Low degree gravitational changes from GRACE: Validation and interpretation

J. L. Chen,[1] C. R. Wilson,[1,2] B. D. Tapley,[1] and J. C. Ries[1]

Received 4 October 2004; accepted 26 October 2004; published 24 November 2004.

[1] We examine low degree gravitational variations ΔC_{21}, ΔS_{21}, and ΔC_{20} observed by the Gravity Recovery and Climate Experiment (GRACE) satellites during the first 2 years of this gravity mission. The GRACE observations are compared with independent estimates from accurately measured Earth rotational changes and predictions from atmospheric, oceanic, and hydrological models. The 18 GRACE monthly gravity solutions, covering the period April 2002 to March 2004, show strong seasonal variability in the ΔC_{21}, ΔS_{21}, and ΔC_{20} time series, and generally agree with Earth rotation-derived changes and geophysical model estimates, in particular for ΔS_{21} and ΔC_{20}. The reason for the poorer agreement between the GRACE results and the Earth rotation-derived estimates for ΔC_{21} is unclear. We demonstrate that the omission of the ocean pole tide in the GRACE data processing does have significant effects on the estimated ΔC_{21} and ΔS_{21}. *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; 1241 Geodesy and Gravity: Satellite orbits; 1255 Geodesy and Gravity: Tides—ocean (4560). **Citation:** Chen, J. L., C. R. Wilson, B. D. Tapley, and J. C. Ries (2004), Low degree gravitational changes from GRACE: Validation and interpretation, *Geophys. Res. Lett.*, *31*, L22607, doi:10.1029/2004GL021670.

1. Introduction

[2] The Gravity Recovery and Climate Experiment (GRACE), a twin satellite gravity mission jointly sponsored by the US National Aeronautics and Space Administration (NASA) and German Aerospace Center (DLR), was launched in March 2002. GRACE measures Earth gravity with unprecedented accuracy by tracking the change in the distance between the two satellites and combining these measurements with data from on-board accelerometers and Global Positioning System (GPS) receivers. During its planned 5-year life, GRACE will produce accurate determinations of spherical harmonics for the global gravity fields, up to degree and order 120, at intervals of approximately 30 days [*Tapley et al.*, 2004]. These time-variable gravity fields can be used to measure mass redistribution within the Earth system associated with a variety of climate processes [*Wahr et al.*, 2004]. In order to use GRACE to understand climate processes, GRACE observations must be first validated through independent measures of changes in the gravity field.

[3] Conservation of angular momentum within the Earth system implies that polar motion (X, Y) and length of day (LOD), collectively termed Earth Orientation Parameters (EOP), will be excited by contributions from surface mass load variations and changes in winds and currents. Surface mass load variations include changes in atmospheric surface pressure, continental water storage (including snow and ice on land), and ocean bottom pressure. Winds and ocean current variations reflect angular momentum exchange between the solid Earth and surrounding geophysical fluids. Atmospheric wind and ocean current excitations are estimated from atmospheric and oceanic general circulation models and removed from observed X, Y, and LOD excitation time series. The residuals are estimates of surface mass load excitations proportional to changes in degree-2 spherical harmonic (Stokes) coefficients of the gravity field, ΔC_{21}, ΔS_{21}, and ΔC_{20} [e.g., *Chen and Wilson*, 2003; *Gross et al.*, 2004; *Chen et al.*, 2004].

[4] Recent studies [e.g., *Chen and Wilson*, 2003; *Chen et al.*, 2004] demonstrate that EOP derived ΔC_{21}, ΔS_{21}, and ΔC_{20} variations agree very well with estimates based on surface mass load changes from atmospheric, oceanic, and hydrological models, particularly for ΔC_{21} and ΔS_{21} over a broad band of frequencies. The EOP derived results and model estimates also agree well with satellite laser ranging (SLR) observation of these low degree gravity changes. *Gross et al.* [2004] indicates that EOP derived degree-2 load changes also show reasonable agreement with GPS-based estimates. These studies demonstrate that estimates of degree-2 gravity change from both EOP and global climate models are useful measures of mass redistribution on a global scale.

[5] We compare estimated degree-2 gravity spherical harmonic changes, ΔC_{21}, ΔS_{21}, and ΔC_{20} from three independent sources: climate models, EOP, and GRACE. We use techniques similar to those of *Chen and Wilson* [2003] and *Chen et al.* [2004], and extend EOP derived time series and climate model estimates to include the period of available GRACE data. In addition, we estimate uncertainties of EOP-derived ΔC_{21}, ΔS_{21}, and ΔC_{20} by examining differences in wind excitations of two atmospheric models.

