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Assessment of terrestrial water contributions to polar motion from GRACE and hydrological models

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ABSTRACT

The hydrological contribution to polar motion is a major challenge in explaining the observed geodetic residual of non-atmospheric and non-oceanic excitations since hydrological models have limited input of comprehensive global direct observations. Although global terrestrial water storage (TWS) estimated from the Gravity Recovery and Climate Experiment (GRACE) provides a new opportunity to study the hydrological excitation of polar motion, the GRACE gridded data are subject to the post-processing de-striping algorithm, spatial gridded mapping and filter smoothing effects as well as aliasing errors. In this paper, the hydrological contributions to polar motion are investigated and evaluated at seasonal and intra-seasonal time scales using the recovered degree-2 harmonic coefficients from all GRACE spherical harmonic coefficients and hydrological models data with the same filter smoothing and recovering methods, including the Global Land Data Assimilation Systems (GLDAS) model, Climate Prediction Center (CPC) model, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis products and European Center for Medium-Range Weather Forecasts (ECMWF) operational model (opECMWF). It is shown that GRACE is better in explaining the geodetic residual of non-atmospheric and non-oceanic polar motion excitations at the annual period, while the models give worse estimates with a larger phase shift or amplitude bias. At the semi-annual period, the GRACE estimates are also generally closer to the geodetic residual, but with some biases in phase or amplitude due mainly to some aliasing errors at near semi-annual period from geophysical models. For periods less than 1-year, the hydrological models and GRACE are generally worse in explaining the intraseasonal polar motion excitations.

1. Introduction

The dynamic motions of atmosphere, oceans, hydrosphere, and cryosphere result in significant Earth's surface mass transport. The mass redistribution and movements within the Earth system are the main excitations of the Earth's rotational changes at timescales of a few years or less. The atmospheric contributions (including winds and surface pressure terms) from climatological assimilation models, e.g. the products of NCEP/NCAR reanalysis, provide a significant part of polar motion excitations (e.g., Barnes et al., 1983; Gross et al., 2003). The oceans, including ocean bottom pressure (OBP) and currents from Ocean General Circulation Models (OGCMs), e.g., the Estimating Circulation and Climate of the Ocean (ECCO) data-assimilating model (ECCO-DA), explain most of the residual of non-atmospheric polar motion excitations (Johnson et al., 1999; Gross et al., 2003). Although the remaining residual after removing the atmospheric and oceanic contributions to polar motion is relatively small, it was believed to arise from changes in terrestrial water storage (TWS), including changes of soil water, snow and ice sheets and ground water (Chao and O'Connor, 1988). The terrestrial water excitation of polar motion, i.e., hydrological angular momentum (HAM), has been investigated using global hydrological models (e.g., Chen and Wilson, 2005; Nastula et al., 2011). However, these models give significantly different results for seasonal polar motion excitations in amplitudes and phases (e.g., Seoane et al., 2011). One conclusion is that they may not represent the complete hydrological variation due to the lack of a comprehensive global

Abbreviations: AAM, atmospheric angular momentum; CPC, climate prediction center; CSR, Center for Space Research; ECCO, estimating the circulation and climate of the ocean; ECMWF, European Center for Medium-Range Weather Forecasts; EOP, Earth orientation parameters; GAC, sum of the atmospheric and oceanic pressure de-aliasing products; GLDAS, global land data assimilation system; GPS, global positioning system; GRACE, gravity recovery and climate experiment; HAM, hydrological angular momentum; IERS, International Earth Rotation and Reference systems Service; NASA, National Aeronautics and Space Administration; NCAR, National Center for Atmospheric Research; NCEP, National Centers for Environmental Prediction; OAM, ocean angular momentum; OGCMs, ocean general circulation models; opECMWF, ECMWF operational model; SLR, satellite laser ranging; TWS, water storage; VLBI, very long baseline interferometry.

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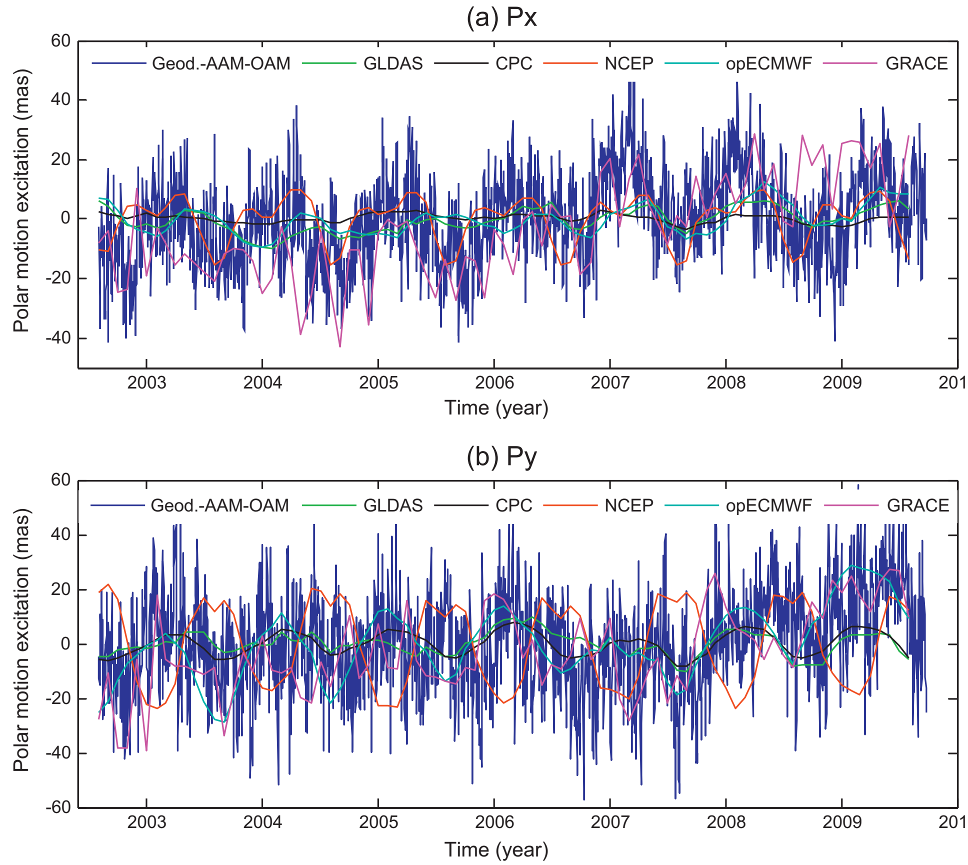

