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Research Article

Hydrological Excitation of Polar Motion Derived from GRACE Gravity Field Solutions

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The influence of the continental water storage on the polar motion is not well known. Different models have been developed to evaluate these effects and compared to geodetic observations. However, previous studies have shown large discrepancies mainly attributed to the lack of global measurements of related hydrological parameters. Now, from the observations of the GRACE mission, we can estimate the polar motion excitation due to the global hydrology. Data processing of GRACE data is carried out by several centers of analysis, we focus on the new solution computed by the Groupe de Recherche de Géodésie Spatiale. At annual scales, excitations derived from GRACE data are in better agreement with geodetic observations than models estimates. The main contribution to the hydrological excitation comes from the monsoon climates regions where GRACE and models estimates are in a very good agreement. Still, the effect of the north high latitudes regions, where the principal areas of snow cover are found, cannot be neglected. At these regions, GRACE and models estimated contributions to polar motion excitations show significant discrepancies. Finally, GRACE-based excitations reveal the possible influence of water storage variations in exciting polar motion around the frequency of 3 cycles per year.

1. Introduction

The excitation of polar motion is, to a large extent, related to the mass redistribution of geophysical fluids. The importance of atmospheric and oceanic angular momentum signals at monthly and seasonal periods is well known. The contribution of the continental hydrological signals, originating from land water, snow, and ice, is, however, less known. A number of previous studies have estimated hydrological excitation from climatological measurements, numerical climate models, and global hydrology models based upon the observed distribution of surface water, snow, ice, and soil moisture [1–5].

The hydrological part of polar motion excitation can also be obtained, as a residual series, by removing atmospheric and oceanic signals from the geodetic excitation of polar motion. The general conclusion of these studies is that the change in continental water storage plays a major role in the seasonal polar motion although the results of the hydrological models do not agree with each other and with observed polar motion [6, 7]. This is mainly due to the lack of global measurements of related hydrological parameters which are difficult to predict (like evaporation, run-off, groundwater, and snow/ice mass change).

Other analyses show that hydrological signals seem to exert a substantial influence at interannual scales [7, 8].

Thanks to the gravity recovery and climate experiment (GRACE) mission, the mass redistributions are observed over whole Earth. Atmospheric mass variations and the corresponding oceanic response are largely removed during GRACE data processing, then the obtained time-variable gravity fields reflect hydrological phenomena (i.e., terrestrial water storage variations from the soil water, groundwater, and snow/ice sheets) plus other non-modeled effects like postglacial rebound, earthquakes, and baroclinic oceanic signal. Thus, considering gravity field variations over continents mainly due to water and ice mass change, we have a new approach to evaluate the effect of the continental Earth's hydrology on polar motion. Other studies [9] show that GRACE observations are useful to evaluate oceanic and hydrological polar motion excitations in order to close global mass budget.

Our main objective is to compare the hydrological excitations computed from different data sets to better understand the influence of water mass variations on polar motion. Additionally, GRACE can help to located significant hydrological mismodelling effects. The data sets used in our study are geodetic observations of polar motion (IERS C04 polar motion series), GRACE gravity field solutions provided by the Groupe de Recherche de Géodésie Spatiale (GRGS), the Climate Prediction Center (CPC) [10] hydrological model, and the newer surface modelling system global land data assimilation system (GLDAS) [11].

2. Data Sets

2.1. Hydrological Models. Latitude-longitude grids providing the charge of continental water by surface unit are predicted by the CPC and the surface model GLDAS.

The CPC uses the Noah land surface model [10] forced by observed precipitation derived from CPC daily and hourly precipitation analyses, downward solar and long-wave radiation, surface pressure, humidity, temperature, and horizontal wind speed from the atmospheric model reanalysis of the National Centers for Environmental Prediction (NCEP). The net water storage Δq at a grid point is estimated using the conservation equation [12]

$$\Delta q = P - E - R, \tag{1}$$

where P, E, and R are precipitation, evapotranspiration, and run-off. CPC water storage grids are estimated from January 1948 to December 2007 with a monthly resolution.

The GLDAS generates optimal fields of land surface states and fluxes by integrating ground- and satellite-based observational data products, using advanced land surface modelling and data assimilation techniques [11]. GLDAS has resulted in a massive archive of modelled and observed global surface meteorological data, parameter maps, and output which includes 1 and 0.25 degrees resolution of the 1979 to present simulations of the Noah, community land (CLM), mosaic, and variable infiltration capacity (VIC) land surface models [13]. In this case, water storage is the sum of soil moisture, snow water equivalent, and canopy surface water not counting changes in groundwater below the depth defined by the model [12], that is, variations below 2 meters depth. Hydrological excitation functions can be computed from the monthly fields of global water storage from January 1979 to February 2008.

2.2. Gravimetric Data. The GRACE time-variable gravity field solutions of the GRGS are provided at 10 day intervals from July 29 2002 to May 27 2008 in the last release RL02 [14]. They use a different data processing strategy than those applied by the other analysis centers (CSR, GFZ, and JPL). The GRGS gravity field solution is computed by a combination of GRACE and LAGEOS-1 and 2 observations. LAGEOS data provide over 90% of the information on the (2,0) degree coefficients [14]. GRACE data provide nearly 100% of the information on all other harmonic coefficients. A different background model is used mainly concerning the nontidal oceanic model. The GRGS uses a barotropic oceanic model Modèle 2D d'Ondes de Gravité (MOG2D). Lastly, it is known that the geoid's height difference plots show a north-south streaking due to systematic errors in higher degree coefficients. To avoid this problem, GRGS constrained the higher degrees coefficients gradually to those of the static solution [15]. The other centers (CSR, GFZ, and JPL) use instead a filtering procedure for avoiding this problem [16].

