

Low Degree Gravitational Changes from Earth Rotation and Geophysical Models

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Abstract: Spherical harmonic degree 2 gravitational variations C_{21} , S_{21} , and C_{20} are estimated from accurately measured Earth rotational changes and compared with predictions from atmospheric, oceanic, and hydrological models. Earth rotation-derived changes agree very well with model predictions over a broad frequency band, and particularly well at intraseasonal and seasonal time scales. The agreement is significantly better compared to previous studies, due mainly to improved oceanic and hydrological models. An independent determination of degree 2 changes serves as an important constraint for satellite-based estimates such as those of the Gravity Recovery and Climate Experiment (GRACE) mission.

Keywords. Gravity, Earth Rotation, Models.

1. Introduction

Earth's rotational changes at periods of a few years and less are forced mainly by mass redistribution and movement in the atmosphere, oceans, and hydrosphere/cryosphere, via the conservation of angular momentum of the Earth system. These polar motion and length of day (LOD) excitations may be divided into contributions from 1) surface mass load variations due to changes of atmospheric surface pressure, continental water storage (including snow and ice), and ocean bottom pressure, and 2) mass movements associated

with wind and ocean current variations causing angular momentum exchange between the solid Earth and the surrounding geophysical fluids. Angular momentum exchange related to flow in terrestrial rivers and streams is likely to contribute negligibly.

When rotational deformation on the gravity field is neglected, excitations of X, Y, and LOD due to surface mass load variations are proportional to changes in degree 2 spherical harmonic (Stokes) coefficients of the gravity field, C_{21} , S_{21} , and C_{20} [e.g., Wahr, 1982; Eubanks, 1993; Chen et al., 2000]. Thus estimates of C_{21} , S_{21} , and C_{20} from accurately measured Earth rotational changes are possible, provided that we can effectively estimate and subtract wind and ocean current contributions. Earth rotation variations are observable at time scales as short as a few hours by some techniques (such as GPS), providing unique measurements of high-frequency variations in the degree 2 gravity fields. Neither satellite laser ranging (SLR) nor GRACE is capable of resolving gravity variations at such high frequencies. The relationship between normalized C_{21} , S_{21} , and C_{20} and mass load driven X, Y, and LOD excitations ($\dot{\theta}_i^{\text{mass}}$, $i=1,2,3$) is [Eubanks, 1993 (eq. A3-1, 3-3); Chen et al., 2000 (eq. 1)],

$$\begin{aligned}
 C_{21} &= -(1 + k_2) \sqrt{\frac{3}{5}} \frac{(C - A)}{1.098R^2M} \dot{\theta}_1^{\text{mass}} \\
 S_{21} &= -(1 + k_2) \sqrt{\frac{3}{5}} \frac{(C - A)}{1.098R^2M} \dot{\theta}_2^{\text{mass}} \\
 C_{20} &= -(1 + k_2) \frac{3}{2\sqrt{5}} \frac{C}{0.753R^2M} \dot{\theta}_3^{\text{mass}}
 \end{aligned} \tag{1}$$

in which, M and R are the mass and mean radius of the Earth, C and A the two principal inertia moments of the Earth. k_2 is the degree 2 load Love number (-0.301), accounting for

elastic deformational effects on gravitational change. Eq. (1) is a modified version of the eq. (1) of Chen et al. (2000) with normalization and load deformation are considered. A recent study by Dickman (2003) derived slightly different representation of the computation of effective excitations, which will lead to a few percents of difference in eq (1). \dot{C}_i^{mass} can be computed from $\dot{C}_i^{\text{mass}} = \dot{C}_i^{\text{obs}} - \dot{C}_i^{\text{motion}}$, where, \dot{C}_i^{obs} are observed excitations computed from X, Y, and LOD, collectively termed Earth Orientation Parameters (EOP) time series, and $\dot{C}_i^{\text{motion}}$ are excitations by atmospheric winds and ocean currents that must be estimated from atmospheric and oceanic models. Chen et al. (2000) estimated degree 2 gravitational changes from rotational variations in this way, and compared them with SLR observations and geophysical model predictions. They found that at intraseasonal time scales, EOP-derived C_{21} and S_{21} are probably superior to SLR estimates, because they agreed better with atmosphere, ocean, and water storage model predictions. However at seasonal time scales, the conclusion was less strong.

