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Hydrological excitations of polar motion, 1993–2002

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SUMMARY

Changes in continental water storage obtained from an advanced land data assimilation system (LDAS) are employed to compute hydrological excitations of polar motion for the 10-yr period of 1993–2002. The results are compared with observed excitations of polar motion and contributions from the atmosphere and ocean, and with results from previous studies. There is remarkably good agreement between LDAS-derived results and remaining observed excitations, i.e. after atmospheric and oceanic effects are removed from the observations. LDAS-predicted hydrological excitations play a major role in closing the excitation budget for prograde and retrograde annual wobble, especially for the prograde component, and show considerably better agreement with observations than previous results. LDAS-predicted results show significantly larger interannual variability and also agree well with observed excitations not accounted for by the atmosphere and ocean. As demonstrated in this study, LDAS shows major improvement in modelling large-scale change in land water storage at both seasonal and interannual timescales.

Key words: excitation, hydrology, polar motion, water.

1 INTRODUCTION

Under the conservation of angular momentum, any change in the Earth's inertia tensor due to redistribution of mass will cause changes in the Earth's rotation. Variations of atmospheric angular momentum (AAM) or oceanic angular momentum (OAM) will also change the Earth's rotation via exchange of angular momentum between the solid Earth and its geophysical fluid envelope. At interannual or shorter timescales, redistribution of air and water mass and movement within the Earth system, including the atmosphere, ocean and hydrosphere (plus snow/ice sheet), are primary driving forces behind changes in the Earth's rotation, while redistribution of mass within the core and mantle plays a more important role at decadal or longer timescales.

Changes in the Earth's rotation are represented by polar motion (X, Y), the equatorial components in a geographical reference frame, and variation in the length of the day (LOD), the axial component measuring the change in the Earth's rotational rate. AAM changes have long been recognized as the primary cause of polar motion and the dominant contributor to change in LOD (e.g. Wilson & Haubrich 1976; Wahr 1983; Barnes *et al.* 1983; Chao & Au 1991; Eubanks 1993). The oceans have also been proved to play an important role in driving the Earth's rotational change (e.g. Dickey *et al.* 1993; Ponte *et al.* 1998, 2001; Johnson *et al.* 1999; Gross *et al.* 2003; Chen *et al.* 2004), in particular at intraseasonal timescales. However, except for LOD variations, observed excitations of polar motion X and Y are far from being satisfactorily explained, especially at annual and interannual timescales.

Changes in water storage over land, including changes of soil water, snow/ice sheets and ground water, are generally believed to be a major contributor to polar motion at seasonal timescales because of the significant seasonal cycle in the hydrosphere. A number of previous studies have estimated hydrological excitations of polar motion using climatological measurements (e.g. Van Hylckama 1970; Hinnove & Wilson 1987; Chao & O'Connor 1988) and numerical climate models (e.g. Kuehne & Wilson 1991; Chen *et al.* 2000). Although the general conclusions are more or less the same, i.e. change in continental water storage plays a major role (judged by the magnitude of the estimated excitations) in causing seasonal polar motion, the results themselves, however, do not agree with each other or with observed polar motion (Chao & O'Connor 1988). This is mainly limited by the lack of global measurements of related hydrological parameters (e.g. precipitation, evapotranspiration, surface run-off, soil moisture, snow water, etc.) and the immaturity of hydrological models. Chao & O'Connor (1988) pointed out the cancellation effects on excitations of polar motion between changes in continental water storage in the eastern and western hemispheres, and also between changes in snow and rain water. This would mean that the determination of hydrological excitations is highly sensitive to data errors, making it a more challenging task.

Previous studies have mostly focused on hydrological excitations of polar motion at seasonal timescales because of the climatological nature of the data resources applied or the lack of interannual variability in model estimates (e.g. Chen *et al.* 2000). Interannual hydrological excitations of polar motion are poorly known. In this study, we will examine both seasonal and interannual excitations from change in continental water storage using the advanced LDAS hydrological model. We will focus on excitations of polar motion at seasonal and interannual timescales. The main objective of this study is to better understand the effects of hydrology on polar motion and to examine how well we could close the global budget of seasonal and interannual excitations of polar motion.

