JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, B03405, doi:10.1029/2006JB004747, 2008

Gravity Recovery and Climate Experiment (GRACE) alias error from ocean tides

K. W. Seo,[1,2] C. R. Wilson,[3] S. C. Han,[4,5] and D. E. Waliser[1]

Received 12 September 2006; revised 6 December 2007; accepted 8 January 2008; published 28 March 2008.

[1] Gravity Recovery and Climate Experiment (GRACE) is able to observe interannual and longer-period mass redistribution driven by climate changes. However, alias errors due to inaccurate ocean tide models may contaminate these signals. To quantify this problem, we estimate alias contamination due to expected errors in eight tidal constituents (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, and K_2) for the period August 2002 to February 2006. Differences between GOT00.2 and TPXO6.2 tide models are used as estimates of tide model errors. The alias estimate is based on an approximate method employing least squares fits of spherical harmonics to potential differences between the two GRACE satellites. Results from this method are similar to previous estimates, confirming this is a useful and efficient way to study the alias problem. New findings are (1) the period of the M_2 tide alias is about 140 d, much longer than the predicted period (13.5 d) because of monthly sampling of the 13.5-d period; (2) there are two alias periods for K_1 (one about 90 d and one longer than 7 years); and (3) the slow decay in the GRACE orbit causes tide component aliases to differ from pure frequencies as the orbit evolves. We also find that aliases can contaminate in both space and time and thus may affect estimates of mass changes over land. Finally, we compare the simulated S_2 alias with the estimated S_2 alias in GRACE data. They are similar, but our approximate method appears to overestimate alias error over high-latitude oceans and along certain coastlines while underestimating error over low-latitude oceans.

Citation: Seo, K. W., C. R. Wilson, S. C. Han, and D. E. Waliser (2008), Gravity Recovery and Climate Experiment (GRACE) alias error from ocean tides, *J. Geophys. Res.*, *113*, B03405, doi:10.1029/2006JB004747.

1. Introduction

[2] The Gravity Recovery and Climate Experiment (GRACE) mission launched in May 2002 measures Earth's gravity with unprecedented accuracy [*Tapley et al.*, 2004]. GRACE's mission funding has been extended at least to 2010, and GRACE measurements of interannual and secular gravity variations offer an opportunity to study global climate variability [*Velicogna and Wahr*, 2006]. However, caution must be exercised when interpreting interannual changes because their signal amplitudes are small compared to seasonal variations, and there may be systematic error sources. Here we examine one such systematic source due to the alias of ocean tide error.

[3] Inaccuracy in ocean tide models used to remove ocean mass redistribution in GRACE processing is an error source that can contaminate GRACE data at a variety of periods. *Ray et al.* [2003] have calculated periods of alias error from ocean tides on the basis of GRACE orbit elements and have shown that errors in K_1, K_2, S_1, S_2, and P_1 constituents alias to periods of 7.48 years, 3.74 years, 322 d, 161 d, and 171 d, respectively. *Han et al.* [2005] showed that the S_2 tide aliasing over the Antarctic ice shelf appears in GRACE data at a period near 161 d, as predicted by *Ray et al.* [2003]. *Seo et al.* [2008] examined GRACE spherical harmonic (SH) degree 2 and order 0 (SH (2, 0)), finding that it is likely to be contaminated by the S_2 atmospheric tide at SH (2, 2). *Schrama and Visser* [2006] simulated alias error associated with ocean tides for 12 months, showing that root-mean-square (RMS) error for periods longer than 3 months was 0.5 mm in geoid and for periods less than 3 months was near 0.1 mm.

[4] It is useful to understand both temporal and spatial alias error associated with individual tide constituents because each will contaminate interannual gravity changes from GRACE at different timescales. We develop a simplified method to estimate this error using gravitational potential differences between the two GRACE satellites and use actual GRACE orbits in the calculation. The approach is computationally efficient and provides estimates for eight

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[2]Now at Korea Polar Research Institute, Incheon, Korea.
[3]Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA.
[4]School of Earth Sciences, Ohio State University, Columbus, Ohio, USA.
[5]Now at Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

0148-0227/08/2006JB004747$09.00

major constituents for the period August 2002 to February 2006.

2. Alias Error From Ocean Tides

2.1. Methods

[5] We use two separate ocean tide models, GOT00.2 and TPXO6.2, to estimate the magnitude of tide model error. The GOT00.2 model uses TOPEX/POSEIDON (T/P) data and ERS-1/2 for supplementary data (an update of *Ray* [1999]). The TPXO6.2 model combines T/P observations with the hydrodynamic equations (an update of *Egbert et al.* [1994]). From these models, we select eight major diurnal and semidiurnal tide constituents (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, and K_2) and calculate differences between the two models (GOT00.2 − TPXO6.2) as error estimates. Because the two models are derived from common data, these differences may underestimate actual error.

[6] GRACE consists of twin satellites separated by about 200 km and detects gravity anomalies using various data, including range rate perturbations between the two. Supplementary measurements include GPS positions and accelerations to account for nongravitational perturbations such as atmospheric drag. Range rate perturbations are approximately proportional to the potential differences experienced by the two satellites. This relationship was shown in the energy integral equation given by *Jekeli* [1999] and *Han et al.* [2006]. Using this relationship, we simulate potential differences between the two GRACE satellites caused by the ocean tide error along GRACE ground tracks, which are available as GNV1B data at the Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center ftp site, http://podaac.jpl.nasa.gov/. These provide three-dimensional positions and velocities of the two GRACE satellites as a function of time. To estimate tide error (the difference (GOT00.2 − TPXO6.2)), we first calculate tide amplitudes and phases in terms of SH representations of GOT00.2 and TPXO6.2 evaluated over a global grid. Then we form differences between the two models in terms of SH amplitudes and phases. Differences in amplitudes and phases for a given tide constituent are C^c_{lm}, C^s_{lm}, S^c_{lm}, and S^s_{lm}. The gravity potentials at the positions of GRACE satellites (r_i, θ_i, and λ_i) due to the residual tides can be derived as follows:

