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Hydrological and oceanic effects on polar motion from GRACE and models

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[1] Terrestrial water storage (TWS) and ocean bottom pressure (OBP) are major contributors to the observed polar motion excitations, second only to atmospheric mass movement. However, quantitative assessment of the hydrological and oceanic effects on polar motion remains unclear because of the lack of global observations. In this paper, hydrological and oceanic mass excitations to polar motion are investigated using monthly TWS and OBP derived from the Gravity Recovery and Climate Experiment (GRACE) for January 2003 until December 2008. The results from this analysis are compared with hydrological model excitations from the European Center for Medium-Range Weather Forecasts (ECMWF) and oceanic model excitations obtained from the Jet Propulsion Laboratory (JPL) using Estimating the Circulation and Climate of the Ocean (ECCO). Results show that the GRACE-derived OBP and TWS better explain the geodetic residual polar motion excitations for the Px component at the annual period, while the GRACE OBP and ECMWF hydrological angular momentum agree better with the geodetic residuals for the annual Py excitation. GRACE ocean and hydrology excitations better explain the geodetic residuals for the semiannual Py excitation. However, the JPL ECCO and ECMWF models better explain the intraseasonal geodetic residual of polar motion excitation in the Px and Py components. The GRACE data demonstrate much higher intraseasonal variability than either the models or the geodetic observations.

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1. Introduction

[2] The factors that influence the Earth's rotation variables, including polar motion (X and Y) and change of rotation rate (or length of day (LOD)), have been investigated for over four decades [*Munk and MacDonald*, 1960]. At time scales of a few years or less, the Earth's rotational changes are driven by mass redistribution in the atmosphere, oceans and hydrosphere. Atmospheric winds and surface pressure changes provide a significant part of polar motion [e.g., *Barnes et al.*, 1983; *Chao and Au*, 1991; *Gross et al.*, 2003], and are particularly dominant contributors to the LOD variation [e.g., *Eubanks et al.*, 1988; *Hide and Dickey*, 1991]. The oceans, including ocean bottom pressure (OBP) and currents, also play a major role in the polar motion excitation based on studies from Ocean General Circulation Models (OGCMs), e.g., the parallel ocean climate model (POCM), the Estimating Circulation and Climate of the Ocean (ECCO) nondata-assimilating model (ECCO-NDA), the ECCO data-assimilating model (ECCO-DA) and a number of barotropic ocean models (BOMs) [*Wahr*, 1983; *Dickey et al.*, 1993; *Ponte et al.*, 1998; *Ponte and Stammer*, 1999; *Johnson et al.*, 1999; *Ponte and Ali*, 2002; *Gross et al.*, 2003]. Results from the model studies suggest that ocean mass redistribution and circulation explain most of the residual of polar motion excitations that has not been accounted for by the atmosphere [*Ponte et al.*, 1998; *Ponte and Ali*, 2002; *Gross et al.*, 2003; *Chen et al.*, 2004]. However, as different methods and strategies were used in the oceanic models, discrepancies exist that affect the quantitative evaluation of the oceanic contribution to polar motion and LOD variations [*Zhou et al.*, 2005]. Therefore, fully understanding oceanic effects on polar motion and LOD remains a challenging issue. The main limitation is the lack of global oceanic observation data, particularly ocean bottom pressure (OBP). Although satellite altimeters provide nearly global sea surface height (SSH) changes, estimating OBP requires steric sea level measurements that are still poorly known, although this will change as the Argo program achieves a 3° global coverage. In addition, terrestrial water storage (TWS) changes also affect polar motion [*Chao and O'Connor*, 1988] and their contribution to polar motion variations have traditionally been estimated from global hydrological models. However, these models give significantly different amplitudes and phases for polar motion excitation and one conclusion drawn from this is that they may not represent the complete hydrological

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variation [*Chen and Wilson*, 2005]. Until recently, TWS has not been adequately measured at the continental scale [*Lettenmaier and Famiglietti*, 2006]. This is primarily due to the lack of a comprehensive global network for routine TWS monitoring. Although ground and satellite based techniques can measure some individual components such as soil moisture [*Njoku et al.*, 2003] and surface water [*Alsdorf and Lettenmaier*, 2003], there has been no integrated measurement of TWS.

[3] A recent source of global TWS and OBP measurements are those from the Gravity Recovery and Climate Experiment (GRACE) mission, launched in March 2002 [*Tapley et al.*, 2004]. Recent studies suggest that GRACE is capable of estimating TWS variations comparable with the Global Land Data Assimilation System (GLDAS) [e.g., *Rodell et al.*, 2006] and local changes in OBP at accuracies comparable to those of in situ OBP recorders [*Morison et al.*, 2007; *Böning et al.*, 2008; *Park et al.*, 2008] and altimetry corrected for steric variations from Argo [*Chambers and Willis*, 2008]. More importantly, the GRACE measurements are the first global, direct observations of TWS and OBP variation, and not an output or simulation from a model. In this study, hydrological and oceanic effects on polar motion are investigated using six years of monthly GRACE solutions (January 2003 to December 2008) at seasonal, intraseasonal and interannual time scales as well as the Chandler wobble (CW) frequency. Daily terrestrial water storage from the European Center for Medium-Range Weather Forecasts (ECMWF) and daily OBP/currents from the JPL Estimating Circulation and Climate of the Ocean (ECCO) model are also used. The hydrological and oceanic contributions to the LOD are not studied, as the winds are the dominant excitation source for this effect. After briefly introducing the geophysical fluid excitations to the polar motion in section 2, data sets and techniques are described in section 3. Section 4 is devoted to analyzing and discussing the observed hydrological and oceanic contributions to the polar motion at annual, semiannual, intraseasonal, and interannual time scales, including the Chandler wobble frequency. A summary is given in section 5.