Fig. 1. Hydrological excitation time series of polar motion from geodetic observation residual (Geod.-AAM-OAM) (blue line), GLDAS (green line), CPC (black line), NCEP (red line), opECMWF (cyan line) and GRACE (magenta line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

monitoring of hydrological parameters (e.g., evapotranspiration, precipitation, surface run-off, ground water, snow water, soil moisture and solid water) (Lettenmaier and Famiglietti, 2006). Although ground and satellite based techniques can measure some individual components such as soil moisture (Njoku et al., 2003), surface water (Alsdorf and Lettenmaier, 2003) and ice, there has been no integrated measurement of terrestrial water storage. Therefore, accurately quantifying hydrological contribution to polar motion remains a challenging issue.

The Gravity Recovery and Climate Experiment (GRACE) mission, launched in March 2002, can estimate global terrestrial water storage (TWS) (Syed et al., 2008), which provides a new opportunity to study the hydrological excitation to polar motion (Jin et al., 2010). However, the GRACE gridded data do not well "understand" high-frequency variations in hydrological excitation due to low temporal–spatial resolutions and high noises in high degree coefficients. Also the TWS estimates from GRACE are subject to the de-striping, gridded mapping and filter smoothing methods as well as aliasing errors (e.g., Jin et al., 2011). In this paper, the hydrological contributions to polar motion are investigated at seasonal and intra-seasonal time scales using the recovered degree-2 harmonic coefficients from all GRACE spherical harmonic coefficients (August 2002–August 2010). Furthermore, the hydrological excitations are compared and assessed from hydrological models using the same filtering and recovering methods, including the GLDAS, CPC, NCEP and ECMWF operation model.

Table 1
Amplitude and phase of annual and semi-annual variations of hydrological polar motion excitations (P_x, P_y) from geodetic observation residual, GRACE and models.[a]

Polar motion	Annual P_x		Semi-annual P_x		Annual P_y		Semi-annual P_y	
	Amp (mas)	Phase (°)	Amp (mas)	Phase (°)	Amp (mas)	Phase (°)	Amp (mas)	Phase (°)
GAO	5.09 ± 0.20	58.69 ± 2.25	1.19 ± 0.20	−7.57 ± 9.58	6.89 ± 0.25	62.38 ± 2.05	4.67 ± 0.25	126.71 ± 3.00
GLDAS	2.42 ± 0.08	−41.09 ± 1.79	0.63 ± 0.08	130.08 ± 6.78	3.18 ± 0.09	23.52 ± 1.53	1.22 ± 0.08	153.00 ± 3.98
CPC	0.84 ± 0.03	1.89 ± 2.11	0.31 ± 0.03	140.28 ± 5.60	5.33 ± 0.04	23.40 ± 0.41	0.60 ± 0.04	−172.12 ± 3.68
NCEP	8.19 ± 0.03	36.55 ± 0.24	6.56 ± 0.03	−157.23 ± 0.30	20.32 ± 0.09	−115.44 ± 0.25	2.65 ± 0.09	−160.65 ± 1.94
opECMWF	4.04 ± 0.09	−54.29 ± 1.24	0.51 ± 0.09	−155.75 ± 9.83	12.10 ± 0.16	50.65 ± 0.74	2.07 ± 0.15	−174.51 ± 4.3
GRACE	4.61 ± 0.28	56.29 ± 3.49	2.82 ± 0.28	−37.10 ± 5.70	6.72 ± 0.29	83.01 ± 2.47	2.13 ± 0.29	132.67 ± 7.75

[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, 2002 and p is the period. Amp is amplitude, mas is milli-arc-second, GAO (Geod-AAM-OAM) is the geodetic observation residual of non-atmospheric and non-oceanic excitations. GLDAS is the hydrological excitation from the GLDAS model, CPC is the CPC model estimate, NCEP is the NCEP model estimate, opECMWF is the hydrological excitation from the ECMWF operational model and GRACE is the hydrological excitation from the recovered GRACE gravity field degree-2 harmonic coefficients.

2. Hydrological excitation of polar motion

The excitation χ of polar motion (P_x and P_y) can be expressed as an integral of gridded fluids mass and motion (e.g. Eubanks, 1993), including surface pressure term (χ^p) and atmospheric winds or ocean currents term (χ^m) [Jin et al., 2010]:

$$\chi^p = \chi_1^p + i\chi_2^p = \frac{-1.0980\bar{R}^4}{g(C-A)} \iint p\ \sin\theta\cos^2\theta\, e^{i\phi}\, d\phi\, d\theta \tag{1}$$

$$\chi^m = \chi_1^m + i\chi_2^m = \frac{1.5913\bar{R}^3}{g\Omega(C-A)} \iiint (u\ \sin\theta + iv)\cos\theta\, e^{i\phi}\, dp\, d\phi\, d\theta \tag{2}$$

where χ_1 and χ_2 are the excitations of polar motion P_x and P_y, respectively, p is the pressure term (mass term), m is the motion term (atmospheric wind or ocean currents), g is the gravitational constant, $\bar{R}$ and Ω are the mean radius and mean rotation rate of the Earth, respectively, C and A are the Earth's axial and equatorial principal moments of inertia, respectively, θ, ϕ and t are the latitude, longitude and time, respectively, u and v are the eastward and northward motion velocities (e.g. wind or ocean current), and the coefficients 1.098 and 1.591 3 account the total influences of the rotational deformation, surface loading and core-mantle decoupling (Barnes et al., 1983). The hydrological excitation of polar motion can be calculated using the terrestrial water storage in place of p in Eq. (1), including soil water, ground water and snow/ice sheets from measurements or models.

