GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 24, 2257, doi:10.1029/2003GL018688, 2003

Low degree gravitational changes from earth rotation and geophysical models

J. L. Chen[1] and C. R. Wilson[1,2]

Received 22 September 2003; revised 12 November 2003; accepted 17 November 2003; published 19 December 2003.

[1] Spherical harmonic degree 2 gravitational variations ΔC_{21}, ΔS_{21}, and ΔC_{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. *INDEX TERMS:* 1214 Geodesy and Gravity: Geopotential theory and determination; 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1239 Geodesy and Gravity: Rotational variations; 1866 Hydrology: Soil moisture; 4532 Oceanography: Physical: General circulation; *KEYWORDS:* Gravity, Earth Rotation, Models. **Citation:** Chen, J. L., and C. R. Wilson, Low degree gravitational changes from earth rotation and geophysical models, *Geophys. Res. Lett.*, *30*(24), 2257, doi:10.1029/2003GL018688, 2003.

1. Introduction

[2] 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.

[3] 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, ΔC_{21}, ΔS_{21}, and ΔC_{20} [e.g., *Wahr*, 1982; *Eubanks*, 1993; *Chen et al.*, 2000]. Thus estimates of ΔC_{21}, ΔS_{21}, and ΔC_{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 ΔC_{21}, ΔS_{21}, and ΔC_{20} and mass load driven X, Y, and LOD excitations (χ_i^{mass}, i = 1, 2, 3) is [*Eubanks*, 1993 (equation A3-1, 3-3); *Chen et al.*, 2000 (equation 1)],

$$
\begin{aligned}
\Delta C_{21} &= -\left(1+k_2'\right)\cdot\sqrt{\frac{3}{5}}\cdot\frac{(C-A)}{1.098R^2M}\cdot\chi_1^{\mathrm{mass}}\\
\Delta S_{21} &= -\left(1+k_2'\right)\cdot\sqrt{\frac{3}{5}}\cdot\frac{(C-A)}{1.098R^2M}\cdot\chi_2^{\mathrm{mass}}\\
\Delta C_{20} &= -\left(1+k_2'\right)\cdot\frac{3}{2\sqrt{5}}\cdot\frac{(C)}{0.753R^2M}\cdot\chi_3^{\mathrm{mass}}
\end{aligned}
\qquad (1)
$$

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. Equation (1) is a modified version of the equation (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 equation (1). χ_i^{mass} can be computed from $\chi_i^{\mathrm{mass}} = \chi_i^{\mathrm{obs}} - \chi_i^{\mathrm{motion}}$, where, χ_i^{obs} are observed excitations computed from X, Y, and LOD, collectively termed Earth Orientation Parameters (EOP) time series, and χ_i^{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 ΔC_{21} and ΔS_{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.

[4] 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

---

[1] Center for Space Research, University of Texas, Austin, Texas, USA.
[2] Department of Geological Sciences, University of Texas, Austin, Texas, USA.

0094-8276/03/2003GL018688$05.00

atmospheric model. NCEP soil and snow fields significantly over-estimate water storage variability [e.g., *Chen et al.*, 2001].

[5] 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

[6] 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 ΔC_{21}, ΔS_{21}, and ΔC_{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

[7] 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°.5S to 78°.5N and has a telescoping latitudinal grid with 1/3-degree resolution in the tropics (−20°S to 20°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.

[8] 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 ΔC_{21}, ΔS_{21}, and ΔC_{20}. Estimated ocean current excitations are subtracted from EOP-derived excitations, and then residuals are used to estimate ΔC_{21}, ΔS_{21}, and ΔC_{20} via equation (1).

2.3. LDAS Hydrological Model

[9] 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° × 0.5° grid for Jan. 1980 to Jul. 2003. We use these monthly soil water fields to estimate hydrological effects on ΔC_{21}, ΔS_{21}, and ΔC_{20}. We interpolate monthly hydrological samples to 10-day intervals to match ECCO samples.

