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The understanding of length-of-day variations from satellite gravity and laser ranging measurements

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SUMMARY

The change in the rate of the Earth's rotation, length-of-day (LOD), is principally the result of movement and redistribution of mass in the Earth's atmosphere, oceans and hydrosphere. Numerous studies on the LOD excitations have been made from climatological/hydrological assimilation systems and models of the general circulation of the ocean. However, quantitative assessment and understanding of the contributions to the LOD remain unclear due mainly to the lack of direct global observations. In this paper, the total Earth's surface fluids mass excitations to the LOD at seasonal and intraseasonal timescales are investigated from the Jet Propulsion Laboratory Estimating Circulation and Climate of the Ocean (ECCO) model, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis and the European Center for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA)-Interim, GRACE-derived surface fluids mass and the spherical harmonics coefficient C_{20} from the satellite laser ranging (SLR) as well as combined GRACE+SLR solutions, respectively. Results show that the GRACE and the combined GRACE and SLR solutions better explain the geodetic residual LOD excitations at annual and semi-annual timescales. For less than 1 yr timescales, GRACE-derived mass is worse to explain the geodetic residuals, whereas SLR agrees better with the geodetic residuals. However, the combined GRACE and SLR results are much improved in explaining the geodetic residual excitations at intraseasonal scales.

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

1 INTRODUCTION

The rate of Earth's rotation, that is, the length-of-day (LOD), is varying with up to a millisecond (ms) per day at the timescales from days to decades (Munk & MacDonald 1960). This change in the rate of the Earth's rotation is mainly driven by fluids mass redistribution and movements within the Earth system, including the atmosphere, ocean, hydrosphere, cryosphere and solid Earth. With the advent and improvements of climatological/hydrological assimilation systems and models of the general circulation of the ocean, it has provided an opportunity to investigate the excitations of the LOD variations (e.g. Barnes *et al.* 1983; Wahr 1983). The atmospheric angular momentum (AAM) from climatological assimilation models, for example, the products of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, was a dominant contributor to the LOD variation (e.g. Eubanks *et al.* 1988). In particular, the zonal wind variations in atmospheric general circulation models are responsible for about 90 per cent of observed LOD variability, while atmospheric pressure also provides important contributions as well (Hopfner 1998; Gross *et al.* 2004). Therefore, interpretation of the LOD change is sensitive to the used climatological model.

Additional variability in LOD arises from variations in oceanic angular momentum (OAM) and hydrological angular momentum (HAM). The OAM, including ocean bottom pressure (OBP) and currents terms, provides a significant part of the non-atmospheric LOD excitations based on studies from Ocean General Circulation Models (OGCMs), for example, the parallel ocean climate model (POCM), the Estimating Circulation and Climate of the Ocean (ECCO) non-data-assimilating model (ECCO-NDA), the ECCO data-assimilating model (ECCO-DA) and a number of barotropic ocean models (BOMs) (Wahr 1983; Marcus *et al.* 1998; Johnson *et al.* 1999; Gross *et al.* 2004). Results from the models studies show that ocean mass redistribution and circulation explain most of the residual of LOD excitations that has not been accounted for by the atmosphere (Marcus *et al*. 1998; Chen *et al.* 2000; Gross *et al.* 2004). Unfortunately, these results rely on ocean models that have relatively few observational data as input. Therefore, fully understanding oceanic effects on the LOD remains a challenging issue.

The main limitation is the lack of global oceanic observation data. The remaining LOD residuals after removing the atmospheric and oceanic contributions are believed to be excited by the terrestrial water storage (TWS), including changes of soil water, snow and ice sheets and ground water. The hydrological excitation has been traditionally studied and estimated from global hydrological models. However, various models give significantly different results in LOD amplitudes and phases at the seasonal timescales and one conclusion drawn from this is that they may not represent the complete hydrological variation (Chen *et al*. 2000). Furthermore, the TWS has not been adequately measured at the continental scale (Lettenmaier & Famiglietti 2006), primarily due to the lack of a comprehensive global network for routine hydrological parameters monitoring.

The Gravity Recovery and Climate Experiment (GRACE) mission, launched in 2002 March, provides a unique opportunity to estimate global mass distribution within the Earth system, for example, terrestrial water storage (TWS; Syed *et al.* 2008) and ocean bottom pressure (OBP; Böning *et al*. 2008; Chambers & Willis 2008). More importantly, the GRACE measurements are the first global direct observations of TWS and OBP variation, rather than the output or simulation from a model. In this paper, we assess the total Earth's surface fluids mass contributions to the LOD at seasonal and intraseasonal timescales for period longer than 1 month from GRACE and the Jet Propulsion Laboratory (JPL) ECCO model, the NCEP/NCAR reanalysis products and the European Center for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA)-Interim data. In addition, as the total mass excitations of the LOD are related to the spherical harmonics coefficient C_{20} of the geopotential (Wahr *et al*. 1998), the mass contributions to the LOD are also estimated from the satellite laser ranging (SLR) that has been an effective technique for measuring the lowest degree even-zonal harmonics (especially C_{20}, also called Earth oblateness J_2 in the literature) (e.g. Yoder *et al.* 1983; Rubincam 1984; Cheng & Tapley 2004). In the following discussion, the mass excitations of the LOD are further compared with the combined solution from GRACE and SLR.

2 LOD EXCITATION

The relationship between the observed LOD and its excitation can be mathematically expressed by complex notation in an earth-fixed coordinate system. The response to the LOD excitation is approximately expressed as (Munk & MacDonald 1960; Lamkeck 1980)

$$m_3 = -\chi_3, \tag{1}$$

where $m_3 = {}^{\Delta \mathrm{LOD}}/_{\mathrm{LOD}}$, LOD is the nominal length of day of 86 400 s, and χ_3 is so-called LOD excitation, including surface mass load change term (χ_3^{mass}) and atmospheric winds or ocean currents term (χ_3^{motion}). In a given gridpoint (latitude φ, longitude λ and time t), the LOD excitations (χ_3^{mass} and χ_3^{motion}) can be written as follows (e.g. Eubanks 1993):

$$\chi_3^{\mathrm{mass}} = \frac{0.753\bar{R}^4}{C_m g} \iint P\cos^3\varphi \,\mathrm{d}\lambda\,\mathrm{d}\varphi, \tag{2}$$

$$\chi_3^{\mathrm{motion}} = \frac{0.998\bar{R}^3}{C_m g\Omega} \iiint U\cos^2\varphi \,\mathrm{d}p\,\mathrm{d}\lambda\,\mathrm{d}\varphi, \tag{3}$$

where $\bar{R}$ and Ω are the mean radius and mean rotation rate of the Earth, respectively, g is the gravitational acceleration on the Earth surface, C_m is the principal inertia moments of the Earth's mantle, and P and U are the surface pressure (mass term) and the zonal velocity (e.g. wind or ocean currents), respectively.