Since surface mass variations can be represented by the spherical harmonics coefficient of the geopotential (e.g., Chao and Gross, 1987), one can derive the following relationship between surface mass excitation (χ^p) and the variations of the normalized spherical harmonic coefficients of the gravitational potential (ΔC_{21}, ΔS_{21}) as (Chen and Wilson, 2008)

$$\chi_1^p = -\sqrt{\frac{5}{3}}\frac{1.098\bar{R}^2 M}{(1+k_2')(C-A)} \cdot \Delta C_{21} \tag{3}$$

$$\chi_2^p = -\sqrt{\frac{5}{3}}\frac{1.098\bar{R}^2 M}{(1+k_2')(C-A)} \cdot \Delta S_{21} \tag{4}$$

where M and $\bar{R}$ are the mass and mean radius of the Earth, respectively, and $k_2' = -0.301$ is the degree-2 load Love number. Therefore, the hydrological excitation to polar motion can be determined using the degree-2 harmonic coefficients of the gravity field.

3. Data and models

3.1. Hydrological excitation from GRACE

The hydrological excitations to polar motion can be estimated from the GRACE-derived spherical harmonics coefficient of the geopotential. However, the original GRACE spherical harmonics coefficients are subject to the north–south stripes correlated errors and noises. The gridded terrestrial water storage (TWS) estimated from the latest GRACE time-varying gravity field coefficients (Release-04) with degree and order of up to 60 (available from the GRACE Tellus Web site: http://gracetellus.jpl.nasa.gov/data/mass/) provided an opportunity to investigate the hydrological excitation

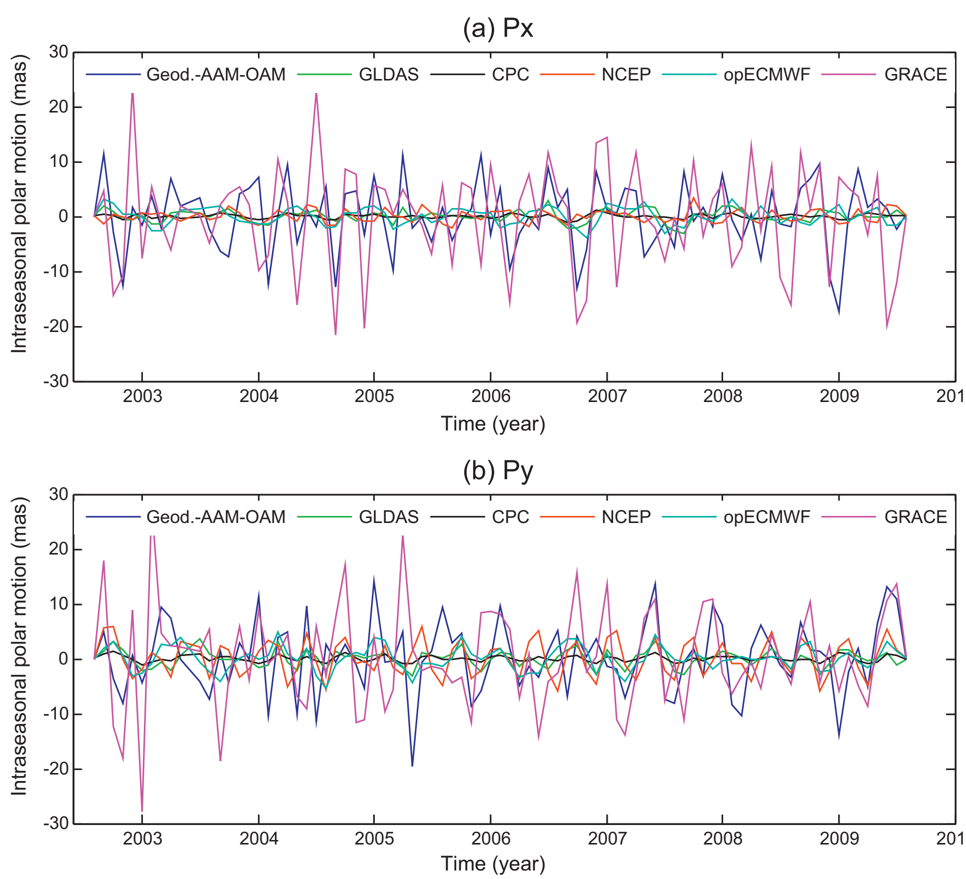

Fig. 2. Intraseasonal hydrological excitations of polar motion P_x (a) and P_y (b) from geodetic observation residual Geod.-AAM-OAM (blue line), GLDAS (green line), CPC (black line), NCEP (red line), opECMWF (cyan line) and GRACE (magenta line). The Mean, trend, annual, semi-annual and periods longer than 1-year have been removed from all time series by least squares fitting and a high-pass filter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

of polar motion. However, the GRACE-derived TWS data gave mixed results (Jin et al., 2010). On one hand, using GRACE it is more difficult to model high-frequency variations in hydrology, particularly in regional basins due to the limited spatial resolution and large noises in high degree coefficients. On the other hand, when the spherical harmonics from GRACE are converted into gridded TWS maps, the hydrology estimate from GRACE depends on the complex post-processing de-striping algorithm, gridded mapping and filter smoothing methods as well as masking spatial leakage aliases between land and oceans. The induced bias of the annual amplitude can reach as large as 3 cm at some basins using different smooth and filtering strategies (Werth et al., 2009). Therefore, the gridded TWS from GRACE using different filter smoothing algorithms and methods probably affect the hydrological excitation of polar motion, particularly in high-frequency variations.