Usually, the excitation based on gravimetric observations is derived from the C_{21} and S_{21} coefficients of the gravity field solution using the classical methodology (see, e.g., [17]). However, these coefficients contain hydrological variations and also residuals over oceans, in our case, this is a baroclinic signal. In this paper, we propose to estimate the hydrological GRACE-based excitation in a different way employing equivalent water height maps (EWH) restricted to continents in order to exclude oceanic effects. In fact, GRGS provides converted maps into meters of EWH from which we estimate the terrestrial water storage grids by $\Delta q = EWH * \rho$ where $\rho = 1000\,\mathrm{kg\,m^{-3}}$ is the water density.

2.3. Geodetic Residuals. The International Earth Rotation and Reference Systems Service (IERS) provides a combined time series C04 of the Earth Orientation Parameters (EOP) at daily intervals [18, 19], in particular the pole coordinates x and y. The geodetic polar motion excitation in polar motion can be written as

$$\chi = \chi_1 + i\chi_2 = p + i\frac{\dot{p}}{\sigma_c}, \tag{2}$$

where $p = x - iy$ is the complex pole coordinate obtained from C04 series and σ_c is the frequency of the Chandler pulsation ($2\pi/433$ rad/days) with an adopted quality factor of 175 [20]. We derived the geodetic excitation according to Wilson [21].

The hydrological influences are obtained by removing atmospheric and oceanic signals from the geodetic excitation. For computing these geodetic residuals, we use the atmospheric excitation series based on the NCEP/NCAR reanalysis [22] and the oceanic excitation series derived from the ECCO model [23]. In order to match the temporal spectral consistency with GRACE gravity field solutions, geodetic, atmospheric, and oceanic excitations are smoothed using Vondrak filter [24, 25] and interpolated every 10 days.

3. Analysis and Results

3.1. Hydrological Polar Motion Excitations. According to Chen and Wilson [7] formulation, by integrating the grids of water thickness of the CPC and GLDAS models over continents (Greenland and Antarctica are excluded), we have reconstituted the hydrological excitation function reduced to its mass term as follows:

$$\begin{bmatrix}\chi_1\\ \chi_2\end{bmatrix} = \frac{-1.098R_e^4}{C-A}\iint \Delta q\,\sin(\theta)\cos^2(\theta)\begin{pmatrix}\cos\lambda\\ \sin\lambda\end{pmatrix} d\theta d\lambda, \tag{3}$$

where R is the Earth's mean radius, C and A are the Earth's principal moments of inertia, and (θ, λ) is the latitude and

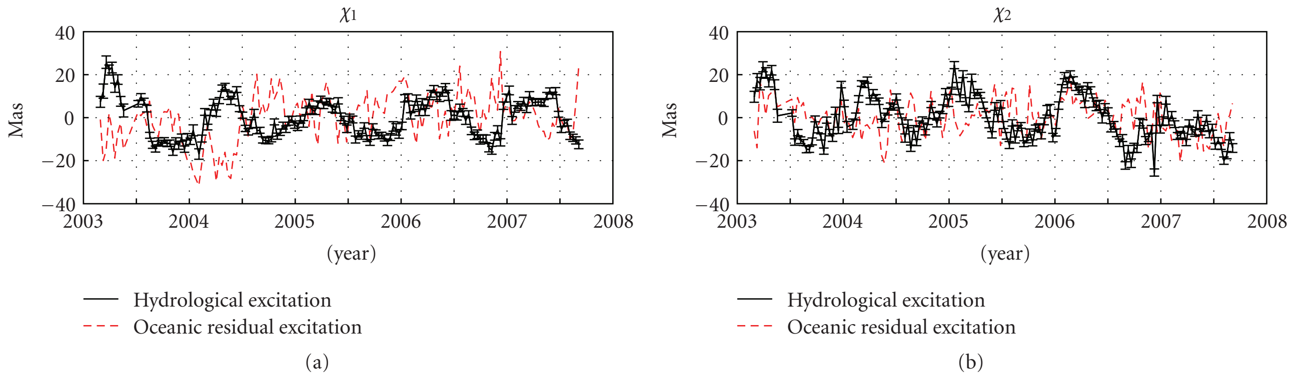

Figure 1: Oceanic residual excitation (mask over continents) and hydrological excitation (mask over oceans) estimated by integrating GRACE equivalent water height grids. We observed a significant oceanic residual signal. Bars represent the calibrated errors provided by the GRGS.