As surface mass change can be represented by the spherical harmonics coefficient of the geopotential (e.g. Chao & Gross 1987; Wahr *et al*. 1998), one can derive the following relationship between surface mass excitation (χ_3^{mass}) and the degree 2 and 0 zonal spherical harmonics (mass decomposition), C_{20} and C_{00} as (Bourda 2008; Chen & Wilson 2008):

$$\chi_3^{\mathrm{mass}} = \frac{0.753\bar{R}^2 M}{(1+k_2')C_m} \cdot \frac{2}{3}(\Delta C_{00} - \sqrt{5}\Delta C_{20}), \tag{4}$$

where M is mass of the Earth, $k_2' = -0.301$ is the degree-2 load Love number and ΔC_{00} represents the total mass change ${}^{\Delta M}/_{M}$. The mass is usually not conserved in individual component of the Earth system, for example, the atmosphere, although its effect is small. Therefore, the ΔC_{00} in eq. (4) is not zero as the total mass of that component will change. However, for global mass loads in which the total mass is conserved, therefore ΔC_{00} is assumed to be zero.

3 DATA AND MODELS

3.1 LOD excitations from models

The AAM variations are responsible for the dominated contribution to the LOD excitations (Eubanks *et al*. 1988; Gross *et al.* 2004; Zhou *et al*. 2006). The atmospheric contributions are well estimated from six hourly excitation series based on the NCEP/NCAR reanalysis (e.g. Salstein 1993). The daily averaged products are obtained from the IERS Special Bureau for the Atmosphere (SBA), a joint effort of Atmospheric and Environmental Research, Inc. (AER) and the U.S. NCEP (http://www.aer.com/scienceResearch/diag/sb.html), including atmospheric winds angular momentum (AAMw) and atmospheric pressure angular momentum (AAMp) computed from the surface to the top of the model at 10 hPa. The angular momentum due to surface pressure variations is used by assuming that the oceans respond as an inverted barometer to the overlying surface pressure variations.

The ocean excitations to the LOD include contributions from ocean currents and OBP variations. Recent advancements in data-assimilating OGCMs have improved studies of oceanic effects on polar motion and LOD (e.g. Gross *et al.* 2004). The model used in many of these studies is the ECCO data-assimilating model (ECCO-DA) run by Jet Propulsion Laboratory (e.g. Fukumori *et al.* 2000). The JPL ECCO-DA is based on the Massachusetts Institute of Technology general circulation model (Marshall *et al.* 1997; Gross *et al.* 2004) and assimilates TOPEX/Poseidon and Jason-1 sea surface height observations as well as *in situ* temperature and salinity measurements. The model is forced by 12 hr surface wind stresses and daily surface heat/freshwater fluxes and evaporation–precipitation fields from the NCEP/NCAR reanalysis products (Fukumori *et al.* 2000). The coverage is nearly global from 80.0°S to 80.0°N latitude with a latitudinal spacing ranging between 1/3 degree at equator to 1 degree at high latitudes and a longitudinal resolution of 1°. The model has 46 levels ranging in thickness from 10 m at the surface to 400 m at depth (Gross 2009). In this study, the OAM, including ocean bottom pressure term ($\mathrm{OAM_p}$) and ocean current term ($\mathrm{OAM_c}$), are determined from the daily averaged values of the ECCO model kf066b provided by the IERS Special Bureau for the Oceans (http://euler.jpl.nasa.gov/sbo/), where the ECCO model is not forced by atmospheric pressure variations.

The hydrological excitations (HAM) of the LOD have been estimated from the new global hydrological land surface discharge model (LSDM) with near real-time input data of daily Precipitation, Evaporation and Temperature from the European Center for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA)-Interim (6h ECMWF operational) (Dill & Walter 2008). The ECMWF interim reanalysis system has been developed with an improved assimilation background model and additional observation data, including considering local effects from swamps and flooded regions like the anthropogenic influences such as dams and irrigation. Thus, the total surface mass excitations to the LOD can be obtained from the models, including atmospheric pressure momentum (AAM_p), ocean bottom pressure momentum (OAM_p) and HAM, that is, AAM_p+OAM_p+HAM (AOH).

3.2 Geodetic LOD excitations

With large improvements in geodetic models and processing strategies, the precise Earth Orientation Parameters (EOPs) have been produced from geodetic techniques, including Global Positioning System (GPS), SLR, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), lunar laser ranging (LLR) and Very Long Baseline Interferometry (VLBI). Here the recent International Earth Rotation and Reference systems Service (IERS) EOP time-series (IERS C04) are used with improved algorithms from the combination of individual EOP series derived from VLBI, GPS and SLR, fully consistent with the International Terrestrial Reference Frame (ITRF) 2005 [http://hpiers.obspm.fr/iers/eop/eopc04_05/C04_05.guide.pdf]. The full geodetic LOD excitation χ_3, that is, geodetic angular momentum (GAM), is derived from geodetic observations of the LOD. We then compute the LOD residual excitations by the Earth's surface fluids mass after removing the atmospheric wind and ocean currents contributions from the full geodetic observation, that is, GAM–AAM_w–OAM_c. Decadal LOD variations, presumed to be related to core–mantle coupling, and a strong 5.6 yr oscillation (Chen *et al*. 2000) were removed via a high-pass filter with cut-off frequency at one cycle in 4 yr. Fig. 1(a) shows the geodetic observed residuals of non-wind/currents excitations, that is, GAM–AAM_w–OAM_c (GWC), where the thick curve represents the low-frequency signals estimated from a low-pass filter with a cut-off frequency at one cycle in 4 yr, and Fig. 1(b) is geodetic observed LOD residuals of non-low-frequency signals.

3.3 Mass excitation from GRACE

The total mass excitations to the LOD can be estimated from the spherical harmonics coefficient C_{20} of the geopotential. Since the GRACE is not sensitive to C_{20}, the original degree-2 coefficient C_{20} from GRACE is not used for LOD excitation computation. While it is determined using the GRACE-derived gridded mass values from the latest full gravity field coefficients (Release-04) with degree and order of up to 60, such as TWS and ocean mass change estimates (Bingham & Hughes 2006; Chambers & Willis 2008; Syed *et al*. 2008), which are available from the GRACE Tellus Web site (http://gracetellus.jpl.nasa.gov/data/mass/). In this study, the surface mass contributions to the LOD are investigated using the latest GRACE gravity field solutions (Release-04) from the Center for Space Research (CSR) at the University of Texas, Austin. The data have been corrected and smoothed into monthly maps of TWS with a 0 km Gaussian smoothing and ocean mass with a 300 km Gaussian smoothing. We use the monthly data from 2002 August until 2008 November, except for 2003 June and 2004 January. No data were available in 2003 June for a solution, and the 2004 January solution was based on less than 15 d of data. The land water and sea water mass excitation to the LOD, χ_3, can be calculated by using TWS and ocean mass (in appropriate units) in place of P in eq. (2). And then the total mass excitations to the LOD