Here the normalized Stokes mass coefficients are recovered from surface density or equivalent water thickness estimated from all GRACE gravity field coefficients as:

$$\left\{\begin{array}{c}\Delta\hat{C_{lm}}\\ \Delta\widehat{S_{lm}}\end{array}\right\} = \frac{1}{4\pi\bar{R}\rho_w}\int_0^{2\pi} d\phi \int_0^{\pi} \sin\ \theta\, d\theta \times \Delta\sigma(\theta,\phi)\widetilde{P_{lm}}(\cos\theta) \times \left\{\begin{array}{c}\cos(m\phi)\\ \sin(m\phi)\end{array}\right\} \quad (5)$$

where $\Delta\sigma(\theta,\phi) = \frac{a\rho_{ave}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l} W_l\tilde{P}_{lm}(\cos\theta)(2l+1)/(1+k_l)(\Delta C_{lm}\cos(m\phi) + \Delta S_{lm}\sin(m\phi))$ is the surface density variation estimated from all GRACE gravity field coefficients, and W_l is the degree l Gaussian averaging function, ρ_w is the density of water, ρ_{ave} is the average density of the Earth, $\widetilde{P_{l,m}}$ is normalized Legendre functions of degree l and order m, k_l is Love number of degree l. The 500 km width of Gaussian filter is used to reduce the errors at high degrees (Swenson and Wahr, 2006). The monthly GRACE solutions (Release-04) from the Center for Space Research (CSR) at the University of Texas, Austin are used from August 2002 until August 2010, except for June 2003 without data. Through Eqs. (3) and (4), the hydrological excitation to polar motion, (χ_1, χ_2), can be calculated from the recovered spherical harmonic coefficients of the gravity field (ΔC_{21}, ΔS_{21}).

3.2. GLDAS model

GLDAS has been jointly developed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). GLDAS provides the land surface state (e.g., soil moisture and surface temperature) and flux (e.g., evaporation and sensible heat flux) products, including a set of 1.0° resolution data products from 1979 to the present and a 0.25° data product from the Noah Land Surface model from 2000 to the present, but does not cover areas from a latitude of 60°S southwards (Rodell et al., 2004). The harmonic coefficients with degree and order of up to 60 are obtained from the 1.0° 3-h data, i.e., GLDAS_NOAH10SUBP_3H (http://disc.sci.gsfc.nasa.gov/services/grads-gds/gldas), using the same filter smoothing methods as the GRACE. The hydrological excitation to polar motion is calculated from the GLDAS recovered harmonic coefficients. The total canopy water storage is not

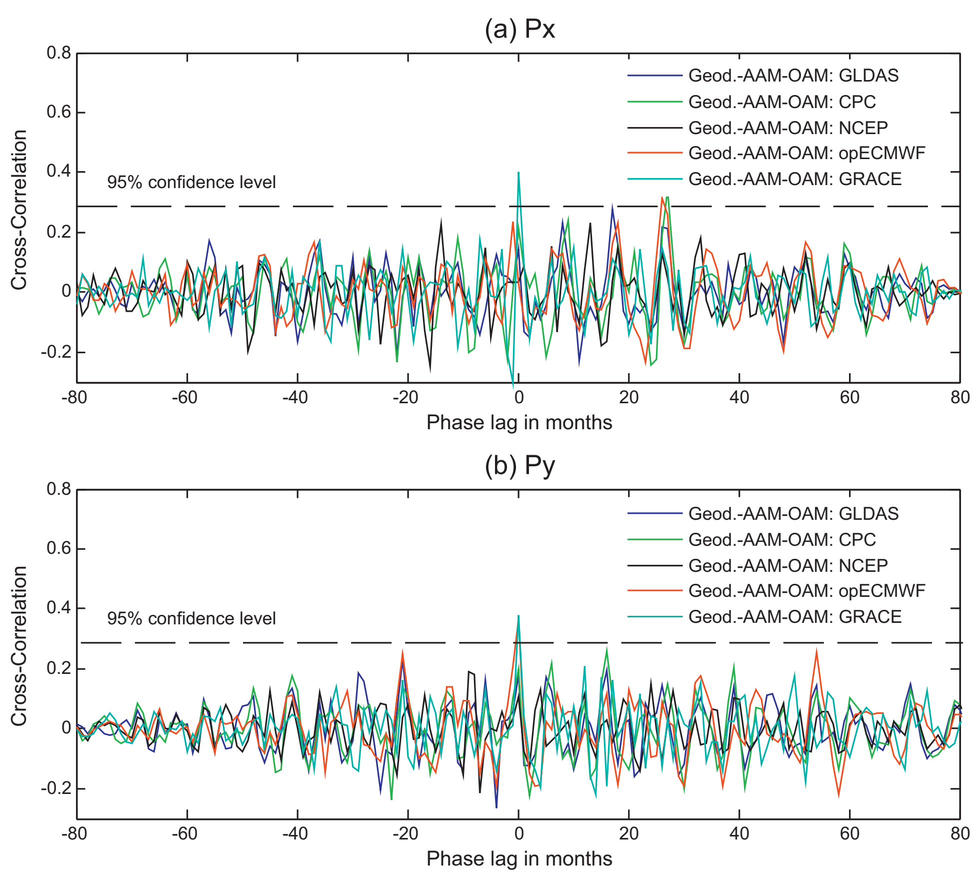

Fig. 3. Cross correlation coefficients on the intraseasonal excitations of polar motion P_x (a) and P_y (b) between geodetic observation residual Geod.-AAM-OAM and hydrological excitations from GLDAS (blue line), CPC (green line), NCEP (black line), opECMWF (red line) and GRACE (cyan), respectively. The two dashed lines in (a) and (b) represent the 95% confidence levels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

included as its changes are very small and negligible compared with the uncertainties of other major components (Rodell et al., 2002).