2. Polar Motion Excitation

[4] The relationship between the observed polar motion and its excitation can be mathematically expressed by complex notation in an Earth-fixed coordinate system. Let the coordinates of the rotation pole *Px* and *Py* be along axes pointing toward the Greenwich meridian and 90°E longitude, respectively. The excitations χ_1 and χ_2 are then proportional to the components of terrestrial angular momentum. The response to Earth rotational excitation is approximately expressed as [*Munk and MacDonald*, 1960; *Lambeck*, 1980; *Gross*, 2007]:

$$P + \frac{1}{\sigma_c}\dot{P} = \chi \tag{1}$$

where $P = Px\text{-}i\,Py$ is the polar motion vector, $\sigma_c = 2\pi F_c\,(1 + i/2Q)$, Fc is the Chandler wobble frequency (about 0.8432 cycle/yr), Q = 179 is the quality factor determined by the Earth's physical properties [*Wilson and Vicente*, 1990] and its reciprocal ($1/Q$) is the associated dissipation factor, and $\chi = (\chi_1^P + \chi_1^m) + i(\chi_2^p + \chi_2^m)$ is the polar motion excitation, where p is the pressure term (mass term) and m is the motion term. The polar motion excitations can be expressed as an integral of gridded pressures and currents [e.g., *Eubanks*, 1993]:

$$\begin{aligned}\chi^p &= \chi_1^p + i\chi_2^p \\ &= \frac{-1.0980\bar{R}^4}{g(C-A)}\iint p\sin\varphi\cos^2\varphi e^{i\lambda}d\lambda d\varphi\end{aligned} \tag{2}$$

$$\begin{aligned}\chi^m &= \chi_1^m + i\chi_2^m \\ &= \frac{1.5913\bar{R}^3}{g\Omega(C-A)}\iiint(u\sin\varphi + iv)\cos\varphi e^{i\lambda}dp d\lambda d\varphi\end{aligned} \tag{3}$$

where χ^p and χ^m are the pressure term and motion term of polar motion excitation, respectively, χ_1 and χ_2 are the polar motion *Px* and *Py* excitations, respectively, 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, φ, λ, and t are the latitude, longitude and time, respectively, and u and v are the eastward and northward motion velocities (e.g., wind or ocean current).

3. Data and Analysis

3.1. OBP and TWS From GRACE

[5] The scientific objectives of the GRACE mission are to produce high-quality terrestrial water storage and ocean mass change estimates [e.g., *Wahr et al.*, 2002]. Over the ocean, these mass variations represent fluctuations in ocean bottom pressure [e.g., *Jayne et al.*, 2003]. *Chambers et al.* [2004] first demonstrated that GRACE could measure the variation in the global mean ocean mass (OBP) quite accurately. *Bingham and Hughes* [2006] found that the seasonal mode of OBP variation in the North Pacific extracted from GRACE data agreed qualitatively with that of an ocean model. More recent studies have quantified significant OBP variations from GRACE at longer periods than the annual in the Arctic [*Morison et al.*, 2007] and in the North Pacific [*Chambers and Willis*, 2008]. The GRACE-derived terrestrial water storage (TWS) compared favorably with the in situ time series for the Mississippi River basin and the two sub-basins [*Rodell et al.*, 2006]. GRACE-based TWS spatial-temporal changes are also in good agreement with those obtained from GLDAS simulations [*Syed et al.*, 2008].

[6] In this study, we use the latest GRACE gravity field solutions (Release-04) from the Center for Space Research (CSR) at the University of Texas, Austin, which are available from the GRACE Tellus Web site (http://gracetellus.jpl.nasa.gov/data/mass). The data have been corrected and smoothed into monthly maps of TWS and OBP with a 300 km Gaussian smoothing (e.g., D. P. Chambers, Converting Release-04 gravity coefficients into maps of equivalent water thickness, available at ftp://podaac.jpl.nasa.gov/pub/tellus/monthly_mass_grids/chambers-destripe-RL04–200711/doc/GRACE-dpc200711_RL04.pdf). We use the monthly data from January 2003 until December 2008, except for June 2003 and January 2004. No data were available in June 2003, and