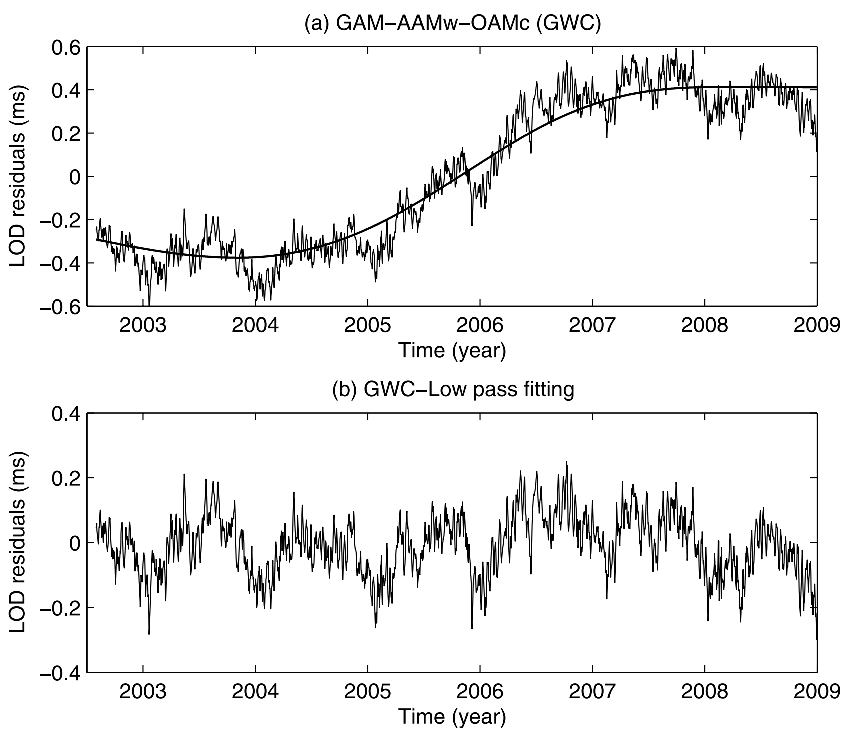

Figure 1. Geodetic observed residuals of non-wind/currents LOD excitations (GAM–AAM_w–OAM_c) (a) and non-low-frequency signals (b). The thick curve represents the low-frequency signals estimated from a low-pass filter with a cut-off frequency at one cycle in 4 yr.

are obtained after adding the surface atmospheric pressure portion from the ECMWF model. Here, the total mass excitations of the LOD are calculated using the GRACE-derived TWS estimate plus GAC product estimate from GRACE data files (representing ocean and atmosphere mass parts).

3.4 LOD excitation from SLR

The SLR is significantly sensitive to the gravity signal, particularly the low degree coefficient C_{20} (e.g. Yoder *et al.* 1983; Rubincam 1984; Cheng & Tapley 2004), so it has been an effective technique to measure low degree gravitational changes. The C_{20} time-series are estimated from the analysis of SLR data with five geodetic satellites: LAGEOS-1 and 2, Starlette, Stella and Ajisai (Cheng & Tapley 2004), provided by the GRACE project (courtesy of Minkang Cheng at CSR) in which they are used to validate GRACE estimates of degree-2 spherical harmonic coefficients. The background gravity models used in the SLR analysis are consistent with the GRACE Release-04 processing, including corrections from solid Earth tides (McCarthy & Petit 2004), oceanic tides using the FES2004 model (Lyard *et al.* 2006) pole tide (McCarthy & Petit 2004) and ocean pole tide (Desai 2002). Therefore, the total mass excitations to the LOD can be derived from the SLR C_{20} products based on eq. (4).

3.5 LOD excitation from combining SLR and GRACE

With improvements and updates of new background gravity models and tide models, recent products in the GRACE 'Release 04' have been greatly improved. However, the coefficient C_{20} obtained from GRACE is still not good and contaminated by ocean tide model errors (Chen & Wilson 2008). Although SLR is an effective technique for measuring the lowest degree even zonal harmonics, especially C_{20} (see Section 3.4), the SLR tracking network is relatively sparse, particularly in the Southern Hemisphere. Therefore, the LAGEOS 1/2 and GRACE data are further combined to estimate the low harmonics coefficient C_{20}.

Fig. 2 shows the flow chart of LAGEOS 1/2 and GRACE combination. LAGEOS 1/2 orbits are computed with the same orbit processing standards as those applied for GRACE. LAGEOS 1/2 SLR data are processed per 10-d arcs, while GRACE data are per 1-d arcs. The combined gravity field solutions are generated through combining normal equation from LAGEOS and GRACE. Here the 10-d combined solutions provided by GRGS (Groupe de Recherche de Géeodéesie Spatiale, Toulouse, France) are used, where LAGEOS data provide over 90 per cent of the information on the coefficient C_{20} of the gravity field. More information is referred as (Biancale *et al*. 2009). The gravitational variations such as solid Earth tides (McCarthy & Petit 2004), oceanic tides using the FES2004 model (Lyard *et al*. 2006), pole tide (McCarthy & Petit 2004) and ocean pole tide (Desai 2002) have been taken into account in the processing of the data, similar with the CSR GRACE Release-04 processing. The combined SLR and GRACE C_{20} products are used to estimate the total mass excitations to the LOD based on eq. (4).

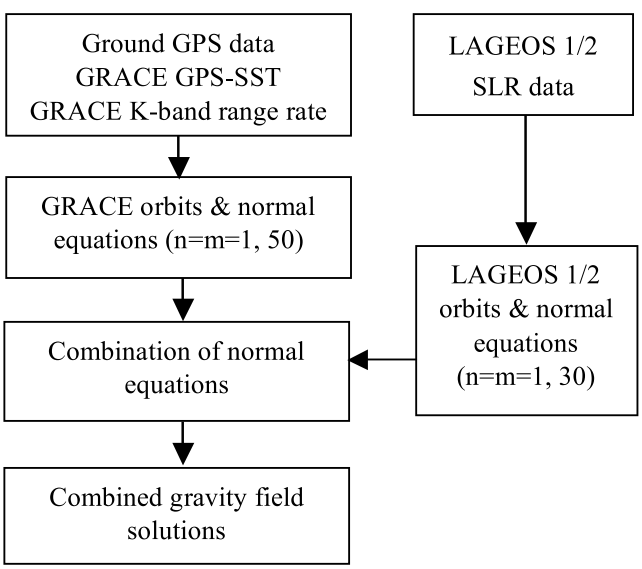

Figure 2. Flow chart of LAGEOS 1/2 and GRACE combination.

4 RESULTS AND DISCUSSIONS

The geodetic LOD residuals ($GAM–AAM_w–OAM_c$) and models' excitations AOH (AAM_p+OAM_p+HAM) are normally given at a sampling of 1 day, while GRACE presents a monthly solution and the combined SLR and GRACE solutions are given at approximately 10-d sampling. These time-series are smoothed by a 30-d sliding window, and resampled at the same 1-month interval as GRACE results. Fig. 3 shows the monthly Earth's surface mass excitation time-series of the LOD (2002 August–2008 November). The blue line stands for the geodetic residual LOD of non-atmospheric wind/currents excitations ($GAM–AAM_w–OAM_c$), the black line is the models' estimate AOH (AAM_p+OAM_p+HAM), the green line is the SLR C_{20} estimate, the cyan line is the estimate from GRACE-derived mass and the red line is the combined SLR and GRACE C_{20} estimate. Table 1 shows the cross-correlation coefficients and rms between geodetic residual (LOD) and excitations from models and observations. The maximum correlation coefficients at the zero phase lag between the geodetic residual LOD and excitations from models and observations are nearly close, indicating a similar variation pattern in different excitation time-series with geodetic observation residual. However, the excitation from the model estimates (AOH) has the biggest rms of 99.39 μs (microsecond) with the geodetic residual LOD, but closer to the excitations from different observations (Table 2), while results from GRACE-derived surface mass, SLR or combined SLR+GRACE C_{20} estimates, are closer to the geodetic residuals with a smaller rms of about 70 μs (Table 1), indicating that GRACE-derived mass, SLR or SLR+GRACE combined solutions better explain the geodetic residual LOD excitations.