3.3. CPC model

The CPC hydrological model is a global land surface data assimilation system, which is forced by global precipitation over land from over 17,000 gauges worldwide, global temperature from global reanalysis, surface pressure, humidity and horizontal wind speed from NCEP reanalysis (Fan and van den Dool, 2004). The output contains the global monthly soil moisture, evaporation, and runoff from January 1948 to present (http://www.esrl.noaa.gov/psd/data/gridded/data.cpcsoil.html), excluding Antarctica and Greenland. Hydrological excitations to polar motion are calculated using the harmonic coefficients estimated from CPC soil water storage data with the same filter smoothing methods.

3.4. NCEP model

The NCEP/NCAR re-analysis provides the various climatological parameters, such as daily soil moisture and snow water from 1948 to the present (Kalnay et al., 1996) (ftp://ftp.cdc.noaa.gov/Datasets/ncep.reanalysis2.dailyavgs/gaussian_grid/). The resolution of Gaussian grid is $1.875 \times \sim 1.904$ degrees in the horizontal (192×94 Gaussian grid points with approximately 200 km horizontal spacing). The soil water has two layers at 10 and 190 cm thickness, respectively. The terrestrial water storage as equivalent water thickness (in cm) is obtained using the pre-factors from the NCEP/NCAR soil water (in volumetric fraction) and snow water (kg m^{-2}). The hydrological excitations of polar motion (P_x, P_y) are then computed using the harmonic coefficients estimated from NCEP/NCAR Reanalysis soil moisture and snow accumulation data with the same filter smoothing methods. Here contributions from Antarctica and Greenland are excluded due to the lack of data.

3.5. ECMWF operational model

The ECMWF provides the climatic data and products for weather forecasting and modelling of the global atmosphere and ocean. The global hydrological land surface discharge model (LSDM) has been developed on the basis of the hydrological discharge model with near real-time input data of daily precipitation, evaporation and temperature from the ECMWF operation model (Dill, 2008), which provides global water storage variations and water flows, groundwater and soil moisture, as well as water accumulated as snow and ice. The hydrological excitation to polar motion has been estimated from hydrological model LSDM forced by the ECMWF operational model (opECMWF) (Dobslaw et al., 2010).

3.6. Geodetic polar motion excitations

The International Earth Rotation and Reference systems Service (IERS) provides high-precision Earth Orientation Parameter (EOP) time series (IERS C04) through using improved algorithms from the combination of individual EOP series derived from Global Positioning System (GPS), Satellite Laser Ranging (SLR), and Very Long Baseline Interferometry (VLBI), fully consistent with the

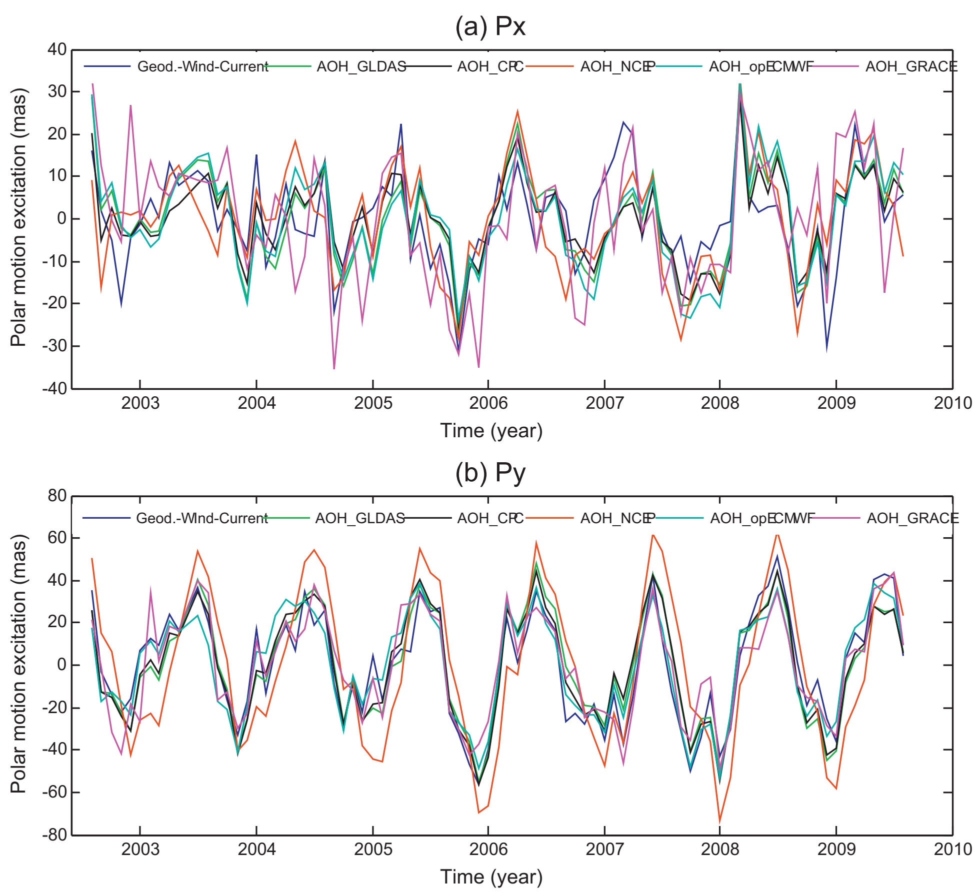

Fig. 4. Total mass excitation time series of polar motion from geodetic observation residual Geod-Wind-Current (blue line) and atmospheric-ocean-hydrological mass excitations (AOH) from the GLDAS (green line), CPC (black line), NCEP (red line), opECMWF (cyan line) and GRACE (magenta line), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