$$V^t_i = \frac{GM}{R}\sum_{l=0}^{L}\sum_{m=0}^{l}\left(\frac{R}{r_i}\right)^{l+1}\tilde{P}_{lm}(\cos\theta_i) \cdot \left[C^t_{lm}\cos(m\lambda_i) + S^t_{lm}\sin(m\lambda_i)\right], \quad (1)$$

in which i is 1 or 2, t is sampling time, G is the gravitational constant, M is the mass of the Earth, R is the mean radius of the Earth, and $\tilde{P}_{lm}$ are normalized associated Legendre functions. C^t_{lm} and S^t_{lm} are Stokes coefficients representing the difference between the two tide models. The coefficients are calculated via

$$C^t_{lm} = C^c_{lm}\cos(2\pi t/T) + C^s_{lm}\sin(2\pi t/T),$$
$$S^t_{lm} = S^c_{lm}\cos(2\pi t/T) + S^s_{lm}\sin(2\pi t/T), \quad (2)$$

where T is the period of the corresponding constituent. Finally, the potential differences due to the error of a given tide constituent are

$$dV^t_{12}(r_1,\theta_1,\lambda_1,r_2,\theta_2,\lambda_2) = V^t_1(r_1,\theta_1,\lambda_1) - V^t_2(r_2,\theta_2,\lambda_2). \quad (3)$$

[7] The measurement epoch of dV_{12} is 60 s, which is the temporal resolution of the current GNV1B product. We sample dV_{12} every 30 d, close to the nominal sampling periods of GRACE products, and estimate SH coefficients up to degree and order 30 from a least squares fit of SH functions to dV_{12}. The SH coefficients provide an estimate of alias error from the ocean tide model difference. Additionally, we estimate SH coefficients from 5-d samples of dV_{12}. The choice of 5 d resolves errors occurring at relatively short periods, such as from M_2 [*Knudsen*, 2003].

2.2. Results

2.2.1. Alias Error in SH

[8] To examine alias error amplitudes and spatial patterns, RMS plots of SH coefficients are used. Figure 1 shows these RMS plots for the diurnal tides. The left plots show error amplitudes in 5-d solutions. For all cases, significant error is observed around order 15. SH order 15 is related to the spatial scale of successive ground tracks of GRACE; thus contamination from unmodeled ocean tides appears around order 15 [*Seo et al.*, 2008], as predicted by *Kaula*'s [1966] resonance formula. Error in 5-d solutions may not significantly impact monthly GRACE products because variations should average to be small in monthly solutions. The right plots show error amplitudes in 30-d solutions. For Q_1 and O_1 tides, insignificant amplitudes remain in 30-d solutions. We conclude that alias error of Q_1 and O_1 is negligible in GRACE products. However, some long-period error, which probably affects GRACE monthly products, remains in the 30-d solution. We examine the cause of this error later in this section. Similar error reduction in monthly solutions is observed for P_1 and K_1 at high degrees and orders with alias periods shorter than 1 month. However, P_1 and K_1 errors at low degrees and orders remain significant in 30-d solutions, implying that associated alias periods at low degrees and orders exceed 1 month.

[9] Figure 2 shows results similar to Figure 1 for semidiurnal tides. Because their amplitudes are greater than for diurnal tides, we use a different scale in Figure 2. Similar to Q_1 and O_1 cases, amplitudes for N_2 and M_2 in 30-d solutions are smaller than in 5-d solutions, but some long-period error remains. As predicted in previous studies [*Ray et al.*, 2003; *Knudsen*, 2003], alias error from S_2 and K_2 tides is predominantly at long periods.

[10] Figures 1 and 2 imply that ocean tide alias error arises in two different ways. The first is orbit resonance from *Kaula*'s [1966] resonance formula, evident near SH order 15. *Seo et al.* [2008] showed that unmodeled nontidal geophysical signals (atmospheric surface pressure and ocean bottom pressure) also contribute to effects near SH order 15. This resonance is mainly the source of well-recognized north-south stripes in GRACE time-varying gravity. Relatively small magnitudes in Figures 1 and 2 indicate that ocean tides are not major causes of the stripes,