2. Data and Models

2.1. GRACE Observations

[6] The 18 GRACE gravity field solutions, spanning the period April 2002 to March 2004, are provided by the Center for Space Research (CSR), University of Texas at Austin. These fields are provided as fully normalized spherical harmonics up to degree and order 120, representing approximately monthly average values, though temporal

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

0094-8276/04/2004GL021670$05.00

sampling and averaging intervals are not completely uniform. The initial mean gravity field used is the GRACE GGM01 gravity model, derived from the first 111 days of GRACE data [*Tapley et al.*, 2004]. Tidal effects, including ocean, solid Earth, and solid Earth pole tides (rotational deformation) have been removed in the level-2 GRACE data processing [*Bettadpur*, 2003]. The solid Earth pole tide effect in ΔC_{21} and ΔS_{21} is several times larger than the signal due to surface mass change. Non-tidal atmospheric and oceanic contributions are also removed in the level-2 de-aliasing process. For each GRACE monthly gravity solution, the GRACE project provides a separate file containing mean non-tidal atmospheric and oceanic contributions for the time interval represented in that solution. To compare GRACE data with EOP and climate models (atmosphere + ocean + land surface water) these mean non-tidal atmospheric and oceanic contributions must be added to the GRACE fields.

2.2. EOP Derived ΔC_{21}, ΔS_{21}, and ΔC_{20} Variations

[7] Normalized ΔC_{21}, ΔS_{21}, and ΔC_{20} variations can be derived from mass load EOP excitations (χ_i^{mass}, i = 1, 2, 3) through [*Chen and Wilson*, 2003, equation (1)],

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

M and R are the mass and mean radius of the Earth, C and A (C − A = 2.61 × 10^{35} kg m^2) the two principal inertia moments of the Earth, and Cm (7.1236 × 10^{37} kg m^2) the principal inertia moment of the Earth's mantle [*Eubanks*, 1993]. k'_2 is the degree-2 load Love number (−0.301), accounting for elastic deformational effects on gravitational change. χ_i^{mass} (i = 1, 2, 3) can be computed from $\chi_i^{mass} = \chi_i^{obs} - \chi_i^{motion}$, where, χ_i^{obs} are observed excitations computed from X, Y, and LOD time series, and χ_i^{motion} are excitations by atmospheric winds and ocean currents that must be estimated from atmospheric and oceanic models.

2.2.1. Observed EOP Excitations

[8] EOP time series are from the International Earth Rotation and Reference Systems (IERS) combined X, Y, and LOD time series (C04), derived from various space geodetic observations. The data are daily values from September 1962 to the present. Daily EOP excitations from January 1993 to May 2004 are computed from the C04 EOP time series using the IERS online interactive tools (http://hpiers.obspm.fr/eop-pc/analysis/excitactive.html) with the Chandler period set at 433 days and the Chandler quality factor Q at 175. Tidal variations in LOD have been removed. Decadal LOD variations presumed to be related to core-mantle coupling and the strong 5.6-year oscillations [*Chen et al.*, 2004] are removed using a low pass filter with a cutoff frequency of 1 cycle in 4 years.

2.2.2. Atmospheric Wind Excitations

[9] Atmospheric wind excitations are computed using daily wind fields from the National Center for Environmental Prediction (NCEP) reanalysis atmospheric model [*Kalnay et al.*, 1996]. The wind fields cover 17 pressure levels from the bottom (1000 mb) to the top (10 mb) of the model. Following the excitation equations by *Eubanks* [1993], we compute daily wind excitations from January 1993 to May 2004. *Aoyama and Naito* [2000], note that atmospheric wind excitation estimates depend significantly on how topography is treated in the calculation. In the commonly used NCEP atmospheric angular momentum (AAM) products [*Salstein and Rosen*, 1997], topographic influences are neglected. Here, we compensate for topography effects by integrating wind momentum from the actual surface (not 1000 mb) to the top (10 mb) of the model. This improves coherence between atmospheric excitation estimates and observations of EOP.

