}-N}(f)| \} \\
 |\text{Res}b_{\text{LDC}}(f)| &= \min \{ |\text{Res}b_{\text{MOD}-1}(f)|, |\text{Res}b_{\text{MOD}-2}(f)|, \dots, |\text{Res}b_{\text{MOD}-N}(f)| \} \\
 \text{Res}a_{\text{MOD}-N}(f) &= a_{\text{REF}}(f) - a_{\text{MOD}-N}(f) \\
 \text{Res}b_{\text{MOD}-N}(f) &= b_{\text{REF}}(f) - b_{\text{MOD}-N}(f)
 \end{aligned} \tag{8}$$

Then apply the inverse FFT to a_{LDC} and b_{LDC} to obtain the LDC series. Special attention should be paid to the signs of $\text{Res}a_{\text{LDC}}(f)$ and $\text{Res}b_{\text{LDC}}(f)$: supposing $\text{Res}a_{\text{MOD}-N}(f)$ ($N = 1, 2, 3$) has the smallest absolute value, then the sign of $\text{Res}a_{\text{LDC}}(f)$ is the same as that of $\text{Res}a_{\text{MOD}-N}(f)$; likewise for $\text{Res}b_{\text{LDC}}(f)$.

3.3 The weighted mean combination method

We propose another combination approach, which is called the WMC method. The main idea of this method is that, each original geophysical model may explain the observed LOD variations to some extent, so the geophysical excitation from those original models nearest to the geodetic excitation should be accepted with a larger weight. This method attempts to retain all the most relevant information of the original models rather than totally reject those modelled data that agree less well with the geodetic excitation. The difficulty is to know what is the best weighting function to apply. Here we test two different weighting schemes (WMC2 and WMC4).

The same FFT progress is applied first (see Section 3.2), and then we obtain the FFT coefficients $a_{\text{dat}}(f)$ and $b_{\text{dat}}(f)$ from geodetic and geophysical excitation combinations. The weights of original model combinations are determined as follows (WMC2):

$$\begin{aligned}
 \Delta a(f) &= a_{\text{REF}}(f) - a_{\text{MOD}-N}(f) \\
 \Delta b(f) &= b_{\text{REF}}(f) - b_{\text{MOD}-N}(f) \\
 P_{\Delta a}(f) &= \frac{1}{\Delta a^2} \\
 P_{\Delta b}(f) &= \frac{1}{\Delta b^2} \\
 a_{\text{WMC}} &= \frac{\sum_{N=1}^3 P_{\Delta a}(f) \cdot a_{\text{MOD}-N}(f)}{\sum_{N=1}^3 P_{\Delta a}(f)} \\
 b_{\text{WMC}} &= \frac{\sum_{N=1}^3 P_{\Delta b}(f) \cdot b_{\text{MOD}-N}(f)}{\sum_{N=1}^3 P_{\Delta b}(f)}
 \end{aligned} \tag{9}$$

Then apply the inverse FFT to a_{WMC} and b_{WMC} to obtain the WMC2 series. Even narrower weighting using the fourth power of the inverse (REF – MOD) differences yields the WMC4 combined series.

Among all the data described in Section 2, the geodetic excitation derived from observed LOD and C_{20} series from SLR are of the highest quality. So, adopting the geodetic excitation as a reference for the total excitation, matter + motion and SLR C_{20} series as a reference for the total matter excitation only, the LDC method gathers together all the frequency components that are closest to the geodetic excitation and SLR total matter excitation from the original geophysical model sets, whereas the WMC method attempts to make fuller use of the information from the original models without excluding any modelled data completely. The detailed iterative processes are as follows (e.g. for the annual component):

(1) Convert all motion and matter terms of the geophysical models to motion and matter excitations according to eqs (3) and (4). Convert SLR C_{20} series to total matter excitations according to eq. (7). Use wavelet decomposition to obtain the annual component of geodetic excitation, total matter excitations, atmospheric excitation from ECMWFop, ESMGFZ and NCEP, oceanic excitation from OMCT, MPIOM and ECCO, hydrological excitation from LSDM, and global mass balance corrections from SLAM, and then make the combination of ECMWFop (ECMWFop + OMCT + LSDM), ESMGFZ (ESMGFZ + MPIOM + LSDM + SLAM) and NCEP (NCEP + ECCO).

