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Seasonal excitation of polar motion estimated from recent geophysical models and observations

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Abstract

Here we investigate the seasonal excitation balance of polar motion using recent geophysical data sets and models. Attention is focused on the contribution of the land hydrology which is expressed either by models, such as CPC, GLDAS, LaD, or by the observations provided by the experiment GRACE. Geophysical excitation series are compared to each other and to the excitation inferred from the space geodetic observations of polar motion. Comparison shows that 3 models of land hydrology considered in this work differ considerably; adding the corresponding excitation series to the combination of atmospheric and oceanic excitation data does not clearly improve agreement with observations. But combination of the GRACE-derived mass term of excitation with the motion terms of atmospheric and oceanic excitations brings the excitation balance considerably closer in case of the retrograde/prograde annual and retrograde semiannual components of polar motion. For other seasonal components as well as for the nonharmonic residuals, the estimated contributions of hydrology do not improve the excitation balance of polar motion.

Key words:

polar motion, atmospheric excitation, oceanic excitation, hydrological excitation, GRACE experiment

1. Introduction

Seasonal signals in Earth rotation are excited by the large-scale processes taking place in the external fluid layers including the atmosphere, the oceans and the land hydrology; see the recent review by Gross (2007) and the references therein. The most significant part of seasonal excitation comes from the atmospheric angular momentum (AAM). The dominant contribution to the equatorial component of excitation, related to polar motion, is from the pressure term of AAM. The earlier investigations by Gross et al. (2003), Brzeziński et al. (2005) demonstrated that adding the nontidal oceanic angular momentum (OAM) estimate to that of the AAM improves the agreement with the seasonal excitation inferred from the geodetic determinations of Earth orientation, nevertheless the remaining differences are still significant. It is expected that the land hydrology is responsible for the discrepancy in the seasonal excitation budget. However, comparisons with the available hydrological angular momentum (HAM) data sets

have been not conclusive so far; see, e.g., Nastula et al. (2007); Chen and Wilson (2008).

Here we investigate the seasonal excitation balance of polar motion using the excitation series computed from recent geophysical data sets and models, and those inferred from space geodetic observations of Earth rotation. Attention is focused on the role played by the land hydrology which is expressed either by hydrological models and data analyses, or by the observations provided by the satellite experiment GRACE (Gravity Recovery and Climate Experiment).

2. Data analysis

2.1. Data sets

The so-called geodetic excitation of polar motion (further denoted Obs) has been computed by the time domain deconvolution procedure applied to the time series of the Earth Orientation Parameters (EOP). We used the following two EOP data sets based on a combination of the space geodetic measurements:

- IERS C04 (Bizouard and Gambis, 2008), <http://hpiers.obspm.fr/iers/eop/>

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- SPACE06 (Gross, 2000), <ftp://euler.jpl.nasa.gov/keof/combinations/>.

The atmospheric excitation of polar motion is expressed here by three time series of AAM estimated by the procedure developed by Salstein and Rosen (1997) on the basis of the output fields of the following reanalysis projects:

- NCEP1 – U.S. NCEP-NCAR reanalysis (Kalnay et al., 1996);
- NCEP2 – NCEP/DOE reanalysis 2 (Kanamitsu et al., 2002);
- ERA-40 – ECMWF reanalysis (Uppala et al., 2005).

All these AAM series are available from the IERS Special Bureau for the Atmosphere, ftp://ftp.aer.com/pub/anon_collaborations/sba/. The first series was used in the previous work by Brzeziński et al. (2005) and in several other excitation studies, e.g., (Gross et al., 2003) (Gross et al., 2003). The last two series have been made publicly available only recently, therefore we find it very interesting to compare them to NCEP1 at the seasonal frequencies.

The nontidal oceanic excitation of polar motion is expressed in this study by two OAM series estimated from the ECCO ocean model forced by atmospheric surface wind stress, heat and freshwater fluxes taken from the output fields of the NCEP-NCAR reanalysis:

- ECCO1 – model without data assimilation, kf066a2 run (Gross et al., 2003);
- ECCO2 – data-assimilating model, kf066b run (Fukumori et al., 2000); (Gross, 2008).