[10] Mass conservation is applied to provide a consistent treatment of total mass of the atmosphere, oceans, and continental water. We first force ECCO to conserved 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

[11] The 3 panels of Figure 1 (a, b, c) show ΔC_{21}, ΔS_{21}, and ΔC_{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 ΔS_{21} matches the geophysical model predictions almost perfectly over a broad frequency band and ΔC_{21} estimates agree nearly as well. The EOP-derived ΔC_{20} show a large semiannual signal and some interannual variability during 1997–1999. This semiannual variation is not likely due to ΔC_{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 ΔC_{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

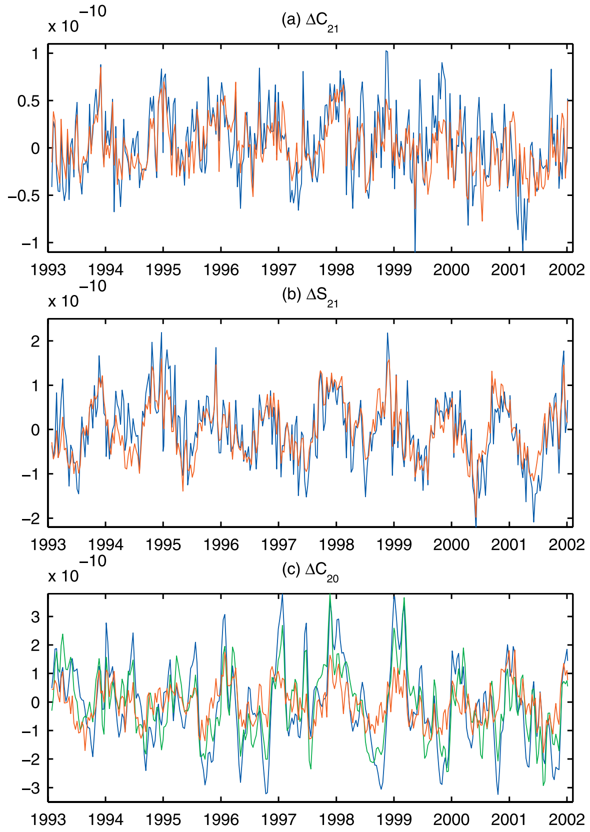

Figure 1. EOP derived ΔC_{21}, ΔS_{21},and ΔC_{20} variations (blue curves) geophysical model predictions (red curves). The green curve in (c) represents ΔC_{20} variations after semiannual signal is removed.

to show relatively larger uncertainties during these abnormal periods, especially in modeling wind circulation.

[12] 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 ΔC_{20} from *Cox and Chao* [2002] are presented for comparison. For a clearer presentation, Figures 2a, 2b, and 2c show the vector plots of annual ΔC_{21}, ΔS_{21}, and ΔC_{20} variations as listed in Table 1. EOP derived annual ΔC_{21} and especially ΔS_{21} variations agree very well with AOW model predictions. These ΔC_{21} and ΔS_{21} estimates from both EOP and new AOW models, however do not agree with SLR observations of *Chen et al.* [2000], and in particularly show large phase differences, which appears indicating that there might be large phase errors in these SLR determined ΔC_{21} and ΔS_{21} variations. LOD derived ΔC_{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 ΔC_{21}, ΔS_{21}, and ΔC_{20} come from two aspects: (1) a better determination of ocean current excitations using the advanced ECCO data assimilation system [*Chen et al.*, 2003a, 2003b]; and (2) a better modeling of oceanic mass (or OBP) change of ECCO and land water storage change of LDAS.

[13] We compute cross correlation coefficients between EOP derived ΔC_{21}, ΔS_{21}, and ΔC_{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. Both ΔC_{21} and ΔC_{20} estimates from this study show improved agreement with model predictions at intraseasonal time scales compared with those of *Chen et al.* [2000], e.g., (0.69 vs. 0.42) for ΔC_{21} and (0.64 vs. 0.54) for ΔC_{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

[14] 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.