2 THEORY

At a given gridpoint (latitude ϕ, longitude λ, time t), $\Delta q(\phi, \lambda, t)$ represents change in water storage in a unit area (in kg m^{-2}). Following the formulation given by Eubanks (1993), hydrological excitations of polar motion, χ_1 and χ_2 can be computed as

$$\begin{bmatrix}\chi_1\\ \chi_2\end{bmatrix} = -\frac{1.098 R_e^2}{C - A} \times \iint \Delta q(\phi, \lambda, t) \sin(\phi) \cos(\phi) \begin{bmatrix}\cos(\lambda)\\ \sin(\lambda)\end{bmatrix} ds \qquad (1)$$

in which, R_e (6.37101×10^6m) is the Earth's mean radius, $ds = R_e^2 \cos(\phi)\, d\phi\, d\lambda$, is the surface area element. C and A are the Earth's principal moments of inertia ($C - A = 2.61 \times 10^{35}$ kg m^2). The factor 1.098 accounts for the combined effects of the yielding of the solid Earth to surface load, core–mantle decoupling, and rotational deformation (Eubanks 1993).

In general, changes in continental water storage (Δq) include changes from three major components, namely soil water, ground water and snow/ice sheets. Change in the water mass in the vegetation canopy associated with seasonality is believed to be minor and negligible (Rodell *et al.* 2002) compared with the uncertainties of other major components. In any given region, Δq can be estimated from the traditional conservation equation

$$\Delta q = P - E - R \qquad (2)$$

where P, E and R are precipitation, evapotranspiration and runoff. P, E and R could come from either measurements or model estimates. Another alternative method of computing Δq is to use measured or model estimated soil moisture and snow/ice change (i.e. Δq = soil + snow water), which represents change in water storage at the Earth's surface down to a certain depth as defined by the measurement or model. The challenging task is how to accurately determine or model these hydrological parameters.

At large spatial scales, the conservation eq. (2) more accurately describes the total change in water storage in a given region than Δq = soil + snow water. $\Delta q = P - E - R$ represents the net change of water in soil and snow/ice sheets, ground water stored in reservoirs, and water in the vegetation canopy (if transpiration is considered). The soil moisture and snow approach, however, leaves changes in water in the deep soil layers (below the depth of measurements or defined by the model) and reservoirs unaccounted for.

3 DATA AND COMPUTATION

3.1 Observed polar motion excitation

Polar motion (X, Y) time-series are taken from the SPACE2002 (SP02) data set (Gross 2002). Daily values are determined from various space geodetic observations by a Kalman filter combination. Time-series cover the period 1976 September to 2003 January. Excitation functions (χ_1 and χ_2) are computed from (X, Y) using the discrete linear polar motion filter developed by Wilson (1985) using a Chandler frequency of 0.843 cycles per year (cpy) and a quality factor (Q) of 175. In order to match the temporal resolution of the OAM results introduced later, the daily χ_1 and χ_2 time-series are averaged into 10-day intervals.

3.2 Atmospheric excitations

Atmospheric excitations of polar motion are derived from the National Centers for Environmental Prediction (NCEP) reanalysis atmospheric model. To be consistent with the OAM time-series introduced below, we apply the effective excitations defined in Eubanks (1993). This will introduce slight difference from the NCEP reanalysis AAM products provided by the Atmospheric and Environmental Research (Salstein & Rosen 1997). The AAM time-series spans 1993 January 1 to the present at daily intervals. Both wind and surface pressure contributions are included. Wind excitations are computed from 1000 mbar to the top of the model (10 mbar). The oceans are assumed to respond as an inverted barometer (IB) to changes in atmospheric surface pressure, i.e. pressure over the oceans is replaced by the mean pressure over the ocean area. Inland seas are treated as land when we compute pressure excitations and apply the IB corrections. The daily AAM time-series are also averaged into 10-day intervals to match the OAM data.

3.3 Oceanic excitations

The OAM time-series, similar to those of Chen *et al.* (2004), are computed from the data assimilating the ocean general circulation model (OGCM) (Fukumori *et al.* 2000), developed at NASA's Jet Propulsion Laboratory, a partner in the Estimating the Circulation and Climate of the Ocean (ECCO) program (hereafter this model is denoted as ECCO). The OAM results include contributions from ocean current, computed by integrating ECCO 10-day averaged zonal (U) and meridional (V) velocity data, and contributions from bottom pressure, estimated from the 12-hourly OBP data from the ECCO (kf047a). Ten-day averaged OAM time-series are computed from the 12-hourly OBP and 10-day averaged U and V estimates. The AAM and OAM excitations are removed from observed excitations before the residual excitations are compared with hydrological effects.