These OAM series are available from the IERS Special Bureau for the Ocean <ftp://euler.jpl.nasa.gov/sbo/>. Note that in the previous study (Brzeziński et al., 2005) the first series was used under the acronym G03.

The hydrological excitation of polar motion is expressed here by three HAM series which we computed from output fields of the following models:

- CPC – Land Data Assimilation System (LDAS) developed at NOAA Climate Prediction Center (Fan et al., 2003), available from the IERS Special Bureau for Hydrology <ftp://ftp.csr.utexas.edu/pub/ggfc/water/>;

- GLDAS – NASA Global Land Data Assimilation System (Rodell et al., 2004), available from the IERS Special Bureau for Hydrology;

- LaD (gascoyne) – Land Dynamics with snow water equivalent, shallow ground water, and soil water (Milly and Shamkin, 2002), courtesy C. Milly.

The GRACE gravity field data has been used to compute the mass term of the polar motion excitation functions (Chen and Wilson, 2005); (Nastula et al., 2007). The so-called Level-2 GAC products representing monthly mean non-tidal atmospheric and oceanic variability have been added back to the GRACE data used in this study. We use the following recent (release 4) GRACE solutions:

- CSR-RL04 – Center for Space Research, Austin, USA;
- GFZ-RL04 – GeoForschungsZentrum, Potsdam, Germany;
- JPL-RL04 – Jet Propulsion Laboratory, Pasadena, USA.

2.2. The procedure

We follow the analysis scheme developed by Brzeziński et al. (2005). As a first step we estimate for each input time series (Obs, AAM, OAM, HAM, GRACE) parameters of the model comprising the 3-rd order polynomial and a sum of complex sinusoids with periods ± 1 , $\pm 1/2$, $\pm 1/3$ years (the sign \pm is for prograde/retrograde motion). The estimation is done by the unweighed least squares (LSQ) fit. In case of the observed excitation series we applied an alternative procedure which consists in fitting the model directly to the polar motion series and then transforming the estimated parameters of the harmonic components and their standard errors to the excitation domain by using the equation of polar motion. This algorithm should give better estimate of the seasonal components than the estimation from the series Obs because the accuracy of estimate is not influenced by possible imperfections of the time domain deconvolution procedure. We also believe that the corresponding error estimates are more realistic than those derived from Obs.

As a next step we compute the residual series by removing the polynomial-harmonic model. Finally, we compare the geodetic excitations of polar motion to each other and to the following combinations of the geophysical excitation series: AAM, AAM + OAM, AAM

+ OAM + HAM, AAM(motion) + OAM(motion) + GRACE.

Here AAM means a combination of the motion (wind) and the matter (pressure) term with the inverted barometer (IB) correction for the ocean response to the surface pressure changes. Similarly, OAM means a combination of the motion (currents) and the matter (bottom pressure) terms. The AAM IB series is also used when adding the atmospheric and oceanic contributions, because the two ocean models considered here are referred to the IB model. The GRACE-derived excitation is assumed to express a total value of the mass term of geophysical excitation including contributions from the atmosphere, the oceans, and the land hydrology. This excitation is combined with the motion terms of AAM and OAM. The motion term of HAM is expected to be very small therefore is not included in the excitation data sets.

We compare parameters of the seasonal harmonics in phasor diagrams, and the residual nonharmonic series in the time domain. In the last case the comparison is done by visual inspection, computation of the correlation coefficient, and estimation of percentage of the observed variance which is explained by geophysical data.

3. Results

3.1. Comparison of seasonal harmonics

Parameters of the observed and estimated geophysical excitations are compared in Figures 1 to 5. Each seasonal component of excitation is presented as combination of two circular motions with the same angular speed but with opposite directions, retrograde (clockwise, with negative frequency) and prograde (counterclockwise, positive frequency). This decomposition makes the physical interpretation easier because the polar motion transfer function, that is the ratio of the amplitude of polar motion to that of the corresponding excitation, depends on frequency and is asymmetric with respect to zero frequency. For periods +1, -1, +1/2, -1/2, +1/3, -1/3 years the magnitude of the transfer function is 5.37, 0.46, 0.73, 0.30, 0.39, 0.22, respectively.