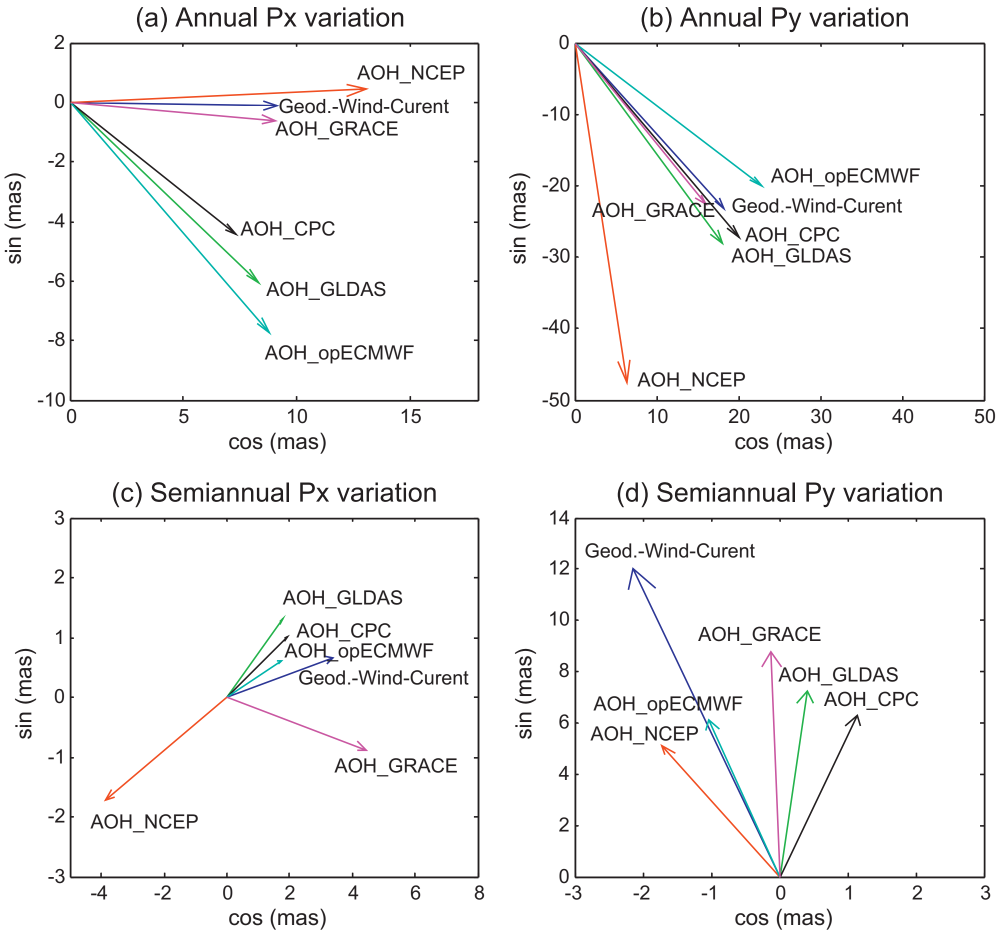

Fig. 5. Phaser plots of annual P_x (a), annual P_y (b), semi-annual P_x (c), and semi-annual P_y (d) excitation variations from geodetic observation residual Geod.-Wind-Current (blue line) and atmospheric-ocean-hydrological (AOH) mass excitations from GLDAS (green line), CPC (black line), NCEP (red line), opECMWF (cyan line) and GRACE (magenta line), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

International Terrestrial Reference Frame (ITRF) 2005 [http://hpiers.obspm.fr/iers/eop/eopc04_05/C04_05.guide.pdf]. The full geodetic polar motion excitations (Geod.) are derived from geodetic observations of polar motion using the discrete equation (Wilson, 1985). The atmospheric pressure and wind contributions estimated from the NCEP–NCAR reanalysis products (Salstein, 1993) are available at the IERS Special Bureau for the Atmosphere (SBA), i.e. Atmospheric Angular Momentum (AAM). The ocean mass and ocean currents excitation (i.e. Ocean Angular Momentum, OAM) 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/). The geodetic residual of total atmospheric-ocean-hydrological (AOH) mass excitations can be obtained after removing the atmospheric wind and oceanic currents contributions from the full geodetic excitations. Here the excitations of mass redistributions on other earth sub-systems (e.g., anthroposphere, crust, mantle, outer/inner core) are not considered.

4. Results and discussions

Since geodetic and GRACE excitations have common atmosphere and ocean mass contributions, the geodetic residual of non-atmospheric and non-oceanic excitations are obtained through removing the common excitations from GRACE GAC products estimated from European Center for Medium-range Weather Forecasts (ECMWF) model and Ocean Model for Circulation Tides (OMCT) baroclinic model. The geodetic residuals of non-atmospheric and non-oceanic excitations and hydrological excitations time series (August 2002–August 2010) are shown in Fig. 1. The blue line is the geodetic residual of non-atmospheric and non-oceanic excitations of polar motion (Geod.-AAM-OAM), the green line is the hydrological excitation from GLDAS model, the black line is the estimate from CPC model, the red line is from NCEP model, the cyan line is from the opECMWF model and the magenta line is the GRACE estimate. The excitation time series from models and geodetic observation are normally with a sampling of 3 h to 1-month, while GRACE presents a monthly solution. These time series are smoothed by a 30-day sliding window, and resampled at the same 1-month interval as GRACE results. In the following, the hydrological excitations to polar motion at seasonal and intraseasonal time scales are analyzed and compared.