In this study we introduce two separate adjustments to conserve the total mass of the atmosphere, ocean and continental water. The first step is to constrain the ECCO OBP fields to conserve total ocean mass (Chen *et al.* 2004). Then a uniform layer of water is added to the oceans equal to the total change in water mass over land. Finally, the change in the total mass of the atmosphere is balanced by adding a uniform layer of water to the oceans and land.

3.4 Hydrological excitations

LDAS is a global land surface model (Fan *et al.* 2003) recently developed at the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). LDAS is forced by observed precipitation, derived from CPC daily and hourly precipitation analyses, downward solar and long-wave radiation, surface pressure, humidity, 2 m temperature and horizontal wind speed from NCEP reanalysis. The output consists of soil temperature and soil moisture in four layers below the ground. At the surface, it includes all components affecting energy and water mass balance, including snow cover, depth and albedo. Monthly average changes in soil water storage are provided on a $0.5^\circ \times 0.5^\circ$ grid for the period 1980 January to 2003 July. No estimate is provided over Antarctica.

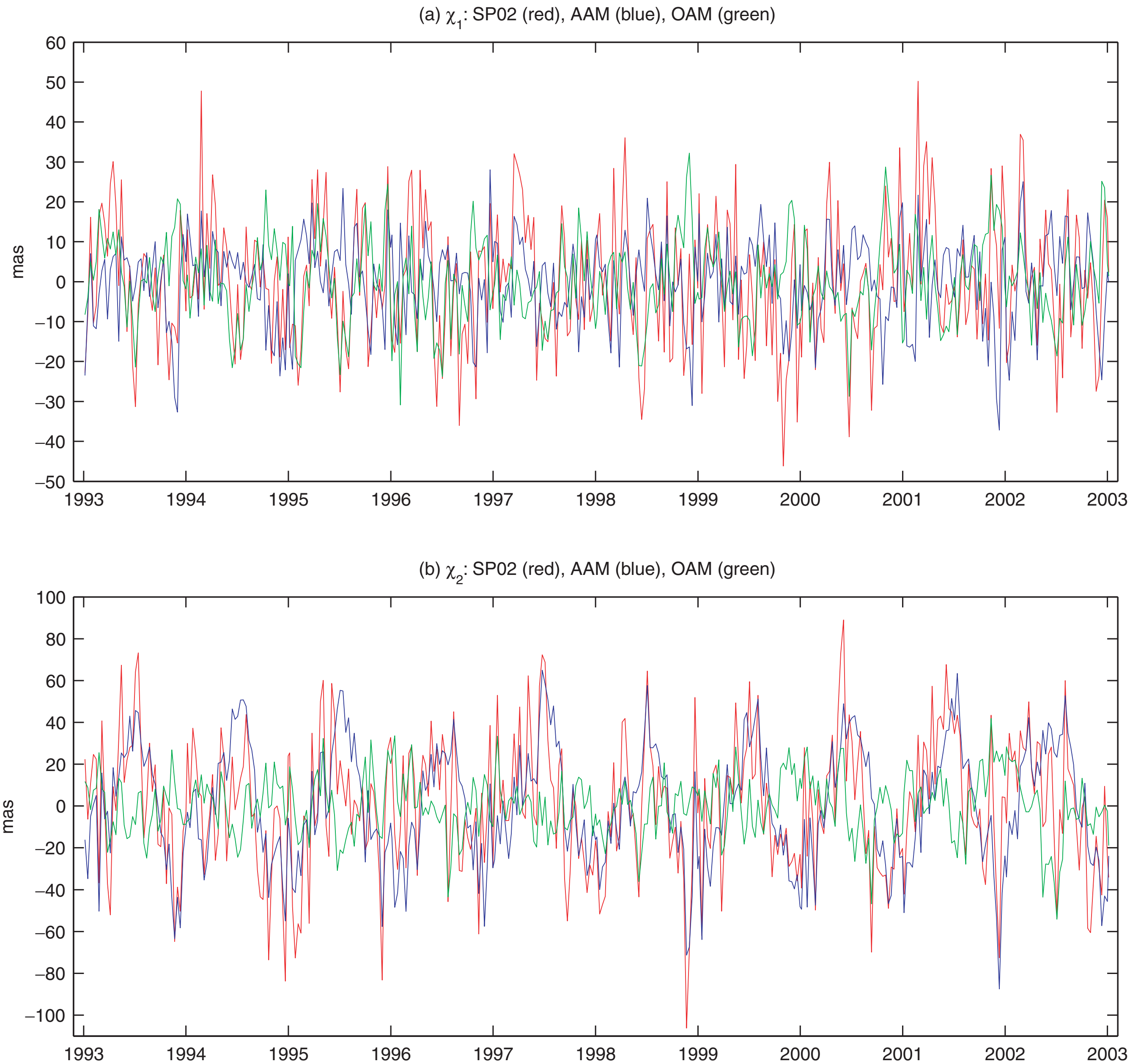

Figure 1. (a) and (b) Observed excitations (χ_1, χ_2) from SP02 (red curves) and NCEP reanalysis AAM (blue curves) and ECCO OAM (green curves) contributions (AOW, red).