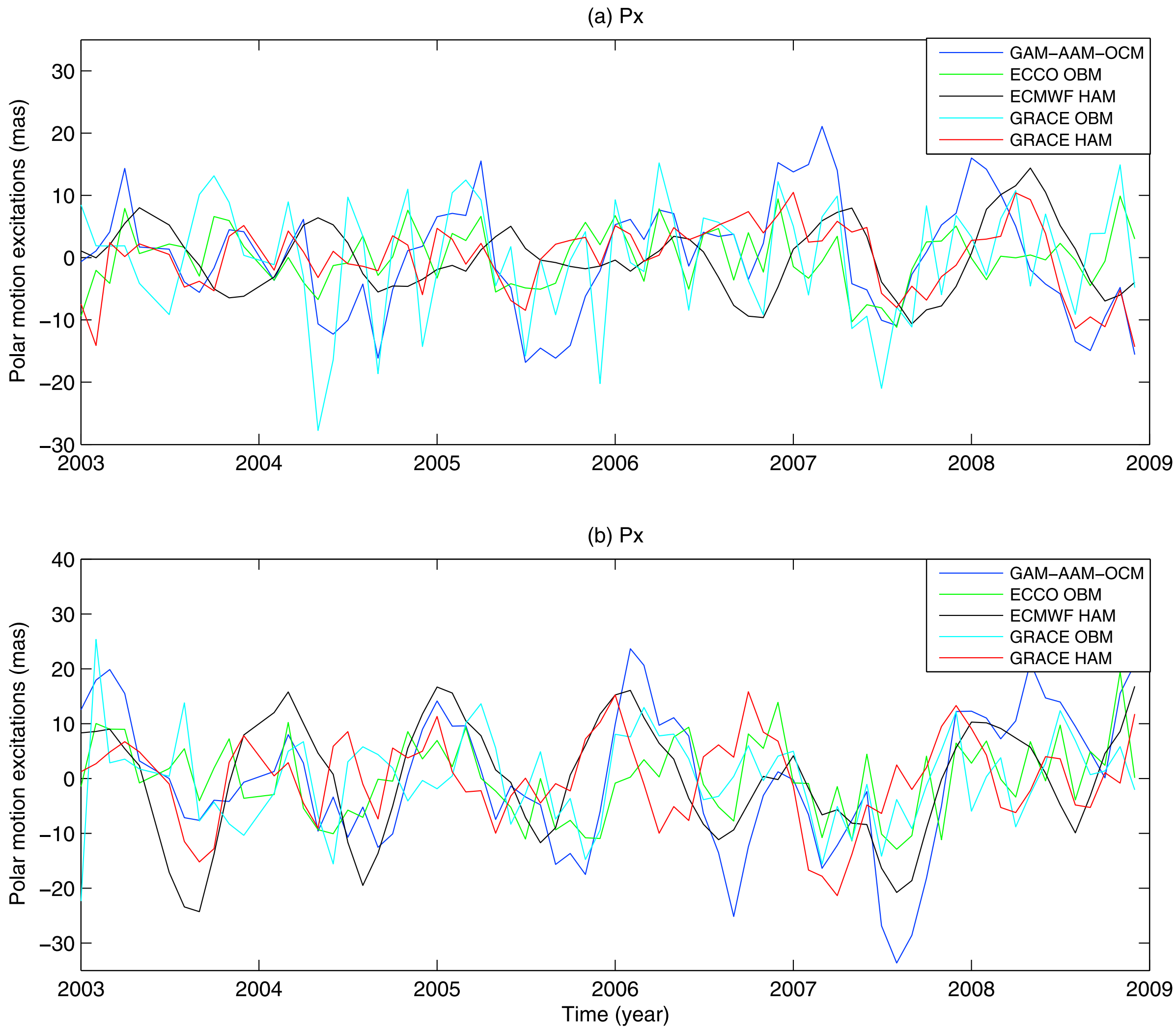

Figure 1. Monthly hydrological and oceanic excitation time series on the polar motion (a) Px and (b) Py from geodetic observation residuals (geodetic angular momentum (GAM) minus atmospheric angular momentum (AAM) and ocean current angular momentum (OCM) (blue line), Estimating the Circulation and Climate of the Ocean (ECCO) ocean bottom pressure angular momentum (OBM) (green line), European Center for Medium-Range Weather Forecasts (ECMWF) hydrological angular momentum (HAM) (black line), Gravity Recovery and Climate Experiment (GRACE) OBM (cyan line), and GRACE HAM (red line).

the January 2004 solution was based on less than 15 d of data. The TWS and OBP excitations to polar motion, χ_1 and χ_2, are calculated by using TWS and OBP (in appropriate units) in place of p in equation (2).

3.2. OBP, Currents, and TWS Excitations From Models

[7] The ocean excitations to polar motion include contributions from both ocean currents and ocean bottom pressure (OBP) variations. Recent advancements in data-assimilating Ocean General Circulation Models (OGCMs) have provided improved studies of oceanic effects on Earth's rotation [e.g., *Ponte et al.*, 2001; *Dickey et al.*, 2002; *Gross et al.*, 2003]. The model used in many of these studies is the ECCO data-assimilating model (ECCO-DA) run at Jet Propulsion Laboratory [e.g., *Fukumori et al.*, 1999]. The JPL ECCO-DA is based on the Massachusetts Institute of Technology general circulation model [*Marshall et al.*, 1997; *Gross et al.*, 2003] 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 h surface wind stresses and daily surface heat/freshwater fluxes and evaporation−precipitation fields from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis products [*Fukumori et al.*, 1999]. Its 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 monthly averaged OBP and ocean current excitation components 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/).

Table 1. Amplitude and Phase of Annual and Semiannual Variations of Polar Motion Excitations From GRACE and Models[a]

Polar Motion (X,Y)	Annual Px		Semiannual Px		Annual Py		Semiannual Py	
	Amp (mas)	Phase (deg)	Amp (mas)	Phase (deg)	Amp (mas)	Phase (deg)	Amp (mas)	Phase (d)
GAM-AAM-OCM	8.79 ± 0.20	52.83 ± 1.28	0.92 ± 0.20	−49.09 ± 12.26	10.53 ± 0.30	44.73 ± 1.65	3.43 ± 0.30	124.41 ± 5.02
ECCO OBM + ECMWF HAM	4.72 ± 0.16	1.93 ± 1.99	2.20 ± 0.16	−158.60 ± 4.20	15.46 ± 0.28	66.36 ± 1.02	3.82 ± 0.28	−171.24 ± 4.21
ECCO OBM + GRACE HAM	3.55 ± 0.22	65.16 ± 3.47	3.18 ± 0.22	−130.66 ± 3.89	8.18 ± 0.33	107.56 ± 2.24	5.44 ± 0.32	136.61 ± 3.41
GRACE OBM + ECMWF HAM	6.45 ± 0.28	18.67 ± 2.57	2.46 ± 0.29	−59.66 ± 6.59	13.58 ± 0.32	58.19 ± 1.33	0.86 ± 0.32	−140.36 ± 21.05
GRACE OBM + HAM	5.89 ± 0.33	60.60 ± 3.19	3.93 ± 0.33	−71.89 ± 4.77	5.39 ± 0.39	106.26 ± 4.02	3.87 ± 0.39	102.65 ± 5.61

[a]The amplitude c and phase φ are defined as $c\sin(2\pi(t - t0)/p + \varphi)$ from monthly time series, where t0 is 1 January and p is the period. GRACE, Gravity Recovery and Climate Experiment; amp, amplitude; mas, milliseconds of arc; GAM, geodetic observation excitation; AAM, atmospheric angular momentum; OCM, ocean currents momentum; HAM, hydrological angular momentum; ECCO, Estimating the Circulation and Climate of the Ocean; ECMWF, the European Center for Medium-Range Weather Forecasts; OBM, ocean bottom pressure angular momentum.

[8] The hydrological excitations to polar motion have been estimated from 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) (6 h ECMWF operational) [*Dill and Walter*, 2008]. The improved ECMWF Reanalysis (ERA) Interim data has to be scaled to the monthly mean level provided by the Global Precipitation Climate Center (GPCC), to obtain comparable river discharges. Evaporation estimates from the ECMWF have to be enhanced according to local effects from swamps and flooded regions like the Anthropogenic influences such as dams and irrigation were incorporated to realistically absorb the high seasonal variability in rainfall.

3.3. Geodetic Observations of Excitations

[9] Current geodetic techniques, such as Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Lunar Laser Ranging (LLR), Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS), can provide precise Earth Orientation Parameters (EOPs). The recent International Earth Rotation and Reference systems Service (IERS) EOP time series (IERS C04), are determined according to 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 polar motion excitations χ_1 and χ_2, i.e., geodetic angular momentum (GAM), are derived from geodetic observations of polar motion X and Y using the discrete polar motion equation [*Wilson*, 1985].

[10] The atmospheric angular momentum (AAM) variations are responsible for part of polar motion excitations [*Eubanks*, 1993; *Gross et al.*, 2003; *Zhou et al.*, 2006]. The atmospheric contributions can be estimated with sufficient accuracy from 6 hourly excitation series based on the NCEP-NCAR reanalysis and were obtained from the IERS Special Bureau for the Atmosphere (SBA) [*Salstein*, 1993]. Here, 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 currents are also responsible for part of polar motion excitations. Since no global current measurements are available, we use output from ECCO provided by the IERS Special Bureau for the Oceans to compute ocean current angular momentum (OCM). We then compute the geodetic residual excitations by removing the atmospheric and ocean currents contributions from the full geodetic angular momentum (GAM), i.e., GAM-AAM-OCM.