This variability of the transfer function implies also that the observed excitations depicted in phasor diagrams are not equally well constrained by geodetic observations of polar motion which is illustrated by the standard error circles in Figures 1 to 5. According to the procedure described in Section 2.2 their radii were computed by taking the formal standard errors of the amplitudes of polar motion in the LSQ adjustment and

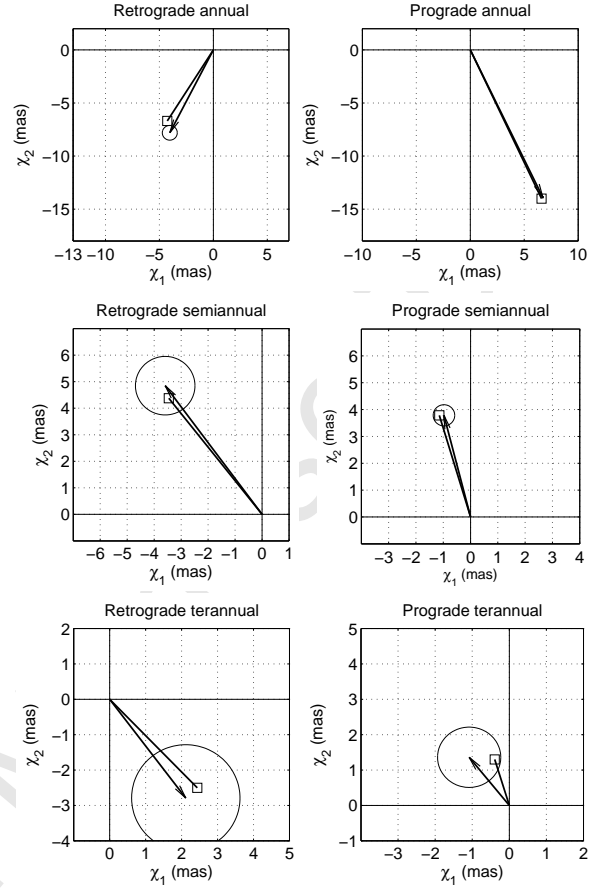


Figure 1: Phasor diagrams of the seasonal components of the observed excitation functions of polar motion, C04 (arrow) and SPACE06 (square). Analysis is done over the period 1976.8 to 2007.1. Phase refers to the epoch J2000.0.

dividing them by the magnitude of the transfer function. As the standard errors of the estimated polar motion amplitudes were of similar size, the errors of the corresponding excitation components are roughly inversely proportional to the magnitude of the transfer function therefore are significantly different. For instance, the estimated error of the prograde annual harmonic of geodetic excitation is about 12 times smaller than that of the retrograde annual one, and the corresponding error circle is hardly visible in the plots.

We compare first in Figure 1 parameters of the seasonal harmonics derived from the observed excitation series C04 and SPACE06 over the common time interval 1976.8 to 2007.1. There is quite good agreement between the two estimates with exception of the retrograde annual harmonic where the difference is about two times larger than the estimated standard error. In the rest of paper the observed excitation will be expressed by the