The LDAS soil water storage changes are estimated using the conservation equation (eq. 2) (H. van den Dool, personal communication). Monthly soil water data are used to compute hydrological excitations of polar motion χ_1 and χ_2 using eq. (1). For comparison, we also compute hydrological excitations using NCEP reanalysis soil moisture and snow data. These hydrological excitations are similar to the results published by Chen *et al.* (2000), covering an extended time period (1993–2003).

4 RESULTS

4.1 Polar motion excitations

Observed polar motion excitations χ_1 and χ_2 are shown in Figs 1(a) and (b) in red curves. AAM and OAM contributions from NCEP reanalysis and ECCO OGCM are in blue and green curves, respectively. Clearly, the atmosphere plays a major role in exciting polar motion, especially in Y. OAM variations also provide significant contributions to both $X(\chi_1)$ and Y (χ_2). Although the agreements between observations and OAM effects are not so explicit, as demonstrated by Chen *et al.* (2004) and Gross *et al.* (2003), combined AAM and OAM excitations agree significantly better with observations than any of the two separate contributions would do.

Figs 2(a) and (b) show hydrological excitations estimated from LDAS soil water change (red curves) and NCEP reanalysis soil and snow data (green curves). These are compared with remaining excitations, i.e. observed excitations minus AAM and OAM contributions. All time-series are detrended. It is clear that LDAS-predicted hydrological excitations agree remarkably well with the remaining excitations, especially in the χ_2 component. In χ_1, the LDAS result