(2) Theoretically, the geophysical excitation with larger contribution and higher accuracy should be compared with the geodetic excitation and SLR excitations first. We regard the residuals of the upper (i.e. earlier) layer as the reference of the next comparison. The cumulative order is designed like this:

(i) Taking total matter excitation χ_{matter} from SLR C_{20} series as reference, comparing the matter term of atmospheric excitations from ECMWFop, ESMGFZ and NCEP with χ_{matter} using LDC/WMC method, obtain the improved matter term of atmospheric excitations, $\chi_{\text{AE.matter}}$.

(ii) Taking the residuals of $r_1 = \chi_{\text{matter}} - \chi_{\text{AE.matter}}$ as the reference, comparing the matter term of oceanic excitations and obtain the improved matter term of oceanic excitations, $\chi_{\text{OE.matter}}$.

(iii) Taking the residuals of $r_2 = r_1 - \chi_{\text{OE.matter}}$ as the reference, comparing the matter term of hydrological excitations (HAM for ECMWFop, and HAM + SLAM for new ESMGFZ), and obtain the improved matter term of hydrological excitations, $\chi_{\text{HE.matter}}$.

(iv) Taking the difference of geodetic excitation and SLR excitations, $\chi_{\text{obs}} - \chi_{\text{matter}}$ as reference, comparing the motion term of atmospheric excitations with $\chi_{\text{obs}} - \chi_{\text{matter}}$ using LDC/WMC method, obtain the improved atmospheric motion excitations, $\chi_{\text{AE.motion}}$.

(v) Taking the residuals of $r_3 = \chi_{\text{obs}} - \chi_{\text{matter}} - \chi_{\text{AE.motion}}$ as the reference, comparing the motion term of oceanic excitations, and obtain the improved oceanic motion excitations, $\chi_{\text{OE.motion}}$.

(vi) We regard the residuals $r_4 = r_3 - \chi_{\text{OE.motion}}$ as the differences between the entire geophysical excitation with the geodetic excitation. We do not take the motion term of hydrological excitations into consideration, because its impact on the LOD variation is generally negligible (e.g. Yan & Chao 2012).

(3) Convert all the improved motion and matter excitations to motion and matter terms of geophysical models according to eqs (3) and (4), obtain the improved AAM, OAM and HAM series in axial direction.

Then apply the same procedure to the intraseasonal frequencies, semiannual and biennial components.

4 RESULTS

We calculate the residuals R_i (where $i = 1, 2, 3$) of original geophysical excitations and our improved combinations with respect to the geodetic excitation: $R_1 = \text{obs} - (\text{AE.motion} + \text{AE.matter})$, $R_2 = R_1 - (\text{OE.motion} + \text{OE.matter})$, $R_3 = R_2 - \text{HE.matter}$. R_3 reflects the quality of each total geophysical model set as measured by its agreement with the geodetic excitation. Comparisons between these R_i are given in Fig. 6 and Table 2, Fig. 7 and Table 3, Fig. 8 and Table 4, and Fig. 9 and Table 5 for the three model families and two of our combinations. The 14C04 and SPACE2015 geodetic references are both tested in Tables 2–5 but because they are so similar, only 14C04 is used for the figures.

From Fig. 6 we can see that, among the R_2 intraseasonal frequencies residual series, those residuals from NCEP and ECMWFop are bigger than the others, which indicates that the ECCO and OMCT ocean models are not so reliable for higher-frequencies variations; their

Figure 6. Comparisons between residuals in the intraseasonal frequencies band. $R_1 = \text{obs} - (\text{AE.motion} + \text{AE.matter})$, $R_2 = R_1 - (\text{OE.motion} + \text{OE.matter})$, $R_3 = R_2 - \text{HE.matter}$.