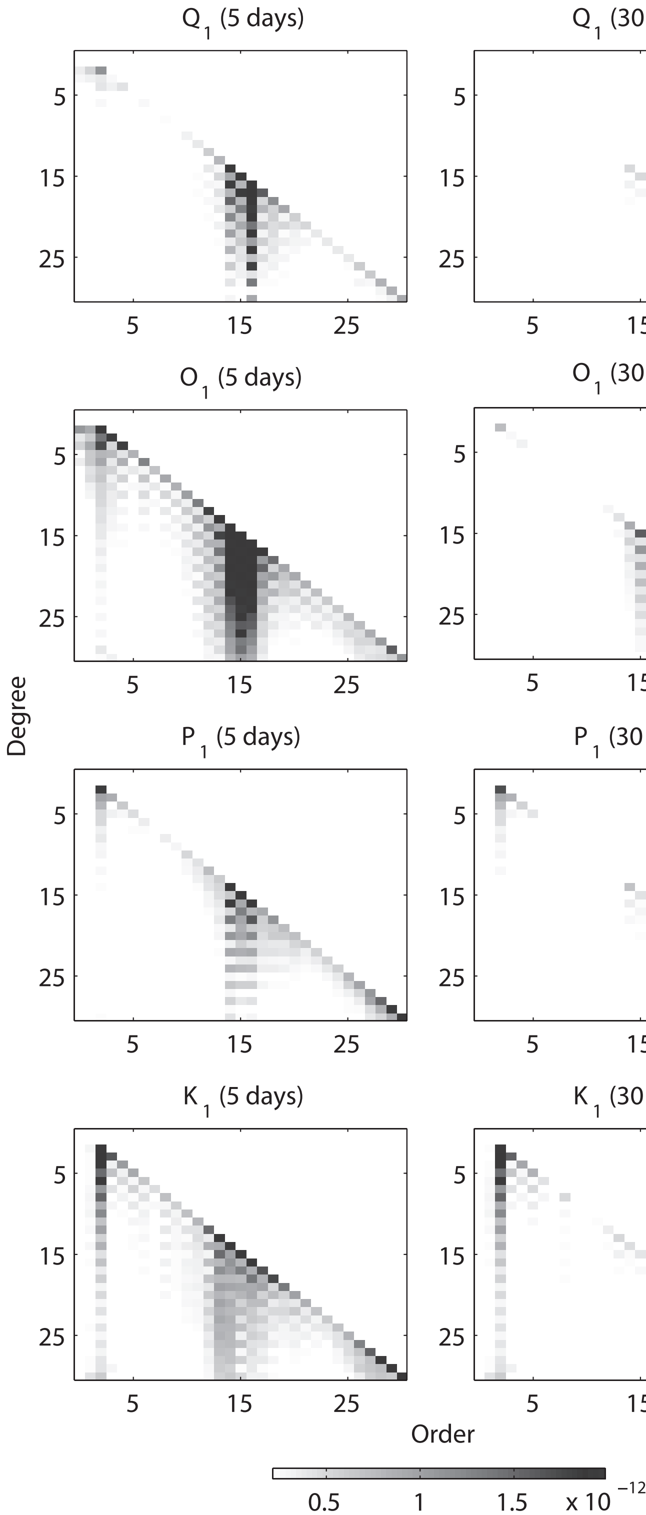

Figure 1. Alias error of diurnal tides. Left plots show RMS amplitudes in 5-d solutions, and right plots show RMS amplitudes in 30-d solutions.

as documented by *Seo et al.* [2008]. The second source of tide alias error is the slow precession of GRACE with respect to the Sun [*Ray et al.*, 2003], causing error at low SH orders. This second type of error has a greater effect on GRACE products because of its large magnitude and period longer than a month.

[11] The alias periods of P_1, K_1, S_2, and K_2 are longer than 1 month, confirming results by *Ray et al.* [2003]. However, RMS amplitudes for P_1 and K_1 in Figure 1, which

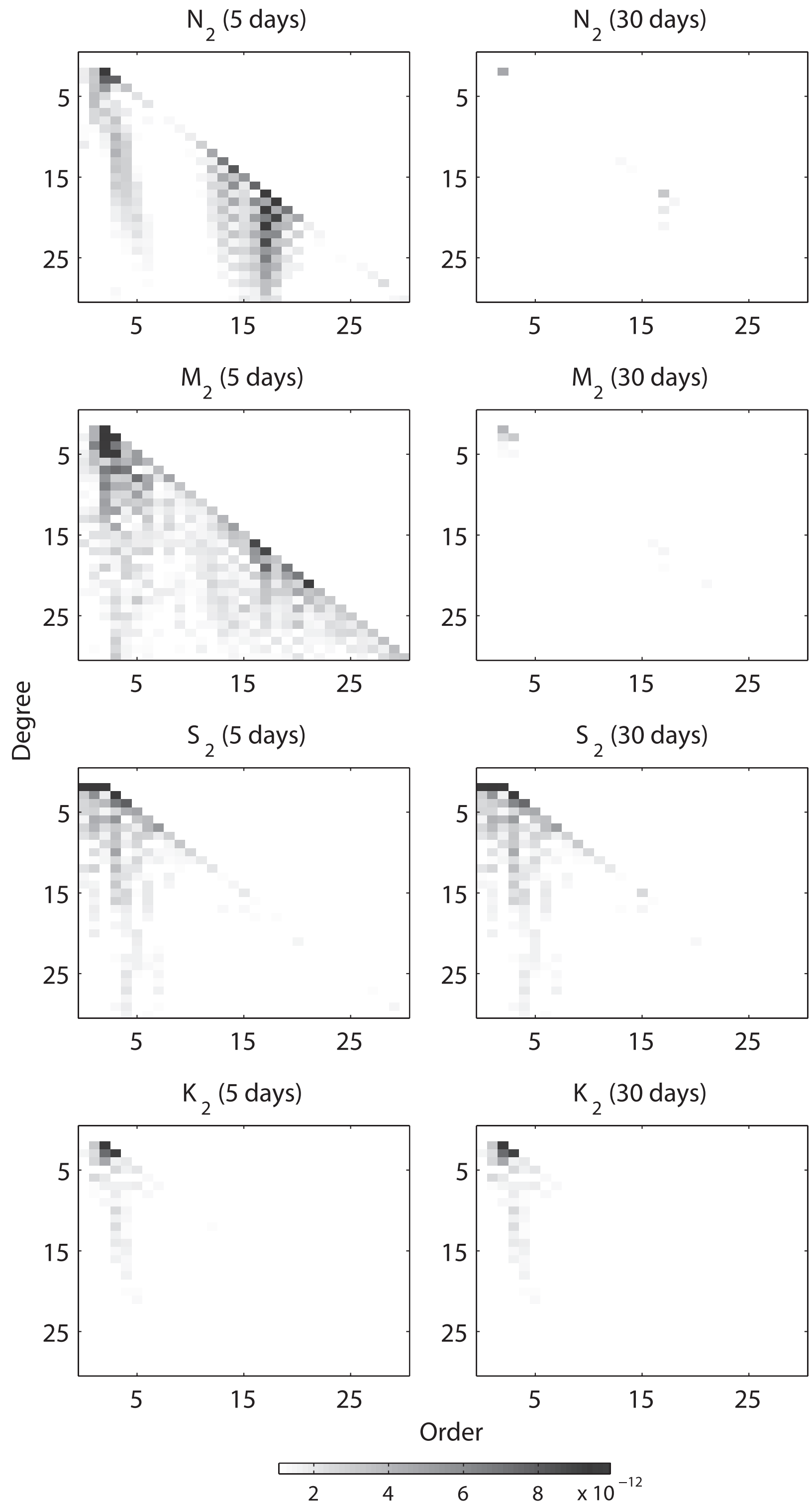

Figure 2. Alias error of semidiurnal tides. Left plots show RMS amplitudes in 5-d solutions, and right plots show RMS amplitudes in 30-d solutions.

differ between 5-d and 30-d solutions at high degrees and orders, clearly show that the alias period of each constituent is not mapped to a single frequency. Therefore, it is necessary to simulate the alias for many months to determine temporal scales in each SH component.