Using the method of least squares fit to a bias, trend, and seasonal period sinusoids, the amplitude and phase of annual and semiannual variations of the hydrological polar motion excitations are estimated from geodetic observation residuals and excitation time series (August 2002–August 2010). Table 1 lists the amplitude and phase of annual and semiannual variations with their uncertainties for the polar motion excitations from geodetic observation residual, GRACE and hydrological models. For the annual P_x excitations, the amplitudes and phases from GRACE and NCEP model excitations are much close to the geodetic residuals of non-atmospheric and non-oceanic excitations, while the GLDAS, CPC and opECMWF models' estimates are all worse to explain the geodetic residuals with a larger phase shift and amplitude bias (e.g., Hengst, 2008). The best agreement with the observed residuals is

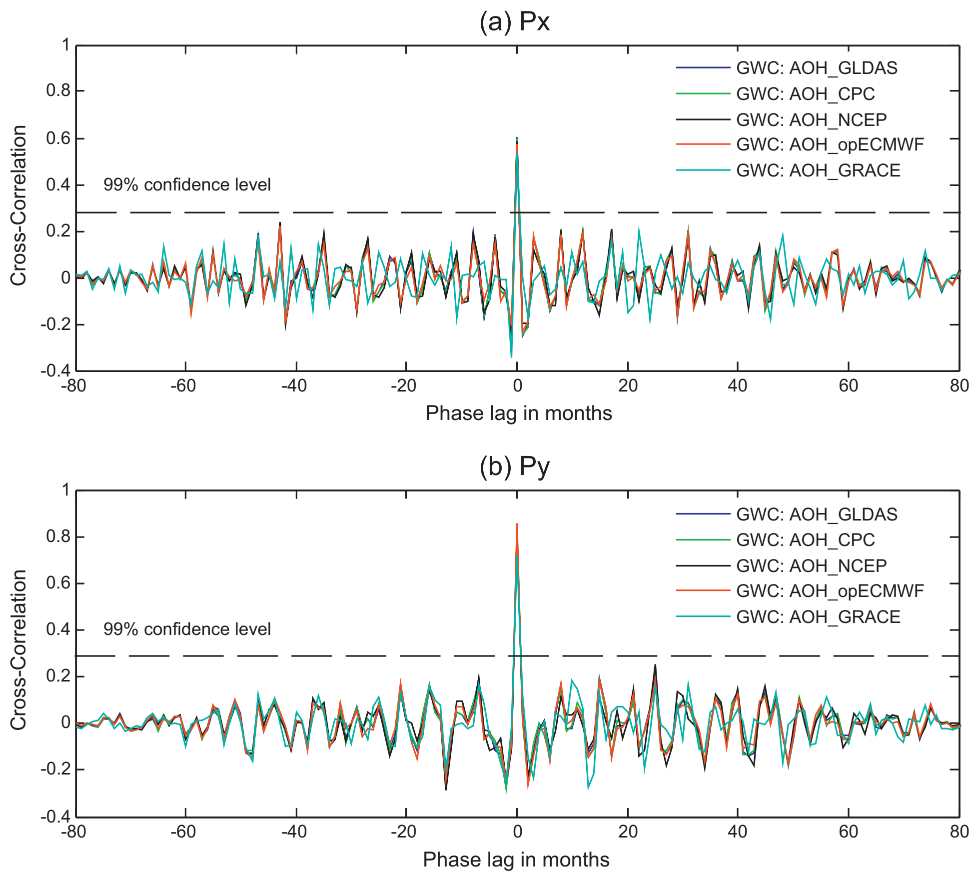

Fig. 6. Cross correlation coefficients on the intraseasonal excitations of polar motion (a) P_x and (b) P_y between geodetic observation residual Geod.-Wind-Current (GWC) and atmospheric-ocean-hydrological (AOH) mass excitations from GLDAS (blue line), CPC (green line), NCEP (black line), opECMWF (red line) and GRACE (cyan line), respectively. The two dashed lines in (a) and (b) represent the 95% confidence levels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

the estimate from GRACE in phase and the amplitude. At the semi-annual period for the P_x excitations, no models explain the geodetic residuals well.

For the annual P_y excitations, GRACE is still better for explaining the geodetic residual, while the NCEP estimate is completely out of phase and the amplitude of the opECMWF estimate is twice the geodetic residual. At the semi-annual P_y excitation, the GRACE estimate is closer to the geodetic residual although the amplitudes are smaller, and the CPC, NCEP and opECMWF are worse in explaining the semi-annual Py excitation. These show again that the hydrological models have larger uncertainties to explain polar motion excitation due to the lack of global direct measurements of hydrological parameters and uncovering global land areas. For example the NCEP Re-analysis as a fixed data assimilating numerical model is mainly for atmospheric and climatological studies, rather than hydrological cycle (Schmidt et al., 2008), NCEP model provides the soil moisture and snow accumulation data without Antarctica and Greenland and CPC model only provides soil moisture data. Furthermore, most hydrological models cannot represent the complete hydrological variation, e.g., without solid glacier water and ground water. Additionally, the hydrological models have the problems of inconsistent combination of data sets (e.g. mass and energy balance). Therefore, the continental water excitation to polar motion from the hydrological models is up to now the component with the largest uncertainty (Göttel, 2008). While the GRACE has provided a new estimate of global total water storage variations, so it is better to explain the geodetic residuals of non-atmospheric and non-oceanic excitations.

The intraseasonal polar motion excitations with more than 1-month are further examined after removing the first annual and semi-annual signals estimated in Table 1 and then over 1-year period terms using a high-pass filter with a cutoff frequency of 1 cycle/year from all polar motion excitations time series. Fig. 2 is the intraseasonal hydrological polar motion excitation time series (a) P_x and (b) P_y from geodetic observation residual Geod.-AAM-OAM (blue line), GLDAS (green line), CPC (black line), NCEP (red line), opECMWF (cyan line) and GRACE (magenta line). In order to quantify which excitations agree better with geodetic residual excitation at intraseasonal scales, we have computed cross correlation coefficients (Fig. 3), where the dashed lines represent the 95% confidence levels calculated from the upper 5% point of the *F*-distribution. The maximum correlation coefficients at the zero phase lag between the GRACE/models estimates and geodetic residual are generally less than 0.4 at intraseasonal P_x and P_y excitations, and the GRACE and opECMWF model are a little better than others. This indicates that the larger 1–3-month period fluctuations from the GRACE and models estimates do not explain well the direct high-frequency variations of the observed polar motion excitations due to the lack of highly frequent hydrological observations and other noises. The terrestrial water storage from GRACE gave worse explanations in intra-seasonal polar motion excitation (Jin et al., 2010), since most high frequency information may be smoothed or filtered during the TWS retrieval procedure from GRACE gravity field coefficients.