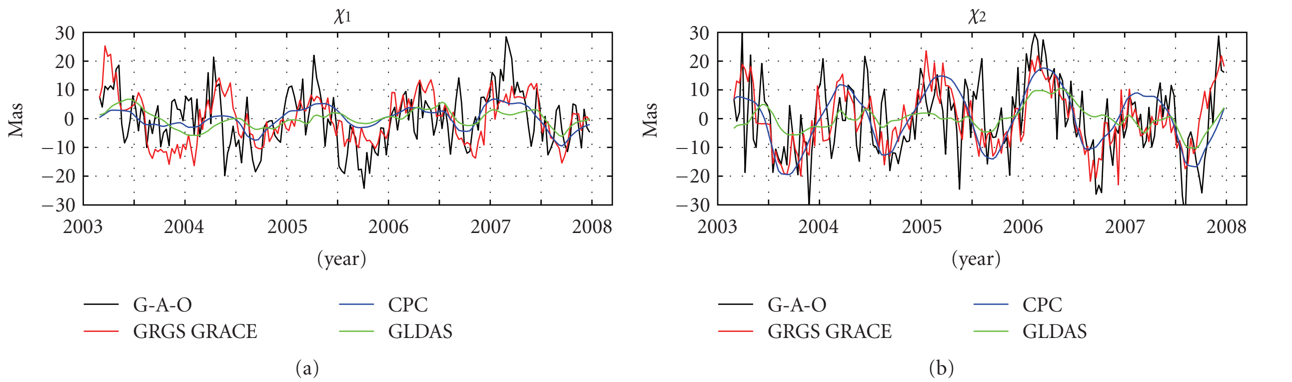

Figure 2: Hydrological excitation functions computed from geodetic residuals (G-A-O), GRACE solutions, and CPC and GLDAS hydrological models. We observe that GRACE-based excitations are well correlated with geodetic residual. We note the large differences between the hydrological models especially in the case of χ_2.

longitude. The factor 1.098 accounts the combined effects of the yielding of the solid Earth to surface load, core-mantle decoupling, and rotational deformation [26]. The series are interpolated to the GRACE temporal resolution. In the same way, that is, integrating over continents the terrestrial water storage derived from GRACE (3), we obtain another approach of the hydrological excitation. From November 2002 to February 2003 are the main GRACE data gaps, and so, our study period is restricted to March 2003 until December 2007, which is the last common date with the hydrological models time span.

Figure 1 shows the estimates of the hydrological excitation (GRACE grids were integrated over continents) and the oceanic residuals (GRACE grids were integrated over oceans only). We can notice significant oceanic variations that we will not consider in our study. Spatial spectral leakage due to using a [0 or 1] mask is expected to be negligible over large regions.

Figure 2 shows the excitation functions obtained from residual geodetic observations, GRACE gravity field solutions, and models estimates. Means and linear trends are removed from all data sets. As expected, we observe that the hydrological signals are dominated by the annual fluctuations. GRACE-based excitations are in agreement with the residual geodetic excitations mainly at annual scales, and both show variations between ±20. Hydrological models underestimate variations, probably because some mismodeled process, except for the χ_2 component derived from CPC.

3.2. Seasonal Variations. Seasonal fluctuations are estimated by least-square fitting (Table 1 and corresponding phaser plots Figure 3). The annual variations of GRACE-based and the residual geodetic excitations are in good agreement for the both components χ_1 and χ_2. Phase differences are more important in the case of χ_1 but not large (23° versus 345°); however, CPC model is closer in phase (23° versus 3°). The χ_1 is more sensitive to the ocean mass redistributions and the uncertainties of the ocean models used for estimating residual geodetic series can probably be a cause of disagreement. To the contrary, χ_2 is affected by the Earth hydrology due to the location of main continents [7]. Whereas, considering the hydrological models predictions with respect to GRACE observations and geodetic residual, there are larger discrepancies in amplitude and the modeled annual signals are generally underestimated. Except for χ_2 computed from the CPC model, which has an amplitude of nearly 3 mas larger than the GRACE estimate. Phases agree

TABLE 1: Amplitude and phase of seasonal variations estimated from geodetic residuals (G-A-O), GRACE, CPC, and GLDAS-based excitations. For the annual variations, we note that GRACE-based excitation reach a better agreement in amplitude with geodetic residuals than the models.[a]

	Annual		Semiannual	
	Amplitude mas	Phase degree	Amplitude mas	Phase degree
χ_1 G-A-O	7.9 ± 1.1	23 ± 8	1.3 ± 1.2	319 ± 54
χ_1 CPC	3.9 ± 0.3	3 ± 4	1.2 ± 0.3	125 ± 16
χ_1 GLDAS	2.2 ± 0.3	311 ± 9	1.1 ± 0.3	120 ± 18
χ_1 GRACE	9.0 ± 0.7	345 ± 4	1.2 ± 0.6	180 ± 27
χ_2 G-A-O	8.6 ± 1.5	20 ± 10	4.2 ± 1.2	90 ± 16
χ_2 CPC	13.0 ± 0.4	18 ± 2	1.9 ± 0.5	156 ± 13
χ_2 GLDAS	2.6 ± 0.4	2 ± 10	1.7 ± 0.6	129 ± 19
χ_2 GRACE	10.0 ± 1.1	27 ± 6	1.6 ± 0.9	174 ± 32

[a]The reference date for the phase is 2004 January 1, 0h UTC.

quite well. In conclusion, the annual hydrological budget estimated by GRACE is more consistent with the geodetic observations than models predictions. In the case of the semiannual oscillations, they have lower amplitudes (up to 4 mas). It seems that there is a reasonably agreement between models predictions and GRACE observations.