4. Results and Discussions

[11] The purpose of this study is to evaluate the relative ability of OBP plus TWS from GRACE or models to close the budget

$$\mathrm{GAM} = \mathrm{AAM} + \mathrm{HAM} + \mathrm{OCM} + \mathrm{OBM} \tag{4}$$

where GAM represents the full geodetic polar motion excitations, AAM is the atmospheric portion, hydrological angular momentum (HAM) is the hydrological portion,

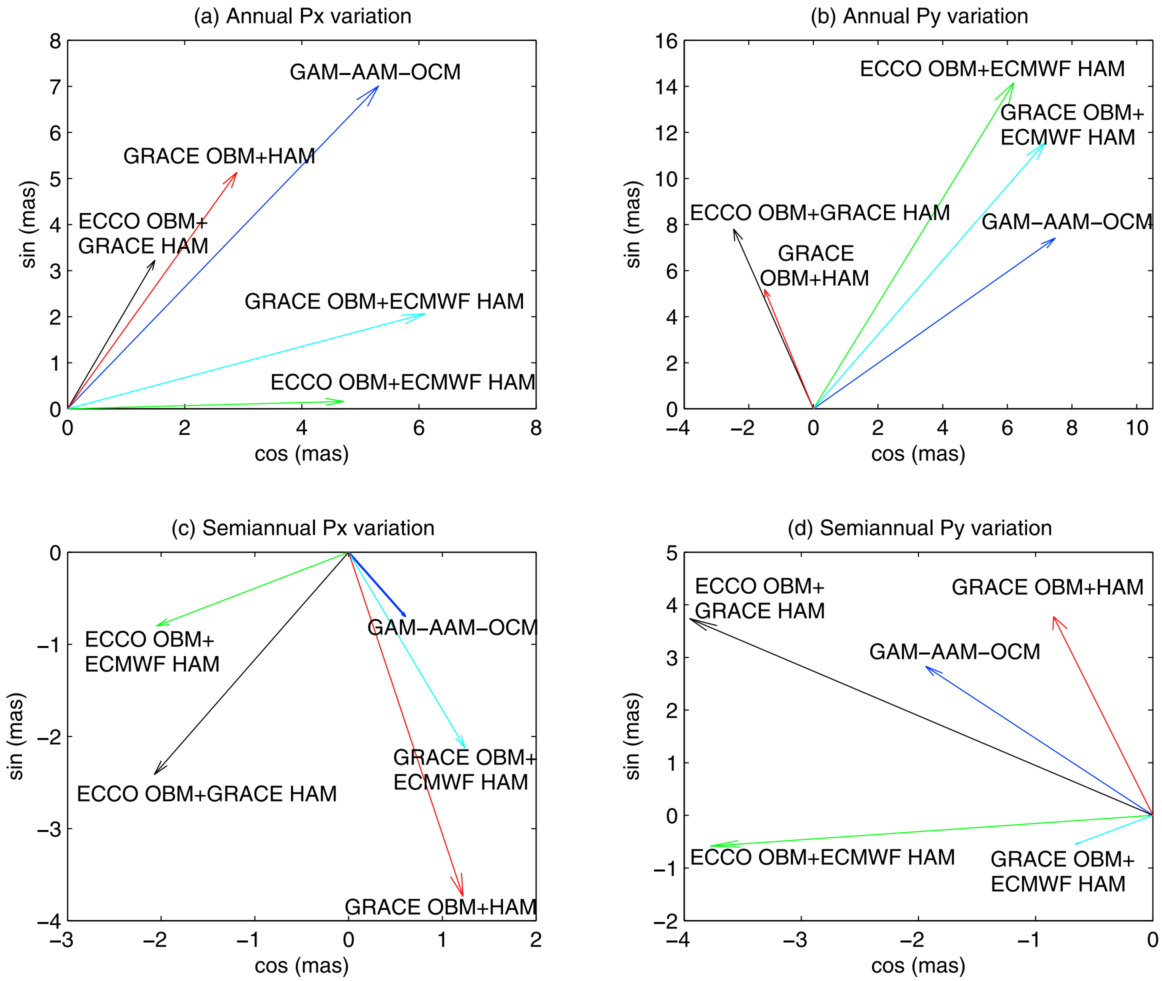

Figure 2. Phaser plots of (a) annual Px, (b) annual Py, (c) semiannual Px, and (d) semiannual Py excitation variations from geodetic observation residuals (GAM-AAM-OCM) (blue line), ECCO OBM plus ECMWF HAM (green line), ECCO OBM plus GRACE HAM (black line), GRACE OBM plus ECMWF HAM (cyan line), and GRACE OBM plus HAM (red line).

OCM is the ocean current portion, and OBM is the portion related to ocean bottom pressure variations. Since the GAM, AAM, and OCM time series are based on single data sets, we will directly compare estimates of OBM plus HAM from GRACE and the JPL_ECCO and climatic model with OBM + HAM = GAM-AAM-OCM.

[12] The AAM values are estimated from 6 hourly excitation series based on the NCEP-NCAR reanalysis [*Salstein*, 1993], the OCM values are from the JPL_ECCO model (section 3.2), and OBM values are from the either the JPL_ECCO model or GRACE. Terrestrial water storage contribution to the polar motion (HAM) is estimated from either global hydrological model (ECMWF-LSDM) or GRACE.

4.1. Seasonal Polar Motion

[13] The daily geodetic observation residuals of nonatmospheric/currents excitation (GAM-AAM-OCM), hydrological model excitation time series (ECMWF HAM) and oceanic model excitation time series (ECCO OBM) for polar motion X and Y are averaged and resampled at the same 1 month interval as GRACE. The monthly excitation time series to polar motion (X and Y) are shown in Figures 1a and 1b, respectively. The blue line represents the geodetic residuals (GAM-AAM-OCM), the green line represents the ECCO OBP excitations (OBM), the black line represents the hydrological ECMWF excitations (HAM), and the cyan and red lines represent the hydrological HAM and oceanic OBM from GRACE, respectively. It can be seen that the pattern of hydrology and ocean excitations to polar motion agree well with the geodetic observation residuals of GAM-AAM-OCM. Much of this is due to significant seasonal variations in both the geodetic observation residuals and oceanic/hydrological excitations.