Table 2. Intraseasonal frequencies (>2 cpy and <6 cpy) residuals of modelled versus geodetic LOD excitation (units: μs).

Residuals	RMS of residual model differences w.r.t. obs											
	ECMWFop		ESMGFZ		NCEP		LDC		WMC2		WMC4	
R_1	18.3	18.4	17.8	17.8	20.7	20.8	14.3	14.4	15.9	16.0	15.3	15.4
R_2	14.9	15.1	12.5	12.6	17.1	17.2	9.2	9.3	11.3	11.4	10.6	10.6
R_3	14.7	14.8	12.6	12.6	–	–	9.5	9.4	11.2	11.2	10.4	10.3

– = component not included;

For reference, the RMS of the 14C04 geodetic excitations in this band is $89.0 \mu\text{s}$, and for SPACE2015 is $88.9 \mu\text{s}$.

amplitudes reach 0.05 ms. The model differences among the R_1 , R_2 and R_3 residuals are mainly in amplitude, not phase, indicating that the original atmosphere, ocean and hydrology models differ mostly in their estimations of the signal strengths. According to the R_3 series, our LDC/WMC combinations are best, as expected; their residuals have maxima that are only about 0.03 ms, while those of the original models reach 0.05 ms.

The first column results for each model set are from 14C04 reference, and the second column results are from SPACE2015 reference; WMC4, where the $P(f)$ weights in eq. (9) are changed from $1/\Delta^2$ to $1/\Delta^4$. Bold font is used to emphasize the smallest residuals for each row.

Table 2 shows that the NCEP model set is generally poorer than the European models in the intraseasonal frequencies band. Overall, the ESMGFZ model components are all better than the other original models. By design, our LDC/WMC combinations always improve over the original geophysical excitations. Of the three weighting variations, those that most strongly emphasize the single best model components agree closest with geodesy. This implies that differences among the models are significant in this band, probably reflecting important systematic errors. While adding the HAM models slightly improves the overall agreement of the WMC2 and WMC4 combinations, it degrades the better performing LDC a bit. For the intraseasonal frequencies variations, residuals are very similar for both the 14C04 and SPACE2015 reference series. This is probably because LOD changes over periods <2 months, where visible divergences between the two series are sometimes striking (see Fig. 2), are not included here.

From Fig. 7, for semiannual components, the NCEP AE residuals (R_1 series, peaks nearly 0.1 ms) and ECCO residuals (R_2 series, peaks nearly 0.08 ms) are both the largest, and have large amplitude differences with both the combined and the original European results. The ocean and hydrology models from ESMGFZ are better than the ECMWFop ones and ESMGFZ is the most reliable original model set overall. The

Figure 7. Comparisons between residuals in the semiannual band. $R_1 = \text{obs} - (\text{AE_motion} + \text{AE_matter})$, $R_2 = R_1 - (\text{OE_motion} + \text{OE_matter})$, $R_3 = R_2 - \text{HE_matter}$.

Table 3. Semiannual residuals of modelled versus geodetic LOD excitation (units: μs).

Residuals	RMS of residual model differences w.r.t. obs											
	ECMWFop		ESMGFZ		NCEP		LDC		WMC2		WMC4	
R_1	16.4	18.6	15.4	17.5	38.2	40.3	12.4	14.8	14.2	16.9	15.3	15.9
R_2	22.4	24.6	12.2	14.2	34.3	36.2	7.6	9.6	10.0	12.6	10.6	11.3
R_3	16.5	17.7	12.5	14.5	–	–	8.7	10.4	10.6	13.0	10.4	11.9

For reference, the RMS of the 14C04 geodetic excitations in this band is 190.3 μs , and for SPACE2015 is 191.4 μs . The format here is the same as Table 2.