The total mass contributions to polar motion among the atmosphere, ocean and continental water are further investigated. Fig. 4 shows monthly time series of total mass excitation to polar motion from geodetic observation residual Geod-Wind-Current (GWC)

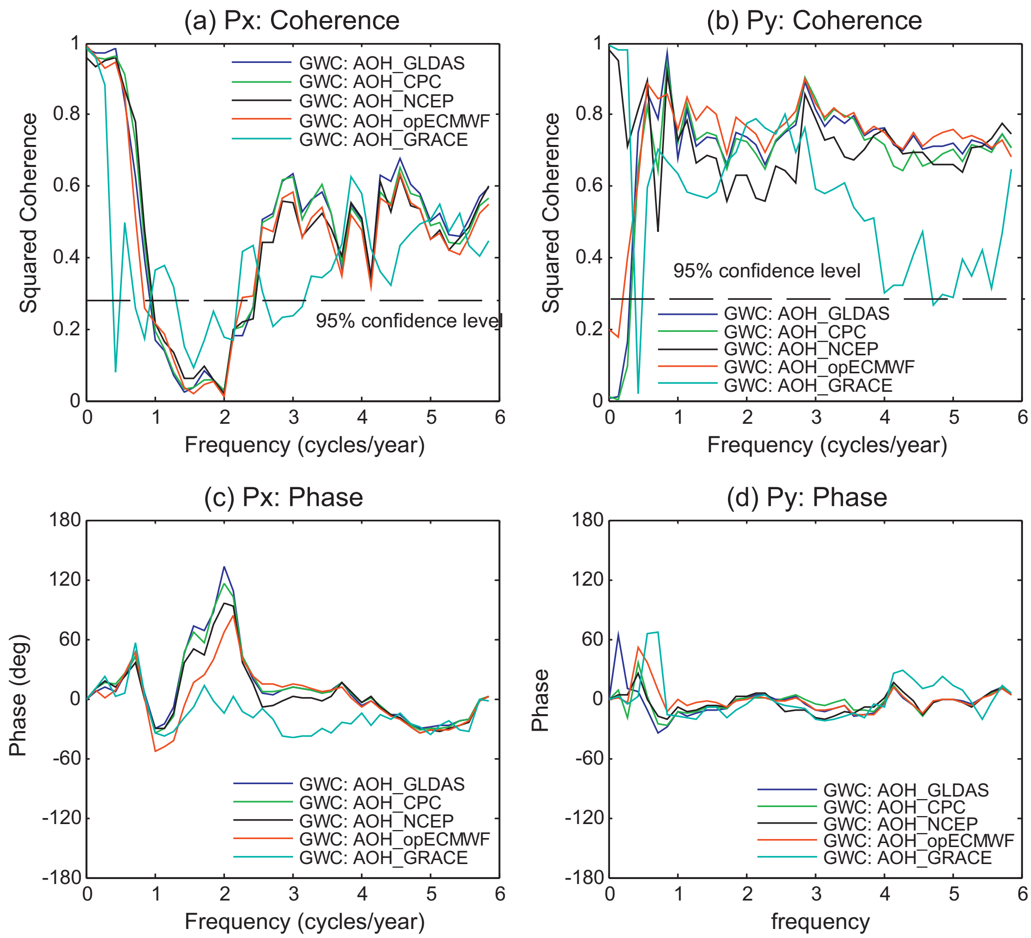

Fig. 7. Magnitude and phase of the squared coherence of geodetic observation residual Geod.-Wind-Current (GWC) with GRACE and models estimates. Annual, semiannual, and periods longer than 1-year have been removed from all time series by least squares fitting and high-pass filter. A mean and trend are also removed. The dashed lines in (a) and (b) represent the 95% confidence levels.

(blue line) and atmospheric-ocean-hydrological (AOH) mass excitations from GLDAS (green line), CPC (black line), NCEP (red line), opECMWF (cyan line) and GRACE (magenta line), respectively. At seasonal total mass excitation of polar motion, the GRACE gives a relatively better explanation at annual and semiannual scales, while models are relatively worse with a larger phase shift or amplitude bias, particularly in NCEP model with out of phase at semiannual P_x excitation (Fig. 5). The maximum correlation coefficients at the zero phase lag are very close between the geodetic residual and excitations from GRACE and models (Fig. 6), while GRACE and opECMWF model are a little better than others at intraseasonal P_x and P_y excitations. However, the squared coherence is lower from GRACE at less than 4 months (Fig. 7), indicating that GRACE is worse in explaining the polar motion excitation at high frequencies, particularly in P_y with less than 4 months.

5. Conclusion

The terrestrial water excitations to polar motion have been investigated and assessed at seasonal and intra-seasonal time scales using the recovered degree-2 harmonic coefficients from all GRACE spherical harmonic coefficients and hydrological models data with the same filter smoothing and recovering methods, including the GLDAS, CPC, NCEP and opECMWF models. For the annual polar motion excitations, the results from the GRACE estimate are closer to the geodetic residuals of non-atmospheric and non-oceanic excitations at amplitudes and phases, while the models' estimates are worse for explaining the geodetic residuals with a larger phase shift or amplitude bias, particularly in NCEP model with out of phase in annual P_x excitation. At the semi-annual P_x and P_y excitations, the GRACE estimates are generally closer to the geodetic residual, but there are still some biases in phase or amplitude. These may be related to some aliasing errors at near semi-annual period from geophysical models, which affect the GRACE estimates in the semi-annual polar motion excitations. In addition, for the periods less than 1-year, excitations from the hydrological models and GRACE are generally worse in explaining the intra-seasonal polar motion excitations with cross correlation coefficients of less than 0.4, while the GRACE and opECMWF models are a little better. In addition, in a mass balanced Earth system with all atmosphere, ocean, and continental water mass, GRACE also gives a better explanation in seasonal polar motion excitations. However, GRACE is still worse in explaining the polar motion excitation at high frequencies, particularly in P_y with less than 4 months.

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