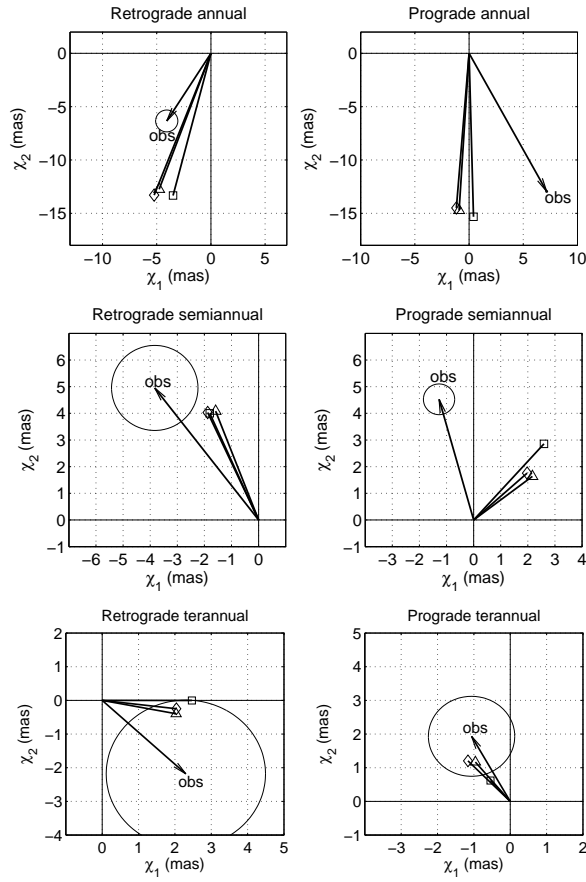


Figure 2: Seasonal components of the observed (IERS C04) and atmospheric excitations of polar motion: NCEP1 (triangle), NCEP2 (diamond), ERA40 (square). Analysis is done over the period 1979.0 to 2002.6. Phase refers to J2000.0.

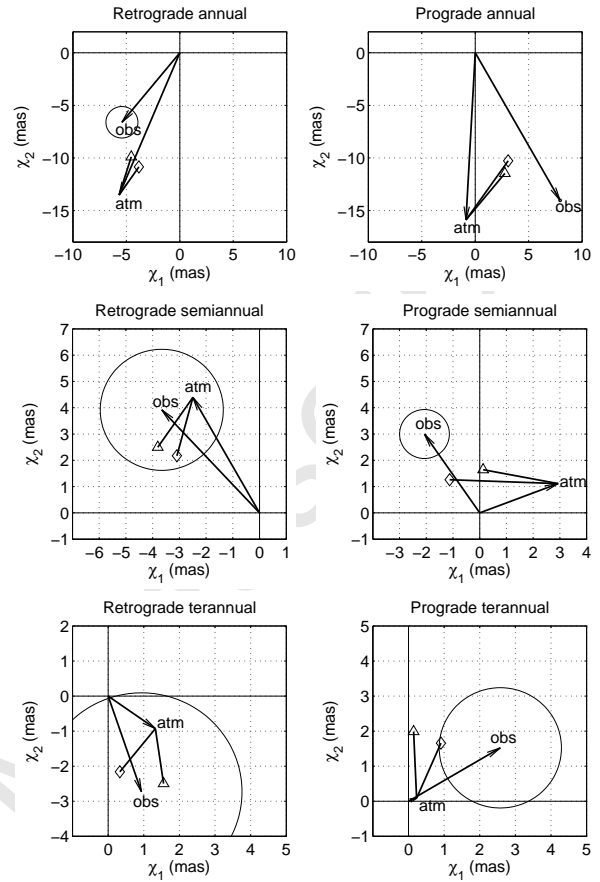


Figure 3: Seasonal components of the observed (C04), atmospheric (NCEP1) and oceanic (ECCO1 – triangle, ECCO2 – diamond) excitations of polar motion. Analysis is done over the period 1993.0 to 2002.2. Phase refers to J2000.0.

C04 series. It should be noted that the amplitude and phase of the observed excitations shown in Figures 2 to 5, which are estimated over the shorter records of polar motion data, differ sometimes from the values shown in Figure 1. Such fluctuation is typical for geophysical effects which are considered in this analysis.

The atmospheric contributions expressed by the AM series NCEP1, NCEP2 and ERA40 are compared in Figure 2. The two NCEP reanalysis series yield the results which are more or less the same. But estimates from ERA40 differ from the NCEP results both in phase (up to 6 degrees for prograde annual harmonic) and in some cases (prograde semiannual and retrograde/prograde terannual terms) also significantly in amplitude. Particularly important is the difference in prograde annual term, about 2 milliarcseconds (mas) which gives more than 10 mas when computing the corresponding polar motion. This difference is probably

caused by mass-transport inconsistencies in the ERA40 reanalysis (Graversen et al., 2007) For further comparisons we adopted the NCEP1 series as representing the atmospheric excitation.