[12] Error amplitudes from 30-d solutions in Figures 1 and 2 may be overestimated or underestimated compared with those in the monthly GRACE products because the approach described in section 2.1 is not precisely the GRACE data processing procedure. Overestimation is pos-

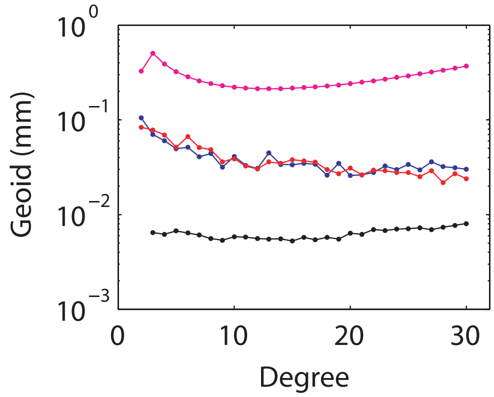

Figure 3. RMS degree amplitudes of GRACE error and predicted alias error from ocean tides during July 2003. The black line is the prelaunch estimate of GRACE error, and the magenta line is the current GRACE error estimated by *Wahr et al.* [2006]. The blue and red lines are the alias error due to ocean tides simulated by *Ray and Luthcke* [2006] and this study, respectively.

sible because empirical parameters, used to calibrate accelerometers in GRACE data processing, were not taken into account in this approach. On the other hand, there are additional range rate residuals due to orbit dynamics associated with unmodeled ocean tides, and these produce error in GRACE monthly products. Results in Figures 1 and 2 do not include effects of orbit dynamics, and this may cause underestimation. The effects on alias error from empirical parameters and the range rate residuals have not been examined yet, but *Desai and Yuan* [2006] implied that empirical parameters were not effective in absorbing unmodeled ocean tides.

[13] To test the accuracy of our alias simulation, we compare RMS degree amplitudes of the alias simulated here with those of *Ray and Luthcke* [2006] in Figure 3. *Ray and Luthcke* [2006] estimated the alias using the same tide models used in this study but followed more closely GRACE data processing methods. The levels of both alias errors showing in Figure 3 are similar, indicating that our simplified approach provides reasonable estimates of alias error. Differences between the two error estimates may be due to two effects. First, the analysis here does not include contributions from orbit dynamic information contributed by GPS, and second, *Ray and Luthcke* [2006] used 24 diurnal and semidiurnal constituents rather than the 8 major constituents in this study. Figure 3 also shows RMS degree amplitudes of prelaunch GRACE error and the current GRACE error estimated by *Wahr et al.* [2006]. Ocean tide alias error is approximately 1 order of magnitude larger than the prelaunch estimate [*Ray and Luthcke*, 2006] but is not considered to be the major limitation of current GRACE monthly products. The effect of the GRACE error at interannual and longer periods, such as ice mass balance, is also likely less than the estimate by *Wahr et al.* [2006]. The GRACE time series is at least a few years (and much longer than a month), and the GRACE error estimate from monthly data is diminished when considering interannual and longer timescales. On the other hand, long-period ocean tide aliases remain unattenuated by the monthly averaging in GRACE data products. This is particularly true of K_2 and K_1 aliases because their periods exceed 3 years. Therefore, these may have a significant impact on estimates of interannual and decadal variations from GRACE products.

[14] In addition to amplitudes, we compare alias periods from our simulation with those from previous studies. Figure 4 is the time series of $\Delta C_{2,0}$ and $\Delta C_{3,0}$ from P_1,

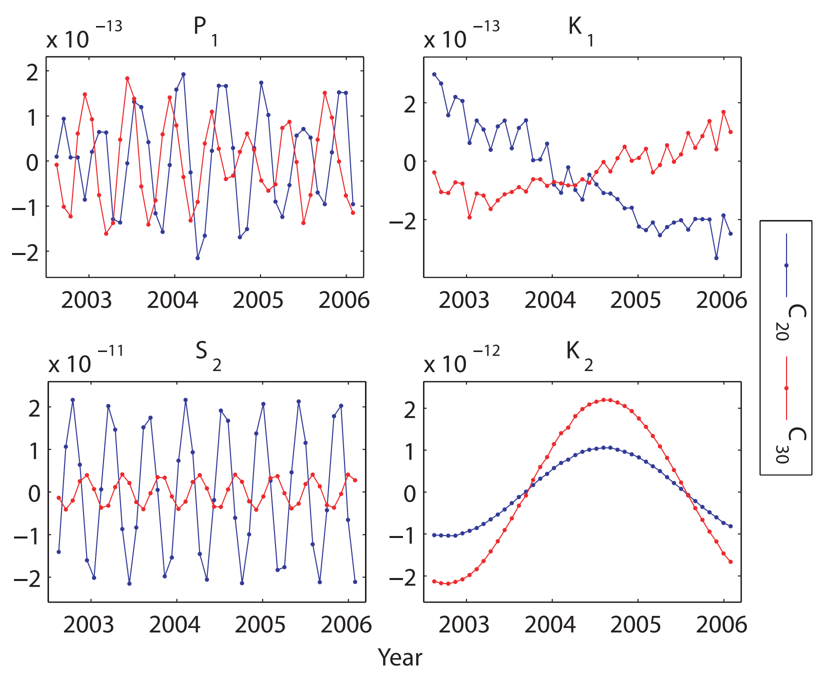

Figure 4. Time series of aliased $\Delta C_{2,0}$ and $\Delta C_{3,0}$ from the P_1, K_1, S_2, and K_2 tides. The alias periods for P_1, S_2, and K_2 are about 171 d, 161 d, and 3.74 years, respectively, close to the results of *Ray et al.* [2003]. The alias error of K_1 consists of two periods, a result not predicted in previous studies. The period of the shorter alias is approximately 90 d, but it is too early to determine the longer period.