[14] The amplitude and phase of the annual and semiannual variations of polar motion excitations (X and Y) are estimated through the method of least squares fit to a bias, trend, and seasonal period sinusoids. Table 1 lists the amplitude and phase of annual and semiannual variations of polar motion excitations from observations and models. For Px, the GRACE OBM + HAM excitations agree well with geodetic residuals at the annual period and are closer in phase than either of the other combinations. The annual amplitude using GRACE OBM is closer to the observed residuals within the uncertainty estimates, while the annual amplitude using ECCO OBP is between 15 to

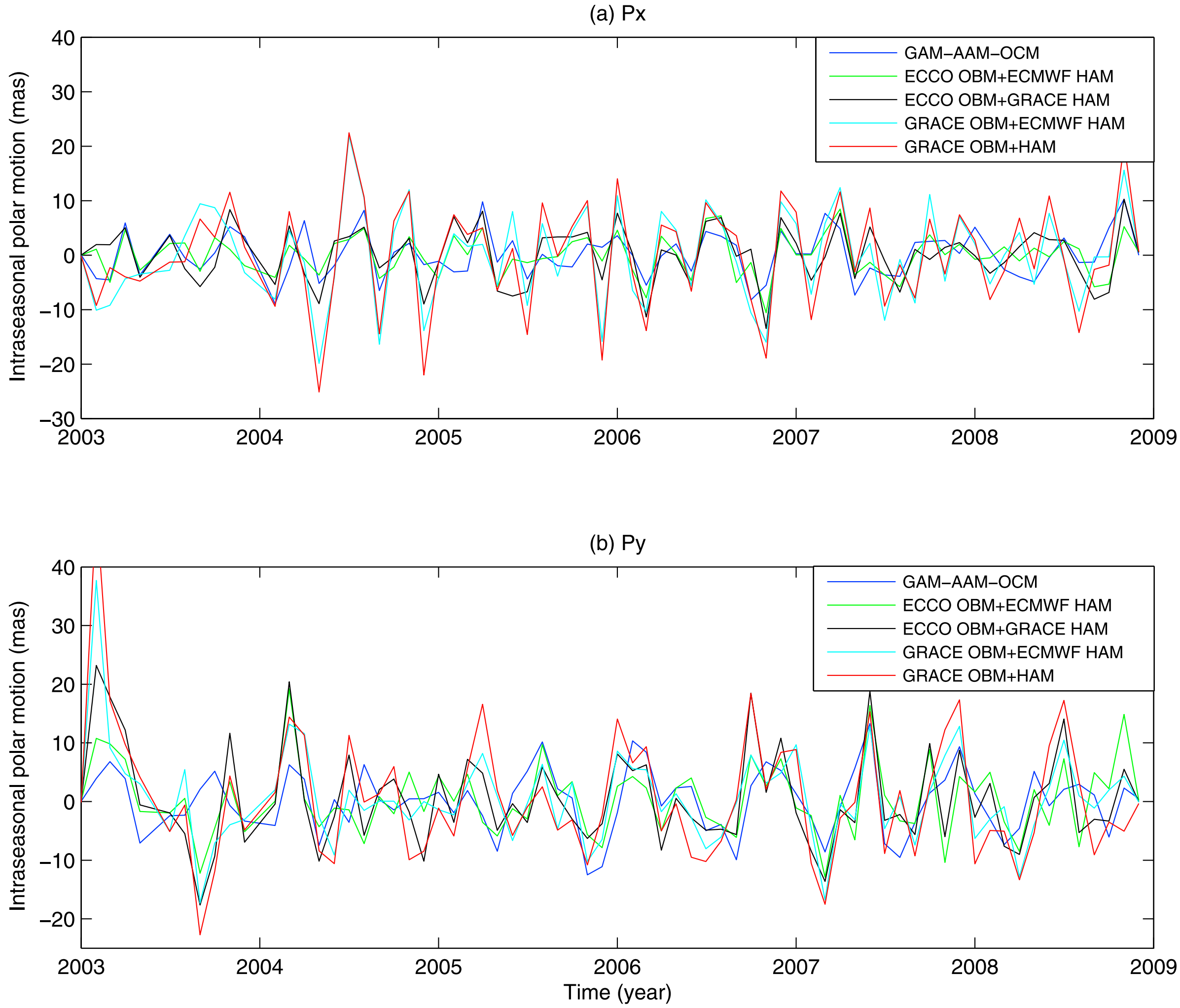

Figure 3. Intraseasonal polar motion (a) Px and (b) Py from geodetic observation residuals (GAM-AAM-OCM) (blue line), ECCO OBM plus ECMWF HAM (green line), ECCO OBM plus GRACE HAM (black line), GRACE OBM plus ECMWF HAM (cyan line), and GRACE OBM plus HAM (red line). The mean, trend, annual, semiannual, and periods longer than 1 year have been removed from all time series by least squares fitting and a high-pass filter.

40% smaller depending on the hydrological model used. For the semiannual variation, the amplitude of Px in the geodetic residual (GAM-AAM-OCM) is small (less than 1 millisecond of arc (mas)), while the amplitudes from combinations of all the other data and models are larger, from 2 to 4 mas.

[15] The results are strikingly different for Py (Figure 2). The annual amplitude for GAM-AAM-OCM is quite large (10.5 mas). The closest combination is for GRACE OBM + ECMWF HAM. Using the GRACE HAM results in an amplitude only half of that from GAM-AAM-OCM and a large phase shift. All other model combinations from models are either too large or too small. For the semiannual component, however, the GRACE OBM + HAM combination is closer to GAM-AAM-OCM than any of the other combinations. While the results for the GRACE HAM data are mixed, these results suggest that the GRACE OBP data are significantly better at estimating seasonal polar motion excitations than the ECCO model.

4.2. Intraseasonal Polar Motion

[16] After removing the seasonal signals at annual, semiannual and periods longer than 1 year from all polar motion excitations time series using the least squares estimate and a high-pass filter, we examine intraseasonal variations, which tend to have large variability (Figure 3). In order to quantify which combination of OBM and HAM agree better with GAM-AAM-OCM at nonseasonal periods, we have computed cross-correlation coefficients (Figure 4), where the dashed lines represents the 99% confidence levels calculated from the upper 1% point of the F distribution. For Px, the zero-lag correlation coefficient between GRACE OBM + HAM and GAM-AAM-OCM is comparable to those of GRACE OBM + ECMWF HAM and ECCO OBM + GRACE HAM, but all are smaller than that of models only combinations (ECCO OBM + ECMWF HAM). The root-mean-square (RMS) of the residuals after removing GRACE OBM + HAM (e.g., GAM-AAM-OCM-OBM-HAM) is also larger (Table 2), suggesting the GRACE data