The Chen et al. (2000) study was clearly limited by the oceanic and hydrological models available at the time. For example, the parallel Ocean Climate Model (POCM) [Stammer, et al., 1996] had been reported to under-estimate oceanic mass variability [e.g., Johnson et al., 1999]. The hydrologic estimate has also been shown to be poor, as it was computed from soil and snow fields of the National Center for Environmental Prediction (NCEP) reanalysis atmospheric model. NCEP soil and snow fields significantly over-estimate water storage variability [e.g., Chen et al., 2001].

Recent advancements in both ocean general circulation models (OGCM) and hydrological models provide an opportunity to re-estimate time variations in degree 2 gravity coefficients and compare them with EOP-derived values. We use here the data assimilating OGCM [Fukumori et al., 2000], developed at NASA's Jet Propulsion Laboratory, as a partner in the Estimating the Circulation and Climate of the Ocean (ECCO) program. Hereafter this model is denoted simply as ECCO. ECCO is used to estimate ocean current contributions as well as ocean mass redistribution. A recent study by Chen et al. (2003a) indicates that the data assimilating ECCO model is superior to many previous OGCMs in its ability to model large scale current and ocean bottom pressure (OBP) variability. Soil water storage fields are taken from the Land Data Assimilation System (LDAS) model, a surface hydrological model newly developed at the NCEP Climate Prediction Center (CPC).

2. Data and Models

2.1 Observed Excitations and Atmospheric Wind Effects

EOP time series are from SPACE 2001 [Gross, 2002], derived from various space geodetic observations by a Kalman filter combination. The data cover the period September 1976 through January 2002, with daily sampling. Tidal variations in LOD have been removed. Observed excitations of X, Y, and LOD are computed using the discrete linear polar motion filter developed by Wilson [1985]. Decadal LOD variations presumed to be

related to core-mantle coupling and longer interannual variations are estimated using a low pass filter with cutoff frequency of 4 years, and removed from observations. Atmospheric wind excitations are removed using NCEP reanalysis atmospheric angular momentum (AAM) products [Salstein and Rosen, 1997]. Atmospheric effects on C_{21} , S_{21} , and C_{20} are estimated from NCEP reanalysis surface pressure with the inverted barometer (IB) correction applied. Wind excitations are computed by integrating the horizontal winds from the surface to the top of the model at 10 hPa. Daily EOP excitations and 6-hourly AAM time series are averaged and interpolated to match the 10-day interval of the ECCO model (see below).

2.2 ECCO Model

The ECCO OGCM is based on the parallel version of the Massachusetts Institute of Technology general circulation model and an approximate Kalman filter method [Fukumori et al., 2000]. Model coverage is nearly global from $-79^{\circ}.5S$ to $78^{\circ}.5N$ and has a telescoping latitudinal grid with $1/3$ -degree resolution in the tropics ($-20^{\circ}S$ to $20^{\circ}N$) that gradually increases to 1-degree resolution away from the equator. The resolution in longitude is 1 degree. There are 46 vertical levels with 10m resolution within 150m of the surface. The model is forced by NCEP reanalysis products (12-hourly wind stress, daily heat and fresh water fluxes) with time-means replaced by those of the Comprehensive Ocean-Atmosphere Data Set. The model assimilates TOPEX/Poseidon (T/P) sea surface

height (SSH) anomalies. Surface temperature and salinity are relaxed towards observed values. Model fields are available at 10-day averages. SSH and OBP are also available at 12-hour intervals, as instantaneous values.