Phasor diagram (Figure 3) confirms that GRACE-based excitation is in better agreement at geodetic residuals (phases are similar and amplitude difference is about 2 mas). However in the case of the semiannual signal, GRACE and models-based excitation are in agreement, but geodetic residuals are large different probably due to atmospheric or oceanic models errors at this frequency.

3.3. Regional Hydrology Contributions at Annual Scale. In order to find the Earth's regions, where models CPC and GLDAS do not predict consistent annual variations with respect to GRACE observations, the amplitudes and phases for every grid point are computed by least-square fitting (Figure 4). In Figure 4, we note that the prominent annual signals are due to the monsoonal climates [27] situated at latitudes smaller than $30^\circ N$. The monsoon regions are located in the Amazon, Central Africa, South Africa, North Australia, India, and Indochina. We observe that CPC model provides stronger amplitudes than the GLDAS model. The groundwater storage not counting in the GLDAS model seems to be the cause of the lower amplitudes over major river basins [12]. In fact, GLDAS model is defined with a surface layer of 2 m depth, then groundwater variations below are not taken into account. So, what is the contribution of the monsoonal climate regions to the polar motion excitation? To answer this question, we compute the hydrological excitations restricting the integration of the water storage grids of CPC, GLDAS, and GRACE (see (3)) over those latitudes smaller than $30^\circ N$. Results are shown in Figure 5. As expected, annual oscillations are clearly dominant, and there is a very good agreement between the GRACE observations and models. Generally, the contribution of this Earth domain does not explain the hydrological annual budget found in Table 1, thus influences of the north high latitudes regions must not be neglected. At these latitudes (latitudes $\geq 30^\circ N$), we find the main areas of snow cover and continental climates. We notice the large discrepancies between the hydrological excitations computed from models and GRACE (Figure 5), especially concerning χ_2, come from this region, where models snow water estimations seems to be inaccurate.

3.4. Interannual Polar Motion Excitations. The hydrology plays an important role at low frequencies. Chen and Wilson [7] have shown significant interannual variations which seem to be of hydrological nature. From wavelet analysis of the excitation functions derived from the geodetic residuals and the hydrological model predictions, Fernández et al. [8] have found strong energy values around 4 years in the retrograde band.

For obtaining interannual variations, we remove seasonal signals (annual and semiannual) from geodetic, CPC, GLDAS, and GRACE-based hydrological excitations. Afterward, we applied a low pass digital filter of cutoff frequency 1 year to the residuals. The interannual signals are shown in Figure 6. For the χ_2 component, models and GRACE-based excitations are well correlated with the geodetic residuals (Table 2). Future longer series of GRACE observations and improvements in the data processing can help to gain a greater understanding of the hydrology influences on polar motion at interannual scales.

3.5. Intraseasonal Polar Motion Excitations. Various studies note the important influence of the atmosphere and oceans on polar motion excitations at interseasonal scales [22, 28–31]. Gross et al. [32] have observed that a third of the geodetic excitation was not explained by atmospheric and oceanic phenomenon. They attribute this discrepancy to the uncertainties in the data sets and also to the effect of other excitation process not considered like the continental hydrology. However, models do not predict enough power at those frequencies. To obtain the intraseasonal variations we removed from all series the annual, semiannual signals, and low frequency fluctuations. The latter are estimated in