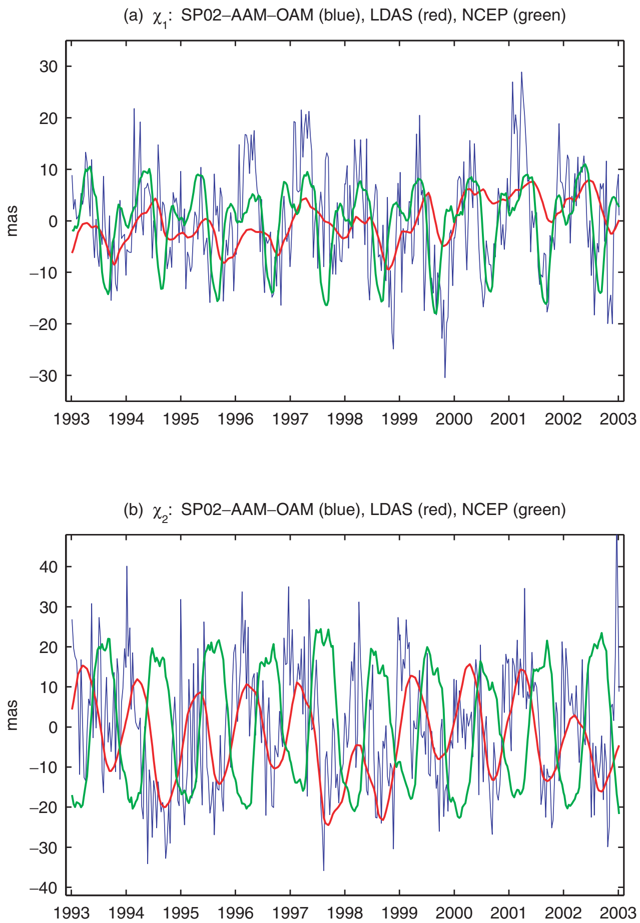

Figure 2. (a) and (b) Residual excitations in χ_1 and χ_2, i.e. SP02-AAM-OAM (blue curves) and hydrological excitations from LDAS (red curves) and NCEP reanalysis soil and snow data (green curves).

follows the remaining excitation closely in each seasonal cycle, and only shows relatively smaller amplitudes. The results derived from NCEP soil and snow data, however, only show good agreement with observations in χ_1, and are out of phase with observations or LDAS predictions in χ_2. This is consistent with the general conclusion of Chen *et al.* (2000).

4.2 Seasonal excitations

We compute the prograde and retrograde components of annual complex polar motion excitations, $\chi_1 + i\chi_2$ ($i = \sqrt{-1}$) for each estimate shown in Figs 2(a) and (b) using least squares. We also estimate separate contributions from atmospheric winds, surface pressure, ocean current (U and V), and OBP. The amplitudes and phases for annual and semi-annual polar motion excitations from each source are listed in Tables 1 and 2. Similar estimates from Chao & O'Connor (1988) based on climatological soil and snow water analysis are also listed for comparison. Change in atmospheric pressure is clearly the most important excitation for both prograde and retrograde polar motion. Oceanic and continental water also provide significant contributions to the seasonal excitation budget.

For a clearer representation, Figs 3 and 4 show the phasor plots of different excitations of annual and semi-annual prograde and retrograde polar motion as listed in Tables 1 and 2. LDAS-estimated hydrological excitations play an important role in closing the annual prograde and retrograde budget, especially for the prograde component (Fig. 3a). The combined excitations of LDAS water effects and NCEP AAM and ECCO AAM contributions (denoted as AOW1) show considerably better agreement with observations than the combination using NCEP reanalysis soil and water results or results from Chao & O'Connor (1988) (denoted as AOW2 and AOW3). For prograde polar motion, AOW1 [15.28 mas (milliarcseconds), 59°] can almost close the annual budget of observed excitations (15.08 mas, 59°). For retrograde annual polar motion, AOW1 also shows the best phase agreement with observations (Table 1). The semi-annual excitations from both AOW1 and AOW2 do not agree with observations, although AOW1 appears to show relatively better phase agreement but smaller magnitude.

Table 1. Amplitudes (in milliarcseconds (mas)) and phases (in degrees) of prograde and retrograde annual wobble. The phases refer to h^0 on 1993 January 1. Estimates from Chao & O'Connor (1988) are also listed for comparison (denoted as Chao). AOW1, AOW2 and AOW3 represent combined excitations of NCEP AAM, ECCO OAM and one of the three hydrological estimates, i.e. LDAS, NCEP and Chao.

Excitation process	Prograde		Retrograde	
	Amplitude (mas)	Phase (deg)	Amplitude (mas)	Phase (deg)
Observed (SP02)	15.08	−59	8.21	−132
NCEP pressure	15.68	−98	15.63	−112
NCEP wind	2.56	−54	2.26	−24
NCEP AAM	17.61	−92	15.88	−104
ECCO OBP	4.28	78	2.11	86
ECCO *U* & *V*	2.92	24	2.45	13
ECCO OAM	6.43	56	3.68	47
Water1 (LDAS)	5.11	−9	7.39	166
Water2 (NCEP)	12.60	−115	8.72	−30
Water3 (Chao)	1.90	286	3.30	29
AOW1 (+LDAS)	15.28	−59	13.92	−127
AOW2 (+NCEP)	23.77	−96	18.19	−70
AOW3 (+Chao)	14.48	−76	11.23	−82

Table 2. Amplitudes (in milliarcseconds (mas)) and phases (in degrees) of prograde and retrograde semi-annual wobble. The phases refer to h^0 on 1993 January 1. AOW1 and AOW2 represent combined excitations of NCEP AAM, ECCO OAM and one of the two hydrological estimates, i.e. LDAS and NCEP. Semi-annual estimates are not available in Chao & O'Connor (1988).