In the following, we will investigate the LOD excitations at seasonal and intraseasonal timescales and evaluate the ability of LOD excitations from GRACE, SLR or models to close the budget of $GAM–AAM_w–OAM_c = AAM_p+OAM_p+HAM$, where the GAM represents the full geodetic LOD excitations, AAM_w is the atmospheric wind portion, OAM_c is the ocean current portion, AAM_p is the atmospheric pressure portion, OAM_p is the portion related to OBP variations and HAM is the hydrological portion.

4.1 Seasonal LOD variations

The monthly excitation time-series of the LOD have shown clearly a significant seasonal variation in the geodetic observation residual and surface mass excitations from observations and models. Using the method of least-squares fit to a bias, trend and seasonal period sinusoids, the amplitude and phase of annual and semi-annual variations of the LOD excitations are estimated from geodetic observation residuals and excitation time-series (2002 August–2008

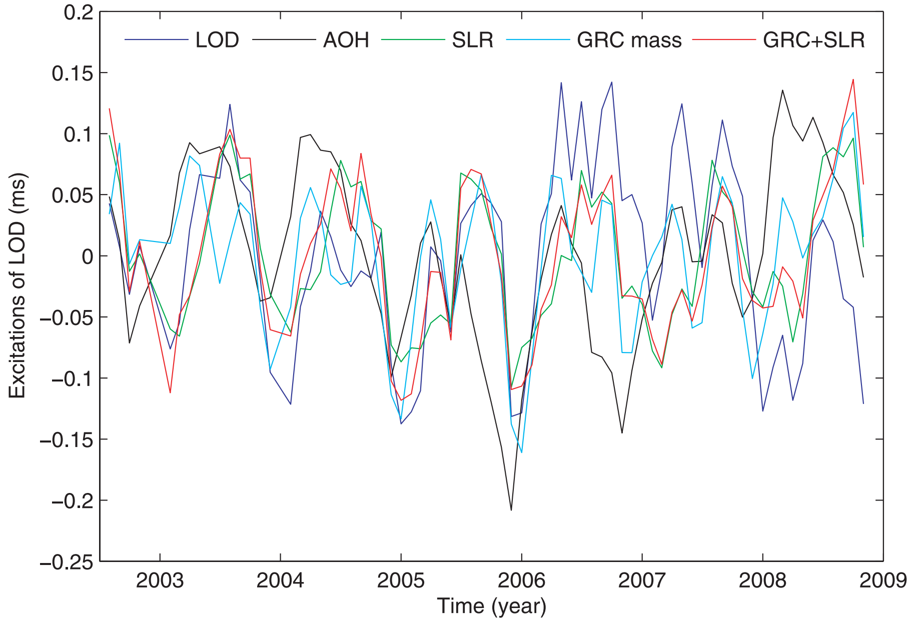

Figure 3. Monthly Earth's surface mass excitation time-series of the length-of-day (LOD) variations from geodetic observation residuals LOD (GAM–AAM_w–OAM_c) (blue line), models' estimates AOH (AAM_p+OAM_p+HAM) (black line), SLR C_{20} estimates (green line), GRC mass estimates (cyan line) and combined SLR and GRC C_{20} estimates (red line).

Table 1. Cross-correlation coefficients and rms between geodetic residual (LOD) and excitations from models and observations.

	Full LOD time-series		Intraseasonal LOD time-series	
Excitations	Max. corr.	rms (μs)	Max. corr.	rms (μs)
AOH	0.56	99.39	0.63	27.40
SLR	0.55	63.07	0.77	23.38
GRC mass	0.46	70.33	0.56	29.30
GRC+SLR	0.56	64.58	0.66	26.57

Table 2. Cross-correlation coefficients and rms between models excitation (AOH) and geodetic residual (LOD) and observation estimates.

	Full AOH time-series		Intraseasonal AOH time-series	
Excitations	Max. corr.	rms (μs)	Max. corr.	rms (μs)
LOD	0.56	99.39	0.63	27.40
SLR	0.67	79.42	0.82	11.85
GRC mass	0.59	63.91	0.71	17.03
GRC+SLR	0.59	78.89	0.81	15.75

Table 3. Amplitude and phase of annual and semi-annual variations of length-of-day excitations from observations and models.[a]

	Annual		Semi-annual	
	Amp (μs)	Phase (°)	Amp (μs)	Phase (°)
LOD	64.7 ± 1.7	-102.0 ± 1.4	27.8 ± 1.7	-104.3 ± 3.3
LOD (all winds)	71.9 ± 1.7	-86.4 ± 1.2	42.5 ± 1.7	-63.6 ± 2.2
AOH	67.2 ± 1.5	-38.3 ± 1.3	23.7 ± 1.5	-30.6 ± 3.7
SLR	68.9 ± 0.7	-126.5 ± 0.6	13.1 ± 0.7	-1.7 ± 3.3
GRC mass	42.2 ± 0.9	-81.4 ± 1.1	62.2 ± 0.9	-62.3 ± 0.8
GRC+SLR	71.0 ± 1.0	-120.3 ± 0.8	22.9 ± 1.0	-58.9 ± 2.5

[a]The amplitude c and phase φ are defined as $c\sin(2\pi(t-t_0)/p+\varphi)$ from monthly time-series, where t_0 is January 1 and p is the period. Amp is amplitude, μs is microsecond, LOD is geodetic observation residual of non-wind/currents excitations (GAM–AAM_w–OAM_c), LOD (all winds) is geodetic observation residual of non-wind/currents excitations with removing all winds' contributions, including upper winds from 10 hPa to 0.3 hPa, AOH is the total excitation of atmospheric pressure from the NCEP-NCAR reanalysis (AAMp), ocean bottom pressure from the ECCO model (OAM_p) and hydrology from the ECMWF Re-analysis (ERA)-Interim, SLR is total mass excitation from SLR C_{20}, GRC mass is total mass excitation from GRACE-derived mass loads and GRC+SLR is total mass excitation from combined GRACE+SLR C_{20}.

November). Table 3 lists the amplitude and phase of annual and semi-annual variations with their uncertainties for the LOD excitations from observations and models. For the annual period, the amplitudes and phases from SLR, GRACE and SLR+GRACE excitations are nearly close to the geodetic residuals of non-wind/currents excitations, excluding a little small amplitude from GRACE mass estimates, while the models' estimate (AOH) is worse to explain the geodetic residuals with a larger phase shift. The better agreement with the observed residuals is the estimate from combined GRACE and SLR C_{20} in phase and in the amplitude. However, agreement at the semi-annual period is relatively poorer, particularly in the phase. The GRACE or the combined GRACE and SLR C_{20} estimate is closer to the LOD residuals in the phase and others are a bit less or larger in the amplitude or phase. The amplitude from GRACE-derived mass excitation is a little smaller than from geodetic residual at annual scale, but much larger at semi-annual scale. This may be the hydrology estimate from GRACE-processing strategies or more contaminated by aliases as the TWS tends to have much larger amplitude over smaller areas.