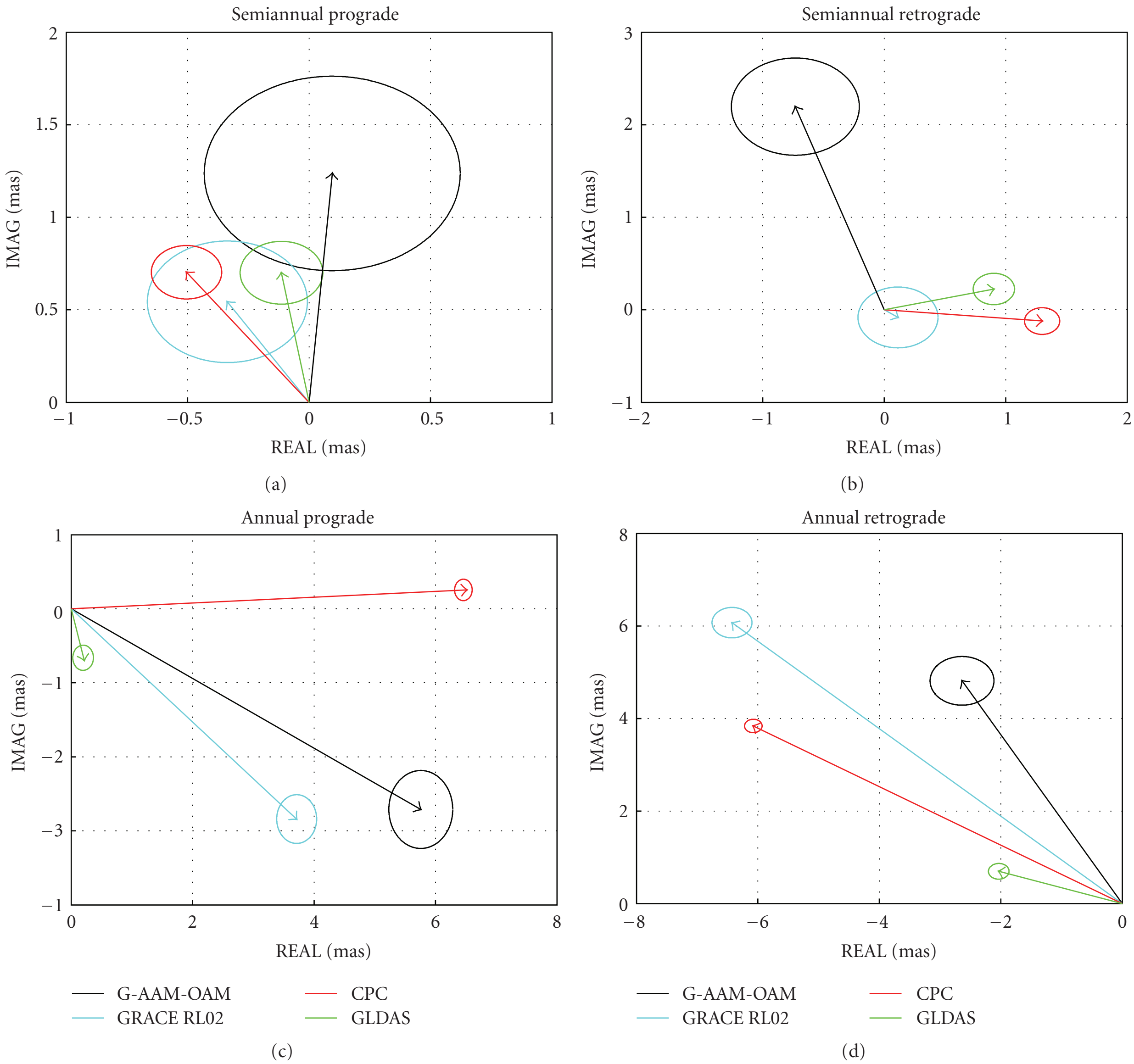

Figure 3: Phasor diagram of seasonal variations. Circles represent the formal errors.

Table 2: Correlations between the polar motion interannual variations estimated from geodetic residuals, GRACE solutions, and CPC and GLDAS hydrological models. Correlation values are better for χ_2 than χ_1. This discrepancy is possibly caused by errors of the oceanic model removed from the geodetic observations.[a]

	Percentage of explained variance		Correlation			
					$\chi_1 + i\chi_2$	
	χ_1	χ_2	χ_1	χ_2	Magnitude	Phase degree
G-A-O/GRACE	−7	40	0.3	0.7	0.6	−34
G-A-O/CPC	9	37	0.3	0.6	0.6	−25
G-A-O/GLDAS	11	45	0.3	0.7	0.6	−22
GRACE/CPC	−22	34	0.2	0.6	0.6	27
GRACE/GLDAS	37	4	0.6	0.4	0.5	23

[a] According to the Student-t test, the 90% significance level of correlation is 0.17. The standard error of the difference between two values of correlation is 0.19. G-A-O: geodetic residuals (geodetic-atmospheric-oceanic excitations), GRACE: GRACE solutions of GRGS, CPC, and GLDAS: hydrological excitations.