[15] 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 ΔS_{21} show larger seasonal variability and agree better with model predictions, evidently dominated by the hydrological model. The larger seasonal signal in ΔS_{21} is related to the geographical orientation of continents, which align more closer along the Y axis (±90° longitude). Atmospheric pressure changes over the oceans are mostly canceled out by the IB response of the oceans.

[16] 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

Table 1. Amplitude and Phase of Annual and Semiannual ΔC_{21}, ΔS_{21},and ΔC_{20} Changes Estimated From EOP and Model Predictions (denoted as AOW)

	Annual		Semiannual	
Gravity Change	Amplitude ($\times 10^{-10}$)	Phase (deg)	Amplitude ($\times 10^{-10}$)	Phase (deg)
ΔC_{21} (EOP)	0.28	120	0.12	126
ΔC_{21} (AOW)	0.19	101	0.05	151
ΔC_{21} (EOP, Chen)	0.20	125	0.12	98
ΔC_{21} (AOW, Chen)	0.25	192	0.31	33
ΔC_{21} (SLR, Chen)	0.35	59	0.17	160
ΔS_{21} (EOP)	0.71	114	0.21	252
ΔS_{21} (AOW)	0.68	128	0.13	252
ΔS_{21} (EOP, Chen)	0.50	125	0.23	265
ΔS_{21} (AOW, Chen)	1.20	68	0.23	234
ΔS_{21} (SLR, Chen)	0.53	65	0.15	206
ΔC_{20} (EOP)	0.87	43	1.21	65
ΔC_{20} (AOW)	0.67	66	0.19	112
ΔC_{20} (EOP, Chen)	0.37	54	0.80	54
ΔC_{20} (AOW, Chen)	1.50	43	0.22	108
ΔC_{20} (SLR, Chen)	1.10	35	0.40	130
ΔC_{20} (Cox)	1.29	28	0.14	171

The phase is defined as ϕ in $\sin(2\pi(t - t_0) + \phi)$, where t_0 refers to h^0 on January 1. Estimates of *Chen et al.* [2000] are denoted as 'Chen'. ΔC_{20} result of *Cox and Chao* [2003] is denoted as 'Cox'.

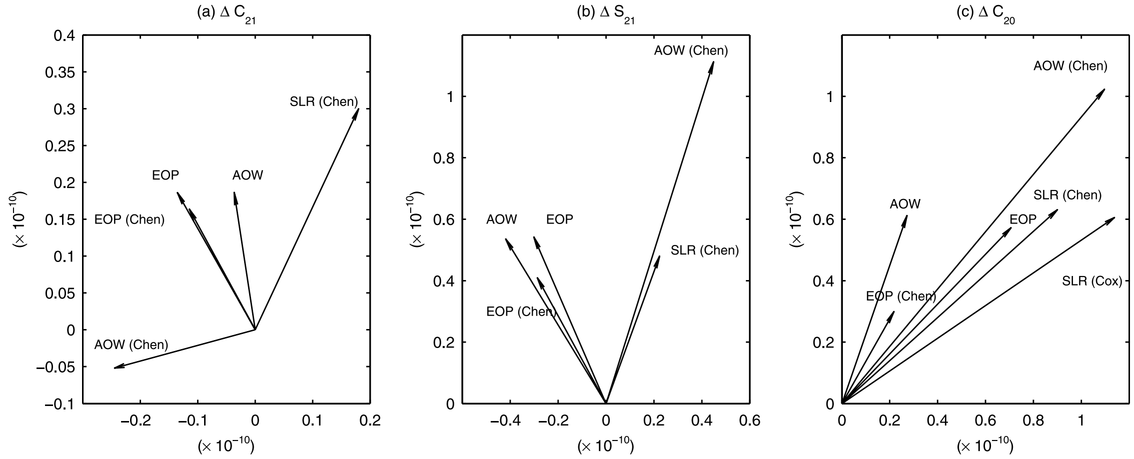

Figure 2. Vector plots of annual ΔC_{21}, ΔS_{21},and ΔC_{20} variations as listed in Table 1.