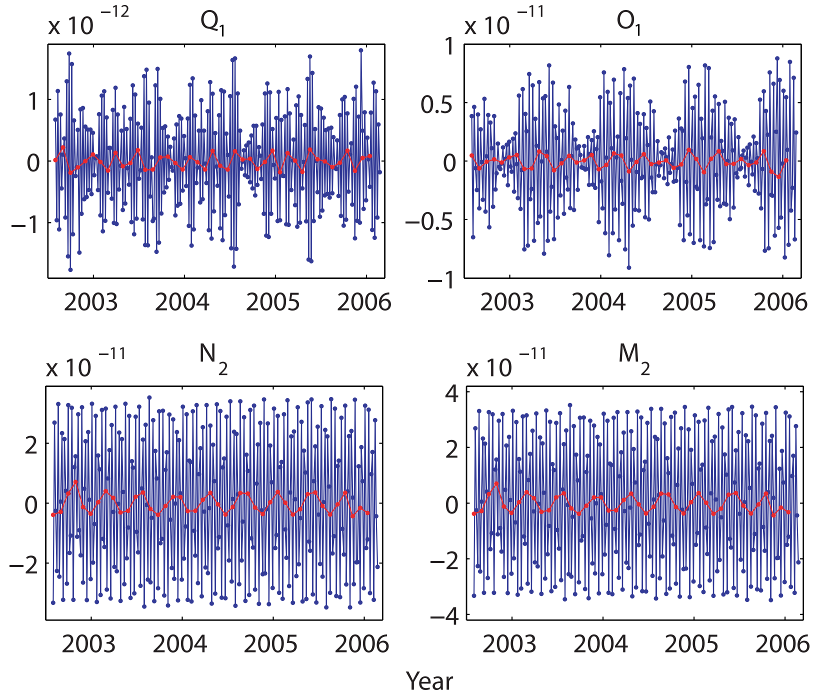

Figure 5. Time series of aliased $\Delta C_{2,2}$ from the Q_1, O_1, N_2, and M_2 tides. The alias periods of the four constituents are shorter than 1 month, as shown by the blue lines (5-d solutions), but the red lines (30-d solutions) show alias error at timescales longer than a month. The short-period error is not canceled by monthly averaging, and residual error remains at long periods in 30-d solutions.

K_1, S_2, and K_2 in 30-d solutions. *Ray et al.* [2003] predicted that periods of alias error are 171 d, 7.48 years, 161 d, and 3.74 years, respectively. Our simulation indicates alias periods of P_1, S_2, and K_2 are close to the earlier prediction. However, the alias of K_1 includes two different periods, a result not anticipated in previous work. It is too early to determine the longer of the two periods from just 4 years of data, but the shorter period is about 90 d. It is not clear how to account for the shorter K_1 period, and we discuss this in section 4. Time series of other SH coefficients for K_1 (not shown) show small amplitudes at the shorter (90-d) period, suggesting it probably does not affect monthly products. Figure 5 is the time series of $\Delta C_{2,2}$ from Q_1, O_1, N_2, and M_2 in both 5- and 30-d solutions. The 5-d solutions identify the alias periods shorter than 1 month, but longer-period error contaminates 30-d solutions. Because 30-d averaging does not completely attenuate shorter-period error, residual error remains in 30-d solutions. In particular, M_2 error may be problematic for GRACE monthly products because this is the largest constituent. The alias period of M_2 in 30-d solutions is about 140 d, much longer than the predicted period, 13.5 d.

[15] The altitude of GRACE is variable, and there may be associated changes in alias errors. Figure 6a shows time series of SH $S_{16,16}$ due to M_2. The blue and red lines represent 5- and 30-d solutions, respectively. SH (16, 16) is the largest alias component near the resonant order for M_2. Figure 6b shows power spectra of the 5-d series in Figure 6a for the first half (August 2002 to April 2004, in blue) and the second half (May 2004 to February 2006, in red). This shows that the dominant frequencies vary. The nonstationary nature of the alias may be due to a changing sampling rate as the GRACE orbit decays. Tests of sampling pure sinusoidal waves at linearly varying rates (not shown) produce nonstationary time series similar to Figure 6a. Figure 6c shows the altitude decrease of GRACE satellites, implying that variations of GRACE sampling rate in longitude, from orbit decay, will produce nonstationary alias error. This nonstationary behavior is not observed at SH orders below the resonant orders. As a result, the effect of frequency changes in alias error for P_1, K_1, S_2, and K_2 tides, dominantly at low SH orders, is small.

2.2.2. Geographic Distribution of Alias Error

[16] Here we examine alias contamination as it depends on geographic location. Although the sources are entirely in the oceans, estimates over land may be affected by either (1) spatial leakage associated with a finite range of SH or (2) spatial aliasing in which variations at one SH contaminate those at another. Although GRACE monthly products include SH coefficients up to degree and order 120, much lower limits are used in practice, generally to 15 or slightly above, with a resolution of many hundreds of kilometers [*Wahr et al.*, 2004]. Thus ocean sources can contaminate signal over land, particularly near coastlines. *Seo et al.* [2008] showed that GRACE suffers from both temporal and spatial aliasing. Spatial aliasing indicates that spatial spectra of ocean tides are not conserved, implying that aliased ocean tides will contaminate areas on land.