Furthermore, we analyse the LOD excitations and geodetic residuals of non-wind/current excitations time-series using an N-point FFT to obtain power spectral densities (PSD) (Fig. 4). A Hanning window is used for the FFT analysis to reduce the errors in the PSD. There is an interesting relationship in the PSDs at the annual and semi-annual periods. Excitations from observations or models have similar energy to the geodetic residuals at the annual period, but the combined GRACE and SLR excitation has closer energy to

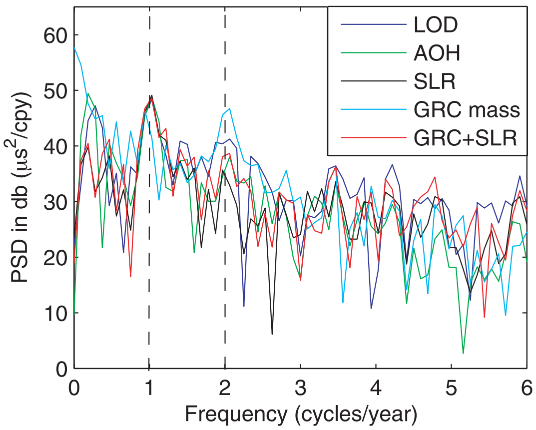

Figure 4. Power spectrum density (μs^2 cycles per year) of the geodetic residual LOD (blue line) and other excitations from observations and models' estimates. The two vertical dashed lines are at periods of 1 and 0.5 yr, respectively.

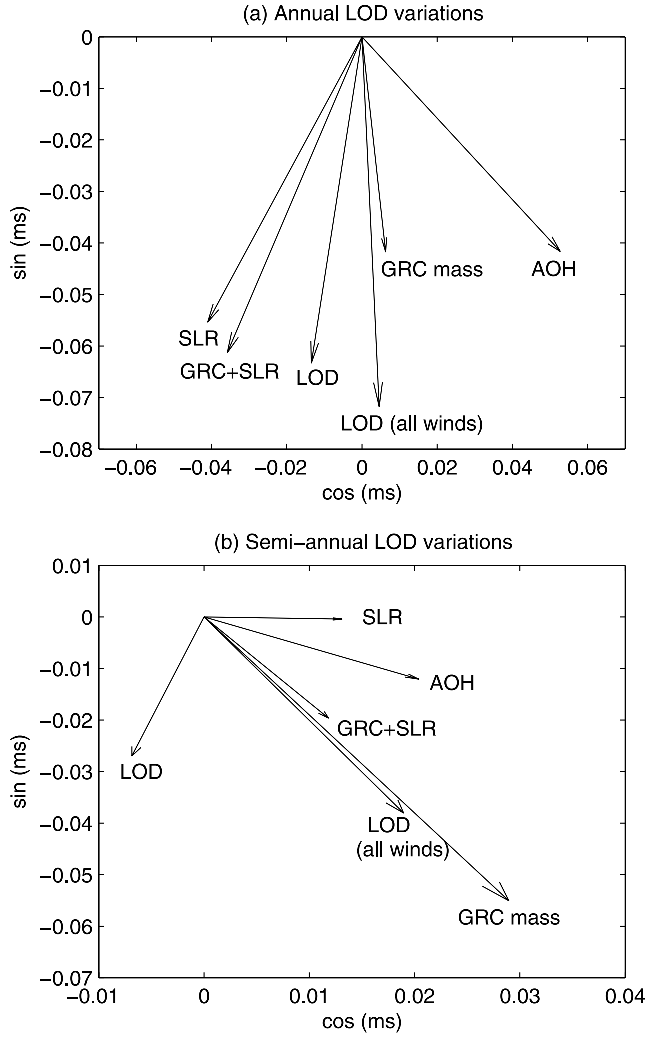

Figure 5. Phasor plots of annual (a) and semi-annual (b) variations for LOD of geodetic observation residuals, LOD (all winds) with removing all winds' contributions, including upper winds from 10 hPa to 0.3 hPa, AOH from models' estimates, SLR from SLR C_{20} estimates, GRC mass from GRACE mass estimates and GRC+SLR from combined SLR and GRC C_{20} estimates.

the geodetic residuals at semi-annual period. These again indicate that the combined GRACE and SLR estimate explains better the observed residuals at seasonal timescales.

In addition, the errors in numerical model wind fields also affect the geodetic residuals of LOD since the winds cause about 90 per cent of LOD variations at seasonal timescales. The atmospheric wind field contributions to the LOD are estimated using the recent NCEP/NCAR model. The mass excitations from the SLR, GRC mass and GRC+SLR observations have the better agreement at annual scale with the geodetic residual LOD of non-wind/currents excitations (Fig. 5a), indicating that the wind field variations at annual timescales are well represented in the NCEP/NCAR model. However, poorer agreements with geodetic residual LOD at the semi-annual period are found (Fig. 5b), showing that the wind field variations at the semi-annual scale are relatively worse determined in the NCEP/NCAR model. Although the recent wind field of the NCEP/NCAR model has made great progresses by adding details of the evolution of tropical and extratropical cyclone wind field feature, winds from pressure levels above 10 hPa are not included in the NCEP/NCAR reanalysis model. In this region it has only 1 per cent of the atmospheric mass, while the strength of the zonal winds is notable enough to affect seasonal LOD variations (Rosen & Salstein 1985). The upper wind fields from 10 hPa to 0.3 hPa (1992–2000) are used to test from the results of Gross *et al.* (2004) using data from the United Kingdom Meteorological Office (UKMO). Table 3 lists the amplitude and phase of annual and semi-annual variations of geodetic residual LOD (all winds), removing all winds contributions from ground to 0.3 hPa. It has shown that the excitations from the GRACE and the combined GRACE and SLR are closer to the geodetic residual LOD with removing all winds' contributions at seasonal timescales, particularly agreeing better at the semi-annual excitation (Fig. 5). In the future, when more precise upper atmospheric wind fields are available, it will further improve the winds contribution and understanding in the LOD excitations.

4.2 Intraseasonal LOD variations

The intraseasonal LOD variations with period greater than 1 month are further examined after removing the annual and semi-annual signals as well as over 1 yr period terms using a high-pass filter with a cut-off frequency of 1 cycle yr^{-1} from all LOD excitations time-series. Fig. 6 is the intraseasonal LOD variation time-series from geodetic observation residuals LOD (blue line), models' estimates AOH (black line), SLR C_{20} estimates (green line), GRC mass estimates (cyan line) and combined SLR and GRC C_{20} estimates (red line), showing large intraseasonal variability. To quantify which excitations agree better with geodetic residual LOD (GAM–AAM_w–OAM_c) at intraseasonal scales, we have computed cross-correlation coefficients (Fig. 7), where the dashed lines represents the 99 per cent confidence levels calculated from the upper 1 per cent point of the F-distribution. The maximum correlation coefficient at the zero phase lag between the SLR estimate and geodetic residual LOD is significantly higher than those from models and GRACE excitations with geodetic residual LOD. Meanwhile, the rms after of the residuals (LOD minus SLR excitation) are also smallest (Table 3). It has indicated that the SLR estimate agrees better with geodetic residual LOD at intraseasonal scales. However, results from GRACE-derived mass excitation are relatively bad in explaining the intraseasonal LOD variations.