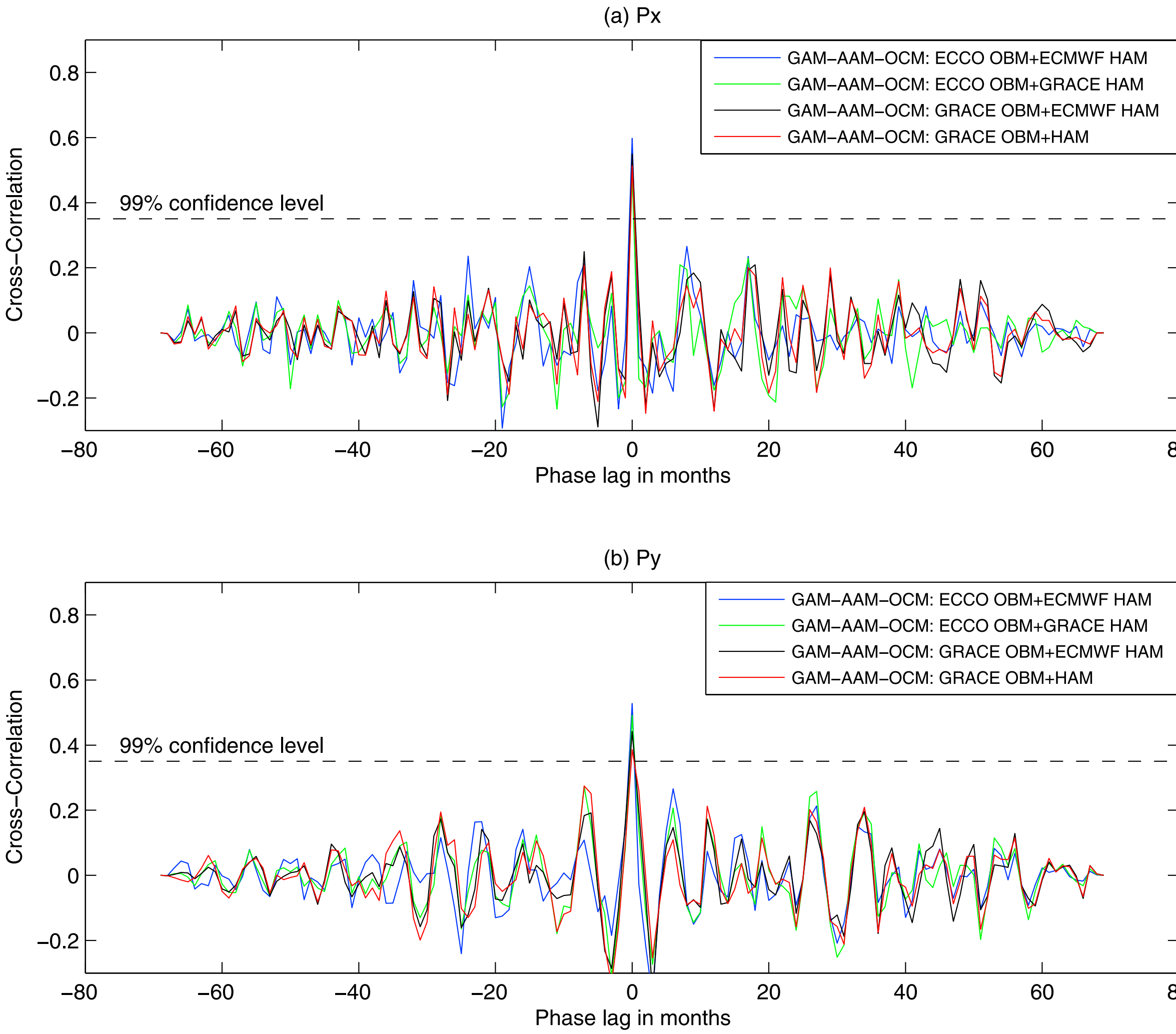

Figure 4. Cross-correlation coefficients for the intraseasonal polar motion (a) Px and (b) Py between geodetic observation residuals of GAM-AAM-OCM and ECCO OBM plus ECMWF HAM (blue line), ECCO OBM plus GRACE HAM (green line), GRACE OBM plus ECMWF HAM (black line), GRACE OBM plus HAM (red line), respectively. The two dashed lines in Figures 4a and 4b represent the 99% confidence levels.

do not completely match the geodetic residuals at these frequencies. This appears to be due to large 1–2 month period fluctuations in 2004 and 2005 in the GRACE Px estimates (Figure 3a). For Py, the maximum correlation coefficient at the zero phase lag between GRACE OBM + HAM and GAM-AAM-OCM is also significantly smaller than that of ECCO OBM + ECMWF HAM, and the RMS of the residuals is much larger. Again, this appears to be due to large 1 to 2 month period oscillations in the GRACE data. These results indicate that GRACE OBM and HAM data have high-frequency variations in the estimated excitations that are not reflected in the direct observations or the models. One can also use coherence analysis to further study excitation series in the frequency domain [*Wilson and Haubrich*, 1976; *Kuehne and Wilson*, 1991; *Furuya et al.*, 1996]. The estimates of the squared coherence of the various excitation time series are shown in Figure 5. It is clear that the coherences between GAM-AAM-OCM and GRACE OBM + HAM in Px and Py are significantly less than that for the model estimates at most high frequencies.

[17] 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. Local large fluctuations in either hydrology or OBP 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, particularly since local fluctuations in hydrology are approximately five to ten times larger than the OBP variations. The only way to fully quantify this effect is through complete simulations of the GRACE data processing given known hydrology and ocean signals. Given the mechanisms of computing gravity from a satellite mission like GRACE, the sampling of subseasonal periods may never be fully solved using satellite gravity data only. However, the combination of GRACE and model data may help.

4.3. Chandler Wobble

[18] Another significant component of the polar motion is the Chandler wobble (CW), which is a resonance in the