The nontidal oceanic contributions to seasonal harmonics, estimated from the models ECCO1 and ECCO2, are compared in Figure 3. The most important difference is again for the prograde annual term, corresponding to about 7 mas in polar motion. We adopt for further analysis the series ECCO2 with data assimilation which is expected to be more realistic than ECCO1. As we will see in the next section, the advantage of ECCO2 is confirmed by the correlation analysis of the irregular nonharmonic residuals.

The hydrological contributions estimated from the models CPC, GLDAS and LaD are compared in Figure 4. The three estimates differ considerably. No one of them can be selected as giving the best closure of the

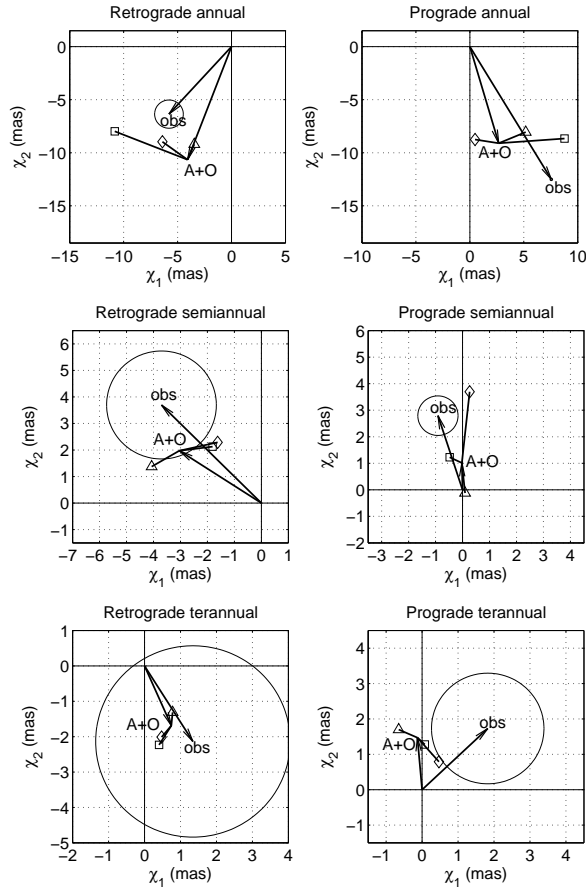


Figure 4: Seasonal components of the observed (C04), combined atmospheric and oceanic ((NCEP1 + ECCO2), and hydrological (CPC - square, GLDAS - triangle, LaD - diamond) excitations of polar motion. Analysis is done over the period 1993.0 to 2005.0. Phase refers to J2000.0.

excitation balance. In case of the prograde annual harmonic the difference between various estimates of HAM as well as difference between the observation and combined contribution of AAM, OAM and HAM exceeds 4 mas corresponding to about 22 mas in polar motion.

The GRACE-derived excitations combined with the motion term of AAM and OAM are compared to the observed excitation in Figure 5. In order to enhance the comparison, we additionally shown the vectors expressing the estimated total excitation by the atmosphere and ocean, as well as the motion term of AAM+OAM which has been earlier added to the GRACE excitation data. Comparison shows that the GRACE-derived excitations give considerably better agreement with observations than AAM+OAM for three out of six seasonal harmonics, namely for the retrograde and prograde annual and for retrograde semiannual ones. For the most important