ESMGFZ residuals are also closest to the LDC/WMC ones, indicating that model contributes most to the combinations. For the ECMWFop set, taking the OMCT model into consideration, the R_2 residuals increase markedly over R_1 although this is overcome by the further addition of the LSDM surface hydrology model, as demonstrated by the R_3 residuals.

From Table 3, among the original models of semiannual variations, the NCEP set is clearly worst and probably contributes little to nothing to the combinations. The ocean and hydrology models of ECMWFop are both distinctly worse than the ESMGFZ ones, especially OMCT alone without LSDM. All our combinations reduce the RMS residuals of the ESMGFZ and ECMWFop models with LDC again being most effective and WMC2 least so. For the semiannual band, adding HAM contributions slightly degrades comparisons with geodetic LOD except for ECMWFop (where LSDM compensates for OMCT) and WMC4 using the 14C04 reference. Differences between the 14C04 and SPACE2015 are more distinct than for higher frequencies with 14C04 yielding decidedly lower residuals than SPACE2015.

Fig. 8 shows that for the annual atmosphere residuals, R_1 , there are quite obvious amplitude and phase difference between NCEP and all the other series. This indicates that the annual axial circulation of the NCEP atmosphere model might be deficient compared to the European models, which contribute more heavily to our combinations. The R_2 series, which take ocean models into consideration, show that the OMCT model used in the ECMWFop set performs even worse at annual periods than semiannual, with residuals exceeding 0.1 ms at times and nearly fully out of phase with the other models. There are also phase differences among the R_2 series of ECCO, MPIOM and the combinations but those differences might come from the phase differences of R_1 NCEP residuals. According to R_3 series, the HE matter of the ECMWFop model still performs more poorly than ESMGFZ but it is able to largely compensate for the large OMCT deficiencies. The ESMGFZ R_3 residuals, with peaks of only about 0.03 ms, illustrate the significance of the SLAM term for global mass balance corrections. The problems of

Figure 8. Comparisons between residuals in the annual band. $R_1 = \text{obs} - (\text{AE_motion} + \text{AE_matter})$, $R_2 = R_1 - (\text{OE_motion} + \text{OE_matter})$, $R_3 = R_2 - \text{HE_matter}$.

Table 4. Annual residuals of modelled versus geodetic LOD excitation (units: μs).

Residuals	RMS of residual model differences w.r.t. obs											
	ECMWFop		ESMGFZ		NCEP		LDC		WMC2		WMC4	
R_1	11.1	10.7	10.5	10.0	21.4	20.7	15.8	15.2	14.4	13.7	15.9	15.1
R_2	55.2	56.0	19.8	19.9	14.2	13.5	15.9	15.7	12.1	12.2	13.4	12.6
R_3	23.7	23.9	17.7	18.3	–	–	10.3	11.0	15.7	16.6	11.2	11.7

For reference, the RMS of the geodetic excitations in this annual band is $247.9 \mu\text{s}$, and for SPACE2015 is $248.6 \mu\text{s}$. The format here is the same as Table 2.

the ECMWFop OMCT matter modelling at annual periods (see Fig. 4) might be related to previous deficiencies in ensuring mass conservation in the operational data products. The new generation of ESMGFZ provides more reliable views for both the OE and HE matter terms.

From Table 4 we can see that the RMS values of NCEP R_2 series are better than both the European R_2 and R_3 residuals. But in view of the phase differences between NCEP and all the other models in Fig. 8, we cannot conclude that the NCEP combination is necessarily the comprehensive best because the RMS values measure only amplitudes. We will return to a discussion of annual phase differences later. At the annual period, our combinations compare best for the WMC2 weighting, except when the HE terms are added where LDC is again best overall. Both LOD geodetic references perform very similarly and neither 14C04 nor SPACE2015 shows a consistent advantage.