2.2.3. Ocean Current Excitations

[10] Similar to *Chen and Wilson* [2003], ocean current excitations are computed from the Estimating the Circulation and Climate of the Ocean (ECCO) data assimilating ocean general circulation model (kf049f run) [*Fukumori et al.*, 2000]. Ocean current excitations are computed for the period January 1993 to May 2004 at 10-day intervals. The 10-day ocean current excitation time series are interpolated to daily intervals. Then ocean current and wind excitation estimates are removed from observed EOP series. The residuals are converted to estimates of ΔC_{21}, ΔS_{21}, and ΔC_{20} variations using equation (1). Finally, time series are smoothed by a 30-day sliding window for comparison with GRACE observations and climate model predictions.

2.3. Climate Model Predictions

[11] Using the same method and similar models as *Chen and Wilson* [2003], we compute ΔC_{21}, ΔS_{21}, and ΔC_{20} due to atmosphere, ocean, and continental water (AOW). The calculations are based upon daily surface pressure data from NCEP reanalysis, 12-hourly ocean bottom pressure (OBP) from ECCO (kf049f), and monthly water storage change from the Climate Prediction Center (CPC)'s land data assimilation system (LDAS) model [*Fan et al.*, 2003]. Individual time series are interpolated to uniform average daily intervals and summed to form a combined AOW time series. This is then smoothed with a 30-day moving average window. To conserve 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. Total atmospheric mass due to changing water vapor is balanced separately by adding a uniform water layer over the land and oceans.

3. Results and Comparison

[12] ΔC_{21}, ΔS_{21}, and ΔC_{20} variations observed in the 18 GRACE monthly solutions are shown in red stars and curves in Figures 1a, 1b, and 1c, together with EOP derived results and geophysical model (denoted as AOW hereafter) estimates. The means of the 18 GRACE solutions are removed, as are means of the other time series. As noted by *Chen and Wilson* [2003], EOP-derived ΔC_{21}, ΔS_{21}, and ΔC_{20} agree very well with AOW model estimates, in particular for ΔC_{21} and ΔS_{21}. For ΔC_{20}, there is poorer but still reasonable agreement with climate model estimates. Because winds are the dominant source of LOD excitation, small errors in wind estimates yield large errors in residual LOD. Thus, EOP-derived ΔC_{20} estimates are not expected to be as good as those of ΔC_{21} and ΔS_{21}.

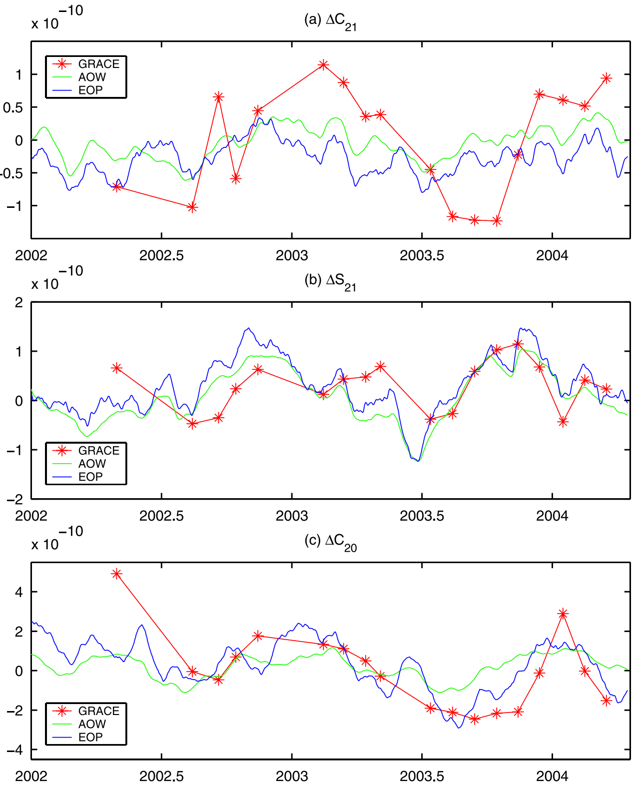

Figure 1. (a) ΔC_{21}, (b) ΔS_{21}, and (c) ΔC_{20} estimates from GRACE (red curves and stars), Earth rotation EOP (blue curves), and AOW models (green curves). 30-day moving average is applied to EOP and AOW model estimates.