This appears to be due to the larger 1–3 month period fluctuations in 2004 and 2005 in the GRACE estimates (Fig. 6). These results

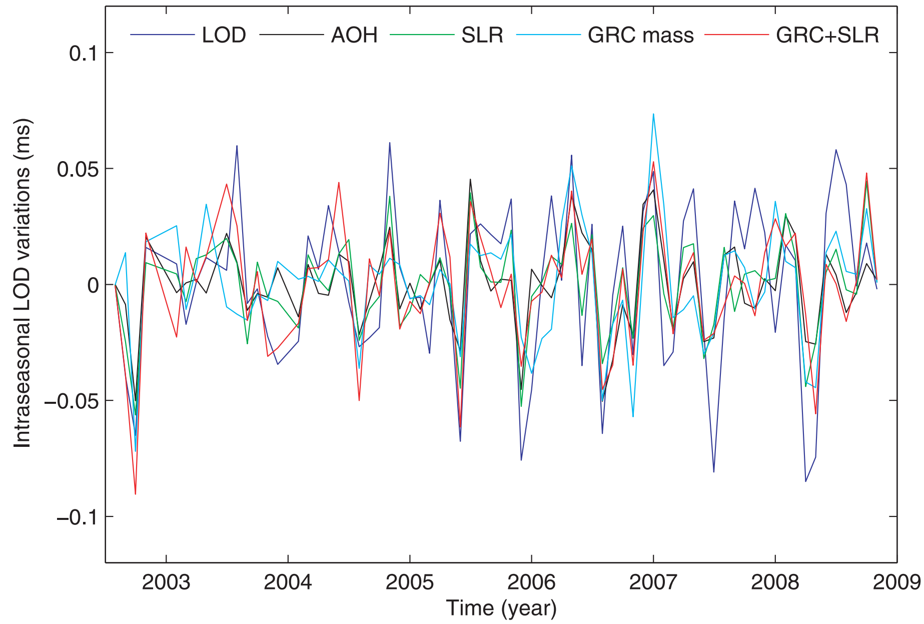

Figure 6. Intraseasonal variations from geodetic observation residuals LOD (blue line), models' estimates AOH (black line), SLR C_{20} estimates (green line), GRC mass estimates (cyan line) and combined SLR and GRC C_{20} estimates (red line). The seasonal signals at annual, semi-annual and over 1 yr period terms are removed from all LOD excitations time-series.

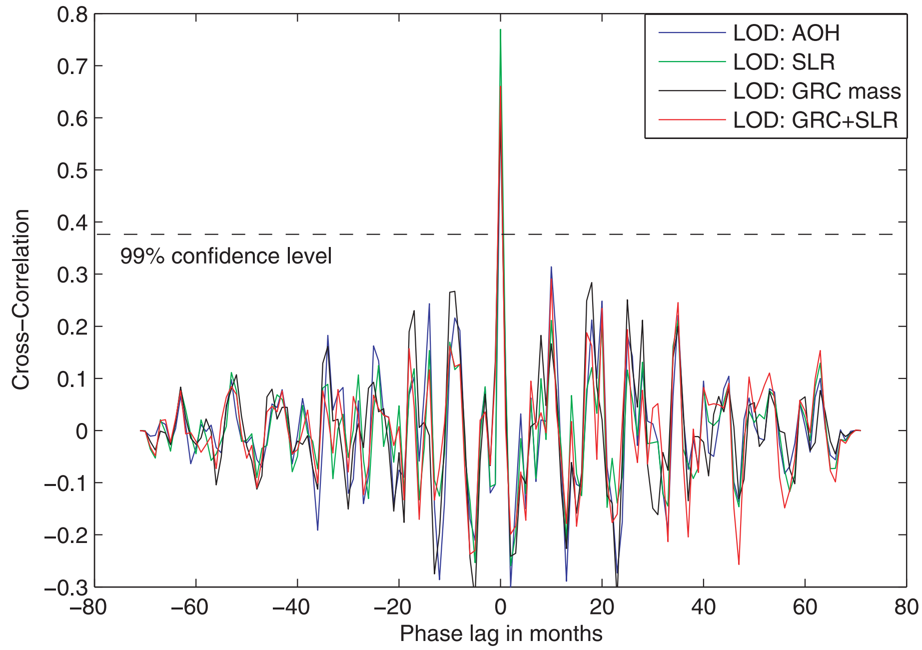

Figure 7. Cross-correlation coefficients on the intraseasonal variations between geodetic observation residuals LOD and models' estimates AOH (blue line), SLR C_{20} estimates (green line), GRC mass estimates (black line) and combined SLR and GRC C_{20} estimates (red line). The horizontal dashed line represents the 99 per cent confidence level.

indicate that the GRACE data cause high-frequency variations in the estimated LOD excitations that are not reflected in the direct observations or the models (Jin *et al*. 2009). One can also use coherence analysis to further study excitation series in the frequency domain (Wilson & Haubrich 1976; Kuehne & Wilson 1991). The estimates of the squared coherence of the various excitation time-series are shown in Fig. 8. It is clear to see that the coherence between SLR and geodetic residuals (LOD) is significantly larger than that for the model estimates at frequencies lower than about three cycles per year (cpy), while the results from GRACE-derived mass excitations are relatively lower than the model estimates at most frequencies.

On one hand, although the latest GRACE gravity field solutions (Release-04) from the CSR at the University of Texas at Austin improved the tide model using the FES2004 (Lyard *et al*. 2006) and other geophysical models, errors in these geophysical models used in GRACE data processing might still contaminate gravity field coefficients, aliasing at certain periods, such as the S_2 tide with a period of 161 d (Seo *et al*. 2008). In addition, Schrama & Visser (2007) estimated aliasing errors through simulated GRACE data and

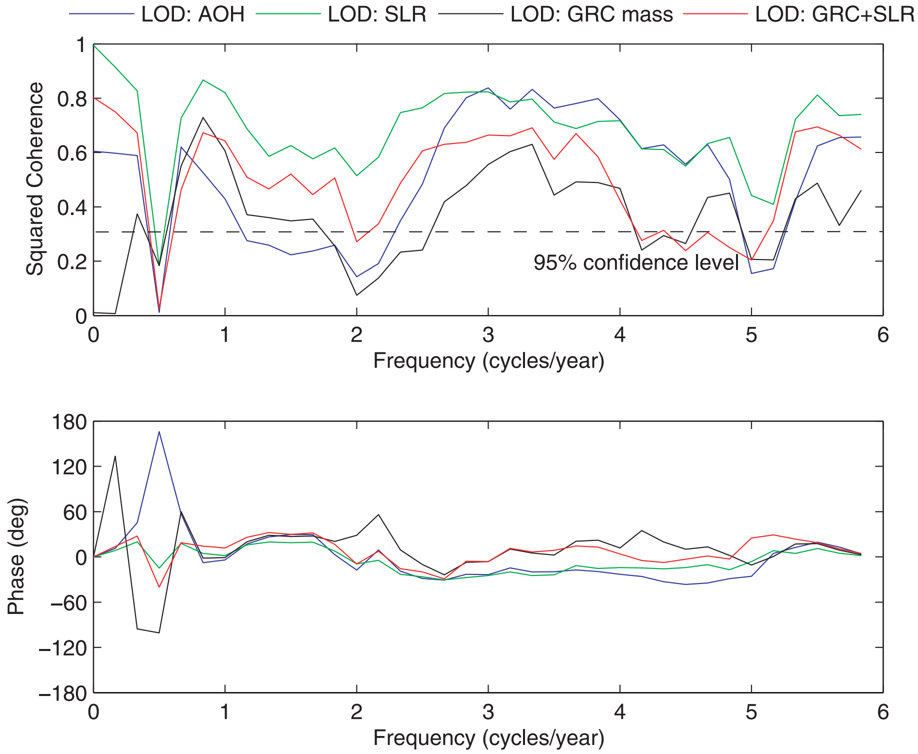

Figure 8. Magnitude and phase of the squared coherence for excitations from observations and models with geodetic observation residuals LOD. Annual, semi-annual and over 1 yr period terms have been removed from all time-series by least-squares fitting and high-pass filter. The mean and trend are also removed.