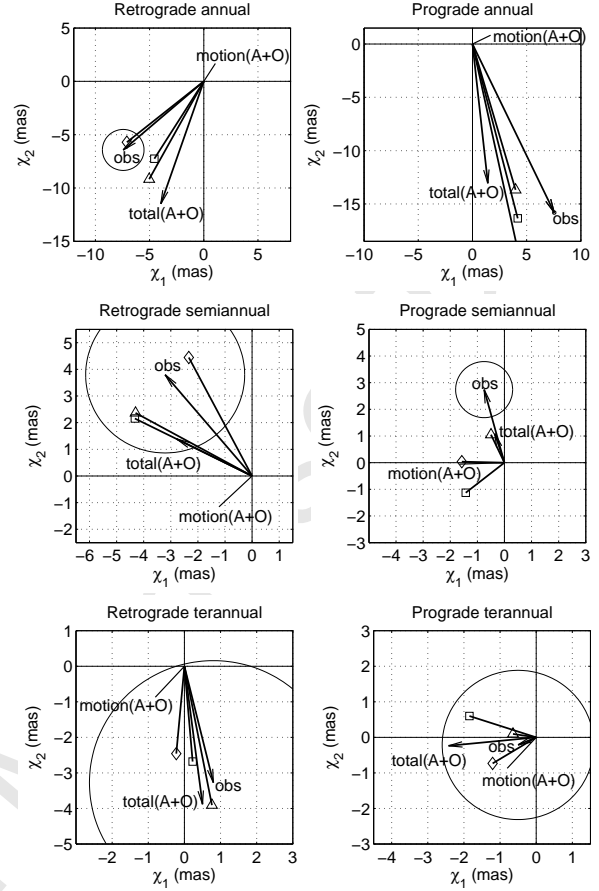


Figure 5: Seasonal components of the observed (C04), combined atmospheric and oceanic ((NCEP1 + ECCO2), and GRACE-observed (i.e. mass(GRACE) + motion(A+O)) excitations of polar motion: CSR (square), GFZ (triangle), JPL (diamond). Additionally shown is also the motion term of A+O. Analysis is done over the period 2002.3 to 2008.7. Phase refers to J2000.0.

prograde annual harmonic, all three GRACE-derived excitations reduce the discrepancy in phase by the factor of about two. But in contrast to phase, their amplitudes are different with mean value close to the observed one. When taking into account the relatively short time interval with GRACE data, about 6 years, and still continuing efforts to improve the data processing schemes, the results are quite promising. Finally we note that the motion term of AAM+OAM, though generally small in comparison to the mass term, nevertheless plays an important role in the comparison. In particular, adding it to the GRACE-derived mass term clearly improved phase agreement with observation in case of the prograde annual harmonic.

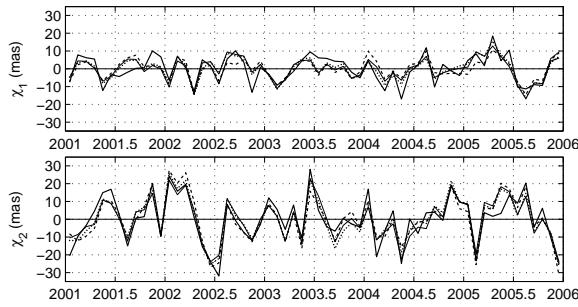


Figure 6: Comparison of the observed excitation (C04 – thick line) with the combinations of the atmospheric (NCEP1), oceanic (ECCO2) and hydrological contributions: CPC – dotted line, GLDAS – dashed line and LaD – thin line. Seasonal-polynomial model has been removed from each series. Analysis is done over the period 2001.0 to 2006.0. Phase refers to J2000.0.

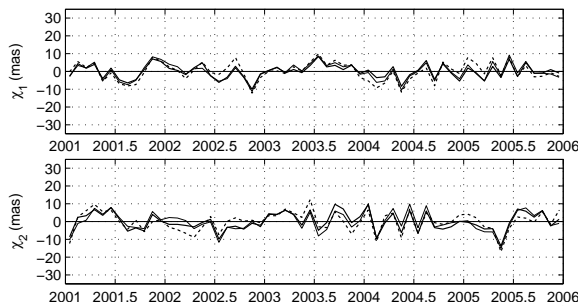


Figure 7: Differences between the observed and modeled geophysical excitations shown in Fig. 6: Geod(C04) – AAM(NCEP1) – OAM(ECCO2) – HAM(CPC – thick line, GLDAS – dashed line, and LaD – thin line). Analysis is done over the period 2001.0 to 2006.0. Phase refers to J2000.0.

3.2. Comparison of nonharmonic components

The residual nonharmonic excitation series, that is the series obtained by subtracting the best LSQ fit of the harmonic-polynomial model, have been compared in the time domain. Prior to the comparison we applied the Gaussian smoother to all the non-GRACE excitation series in order to remove the intraseasonal signals and to re-sample the series to the monthly intervals consistent with those of GRACE data. Comparison was done over a common 5-year time intervals, namely 2002.5 to 2007.5 when using the GRACE data, and 2001.0 to 2006.0 in case of the hydrology model data.