[13] GRACE ΔC_{21}, ΔS_{21}, and ΔC_{20} time series show clear seasonal variations, similar to EOP results model estimates. The annual signal is more prominent in ΔS_{21} and ΔC_{20}. For ΔC_{21}, however, GRACE values shows significantly greater variability than EOP and climate model estimates. Among the 18 GRACE solutions, the first for April/May 2002 is a two-month average from data early in the commissioning phase and is viewed with less confidence than the remaining solutions, and does not agree well with the EOP and climate model values as evident in ΔS_{21} and ΔC_{20} comparisons. The January 2004 GRACE solution uses only 13 days of data, which leads to greater error in ΔC_{20}. Longer term, perhaps interannual signals in GRACE data are evident especially in ΔS_{21} and ΔC_{20}. EOP ΔC_{20} show relatively larger variability than climate model estimates and agree better with GRACE values.

[14] The solid Earth pole tide effects on ΔC_{21} and ΔS_{21} have been removed in the GRACE data processing. However, the effects from global oceanic response to the Earth rotational changes are neglected in the GRACE data processing. The ocean pole tide (OPT) effects, though relatively smaller than the solid Earth pole tide effects, may still make significant contributions to ΔC_{21} and ΔS_{21}, since the solid Earth pole tide is so dominant in the ΔC_{21} and ΔS_{21} variations. We use an equilibrium OPT model [*Wahr*, 1985] to estimate possible OPT effects on ΔC_{21} and ΔS_{21}. The results shown in Figure 2, indicate that the OPT effects on ΔC_{21} and ΔS_{21} are about 14.1% and 11.5% of the solid Earth pole tide contributions, respectively, and are therefore significant.

[15] Because EOP measurements are very precise, errors in EOP-derived ΔC_{21}, ΔS_{21}, and ΔC_{20} are dominantly due to errors in estimated wind and/or ocean current contributions that must be subtracted. We estimate uncertainties in EOP-derived ΔC_{21}, ΔS_{21}, and ΔC_{20} by taking the difference between wind excitations from two different atmospheric models. The two 6-hourly wind excitation time series are from NCEP reanalysis and European Centre for Medium-Range Weather Forecasting (ECMWF) atmospheric models, archived at the Atmospheric and Environmental Research [*Salstein and Rosen*, 1997]. There is a 2-year overlapping period, July 1997–June 1999 which includes the 1997/1998 strong El Nino event. During this period larger uncertainties in the wind fields are likely. The standard deviation of the differences time series is converted to error bars for ΔC_{21}, ΔS_{21}, and ΔC_{20} by equation (1) to yield 1.7×10^{-11} for ΔC_{21} and ΔS_{21}, and 7.8×10^{-11} for ΔC_{20}. This is only a rough estimate, since errors in ocean currents are not included (limited by the availability of data), and taking the difference between two models will not capture the effects of common errors.

[16] It is impossible to precisely calibrate the uncertainties for these GRACE solutions on a month-to-month basis. We may rely on comparison of different solutions for the same month, such as those from the Jet Propulsion Laboratory (JPL), as well as a certain amount of speculation based on the calibration of the mean solutions. We use the differences between the CSR and JPL solutions for the same month to estimate the error bars for the GRACE data. The Sept. and Oct. 2002 solutions are not included in the 16 solutions recently released by JPL. Therefore, we use the mean errors for the 16 solutions as an estimate for the errors of these two months. This is also a very rough estimate, since the CSR and JPL solutions are not completely independent. Background model errors (e.g., OPT) and instrument errors will not be captured by taking the difference of the two.

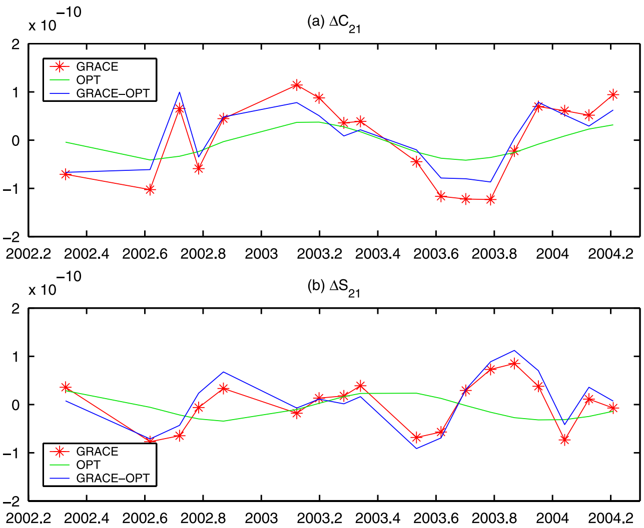

Figure 2. Ocean pole tide (OPT) effects (green curves) on (a) ΔC_{21} and (b) ΔS_{21}. The red curves show the GRACE observations (with AOD atmospheric and ocean effects added back) and the blue curves show the GRACE results if OPT is included.