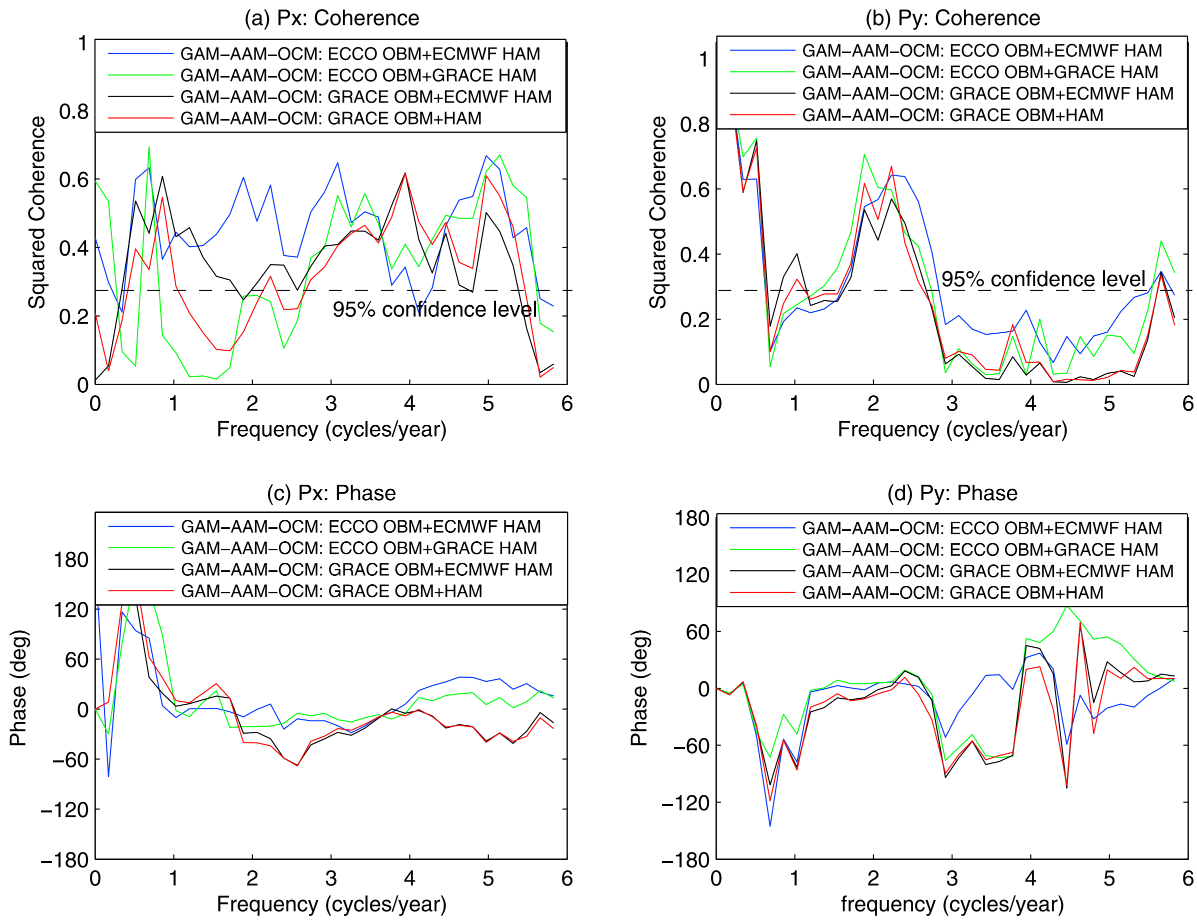

Figure 5. Magnitude and phase of the squared coherence of GAM-AAM-OCM with GRACE and model excitations. Annual, semiannual, and periods longer than 1 year have been removed from all time series by least squares fitting and high-pass filter. A mean and trend are also removed. The dashed lines in Figures 5a and 5b represent the 95% confidence levels.

Earth's rotation with a period of about 433.0 d and a quality factor Q of 179 [*Wilson and Vicente*, 1990] because the Earth is not rotating about its figure axis [*Munk and MacDonald*, 1960; *Eubanks*, 1993]. If there were no excitation sources, however, the Chandler wobble would freely decay with a time constant of about 68 years to the minimum rotational energy state of rotation about the figure axis. Therefore, since the CW was first discovered in 1891, excitation sources or mechanisms have been investigated by many authors [*Munk and MacDonald*, 1960; *Wilson and Haubrich*, 1976; *Wilson and Vicente*, 1990; *Furuya et al.*, 1996; *Kuehne et al.*, 1996; *Gross*, 2000]. Atmospheric processes (wind and surface pressure variations) were the initial proposed mechanisms to excite the Chandler wobble. However, it has generally been concluded that atmospheric contributions have only about 25% of the required power energy [e.g., *Wahr*, 1983]. More recently, the excitation of oceanic processes to the Chandler wobble has been studied [*Gross*, 2000; *Brzezinski and Nastula*, 2002]. Although the ocean models do show excitation at CW frequencies, the results of comparisons with observations have been mixed.

[19] We analyze the oceanic plus hydrological excitations and geodetic residuals time series using an *N*-point fast Fourier transform (FFT) to obtain power spectral densities (PSD) (Figure 6). A Hanning window is used for the FFT analysis to reduce the errors in the PSD. In order to reduce

Table 2. Cross-Correlation Coefficients at the Zero Phase Lag and Root-Mean-Square of Difference Between Nonatmosphere/Currents Intraseasonal Polar Motion and Excitations From Models and GRACE

	GAM-AAM-OCM			
	(Px)		(Py)	
Excitations	Coefficients	RMS	Coefficients	RMS
ECCO OBM + ECMWF HAM	0.60	3.55	0.53	5.68
ECCO OBM + GRACE HAM	0.49	4.73	0.49	7.25
GRACE OBM + ECMWF HAM	0.55	7.04	0.44	7.29
GRACE OBM + HAM	0.51	8.20	0.39	10.11

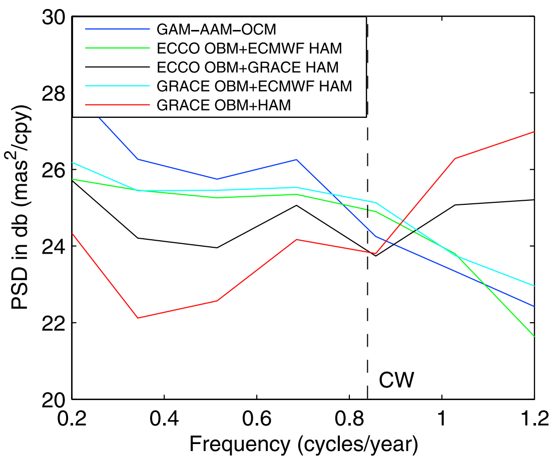

Figure 6. Power spectral density (mas^2/cpy) for polar motion $Px + i\ Py$ of the geodetic observation residuals of GAM-AAM-OCM (blue line) with GRACE and models' estimates. A mean, trend, and seasonal signals at the annual and semiannual frequencies have been removed from all time series prior to the fast Fourier transform analysis. The vertical dashed line is at the Chandler wobble period.

the spectral leakage of the forced nonseasonal excitations to the polar motion, the seasonal components (annual and semiannual terms) together with a mean and trend terms are removed from all time series before the FFT analysis. There is an interesting separation in the PSDs at the CW period. Excitations combining either GRACE or ECCO OBP with ECMWF HAM have slightly more energy at the CW period than the geodetic residuals, while the combination with GRACE HAM has slightly less power. There appears to be no difference between the GRACE or ECCO OBP at the CW frequency.