The correlation analysis shown in Table 1 confirms the earlier results that adding the OAM to the AAM improves considerably the agreement with the observed excitation. It can be also seen that for both time intervals the data-assimilating ocean model ECCO2 yields higher correlation with observation and explains more of the observed variance than the model ECCO1. When considering the hydrological models, only CPC yields a

slight improvement with observation for the χ_1 coordinate of excitation but not for χ_2 . The other two models do not introduce any improvement in comparison to the atmosphere-ocean system. The GRACE-derived excitations are slightly worse correlated with observations in χ_2 than the combination of the atmospheric and oceanic excitations, and much worse in χ_1 . A similar observation can be done when considering the percentage of the observed variance explained by the excitation data. This asymmetry indicates that the GRACE excitation data sets contain considerably higher noise in χ_1 than in χ_2 which is probably associated with the land–water distribution with respect to the equatorial axes of the terrestrial system.

All geophysical excitation series shown in Figures 6 and 7 are very consistent with each other. The reason is that the modeled HAM series contain a little power after removal of the seasonal harmonics and the polynomial trend. That is the figures show basically comparison between the combination AAM(NCEP1)+OAM(ECCO2) and observation. Also from Table 1 it can be seen that adding the HAM series to the combination of AAM+OAM introduces only minor, statistically insignificant changes to the correlation parameters. The residual series plotted in Figure 7 represent a common missing excitation mechanism and/or common error in AAM+OAM. A possible missing excitation can be the combined effect of river runoff and precipitation-evaporation over the oceans which are not included in the ECCO models (Gross, private communication).

The differences of the nonharmonic component of the three GRACE excitation series, shown in Figures 8 and 9, are larger than the effect of errors in AAM+OAM+HAM plus missing excitation, shown in Figure 7. These differences are not due to the noise in the GRACE measurements which are common to all three series but are due to differences in the data reduction procedures used at the different centers. The best procedure should be that which produces the smallest residual in Figure 9. This is the case of JPL series, as can be deduced from Table 1. But when considering the harmonic components of excitation, shown in Figure 5, the advantage of JPL data is not so clear.

4. Summary and conclusions

Our comparative analysis shows a good agreement between the excitations inferred from the C04 and SPACE06 data, except of the retrograde annual harmonic. In case of the AAM data, the seasonal components from the NCEP1 and NCEP2 series are practically the same, while the estimates from ERA-40 reanalysis

Table 1: Comparison of the observed (IERS C04) and modeled excitations of polar motion. The seasonal-polynomial model has been removed from each series prior to analysis. Note: 1) complex correlation coefficient is expressed by its magnitude and argument, 2) variance explained means the coefficient $100\% \times [\text{var}(\text{obs.}) - \text{var}(\text{obs.} - \text{model})] / \text{var}(\text{obs.})$.

| Geophysical excitation series compared to C04 | Correlation | | | | Var.expl.(%) | |
|--|-------------|----------|--------------------|---------------|--------------|----------|
| | χ_1 | χ_2 | $\chi_1 + i\chi_2$ | | χ_1 | χ_2 |
| AAM, OAM, and HAM (Fig. 6), period: 2001.0–2006.0, $\Delta t = 1$ month, 90% significance level: 0.24 | | | | | | |
| NCEP1 | 0.39 | 0.55 | 0.51 | -3.6° | 10.0 | 29.4 |
| NCEP1+ECCO1 | 0.76 | 0.91 | 0.88 | -6.2° | 57.5 | 81.9 |
| NCEP1+ECCO2 | 0.82 | 0.93 | 0.91 | -5.8° | 67.0 | 86.6 |
| NCEP1+ECCO2+CPC | 0.85 | 0.92 | 0.91 | -6.2° | 71.7 | 85.2 |
| NCEP1+ECCO2+GLDAS | 0.72 | 0.92 | 0.88 | -5.3° | 52.3 | 83.8 |
| NCEP1+ECCO2+LaD | 0.79 | 0.91 | 0.90 | -10.4° | 62.7 | 83.3 |
| AAM, OAM and GRACE (Fig. 8), period: 2002.5–2007.5, $\Delta t = 1$ month, 90% significance level: 0.36 | | | | | | |
| NCEP1 | 0.51 | 0.64 | 0.62 | -10.1° | 21.5 | 41.0 |
| NCEP1+ECCO1 | 0.74 | 0.84 | 0.83 | -8.0° | 55.6 | 70.4 |
| NCEP1+ECCO2 | 0.80 | 0.90 | 0.88 | -7.6° | 64.2 | 80.1 |
| NCEP1(motion)+ECCO2(motion)+CSR | 0.69 | 0.80 | 0.76 | -1.6° | -44.3 | 37.7 |
| NCEP1(motion)+ECCO2(motion)+JPL | 0.70 | 0.88 | 0.83 | 0.4° | 9.2 | 75.6 |
| NCEP1(motion)+ECCO2(motion)+GFZ | 0.62 | 0.90 | 0.82 | -7.8° | -64.1 | 73.3 |