For the biennial component (Fig. 9) the modelling of ESMGFZ AE, OE and HE are all better than the other original models. The peak amplitudes of ECMWFop R_2 and R_3 residuals are about 0.05 ms, much bigger than the others, indicating once again that its modelling of ocean and continental hydrology is not ideal. For R_1 from 2002 to 2006, there are amplitude differences between ECMWFop and the other models, but phases correspond well. NCEP phases differ more seriously compared with the others. Only from 2012 to 2016 do the three original AE models match each other and the combinations rather well. It seems, therefore, that no single geophysical model set can reliably model all components of the biennial band, a conclusion supported by the RMS differences in Table 5.

Among the original models, ESMGFZ is the best in the biennial band but not overwhelmingly. None of the modelled OE and HE components adds any value here and ECMWFop is even degraded. The combinations are likewise degraded by adding HE terms. But the combinations, especially LDC, benefit from the variety of AE and OE contributions as seen by their relative improvements over the original models. The 14C04 and SPACE2015 geodetic references produce nearly equivalent results at biennial periods (differences $<0.3 \mu\text{s}$) for both the original models and combinations, though 14C04 is nearly always slightly better.

Figure 9. Comparisons between residuals in the biennial band. $R_1 = \text{obs} - (\text{AE_motion} + \text{AE_matter})$, $R_2 = R_1 - (\text{OE_motion} + \text{OE_matter})$, $R_3 = R_2 - \text{HE_matter}$.

Table 5. Biennial residuals of modelled versus geodetic LOD excitation (units: μs).

Residuals	RMS of residual model differences w.r.t. obs											
	ECMWFop		ESMGFZ		NCEP		LDC		WMC2		WMC4	
R_1	15.5	15.4	13.0	13.1	16.2	16.4	10.4	10.3	11.6	11.7	10.8	11.1
R_2	17.5	17.7	13.0	13.2	16.8	17.0	7.5	7.5	10.4	10.5	9.5	9.7
R_3	20.4	20.2	13.3	13.4	–	–	9.3	9.3	11.1	11.3	10.1	10.3

For reference, the RMS of the 14C04 geodetic excitations in this band is 76.0 μs , and for SPACE2015 is 76.2 μs . The format here is the same as Table 2.

From Tables 2–5, we find that accounting for the matter term of land hydrology degrades the quality of the geophysical excitation series in all frequency bands except for the annual one. This confirms the well-known fact that practically the only signal in the HAM series derived from geophysical models is concentrated in the annual frequency band; see also the lower panel in Fig. 4.

5 DISCUSSION OF RESULTS

The results above demonstrate that our LDC/WMC combinations make obvious, major improvements over the original environmental models in explaining intraseasonal, semiannual, annual and biennial LOD excitations. LDC/WMC methods take maximum advantage of the geophysical models to reduce the residuals compared with geodetic excitation. Considering that at most frequencies the addition of modelled HE components degrades comparisons with geodetic LOD, Table 6 collects a summary of R_2 residual results from all four bands examined above. The best original model sets (usually ESMGFZ) are tabulated together with the best multimodel combination (usually LDC). Results for both 14C04 and SPACE2015 references are included.

Several general observations can be made from Table 6. First, the level of residuals is remarkably constant regardless of frequency band, around 12 to 14 μs for the best original models and 7 to 12 μs for our combinations. This is not obviously expected considering that non-tidal LOD excitation follows a general ‘red’ power-law behaviour, close to random walk (power proportional to the inverse of f^2) in the subannual domain (e.g. Morabito *et al.* 1988). This implies that the inherent signal-to-noise content of the geophysical models must follow much the same frequency dependence as LOD itself with a noise floor of roughly 10 μs . The geodetic data noise probably adds only a few μs of scatter to the comparisons over the frequency range examined here, based on our experience with the 14C04 and SPACE2015 differences, although

Table 6. Summary of R_2 residuals from the best geophysical model sets and the best model combinations, each versus geodetic LOD excitation (units: μs).