[17] Figure 7 shows RMS ocean tide error (GOT00.2 − TPXO6.2) for July 2003 for five constituents, P_1, K_1, S_2, K_2, and M_2. The error is smoothed by 800-km Gaussian filtering. These maps are independent of GRACE and suggest that tide error exists over land, especially in coastal areas, where Gaussian smoothing [*Swenson et al.*, 2003]

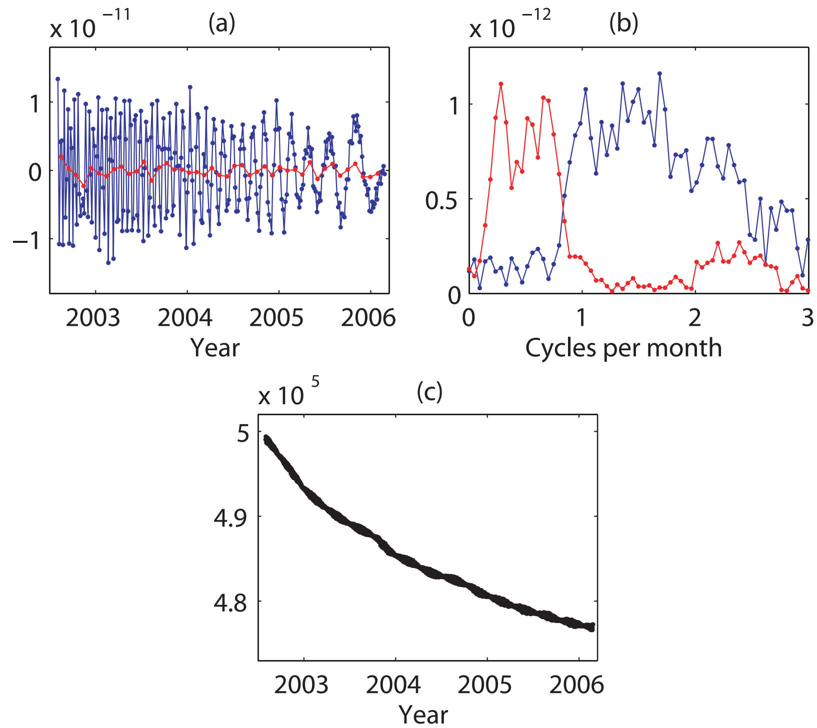

Figure 6. (a) Time series of $S_{16,16}$ for M_2 from 5-d (blue) and 30-d (red) solutions. Both solutions show nonstationary behavior. (b) Power spectra of time series of 5-d solutions in Figure 6a. The blue line is the spectrum from August 2002 to April 2004, and the red line is the spectrum from May 2004 to February 2006. These show that aliasing is not narrowband and that frequency changes over time. This may be related to orbit decay. (c) Altitude decrease of GRACE satellites.

causes leakage to adjacent land areas. Areas around the Arctic Ocean appear to suffer from this in particular.

[18] Figure 8 shows maps of alias error from GRACE's along-track sampling. Amplitudes are smaller than in Figure 7, but contributions remain in polar regions, including the Arctic Ocean and the West Antarctic Ice Sheet [*Han et al.*, 2005]. Errors from P_1, K_1, and K_2 have similar spatial patterns, predominantly at SH order 2. RMS amplitudes of SH degrees and orders in Figures 1 and 2 also show an order 2 pattern. Connections between ocean tide error and individual GRACE SH are complicated. However, *Seo et al.* [2008] qualitatively explained how the SH (2, 0) semidiurnal tide aliased to SH (2, 2) because the sign of a semidiurnal tide changes about twice every 12 h, while GRACE surveys the globe during this time span. This suggests that all zonal terms in semidiurnal tides will alias to SH order 2. Since the Arctic Ocean is mainly zonal in shape, tide error there may alias to order 2 as well. We may explain the SH order 2 error in P_1 and K_1 on the basis of analysis of the semidiurnal tide. The amplitudes of diurnal tides are strong at SH order 1, and the sign of a diurnal tide changes about once every 12 h. This likely leads to alias error at SH order 2 from a linear combination of SH order 1 in a diurnal tide and apparent GRACE observation of SH order 1.

3. Comparing the Alias in GRACE Data to the Simulated Alias

[19] We examine alias error in GRACE data, starting with the GeoForschungsZentrum (GFZ) RL04 [*Flechtner*, 2007] and Goddard Space Flight Center (GSFC) RL01 [*Luthcke et al.*, 2006] monthly gravity fields, and compare them with our simulation of alias error. GFZ RL04 uses the FES2004 tide model (an update of *Lefevre et al.* [2002]), and GSFC RL01 incorporates the GOT00.2 tide model. Again, tide error is estimated from the difference between GOT00.2 and TPXO6.2. Comparisons among the three different alias estimates can be useful both to understand properties of our alias simulation and to examine accuracies of modern ocean tide models. Among the five problematic errors shown in Figure 8, we have only examined that of S_2. Errors in other constituents (K_1, K_2, P_1, and M_2) in GRACE data are harder to quantify because of factors that include the following: (1) current GRACE observation period is less than the alias period of K_1; (2) K_2 alias error and interannual geophysical signal cannot be separated well; (3) error from P_1 (at 171 d) may be small and difficult to separate from that of S_2 (161 d) from monthly sampling over 4 years; and (4) the alias period of M_2 cannot be determined from orbit decay, as shown in Figure 6.

[20] To estimate S_2 error, we apply 800-km Gaussian smoothing to GRACE fields to suppress measurement noise and then calculate mass fields at grid points in units of equivalent surface water layer thickness. The $C_{2,0}$ coefficient is excluded because it may be corrupted by an unmodeled atmospheric S_2 tide [*Seo et al.*, 2008] not included in our simulation. We estimate sinusoids at a period of 161 d at each grid point by least squares using residual mass fields of GRACE data after removing annual and semiannual variations. The left plot of Figure 9 shows