ECCO fields include 10-day averaged OBP, SSH, zonal (U) and meridional (V) velocities, from Jan. 1993 to Jan. 2003. U and V are used to estimate ocean current excitations [for details, see Chen et al., 2003b] and OBP is used to estimate oceanic contributions to C_{21} , S_{21} , and C_{20} . Estimated ocean current excitations are subtracted from EOP-derived excitations, and then residuals are used to estimate C_{21} , S_{21} , and C_{20} via eq. (1).

2.3 LDAS Hydrological Model

The LDAS model is forced by observed precipitation, derived from CPC daily and hourly precipitation analysis, 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 moisture in four soil layers below the ground. At the surface, it includes all components affecting energy and water mass balance, including snow cover, depth, and albedo. Runoff can be routed into stream flow [Fan et al. 2003]. Monthly averaged soil water is provided on a $0.5^\circ \times 0.5^\circ$ grid for Jan., 1980 to Jul., 2003. We use these monthly soil water fields to estimate hydrological effects on C_{21} , S_{21} , and C_{20} . We interpolate monthly hydrological samples to 10-day intervals to match ECCO samples.

Mass conservation is applied to provide a consistent treatment of total mass of the atmosphere, oceans, and continental water. We first force ECCO to conserve total mass, then add a thin layer over the oceans equal to total water mass change over land. The change of total mass of the atmosphere due to changing water vapor is balanced in a separate adjustment, by adding a uniform water layer over the land and oceans.

3. Results

The 3 panels of Figure 1(a, b, c) show C_{21} , S_{21} , and C_{20} time series (in blue curves) estimated from the residual excitations of X, Y, and LOD. Geophysical model predictions, the sum of atmosphere, ocean, and water (AOW) effects are shown in red. All time series are interpolated to 10-day intervals. EOP-derived S_{21} matches the geophysical model predictions almost perfectly over a broad frequency band and C_{21} estimates agree nearly as well. The EOP-derived C_{20} show a large semiannual signal and some interannual variability during 1997 - 1999. This semiannual variation is not likely due to C_{20} change, but instead from incomplete removal of wind and current effects from the LOD data [Chen et al., 2000]. Atmospheric wind effects are so dominant in driving LOD, that small errors in wind field estimates, especially in the upper atmosphere, significantly contaminate the residual used to compute C_{20} . If this semiannual signal is removed using least squares, the remainder (the green curve in Figure 1c) agrees considerably better with model predictions (at annual and other intraseasonal time scales). The relatively larger discrepancies during

1997 - 1999 are apparently associated with the 1997/1998 El Niño and the follow-on La Niña event. Atmospheric models are expected to show relatively larger uncertainties during these abnormal periods, especially in modeling wind circulation.

Amplitudes and phases of annual and semiannual variations are estimated by least squares for each time series and given in Table 1. Similar estimates from Chen et al., (2000) and SLR measured C_{20} from Cox and Chao (2002) are presented for comparison. For a clearer presentation, Figure 2a, b, and c show the vector plots of annual C_{21} , S_{21} , and C_{20} variations as listed in Table 1. EOP derived annual C_{21} and especially S_{21} variations agree very well with AOW model predictions. These C_{21} and S_{21} estimates from both EOP and new AOW models, however do not agree with SLR observations of Chen et al. (2000), and in particular show large phase differences, which appears indicating that there might be large phase errors in these SLR determined C_{21} and S_{21} variations. LOD derived C_{20} from this study agrees considerably better with both model predictions and SLR measurements than that of Chen et al. (2000) does. The improved agreements between EOP derived and model predicted C_{21} , S_{21} , and C_{20} come from two aspects: 1) a better determination of ocean current excitations using the advanced ECCO data assimilation system [Chen et al., 2003]; and 2) a better modeling of oceanic mass (or OBP) change of ECCO and land water storage change of LDAS.