Excitation process	Prograde		Retrograde	
	Amplitude (mas)	Phase (deg)	Amplitude (mas)	Phase (deg)
Observed (SP02)	3.01	119	5.31	137
NCEP pressure	2.82	20	4.89	118
NCEP wind	0.48	−25	0.65	−130
NCEP AAM	3.18	14	4.68	125
ECCO OBP	1.72	−176	1.58	−110
ECCO *U* & *V*	1.70	−173	1.23	−106
ECCO OAM	3.42	−175	2.80	−108
Water1 (LDAS)	0.20	−81	0.75	24
Water2 (NCEP)	3.88	89	2.60	−83
AOW1 (+LDAS)	0.38	139	3.23	153
AOW2 (+NCEP)	4.34	94	3.54	−156

4.3 Interannual excitations

Figs 5(a) and (b) shows the comparison between interannual excitations from two hydrological excitations (i.e. LDAS and NCEP) and SP02-AAM-OAM residuals. Annual and semi-annual variations are

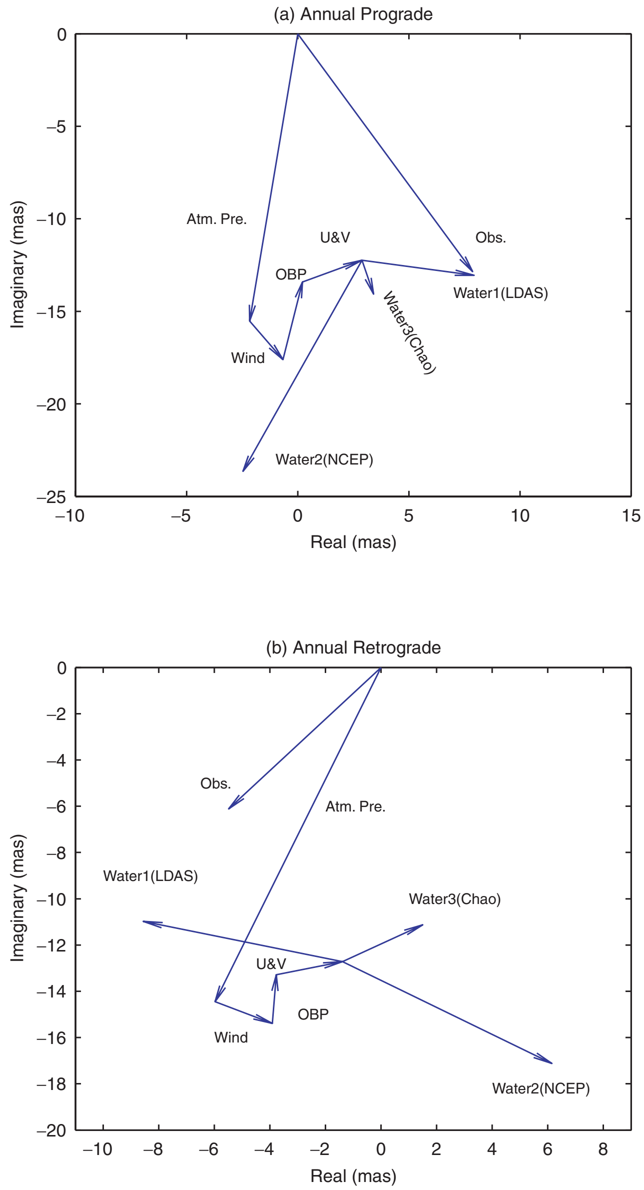

Figure 3. Phasor plots for annual prograde (a) and retrograde (b) excitations from values listed in Table 1.