[17] Figures 3a, 3b, and 3c are similar to Figures 1a, 1b, and 1c, but now show estimated error bars for the EOP and GRACE series. To focus on seasonal time scales, trends in these time series are estimated by least squares, (excluding Apr/May 2002) and removed. Agreement among GRACE, EOP and AOW model estimates improve for ΔS_{21} and ΔC_{20}. When the OPT correction is applied (the black curves), the GRACE observed ΔC_{21} shows reduced variability and less discrepancy with EOP and AOW estimates, while ΔS_{21} shows apparently improved agreement with EOP and AOW estimates. The improvement is further demonstrated in the seasonal amplitude and phase of each time series estimated from least squares (Table 1). The EOP and AOW time series are first averaged and interpolated into the GRACE time steps (with the April/May 2002 solution excluded) before the seasonal fit. The annual amplitude and phase of GRACE estimated ΔC_{20} (1.52×10^{-10}, 62deg) agree significantly better with EOP estimates (1.32×10^{-10}, 70deg) than AOW model predictions (0.74×10^{-10}, 78deg). These seasonal estimates are based on only a 1.5-year time period. Large uncertainties should be expected.

4. Discussion

[18] Degree-2 spherical harmonic variations ΔC_{21}, ΔS_{21}, and ΔC_{20} from the first 2 years of GRACE data show encouraging agreement with independent estimates from Earth rotation and climate models, in particular in for ΔS_{21} and ΔC_{20}. Larger discrepancies for ΔC_{21} may be related to errors in the GRACE solutions, such as a deficiency in the background models for rotational deformation or ocean tides. Both EOP and AOW model estimates show seasonal variability of ΔC_{21} to be significantly smaller than ΔS_{21}. A consequence of a smaller signal level for ΔC_{21} is a lower signal to noise ratio for the GRACE estimate of this quantity. This is one of the probable causes of the discrepancy for ΔC_{21}. The estimated errors in the EOP-derived ΔC_{21} do not account for the discrepancy. Our preliminary analysis indicates the omission of OPT effects in the GRACE data processing has significant effects on the ΔC_{21} and ΔS_{21} estimates. The OPT correction improves the agreement with EOP and AOW model estimates.

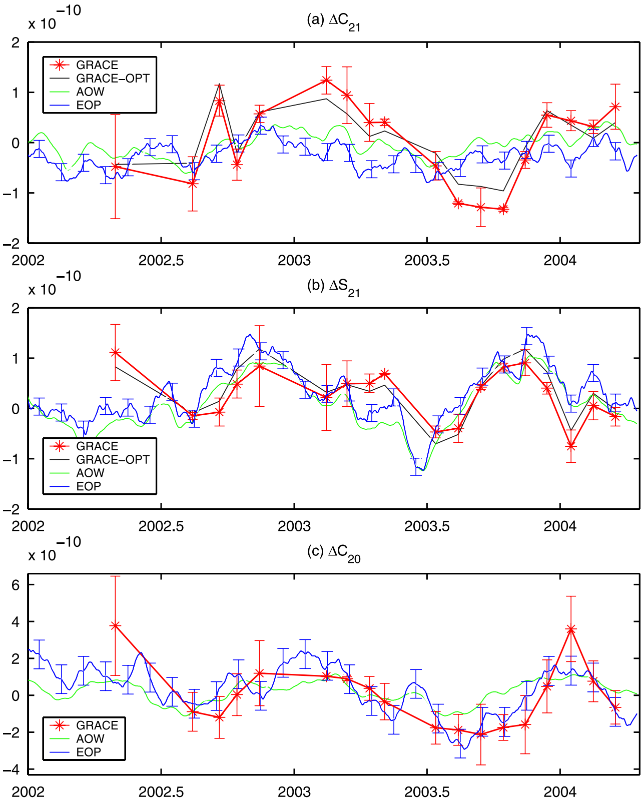

Figure 3. (a) ΔC_{21}, (b) ΔS_{21}, and (c) ΔC_{20} variations from GRACE (red curves and stars), Earth rotation EOP (blue curves), and AOW models AOW (green curves). 30-day moving average is applied to EOP and AOW estimates. Error bars represent uncertainties estimated from the NCEP and ECMWF models, and differences between CSR and JPL solutions. The trends are removed in all time series.