We compute cross correlation coefficients between EOP derived C_{21} , S_{21} , and C_{20} time series and model predictions. Signals of seasonal or longer periods are first removed from all time series using least squares. A strong peak of correlation coefficients at zero phase lag, well beyond the 99.9% significance level is found in all 3 cases. EOP derived estimates from this study show improved agreement with model predictions at intraseasonal time scales compared with those of Chen et al. (2000), e.g. (0.80 vs. 0.42) for C_{21} , (0.85 vs. 0.82) for S_{21} and (0.68 vs. 0.54) for C_{20} . This improvement apparently comes from the use of the ECCO model. Hydrological model predictions are dominated by seasonal change and the LDAS monthly averaged soil water data does not contribute much to intraseasonal variability.

4. Discussion

The improved agreement between EOP derived results and model predictions supports the conclusion that ECCO provides more accurate estimates of global scale current and OBP variations than POCM at both intraseasonal and seasonal time scales [e.g., Chen et al., 2003b]. Improved agreement at seasonal time scale indicates that LDAS is superior in representing large scale surface water storage change compared with the NCEP reanalysis.

EOP based estimates of gravity change may be affected by errors in EOP measurements, but we suspect this is a relatively minor contaminant. Instead, improper

estimates of atmospheric wind and ocean currents are a more significant error source. EOP estimated of S_{21} show larger seasonal variability and agree better with model predictions, evidently dominated by the hydrological model. The larger seasonal signal in S_{21} is related to the geographical orientation of continents, which align more closely along the Y axis ($\pm 90^\circ$ longitude). Atmospheric pressure changes over the oceans are mostly canceled out by the IB response of the oceans.

This study further demonstrates the advantages of using Earth rotational observations to study low degree gravitational variations. Combining accurately determined EOP time series with atmospheric and oceanic general circulation models creates a unique and successful method to estimate degree 2 gravitational variations independently of satellite-based methods such as GRACE. These should be useful in validation of low degree GRACE observations, and in strengthening overall time variable gravity solutions.

Acknowledgments. We are grateful to S. Dickman and A. Brzezinski for their insightful review comments, which led to improved presentation of the results. We would like to thank the ECCO and LDAS teams for providing the model data. The authors benefit from discussions with J. Wahr and R. Gross during the study. This research was supported by NASA's Solid Earth and Natural Hazards and GRACE Science Program.

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Figures:

Figure 1a, b, & c. EOP derived C_{21} , S_{21} , and C_{20} variations (blue curves) geophysical model predictions (red curves). The green curve in (c) represents C_{20} variations after semiannual signal is removed.

Figure 2a, b, & c. Vector plots of annual C_{21} , S_{21} , and C_{20} variations as listed in Table 1.

Table 1. Amplitude and phase of annual and semiannual C_{21} , S_{21} , and C_{20} changes estimated from EOP and model predictions (denoted as AOW). The phase is defined as ϕ in $\sin(2(t - t_0) + \phi)$, where t_0 refers to h^0 on January 1. Estimates of Chen et al. (2000) are denoted as 'Chen'. C_{20} result of Cox and Chao (2003) is denoted as 'Cox'.

Gravity Change	Annual		Semiannual	
	Amplitude ($\times 10^{-10}$)	Phase (deg)	Amplitude ($\times 10^{-10}$)	Phase (deg)
C_{21} (EOP)	0.23	126	0.12	126
C_{21} (AOW)	0.19	101	0.05	151
C_{21} (EOP, Chen)	0.20	125	0.12	98
C_{21} (AOW, Chen)	0.25	192	0.31	33
C_{21} (SLR, Chen)	0.35	59	0.17	160
S_{21} (EOP)	0.62	119	0.21	252
S_{21} (AOW)	0.68	128	0.13	252
S_{21} (EOP, Chen)	0.50	125	0.23	265
S_{21} (AOW, Chen)	1.20	68	0.23	234
S_{21} (SLR, Chen)	0.53	65	0.15	206
C_{20} (EOP)	0.91	39	1.26	66
C_{20} (AOW)	0.67	66	0.19	112
C_{20} (EOP, Chen)	0.37	54	0.80	54
C_{20} (AOW, Chen)	1.50	43	0.22	108
C_{20} (SLR, Chen)	1.10	35	0.40	130
C_{20} (Cox)	1.29	28	0.14	171