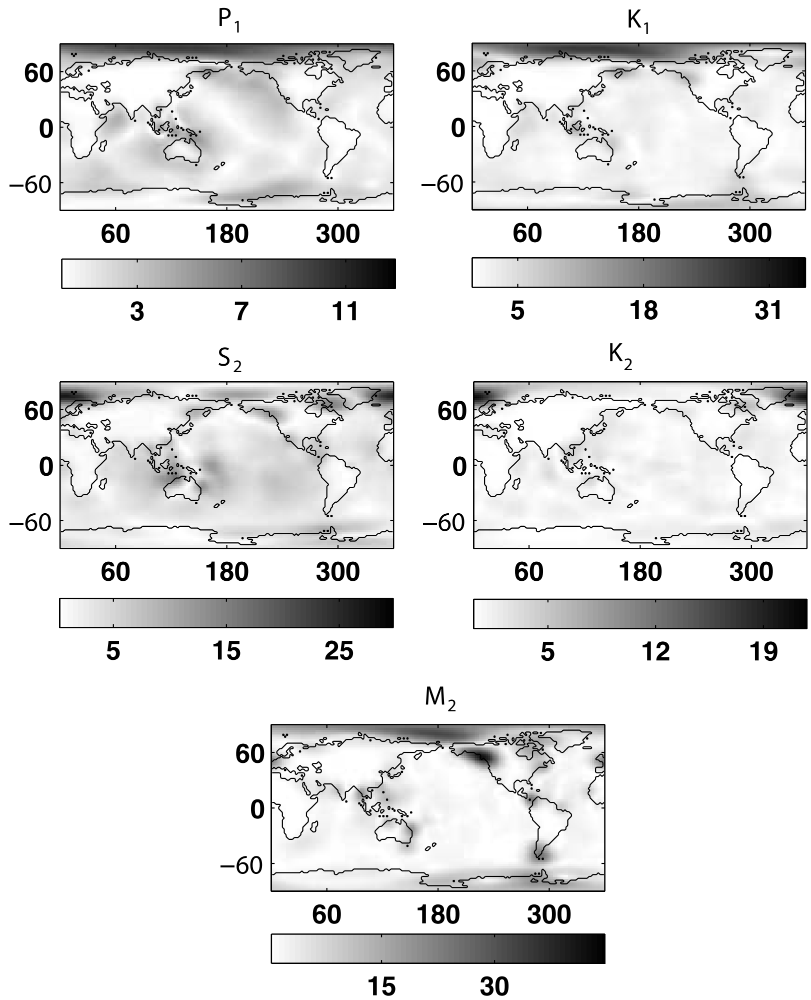

Figure 7. RMS amplitudes of error in ocean tide models for July 2003. Amplitudes for the five constituents are strong in the Arctic Ocean. We apply 800-km Gaussian smoothing, leading to leakage to land areas. The unit is water height in millimeters.

the S_2 alias in GFZ RL04 monthly data. There is significant error near Indonesia and the east Amazon basin. The middle plot of Figure 9 shows the S_2 alias in GSFC RL01 monthly data. The error near Indonesia is not present, but overall, the S_2 alias in GSFC RL01 is stronger than in GFZ RL04, particularly over the central Pacific and high-latitude oceans. Large amplitudes over the Amazon basin in both GFZ RL04 and GSFC RL01 are probably leakage from the semiannual component of water storage changes. The right plot of Figure 9 is the S_2 alias from the simulation. Relative to GRACE, the simulated alias is smaller over the Pacific and Atlantic but larger over the Indian and Arctic oceans.

[21] A comparison between the left plot (GFZ RL04 using FES2004) and the middle plot (GSFC RL01 using GOT00.2) of Figure 9 reveals relative accuracies of the two ocean tide models (FES2004 versus GOT00.2). FES2004 (one of the models for GRACE RL04) performs better than GOT00.2 except around Indonesia. The significant error near Indonesia and high-latitude oceans in the right plot of Figure 9 (GOT00.2 − TPXO6.2) may be due to error in TPXO6.2 because the error is not evident in the alias associated with GOT00.2. Because the S_2 alias (161 d) and semiannual periods (about 183 d) are close, a longer time series is required to separate the two terms well. This analysis is therefore preliminary.

[22] Comparisons among the three estimates of the S_2 alias indicate that our alias simulation method may underestimate the effect over low-latitude oceans except the Indian Ocean and may overestimate effects over high-latitude oceans and coastlines. However, it is useful to understand the aliases of other constituents in GRACE data.

4. Conclusions

[23] We simulate alias error from eight ocean tide constituents, Q_1, O_1, P_1, K_1, N_2, M_2, S_2, and K_2. Of these, P_1, K_1, S_2, K_2, and M_2 are found to be problematic for GRACE monthly products because their alias periods are longer than 30 d. For P_1, S_2, and K_2, periods are 171 d, 161 d, and 3.74 years, respectively, in agreement with a previous study [*Ray et al.*, 2003]. The alias period of M_2 is 13.5 d, but it appears at 140 d at low SH degrees and orders in 30-d solutions. The K_1 alias produces two different alias periods. The longer period exceeds the GRACE measure-