Table 1. Amplitude and Phase of Annual and Semiannual ΔC_{21}, ΔS_{21}, and ΔC_{20} Changes Estimated From GRACE (GRC), GRACE With OPT Correction (GRC-OPT), EOP and AOW. The phase is defined as ϕ in $\sin(2\pi(t - t_0) + \phi)$, where t_0 refers to h^0 on January 1.

	Annual		Semiannual	
Gravity Change	Amplitude ($\times 10^{-10}$)	Phase (deg)	Amplitude ($\times 10^{-10}$)	Phase (deg)
ΔC_{21} (GRC)	0.86	40	0.11	117
ΔC_{21} (GRC-OPT)	0.54	51	0.12	105
ΔC_{21} (EOP)	0.26	98	0.08	223
ΔC_{21} (AOW)	0.28	78	0.08	244
ΔS_{21} (GRC)	0.24	91	0.45	212
ΔS_{21} (GRC-OPT)	0.51	104	0.45	216
ΔS_{21} (EOP)	0.74	119	0.34	241
ΔS_{21} (AOW)	0.76	122	0.22	247
ΔC_{20} (GRC)	1.52	62	0.44	80
ΔC_{20} (EOP)	1.32	70	0.54	84
ΔC_{20} (AOW)	0.74	78	0.14	186

[19] EOP and AOW model estimates of the degree-2 spherical harmonics, ΔC_{21}, ΔS_{21}, and ΔC_{20} provide useful validation of GRACE measurements at the lowest degree, a region of the spherical harmonic spectrum where GRACE errors are expected to be relatively large. These independently determined low degree gravity changes are also available to improve the quality of time variable gravity fields from GRACE, and support studies of global scale mass redistribution. It would be also interesting to compare GRACE data with SLR observations. However, published SLR time series covering this GRACE observation period are not yet available, and this comparison is not included here.

[20] **Acknowledgments.** We would like to thank R. Gross and another anonymous reviewer for their insightful review comments, which led to improved presentation of the results. This research was supported by NASA's Solid Earth and Natural Hazards and GRACE Science Program (under Grants NNG04GF10G, NNG04GF22G).

References

Aoyama, Y., and I. Naito (2000), Wind contribution to the Earth's angular momentum budgets in seasonal variations, *J. Geophys. Res.*, *105*, 12,417–12,431.

Bettadpur, S. (2003), *Level-2 Gravity Field Product User Handbook*, The GRACE Proj., Univ. of Tex., Austin.

Chen, J. L., and C. R. Wilson (2003), Low degree gravitational changes from earth rotation and geophysical models, *Geophys. Res. Lett.*, *30*(24), 2257, doi:10.1029/2003GL018688.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2004), Interannual variability of low degree gravitational change, 1980–2002, *J. Geod.*, in press.

Eubanks, T. M. (1993), 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.

Fan, Y., H. Van del Dool, K. Mitchell, and D. Lohmann (2003), A 51-year reanalysis of the U.S. land-surface hydrology, *GEWEX Newsl.*, *13*, 6–10.

Fukumori, I., T. Lee, D. Menemenlis, L.-L. Fu, B. Cheng, B. Tang, Z. Xing, and R. Giering (2000), A dual assimilation system for satellite altimetry, paper presented at Joint TOPEX/Poseidon and Jason-1 Science Working Team Meeting, Miami Beach, Florida.

Gross, R. S., G. Blewitt, P. J. Clarke, and D. Lavallée (2004), Degree-2 harmonics of the Earth's mass load estimated from GPS and Earth rotation data, *Geophys. Res. Lett.*, *31*, L07601, doi:10.1029/2004GL019589.

Kalnay, E. M., et al. (1996), The NCEP/NCAR 40–year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Salstein, D. A., and R. D. Rosen (1997), Global momentum and energy signals from reanalysis systems, paper presented at 7th Conference on Climate Variations, Am. Meteorol. Soc., Long Beach, Calif.

Tapley, B. D., S. Bettadpur, M. M. Watkins, and C. Reigber (2004), The gravity recovery and climate experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.

Wahr, J. (1985), Deformation induced by polar motion, *J. Geophys. Res.*, *90*, 9363–9368.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, *31*, L11501, doi:10.1029/2004GL019779.

J. L. Chen, J. C. Ries, B. D. Tapley, and C. R. Wilson, Center for Space Research, University of Texas, Austin, TX 78712, USA. (chen@csr.utexas.edu)