Frequency band (raw geodetic RMS)	RMS of residual model differences w.r.t. obs					
	Best original model			Best combination		
Intraseasonal frequencies (89.0, 88.9)	12.5	12.6	ESMGFZ	9.2	9.3	LDC
Semiannual (190.3, 191.4)	12.2	14.2	ESMGFZ	7.6	9.6	LDC
Annual (247.9, 248.6)	14.2	13.5	NCEP	12.1	12.2	WMC2
Biennial (76.0, 76.2)	13.0	13.2	ESMGFZ	7.5	7.5	LDC

The first of each pair of RMS columns uses the 14C04 reference while the second of each pair uses the SPACE2015 reference. $R_2 = \text{obs} - (\text{AE}_{\text{motion}} + \text{AE}_{\text{matter}}) - (\text{OE}_{\text{motion}} + \text{OE}_{\text{matter}})$.

Table 7. Comparisons of the annual components of geodetic and geophysical excitations.

	ECMWFop		ESMGFZ		NCEP		LDC		WMC4	
A	341.1 $\pm$ 6.9	24.0 $\pm$ 1.2	341.7 $\pm$ 6.9	24.0 $\pm$ 1.2	364.3 $\pm$ 6.9	22.2 $\pm$ 1.1	346.9 $\pm$ 6.9	25.0 $\pm$ 1.2	348.1 $\pm$ 6.9	24.9 $\pm$ 1.2
AO	288.8 $\pm$ 6.9	11.7 $\pm$ 1.4	322.3 $\pm$ 6.9	25.9 $\pm$ 1.2	351.3 $\pm$ 6.9	23.3 $\pm$ 1.1	335.4 $\pm$ 6.9	25.4 $\pm$ 1.2	331.8 $\pm$ 6.9	24.7 $\pm$ 1.2
AOH	317.3 $\pm$ 6.9	25.2 $\pm$ 1.3	314.6 $\pm$ 6.9	22.9 $\pm$ 1.3	–	–	327.3 $\pm$ 6.9	22.6 $\pm$ 1.2	324.5 $\pm$ 6.9	21.8 $\pm$ 1.2

From top to bottom, A: atmosphere, AO: atmosphere + ocean, AOH: atmosphere + ocean + hydrology. First column of each pair is the amplitude (μs) and second column is phase (deg). Note that the annual amplitude of obs (14C04) is $337.1 \pm 6.9 \mu\text{s}$ and the annual phase of obs is $22.0 \pm 1.2^\circ$.

some common-mode geodetic errors may not be visible. The annual band does stand out somewhat in having mostly higher residuals and with the NCEP and WMC2 models performing best only in this band. That could indicate higher non-excitation contributions to measured LOD at annual periods, such as seasonal systematic technique errors. Another general conclusion is that the 14C04 reference nearly always yields lower residuals than SPACE2015 (except annual NCEP), although the differences are usually quite small (except semiannual ESGMFZ and LDC). Based on Fig. 2, the situation could be different for LOD variations shorter than ~ 2 months, which should be investigated in future studies.

As the dominant part of LOD excitation, the annual component deserves special attention. Here the annual LOD excitation is assumed to be harmonic and thus can be described by the amplitude A and phase φ (e.g. Gross *et al.* 2003; Brzeziński *et al.* 2009)

$$\chi_{\text{LOD}} = A \cdot \sin(\delta_{\text{annual}} \cdot t + \varphi), \quad (10)$$

where δ_{annual} is the annual frequency. By least-squares fitting of the annual time-series χ_{obs} , χ_{ECMWFop} , χ_{ESMGFZ} , χ_{NCEP} , χ_{LDC} and χ_{WMC} to eq. (10), the annual components of their amplitudes and phases can be obtained, which are listed in Table 7 and displayed in Fig. 10.