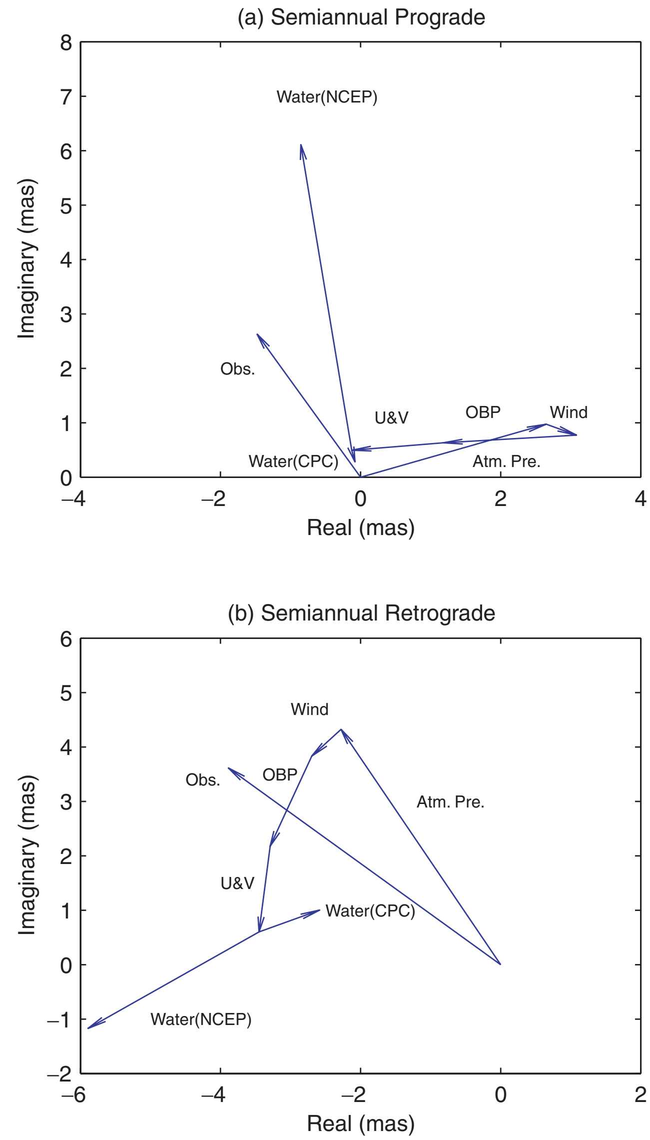

Figure 4. Phasor plots for semi-annual prograde (a) and retrograde (b) excitations from values listed in Table 2.

first removed from all time-series using least squares. The residual time-series are then smoothed using a 1 yr sliding window. As shown in Figs 1(a) and (b) and further confirmed in Figs 5(a) and (b), the SP02-AAM-OAM residuals show significant interannual variations. Interestingly, the LDAS hydrological model also predicts strong interannual variability and matches the SP02-AAM-OAM residuals remarkably well. For example, the maximum cross-correlation coefficient (at zero phase lag) between residual excitations and LDAS estimates could reach 0.65 in χ_1, while in χ_2 it is only about 0.22, limited by the increased disagreement from around 1999. The NCEP reanalysis soil and snow data, however, predict much smaller interannual variations.

5 DISCUSSION

Similar to atmospheric surface pressure, changes in continental water storage play a more significant role in polar motion in χ_2 than in χ_1, and also agree better with observations in χ_2. This can be explained as due to the geographical locations of major continents, aligning closer along the Y-axis (i.e. along 90/270° E longitude). Therefore, polar motion Y is more sensitive to mass changes over the land and X is more sensitive to mass changes over the oceans. X and Y are relatively more closely tied to χ_1 and χ_2, respectively, via the discrete linear polar motion filter (Wilson 1985). An interesting observation is that χ_1 excitations based on NCEP reanalysis changes in soil and snow agree well with residual observations (unaccounted for by the atmosphere and ocean), while in χ_2, however, they are completely out of phase. This is simply contrary to the above interpretation. If NCEP reanalysis correctly models change in soil and snow, we are more likely to see good agreements in χ_2 than in χ_1, as demonstrated by the results from LDAS (see Fig. 2). This out-of-phase character is clearly reflected in the disagreements between annual NCEP soil and snow estimates and observations in prograde and retrograde polar motion (Table 1 and Fig. 3).