showed that signals at periods shorter than 3 months were not well retrieved due to errors in geophysical background models. These aliasing errors may degrade the explaining in the intraseasonal LOD excitations from GRACE estimate.

On the other hand, the different high-frequency signals may be related to the fact that while the GRACE coefficients are computed monthly, they do not represent the same average as a monthly mean of global daily variations (Jin *et al*. 2009). Local large fluctuations in GRACE-derived mass loads when GRACE overflies the region once during the month, may alias into a larger or smaller monthly solution than a complete averaging of daily observations will give. The combination of GRACE and other data may help explain the low-frequency variations in LOD excitations, for example, combining with SLR. The maximum cross-correlation coefficient from the combined GRACE and SLR C_{20} estimate is much improved, larger than from models or GRACE data alone, but still smaller than from SLR data alone (Table 1). Meanwhile the rms of the residual (LOD minus GRC+SLR excitation) is reduced, and the squared coherence is improved at almost all frequencies (Fig. 8). Therefore, the LOD excitation from combining GRACE and SLR C_{20} estimate is better than models or GRACE data alone to explain the intraseasonal LOD variations, while it is still not better than SLR alone. In addition, the SLR estimate agrees best with the models in explaining the intraseasonal variations (Table 2), while combining GRACE and SLR C_{20} estimate is better than GRACE data alone at most frequencies (Fig. 9).

5 CONCLUSION

The total Earth's surface mass excitations to the LOD at seasonal and intraseasonal timescales are investigated and compared with the GRACE-derived surface mass, the JPL ECCO model, the NCEP/NCAR reanalysis products and the European Center for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA)-Interim and spherical harmonics coefficient C_{20} from SLR as well as their combined GRACE+SLR estimates. For the annual period, the excitations from GRACE and SLR observations are better than models' estimates to explain the geodetic residuals of non-wind/currents excitations, while the excitation from combined GRACE and SLR C_{20} is much improved in explaining geodetic residual LOD. However, the semi-annual excitations are relatively poorer agreement with geodetic residuals. This is due mainly to the effect of the upper atmospheric winds above 10 hPa. After removing all winds' contributions from ground to 0.3 hPa, the excitations from the GRACE or the combined GRACE and SLR data agree better with the geodetic residual LOD at seasonal timescales, particularly at the semi-annual excitation. For the periods less than 1 yr, results from GRACE-derived mass excitations are worse in explaining the intraseasonal LOD variations, while the SLR solutions better explain the intraseasonal residual of the LOD excitation. However, the combined GRACE and SLR are better than GRACE alone in explaining the geodetic residuals at intraseasonal timescales, but still not better than SLR alone.

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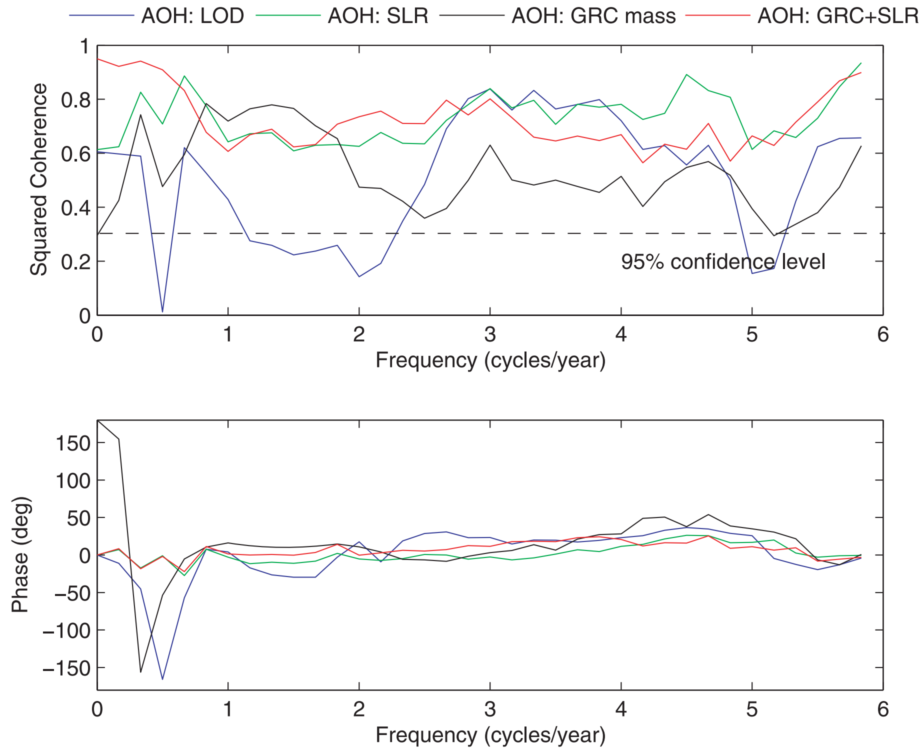

Figure 9. Magnitude and phase of the squared coherence for excitations from observations and geodetic observation residuals LOD with the models' estimate AOH. Annual, semi-annual and over 1 yr period terms have been removed from all time-series by least-squares fitting and high-pass filter. The mean and trend are also removed.

System Data Records for Use in Research Environments' (MEASURES) Programs, and are available at http://grace.jpl.nasa.gov. This work was supported by the National Natural Science Foundation of China (NSFC) (Grant No.11043008), the key program of Chinese Academy of Sciences (Grant No. KJCX2-YW-T26) and a grant from the NASA GRACE Science Team.

REFERENCES

Barnes, R., Hide, R., White, A. & Wilson, C., 1983. Atmospheric angular momentum functions, length of day changes and polar motion, *Proc. R. Soc. London, Ser. A,* **387,** 31–73.

Biancale, R. *et al*. 2009. 6 years of gravity variations from GRACE and LAGEOS data at 10-day intervals, available at: http://grgs.obs-mip.fr/index.php/fre/Donnees-scientifiques/Champ-de-gravite/grace.

Bingham, R.J. & Hughes, C.W., 2006. Observing seasonal bottom pressure variability in the North Pacific with GRACE, *Geophys. Res. Lett.,* **33,** L08607, doi:10.1029/2005GL025489.

Böning, C., Timmermann, R., Macrander, A. & Schröter, J. 2008. A pattern-filtering method for the determination of ocean bottom pressure anomalies from GRACE solutions, *Geophys. Res. Lett.,* **35,** L18611, doi:10.1029/2008GL034974.