For the annual LOD variations from 2002 to 2016, the amplitude of geodetic excitation is $337.1 \mu\text{s}$, and the phase is 22.0° . Taking the total atmosphere, ocean and continental hydrology into consideration, the closest amplitude of the original model excitations to geodetic excitation is ECMWFop, with an annual amplitude of $317.3 \mu\text{s}$, and the closest model phase is ESGMFZ, with an annual phase of 22.9° . Due to the annual systemic error of OMCT, the AO results (amplitude 288.8, phase 11.7) of ECMWFop differ greatly from both the other original models and our improved combinations, which corresponds with earlier results shown in Figs 4, 8 and Table 4. Continuing with Table 7, note that the amplitude of NCEP AO, $351.3 \mu\text{s}$, differs greatly from the AO amplitude of ESGMFZ and LDC/WMC4 as well as all AOH results. This indicates that the annual model of NCEP AE + ECCO OE is not reliable despite the earlier evidence in Table 4 of its lowest annual RMS residuals among the original model families. Among those original models, ESGMFZ is better (its amplitude $314.6 \mu\text{s}$ is close to ECMWFop with $317.3 \mu\text{s}$, but its phase 22.9° is closest to the geodetic excitation 22.0°). Our improved combination phasors come closest of all to the annual geodetic excitation, with LDC better in amplitude and WMC4 closer in phase.

According to all the models, atmospheric excitation explains most of the annual LOD variation, consistent with prior studies. The phase of annual NCEP AE is very close to the annual geodetic phase, but its amplitude is excessive. The annual phases of other atmosphere models are different from geodetic excitation, but their amplitudes are closer. The phase effects of the oceans from different original models are different, and OMCT matter excitation, has a great deviation from both the geodetic and the other original excitations. From the former discussion, we know that the OMCT annual ocean matter models are not reliable. The other two ocean models are similar, both reducing the amplitudes of annual LOD excitation closer to geodesy while shifting the model phases away from geodesy.

From our LDC/WMC improved results, the ocean effect is to reduce the excessive atmosphere excitation amplitudes, making the sum closer to geodesy but unlike the original models, the LDC/WMC oceans cause no phase shift. The effect of HE matter is to correct the phase of total geophysical excitation, moving it closer to geodetic excitation. Most investigators fail to take HE matter into consideration or they regard GRACE $C_{20} - (\text{AE} + \text{OE})_{\text{matter}}$ directly as a reliable measure of the HE matter term, for example, to validate hydrological models. But due to the errors in both GRACE C_{20} and OE models (especially for OE matter), deriving HE matter from the difference between GRACE C_{20} and AE + OE excitations directly is not a good choice. HE matter should not be ignored, but can play a more important role than oceans.

To further consider the effects of annual AE, OE and HE matter excitations, we compare those components with SLR excitations (see Table 8 and Fig. 11) in view of longstanding disputes over the roles of ocean and continental hydrology (e.g. Chao & O'Connor 1988; Chen 2005; Yan *et al.* 2006).

The annual LOD matter excitation from SLR for 2002 to 2016 has an amplitude of $61.3 \mu\text{s}$ and a phase of 38.3° . The annual AE matter excitations are very similar from all three original models, which merely reflects the fact that this component derives from the global

Figure 10. Annual signals in LOD variation (motion and matter excitations) shown as phasors (vector length is amplitude; angle counterclockwise about the origin is phase) for the original geophysical models (ECMWFop, ESMGFZ and NCEP), our multimodel combinations (LDC, WMC4) and the IERS 14C04 geodetic series. Different segments of the same colour decompose the model totals into the individual AE, OE and HE components according to Table 7.

Table 8. Comparisons of the annual components of geodetic and geophysical matter-only excitations.