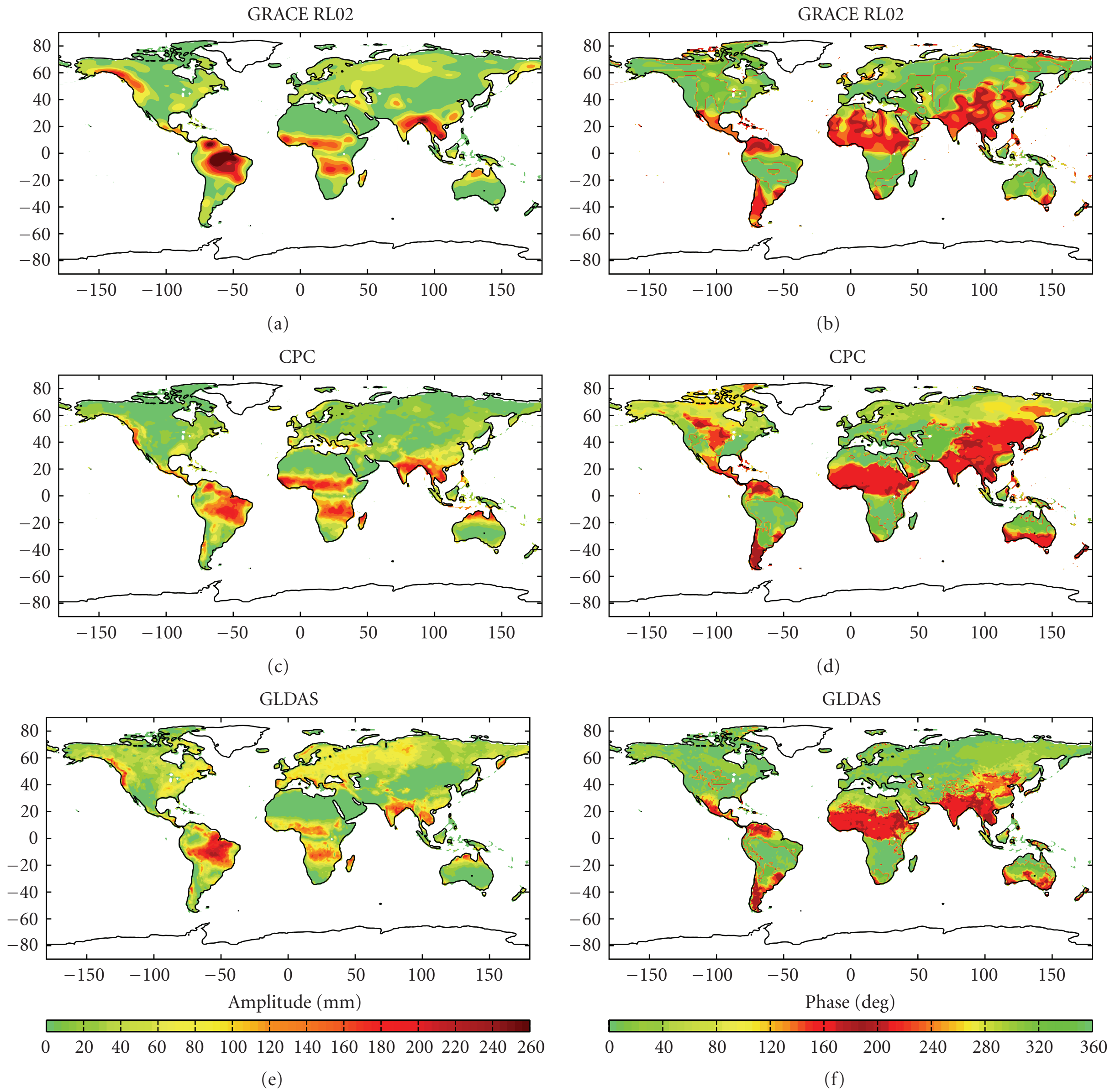

Figure 4: Amplitudes (left column) and phases (right column) of annual oscillations at every grid point computed from GRACE solutions and CPC and GLDAS models. The reference date for the phase is 2004 January 1, 0h UTC. The prominent annual signal are located in the monsoon regions.

the previous section. Figure 7 shows the spectrum of the different hydrological excitation data sets. GRACE observations provide more power than hydrological models, especially in the prograde and retrograde bands around the frequency of 3 cycles per year. At those frequencies, the power of the hydrological excitation derived from GRACE is comparable to those derived from geodetic residual and the hydrology seems to be a nonnegligible process of intraseasonal polar motion excitation.

4. Conclusion

This study explores the hydrological excitation of the polar motion computed from GRACE gravity field observations. So far, the excitation produced by the water storage variations was estimated using advanced hydrological models. These models include algorithms to assimilate observations of terrestrial hydrology. However, the main causes of errors are the lack of the global measurements of related hydrological parameters. The GRACE mission provides continental water change with unprecedented accuracy. After removing the atmospheric and oceanic effect from geodetic observations, we compare these residual signals to the excitations computed by GRACE estimates. At the annual timescale, we find that the GRACE-based excitations are in better agreement with geodetic residuals than the excitations predicted by the hydrological models. The prominent annual excitation is mainly due to the monsoon regions located at latitudes smaller than $30^\circ N$, where GRACE and models are in a very good agreement, in particular for CPC. In fact, we note