Bourda, G., 2008. Length-of-day and space-geodetic determination of the Earth's variable gravity field, *J. Geodyn.,* **82**(4–5), 295–305, doi: 10.1007/s00190–007-0180-y.

Chambers, D.P. & Willis, J.K., 2008. Analysis of large-scale ocean bottom pressure variability in the North Pacific, *J. geophys. Res.,* **113,** C11003, doi: 10.1029/2008JC004930.

Chao, B. & Gross, R., 1987. Changes in the Earth's rotation and low-degree gravitational field induced by earthquakes, *Geophys. J. R. astr. Soc.,* **91,** 569–596.

Chen, J. & Wilson, C.R., 2008. Low degree gravitational changes from GRACE, Earth rotation, geophysical models, and satellite laser ranging, *J. geophys. Res.,* **113,** B06402, 10.1029/2007JB005397.

Chen, J., Wilson, C.R., Chao, B.F., Shum, C.K. & Tapley, B.D., 2000. Hydrological and oceanic excitations to polar motion and length-of-day variation, *Geophys. J. Int.,* **141**(1), 149–156.

Cheng, M. & Tapley, B.D., 2004 Variations in the Earth's oblateness during the past 28 years, *J. geophys. Res.,* **109,** B09402, doi: 10.1029/2004JB003028.

Desai, S., 2002. Observing the pole tide with satellite altimetry, *J. geophys. Res.,* **107**(C11), 3186, doi:10.1029/2001JC001224.

Dill, R. & Walter, C., 2008 Operational simulation of continental water masses consistent with atmospheric and oceanic data, *Geophys. Res. Abstr.,* **10,** EGU2008-A-09304.

Eubanks, T.M., 1993. Variations in the orientation of the Earth, in *Contributions of Space Geodesy to Geodynamics: Earth Dynamics*, Geodynamics Series Vol. 24, eds, Smith, D. E., Turcotte, D. L., pp. 1–54, AGU, Washington, D.C.

Eubanks, T.M., Steppe, J.A., Dickey, J.O., Rosen, R.D. & Salstein, D.A., 1988. Causes of rapid motions of the Earth's pole, *Nature,* **334,** 115–119.

Fukumori, I., Lee, T., Menemenlis, D., Fu, L.-L., Cheng, B., Tang, B., Xing, Z. & Giering, R., 2000. A dual assimilation system for satellite altimetry, paper presented at Joint TOPEX/Poseidon and Jason-1 Science Working Team Meeting, NASA, Miami Beach, Fla., 15–17 Nov.

Gross, R.S., 2009. An improved empirical model for the effect of long-period ocean tides on polar motion, *J. Geodyn.,* **83**(7), 635–644, doi: 10.1007/s00190–008-0277-y.

Gross, R.S., Fukumori, I., Menemenlis, D. & Gegout, P., 2004. Atmospheric and oceanic excitation of length-of-day variations during 1980–2000, *J. geophys. Res.,* **109,** B01406, doi:10.1029/2003JB002432.

Hopfner, J., 1998. Seasonal variations in length of day and atmospheric angular momentum, *Geophys. J. Int.,* **135,** 407– 437.

Jin, S.G., Chambers, D.P. & Tapley, B.D., 2009. Hydrological and oceanic effects on polar motion from GRACE and models, *J. geophys. Res.,* **115,** B02403, doi: 10.1029/2009JB006635

Johnson, T. J., Wilson, C.R. & Chao, B.F., 1999. Oceanic angular momentum variability estimated from the Parallel Ocean Climate Model, 1988–1998, *J. geophys. Res.,* **104,** 25 183–25 195.

Kuehne, J. & Wilson, C.R., 1991. Terrestrial water storage and polar motion, *J. geophys. Res.,* **96,** 4337–4345.

Lambeck, K., 1980. *The Earth's Variable Rotation,* Cambridge University Press, New York.

Lettenmaier, D.P. & Famiglietti, J.S., 2006. Water from on high, *Nature,* **444,** 562–563.

Lyard, F., Lefevre, F., Letellier, T. & Francis, O., 2006. Modelling the global ocean tides: insights from FES2004, *Ocean Dyn.,* **56,** 394–415.

McCarthy, D. & Petit, G., 2004. IERS Conventions, 2003. IERS Technical Note 32, Verlag des BKG, pp. 127, ISBN 3–89888-884–3.

Marcus, S., Chao, Y., Dickey, J. & Gegout, P., 1998. Detection and modeling of nontidal oceanic effects on Earth's rotation rate, *Science,* **281,** 1656–1659.

Marshall, J., Adcroft, A., Hill, C., Perelman, L. & Heisey, C., 1997. A finite volume, incompressible, Navier Stokes model for studies of the ocean on parallel computers, *J. geophys. Res.,* **102,** 5753–5766.

Munk, W.H. & MacDonald, G.J.F., 1960. *The Rotation of the Earth,* pp. 323, Cambridge Univ. Press, New York.

Rosen, R.D. & Salstein, D.A., 1985. Contribution of stratospheric winds to annual and semi-annual fluctuations in atmospheric angular momentum and the length of day, *J. geophys. Res.,* **90**(D5), 8033–8041.

Rubincam, D.P., 1984. Postglacial rebound observed by Lageos and the effective viscosity of the lower mantle, *J. geophys. Res.,* **89**(B2), 1077–1087.

Salstein, D.A. (1993), Monitoring atmospheric winds and pressures for Earth orientation studies. *Adv. Space Res.,* **13,** 11 175–11 184.

Schrama, E.J.O. & Visser, P.N.A.M., 2007. Accuracy assessment of the monthly GRACE geoids based upon a simulation, *J. Geodyn.,* **81,** 67–80.

Seo, K., Wilson, C.R., Chen, J.L. & Waliser, D.E., 2008. GRACE's spatial aliasing error, *Geophys. J. Int.,* **172**(1), 41–48.

Syed, T.H., Famiglietti, J.S., Rodell, M., Chen, J.L. & Wilson, C.R., 2008 Analysis of terrestrial water storage changes from GRACE and GLDAS, *Water Resour. Res.,* **44,** W02433, doi:10.1029/2006WR005779.

Wahr, J., 1983. The effects of the atmosphere and oceans on the Earth's wobble and on the seasonal variations in the length of day: II. Results, *Geophys. J. R. astr. Soc.,* **74,** 451–487.

Wahr, J., Molenaar, M. & Bryan, F. 1998. Time-variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE, *J. geophys. Res.,* **103**(B12), 30 205–30 229.

Wilson, C.R. & Haubrich, R.A., 1976. Meteorological excitation of the Earth's wobble, *Geophys. J. R. astr. Soc.,* **d6,** 707–743.

Yoder, C.F., Williams, J.G., Dickey, J.O., Schutz, B.E., Eanes, R.J. & Tapley, B.D., 1983. Secular variation of Earth's gravitational harmonic J coefficient from Lageos and non-tidal acceleration of Earth rotation, *Nature,* **303,** 757–762.

Zhou, Y., Salstein, D. and Chen, J., 2006. Revised atmospheric excitation function series related to Earth's variable rotation under consideration of surface topography, *J. geophys. Res.,* **111,** D12108, doi:10.1029/2005JD006608.