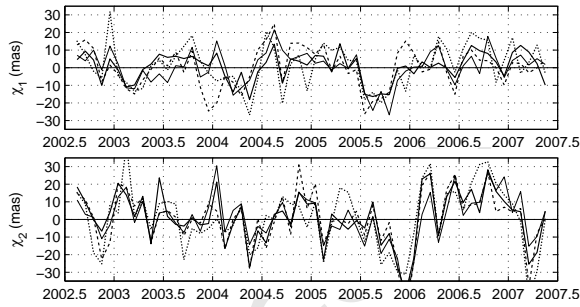


Figure 8: Comparison of the observed excitation (C04 – thick line) with the combinations of the atmospheric (AAM motion – NCEP1), oceanic (OAM motion – ECCO2) and GRACE-observed mass excitations: CSR (dotted line), GFZ (dashed line), and JPL (thin line). Seasonal-polynomial model has been removed from each series. Analysis is done over the period 2002.5 to 2007.5. Phase refers to J2000.0.

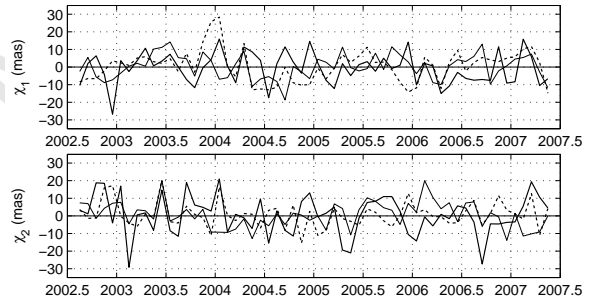


Figure 9: Differences between the observed and modeled geophysical excitations shown in Fig. 8: Geod(C04) – AAM motion (NCEP1) – OAM motion (ECCO2) – GRACE mass (CSR – thick line, GFZ – dashed line, JPL – thin line). Analysis is done over the period 2002.5 to 2007.5. Phase refers to J2000.0.

differ from the NCEP results in phase (up to 6 degrees) and in some cases (prograde semiannual and terannual terms) also remarkably in amplitude. Concerning the OAM data, we found a non-negligible difference between results from the ECCO models with and without data assimilation. As expected, data-assimilating model yields better correlation with the observed excitation.

Our attention was focused on the hydrological contributions to the excitation of polar motion. We found that the seasonal harmonics from 3 models considered in this work differ considerably; adding the HAM excitation series to the atmospheric and oceanic excitation data does not clearly improve agreement with observation. The most promising result found is consid-

erably better agreement with observations of the combination of GRACE-derived mass term with the motion terms of AAM and OAM than of the combination AAM and OAM alone, for the retrograde/prograde annual and retrograde semiannual harmonics. For other seasonal harmonics as well as for the nonharmonic component, the GRACE polar motion excitation data gives no improvement with respect to the atmosphere-ocean model. Possible sources of the remaining gaps in the seasonal excitation budget, which should be considered in future studies, are inconsistencies in the treatment of mass conservation problem in models of different components of the coupled system atmosphere - oceans - land hydrology.

Note added in proof:

Since the paper was submitted, another study concerning the use of gravimetric data from GRACE mission for understanding of polar motion variations (Seoane et al., 2009) has appeared in the literature.

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