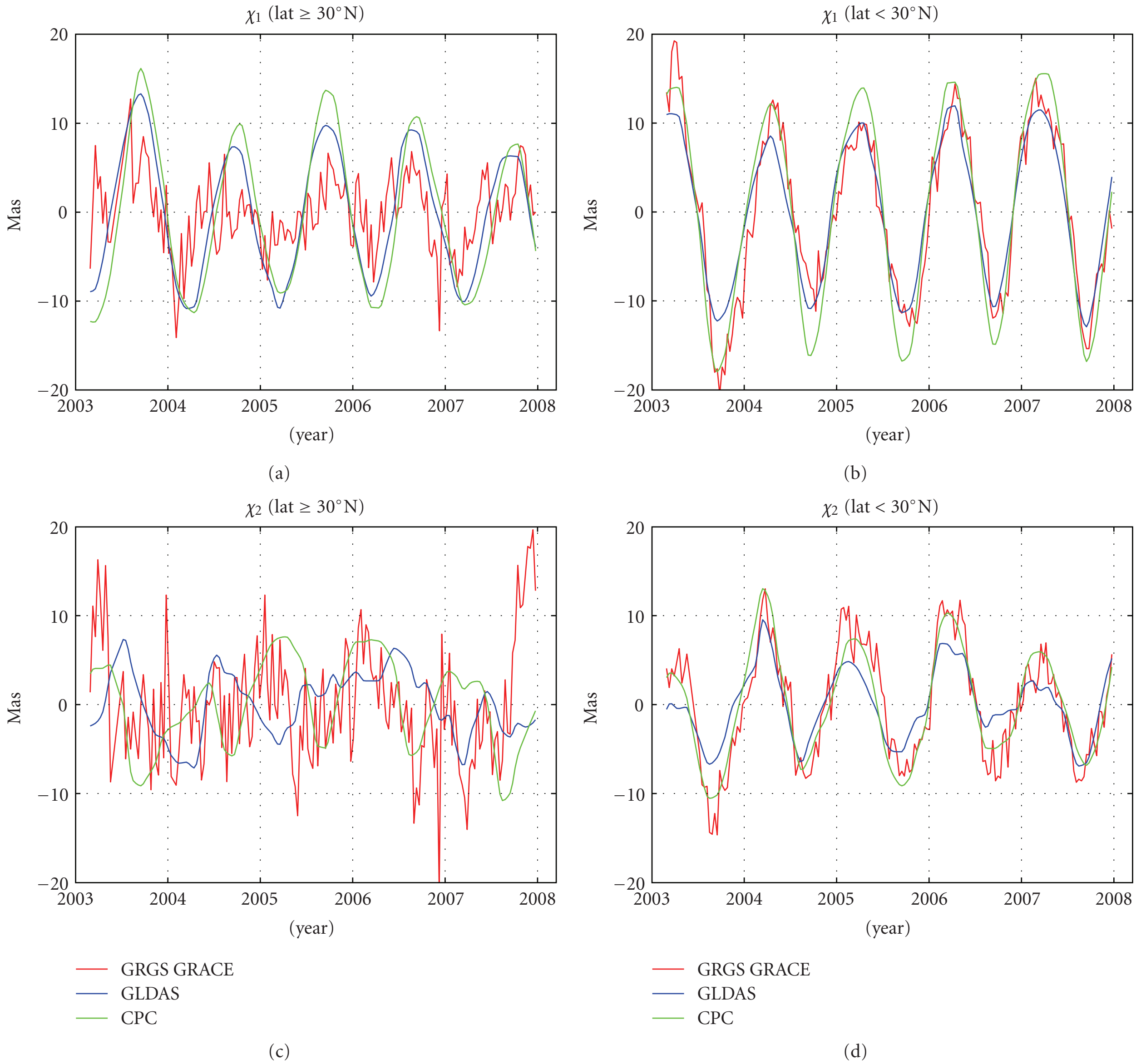

Figure 5: Polar motion excitations integrated over the Earth's north high latitudes (latitudes $\geq 30^{\circ}N$) and over the other latitudes (latitudes $< 30^{\circ}N$) using GRACE solutions and CPC and GLDAS models. Larger discrepancies between the models and GRACE observations come from the north high latitudes estimations.

that the groundwater variations unaccounted in the GLDAS model can have significant influences. Moreover, the annual signal observed by GRACE and obtained by the models at the high latitudes regions show important discrepancies probably due to the inaccurate snow water and ice estimations. We find also considerable interannual variations which confirms that the continental hydrology exerts a significant influence on the variations at low frequencies. Even so, the models or the GRACE solutions cannot explain the fluctuations of the geodetic residuals especially concerning the χ_1 component. Finally, from the spectral analysis of interseasonal variations, GRACE observations show that continental hydrology can excite polar motion at frequencies of about 3 cpy.

In conclusion, mass water variations of terrestrial water storage components (like groundwater or ice/snow sheets) are very difficult to model precisely. The mismodelling signals have a significant impact in the determination of hydrological influence on polar motion. Still, terrestrial water storage variations are observed by the GRACE mission, and it could be useful to constrain the models. We can expect that data processing improvements and longer series of GRACE observations will help in the understanding of

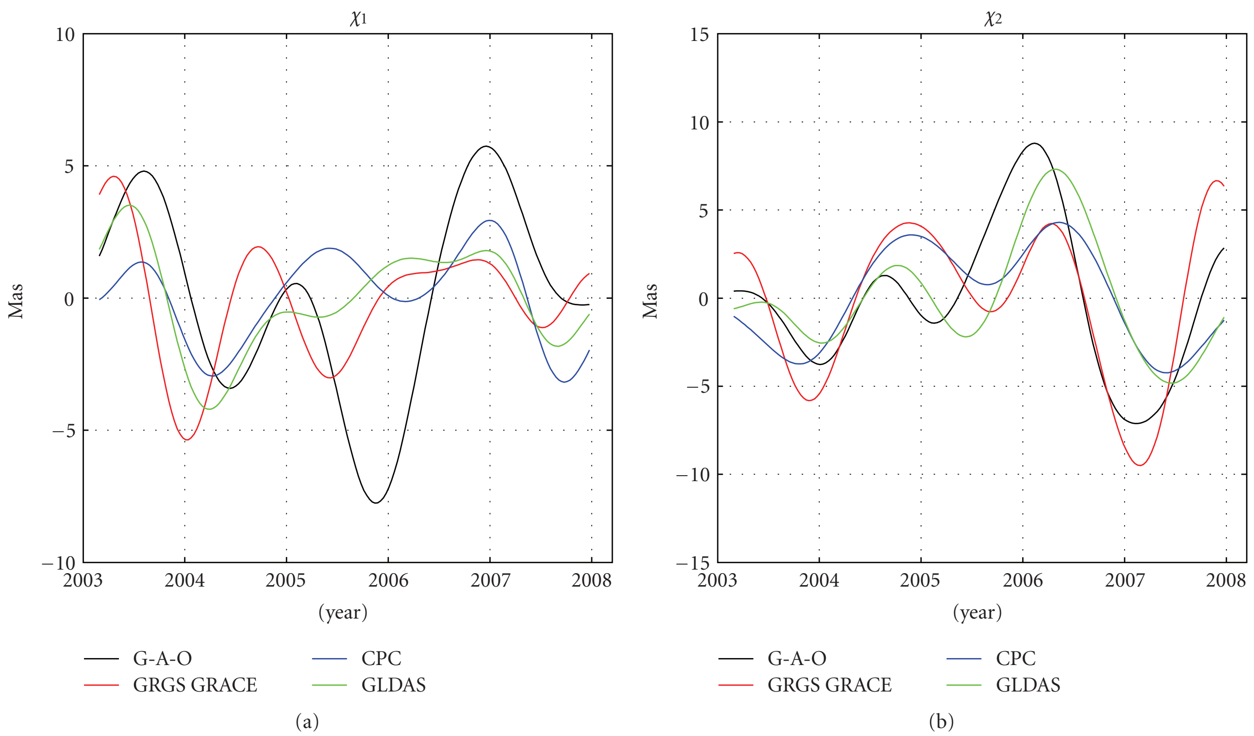

FIGURE 6: Interannual variations derived from the geodetic residual (G-A-O), GRACE, CPC, and GLDAS-based excitations. We observed a reasonably agreement for the χ_2 term.