[20] However, one should be cautious about overanalyzing the PSDs for such a short time span. Because of the resonance at frequencies near the real Chandler frequency, the observed CW excitation expands to a broad band (normally 0.75–0.92 cpy). Since we are limited to month-averaged samples because of GRACE, the resolution of the 6 year PSD is only 0.1579 cpy, which is insufficient to analyze such a broad band. Moreover, a longer time series is necessary to fully separate the CW band from the annual period. To more clearly understand the differences in the hydrological contribution to CW, the analysis of much longer data series is necessary in the future.

4.4. Interannual Polar Motion

[21] One other interesting aspect of Figure 6 is the relatively high power at frequencies shorter than the CW frequency. Again, the time series is too short to fully quantify such variations, but when the nonseasonal time series are smoothed using a 1 year sliding window (Figure 7), we find significant interannual fluctuations, with excursions of the same order as the seasonal amplitude. The GRACE OBM + HAM time series for Px matches the GAM-AAM-OCM residuals remarkably well in 2006, capturing the rise then subsequent fall, although there is a slight phase difference. None of the model combinations, however, captured the large 2006 anomaly, and they all suggest an increase in 2008, whereas both GRACE and the geodetic residuals show a large negative anomaly.

[22] The Py time series (Figure 7b) have larger variations than Px, as well as more consistency between the geodetic residuals and the various combinations. All show a large negative anomaly in early 2007 and a subsequent rise. However, the combinations with ECMWF HAM agree better with the geodetic residuals than the combinations with GRACE HAM, at the 30% level. However, the combinations with GRACE OBP are both slightly closer than the combinations with ECCO OBP.

5. Conclusion

[23] In this paper, we have compared monthly excitations of polar motion derived from GRACE gravity solutions for ocean bottom pressure plus terrestrial water storage with excitations computed from ocean and hydrology models, along with geodetic residuals of the polar motion. Our results have been slightly mixed. For annual periods and Px, the excitations form GRACE OBP and TWS are much closer to the observed excitations after removing atmospheric

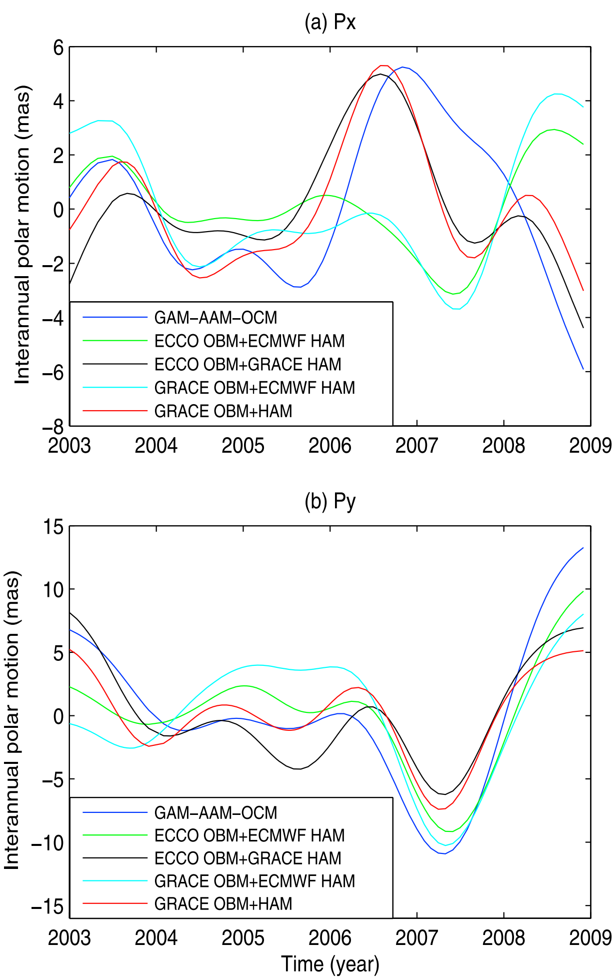

Figure 7. Residual interannual excitations in (a) Px and (b) Py after removing seasonal variations and smoothing over 1 year.

and ocean current effects. The model results have significant phase differences. For annual Py, however, the best combination is the one with GRACE OBP and ECMWF HAM, and any combination with GRACE HAM gives significantly poorer results. For semiannual Py, however, GRACE OBM + HAM agrees better with the geodetic residuals.

[24] For periods less than 1 year, however, the JPL ECCO and ECMWF models better explain the intraseasonal geodetic residual of polar motion excitation in both Px and Py components. The GRACE data have much higher variability than either the models or the geodetic observations. This is probably related to the fact that the GRACE data are not exact monthly averages in both time and space, and so higher-frequency variations by hydrology within the month can cause some longer period aliases.

[25] We have also analyzed the variations at periods longer than 1 year. Although the time series is too short to fully quantify long period fluctuations in polar motion, we do find some differences in the hydrological contribution computed from GRACE and a model at the Chandler wobble frequency. The model appears to better match the power of the observed Chandler wobble excitation than GRACE at the Chandler wobble frequency (normally 0.75–0.92 cpy). However, at longer periods, the GRACE data appear to better capture the amplitude of large interannual anomaly in 2006 through 2008 in Px, although the phase is early by two months. There was also a significant negative anomaly in early 2007 in Py that is better captured by the GRACE OBP data than that from the ECCO model.

[26] In all the examples we have studied, the GRACE OBP data appear to estimate the polar motion variations better than that of the ECCO model. However, the TWS data from GRACE give mixed results. One reason for this may be the aliasing we mentioned earlier. The GRACE processing does model high-frequency variations in OBP, but do not model such variations in hydrology because short-term hydrology variations are harder to model. Because of this, the hydrology estimates from GRACE may be more contaminated by aliases than the ocean estimates. The other problem may be in resolution. OBP is generally a very long wave, low amplitude variation. TWS, on the other hand, tends to have a much larger amplitude over smaller areas. The smoothing and gridding of the GRACE data used in this study was optimized for ocean studies (e.g., D. P. Chambers, Converting Release-04 gravity coefficients into maps of equivalent water thickness, available at ftp://podaac.jpl.nasa.gov/pub/tellus/monthly_mass_grids/chambers-destripe-RL04–200711/doc/GRACE-dpc200711_RL04.pdf). It may be that the hydrology component may be oversmoothed for this type of study, and different mapping and smoothing methods might give more consistent results. This is something we hope to study in the near future.

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