LDAS appears to show a major improvement over previous models (e.g. NCEP reanalysis) and climatological analysis in modelling

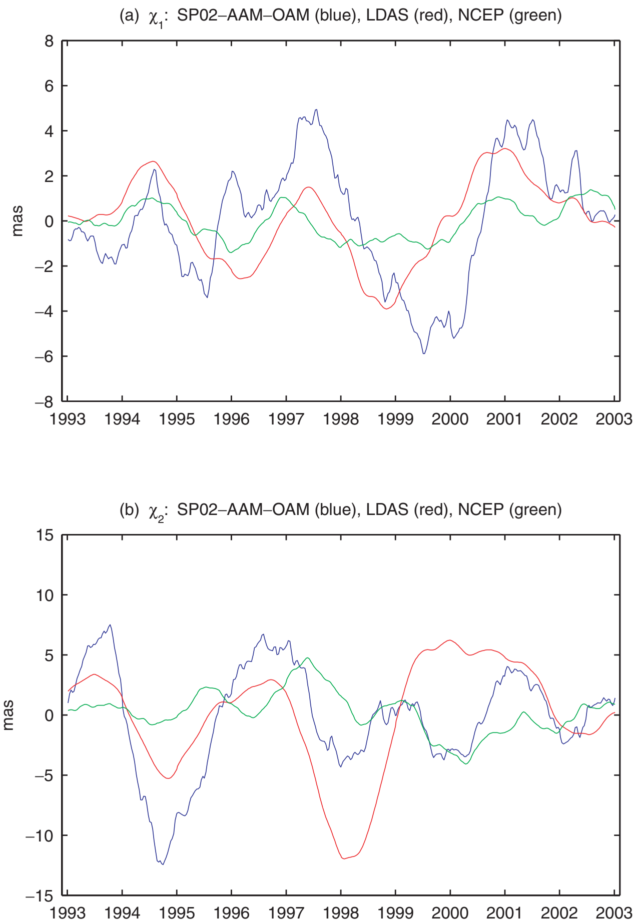

Figure 5. Residual interannual excitations in χ_1 (a) and χ_2 (b), i.e. SP02-AAM-OAM (blue curves) and hydrological excitations from LDAS (red curves) and NCEP reanalysis soil and snow data (green curves).

changes in water storage on a large spatial scale. The improvement could be seen at both seasonal and interannual time-scales. Hydrological excitations estimated from LDAS are nearly able to close the annual budget in prograde polar motion when combined with excitations from NCEP reanalysis AAM and ECCO OAM. LDAS also shows remarkable agreement with the residual polar motion excitations at interannual time-scales during much of the 10-yr period. The results from this study lead to a better understanding and interpretation of observed polar motion excitations at seasonal and interannual time-scales.

The NCEP reanalysis model is a fixed data-assimilating global numerical model, designed mainly for atmospheric studies. The hydrological part of this model is primitive, and reflects a combination of an imposed (non-data-assimilating) hydrological cycle and some interaction with the atmosphere and climate. Notably, with regard to soil and snow water NCEP overestimates seasonal water storage in some regions and lacks the interannual variability expected in the real hydrological cycle. This is reflected in polar motion excitations shown in this study. The strong interannual variability (Fig. 5) and unstable seasonal variability, especially in χ_1 (Fig. 2a), suggest that the use of climatological averages (i.e. a mean seasonal cycle) will not appropriately represent real hydrological change. LDAS, however, employs an advanced land model (Huang *et al.* 1996), and assimilates observed precipitation data. LDAS-predicted change in land water storage apparently better represents real hydrological signals, as demonstrated through this study.

The comparison between model-predicted hydrological excitations and the SP02-AAM-OAM residuals could be affected by errors or uncertainties not only in the hydrological models themselves but also in observations of polar motion and AAM and OAM excitation estimates. AAM excitations are relatively the best determined geophysical contributions. The ECCO data-assimilating OGCM is proved to be superior to other models (e.g. Chen *et al.* 2004), but the development is still on-going and we need to see internal consistency with other advanced ocean models. This study demonstrates that accurately measured change in polar motion (and other geodetic measurements) can serve as an observational constraint to large-scale changes in continental water storage and be used to validate numerical model estimates, such as those from LDAS and NCEP reanalysis. In addition to the advancement in 'state-of-art' hydrological models (such as LDAS), we may anticipate major improvement in quantifying change in continental water storage using satellite gravity measurements, such as those of the Gravity Recovery and Climate Experiment (GRACE) mission.

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