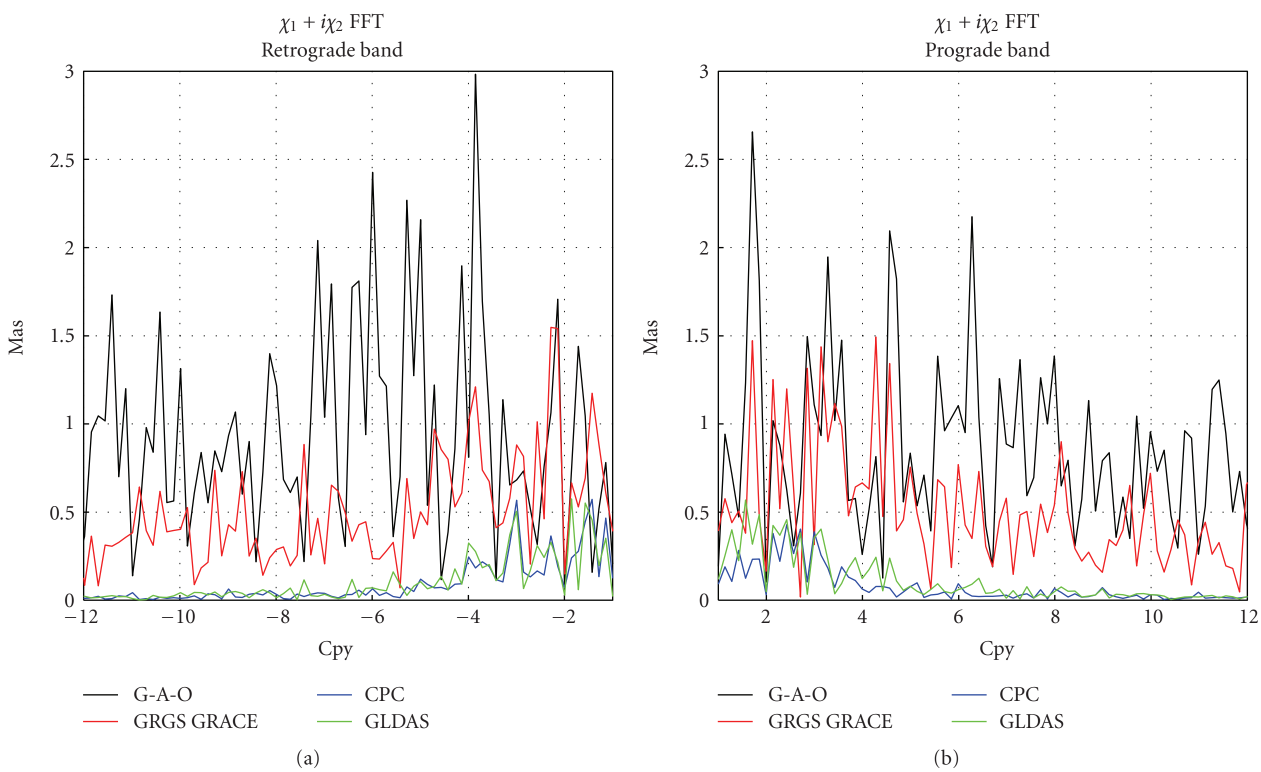

FIGURE 7: Intraseasonal variations spectrum computed from the geodetic residuals (G-A-O), GRACE, CPC, and GLDAS-based excitations. Data sets are interpolated with an uniform sampling of 10-days. GRACE observations provide more power than hydrological models, especially in the prograde and retrograde bands around the frequency of 3 cycles per year.

polar motion excitation caused by the Earth's hydrology and closing the global mass budget.

Abbreviations

CLM:	Community land model
CSR:	Center for Space Research
CPC:	Climate Prediction Center
ECCO:	Estimating the circulation and climate of the ocean
EOP:	Earth orientation parameters
EWH:	Equivalent water height
G-A-O:	Geodetic-atmospheric-oceanic excitations
GFZ:	Geoforschungs Zentrum
GLDAS:	Global land assimilation system
GRACE:	Gravity recovery and climate experiment
GRGS:	Groupe de Recherche de Géodésie Spatiale
IERS:	International Earth Rotation and Reference Systems Service
JPL:	Jet Propulsion Laboratory
MOG2D:	Modèle 2D d'Ondes de Gravité
NCAR:	National Centers for Atmospheric Research
NCEP:	National Centers for Environmental Prediction
LAGEOS:	Laser geodynamics satellite
SH:	Spherical harmonics
VIC:	Variable infiltration capacity.

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