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.

[17] **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.

References

Chen, J. L., C. R. Wilson, R. J. Eanes, and B. D. Tapley, A New Assessment of Long Wavelength Gravitational Variations, *J. Geophys. Res.*, *105*(B7), 16,271–16,278, 2000.

Chen, J. L., C. R. Wilson, B. D. Tapley, D. P. Chambers, and T. Pekker, Hydrological Impacts on Seasonal Sea Level Change, *Global Planet. Change*, *32*(1), 25–32, 2001.

Chen, J. L., C. R. Wilson, X. G. Hu, and B. D. Tapley, Large-Scale Mass Redistribution in the Oceans, 1993–2001, *Geophys. Res. Lett.*, *30*(20), 2024, doi:10.1029/2003GL018048, 2003a.

Chen, J. L., C. R. Wilson, and X. G. Hu, Oceanic Effects on Polar Motion from Data Assimilating Ocean General Circulation Model and Satellite Altimetry: 1993–2001, *J. Geophys. Res.*, submitted, 2003b.

Cox, C. M., and B. F. Chao, Detection of a large-scale mass redistribution in the terrestrial system since 1998, *Science*, *297*, 831–833, 2002.

Dickman, S. R., Evaluation of "effective angular momentum function" formulations with respect to core-mantle coupling, *J. Geophys. Res.*, *108*(B3), 2150, doi:10.1029/2001JB001603, 2003.

Eubanks, T. M., Variations in the orientation of the earth, in Contributions of Space Geodesy to Geodynamic: Earth Dynamics, Geodyn. Ser., vol. 24, edited by D. Smith and D. Turcotte, pp. 1–54, AGU, Washington, D. C., 1993.

Fan, Y., H. Van del Dool, K. Mitchell, and D. Lohmann, A 51-Year Reanalysis of the U.S. land-Surface Hydrology, *GEWEX News*, *13*(2), pp. 6 and 10, May , 2003.

Fukumori, I., T. Lee, D. Menemenlis, L.-L. Fu, B. Cheng, B. Tang, Z. Xing, and R. Giering, A Dual Assimilation System for Satellite Altimetry, Joint TOPEX/POSEIDON and Jason-1 Science Working Team Meeting, Miami Beach, Florida, 15 –17 November , 2000.

Gross, R., Combinations of Earth Orientation Measurements, SPACE2001, COMB2001, and POLE2001, Jet Propulsion Laboratory Pub., 02–08, 27 pp., Pasadena, Calif., 2002.

Johnson, T. J., C. R. Wilson, and B. F. Chao, Oceanic angular momentum variability estimated from the Parallel Ocean Climate Model, 1988–1998, *J. Geophys. Res.*, *104*(B11), 25,183–25,195, 1999.

Salstein, D. A., and R. D. Rosen, Global momentum and energy signals from reanalysis systems. Preprints, 7th Conf. on Climate Variations, *American Meteorological Society*, Boston, 344–348, 1997.

Stammer, D., R. Tokmakian, and A. Semtner, How well does a 1/4 deg. global circulation model simulate large-scale oce anic observations?, *J. Geophys. Res.*, *101*, 25,779–25,812, 1996.

Wahr, J. M., The effects of the atmosphere and oceans on the Earth's wobble and the seasonal variations in the length of day. I: Theory, *Geoph. J. R. Astr. Soc.*, *70*, 349–372, 1982.

Wilson, C. R., Discrete polar motion equations, *Geophys. J. R. Astron. Soc.*, *80*, 551–554, 1985.

J. L. Chen and C. R. Wilson, Center for Space Research, University of Texas, 3925 W. Braker Lane, Suite 200, Austin, TX 78759-5321, USA. (chen@csr.utexas.edu)