	ECMWFop		ESMGFZ		NCEP		LDC		WMC4	
A	34.8 ± 6.9	8.3 ± 11.5	35.3 ± 6.9	8.6 ± 11.3	39.5 ± 6.9	10.3 ± 10.1	37.8 ± 6.9	12.2 ± 10.6	36.8 ± 6.9	9.7 ± 10.9
AO	99.4 ± 6.9	57.5 ± 4.0	51.9 ± 6.9	5.9 ± 7.7	46.4 ± 6.9	8.1 ± 8.6	45.5 ± 6.9	16.7 ± 8.8	47.3 ± 6.9	18.9 ± 8.5
AOH	50.3 ± 6.9	8.4 ± 8.0	56.9 ± 6.9	24.4 ± 7.0	–	–	54.1 ± 6.9	34.6 ± 7.4	55.9 ± 6.9	36.6 ± 7.2

From top to bottom, A: AE matter, AO: AE matter + OE matter, AOH: AE matter + OE matter + HE matter. First column is the amplitude (μ s), and second column is phase ($^{\circ}$). Note that the annual SLR matter excitation has an amplitude of $61.3 \pm 6.9 \mu$ s and a phase of $38.3 \pm 6.5^{\circ}$.

pressure fields that all depend on basically the same sets of barometric measurements. On the other hand, the associated OE and HE matter excitations are quite different (especially OMCT, as we have seen already). For the total AOH matter excitations, the closest original model set to SLR excitation is ESMGFZ for both amplitude (56.9μ s) and phase (24.4°). This means that the updated MPIOM OE matter and the mass-corrected HE matter models from ESMGFZ provide the best explanation for the annual matter excitation of LOD that is not caused by the atmosphere. Compared with geodetic SLR excitation, the amplitudes of our combinations are not as good a match as ESMGFZ, being too small by 1.0 to 2.8μ s, but our combined model phases are much better than ESMGFZ, closer to SLR excitation by about 10 to 12° . Overall, our improved model combinations are the best. While the impact of HE matter was found in the previous section to be minor or even negative for all the other frequency bands, the annual variations of HE matter excitation are obviously significant and should not be ignored despite the equivocal situation shown in Table 7 for the total annual matter + motion excitation amplitudes.

Figure 11. Phasor diagram (same plotting conventions as Fig. 10) of annual signals in LOD matter-only excitations.

6 CONCLUSIONS

In this study, we evaluated the quality of geophysical models for non-tidal LOD excitation and formed improved multimodel combinations using geodetic LOD and SLR observations. The combined model excitations, LDC/WMC, show major advantages over the original individual models from different institutes, which permits an enhanced analysis of the mechanics of axial angular momentum transfer between the Earth's surficial fluids and the solid part. In principle, our LDC/WMC method could be applied to improve LOD predictions also. But the proper LDC combination weights would need to be redetermined using predicted excitation series rather than observations since their respective qualities should not be assumed to be equivalent.

We find that (1) the ECCO and MPIOM models give a more reliable view of the non-tidal ocean mass motions than the OMCT model used by ECMWFop, especially for the annual component; (2) C_{20} series from SLR can provide a rigorous constraint for the total matter excitation of the geophysical fluids, which is otherwise imperfectly modelled, especially for broad-band parts; (3) the SLAM corrections of sea-level variations put forward by the new ESMGFZ model version can significantly improve the HE matter terms, especially compared with the LSDM continental hydrology model without such corrections used by ECMWFop; (4) the LDC/WMC combinations are much better than the original individual geophysical model excitations, reducing the magnitude of unexplained LOD excitations to roughly the $10 \mu\text{s}$ level; (5) the level of residual LOD variations after removing models or model combinations are remarkably invariant with respect to LOD periods between ~ 2 months and ~ 3 yr, being 12 to $14 \mu\text{s}$ for the best original models and 7 to $12 \mu\text{s}$ for our combinations; (6) while differences between the IERS 14C04 and the JPL SPACE2015 geodetic LOD time-series are not negligible, errors in both series are still not large compared to the geophysical models (for periods > 2 months) so the impact on excitation studies is minimal except at semiannual periods and usually 14C04 compares better with excitation models.

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