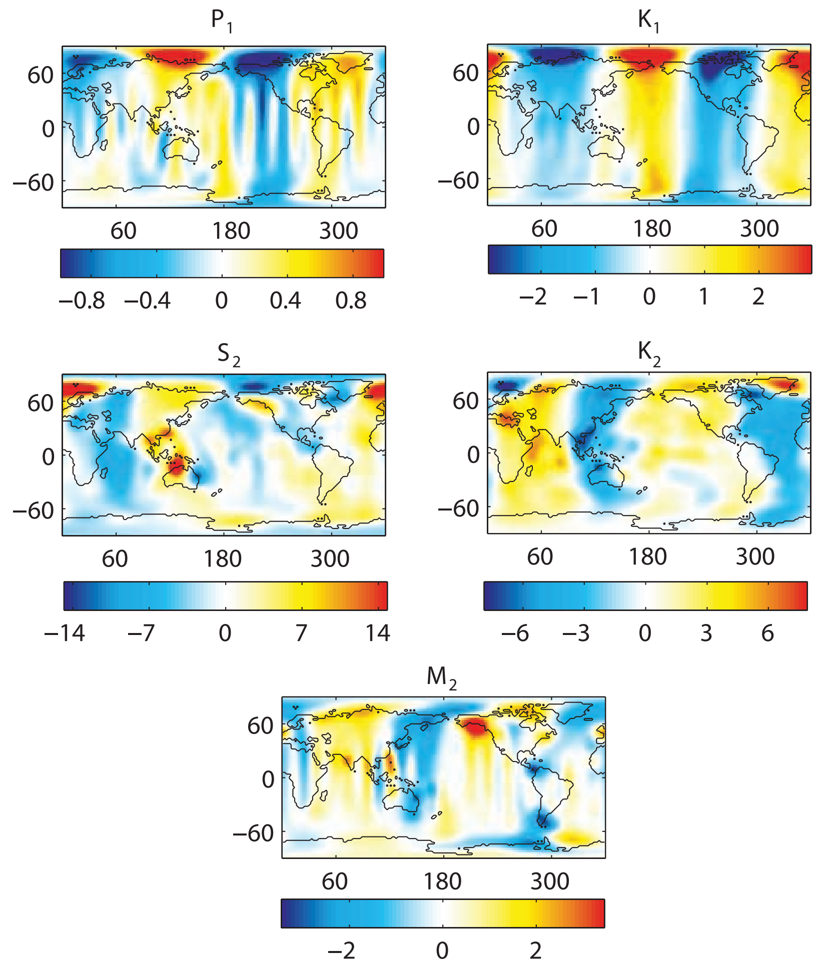

Figure 8. Geographic distribution of the simulated alias error from ocean tides for July 2003. Error occurs over land even though error sources are entirely from oceans. The unit is water height in millimeters.

ment time span and is about 7.48 years. The shorter period is near 90 d and was not previously recognized. Its cause is uncertain, but numerical simulations provide some indication of its cause. Alias simulations (not shown) using mass fields with single SH components at the K_1 period show that the SH (2, 1) component of K_1 aliases to SH (2, 0) at the longer period, and the SH (3, 1) component aliases to SH (2, 0) at the shorter period. There should be additional SH terms which alias to SH (2, 0). This illustrates the complicated nature of GRACE aliasing, which occurs both temporally and spatially. Further study to identify connections between cause and effect of GRACE aliases will be necessary.

[24] Alias error may affect estimates of mass change over land, and there may be significant effects from K_1 and K_2 at high latitudes. Therefore, estimates of interannual variability of continental groundwater and ice may be corrupted.

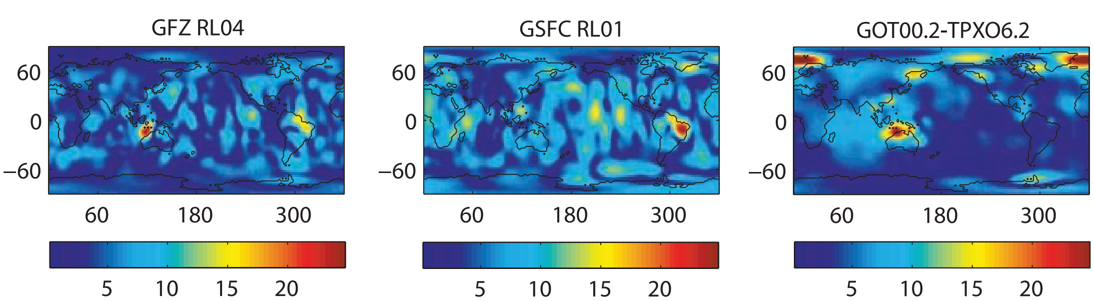

Figure 9. Amplitudes of sinusoids at a 161-d period. The left plot is from GFZ RL04, the middle plot is from GSFC RL01, and the right plot is from our alias simulation. Each plot from left to right represents S_2 alias error associated with the difference between the actual tide and FES2004, between the actual tide and GOT00.2, and between GOT00.2 and TPXO6.2, respectively.

Understanding alias error is critical to correctly interpreting the longer-period signal in GRACE.

[25] We compare the simulated S_2 alias error with the estimated S_2 error in GRACE data. Generally, these error levels are similar. However, simulated error from ocean tide models appears to overestimate the effect over the Arctic Ocean and some coastal areas and to underestimate it over most low-latitude oceans. Because GRACE measures unmodeled ocean tides, GRACE alias error may be used to assess ocean tide models. On a more positive note, GRACE may be used to improve ocean tide models if other signals can be estimated and removed. This should become possible as the GRACE mission proceeds and longer time series become available.

[26] **Acknowledgments.** This study was supported by the NASA Postdoctoral Program and the NASA Solid Earth and Natural Hazards and GRACE Program (under grants NNG04G060G, NNG04GP70G, and NNG04GF22G). The first author was also partly supported by Korea Polar Research Institute project (PE07020). In addition, the fourth author was supported by JPL's Human Resources Development fund. We are very grateful to Victor Zlotnicki, Dahning Yuan, Richard Ray, and two anonymous reviewers for their helpful discussion and comments. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

Desai, S. D., and D.-N. Yuan (2006), Application of the convolution formalism to the ocean tide potential: Results from the Gravity Recovery and Climate Experiment (GRACE), *J. Geophys. Res.*, *111*, C06023, doi:10.1029/2005JC003361.

Egbert, G., A. Bennett, and M. Foreman (1994), TOPEX/POSEIDON tides estimated using a global inverse model, *J. Geophys. Res.*, *99*(C12), 24,821–24,852.

Flechtner, F. (2007), GFZ level-2 processing standards document for level-2 product release 0004, 17 pp., GeoForschungsZentrum Potsdam, Potsdam, Germany.

Han, S.-C., C. K. Shum, and K. Matsumoto (2005), GRACE observations of M2 and S2 ocean tides underneath the Flichner-Ronne and Larsen ice shelves, Antarctica, *Geophys. Res. Lett.*, *32*, L20311, doi:10.1029/2005GL024296.

Han, S.-C., C. K. Shum, and C. Jekeli (2006), Precise estimation of in situ geopotential differences from GRACE low-low satellite-to-satellite tracking and accelerometer data, *J. Geophys. Res.*, *111*, B04411, doi:10.1029/2005JB003719.

Jekeli, C. (1999), The determination of gravitational potential differences from satellite-to-satellite tracking, *Celestial Mech. Dyn. Astron.*, *75*, 85–100.

Kaula, W. M. (1966), *Theory of Satellite Geodesy: Applications of Satellites to Geodesy*, 120 pp., Blaisdell, Waltham, Mass.

Knudsen, P. (2003), Ocean tides in GRACE monthly averaged gravity fields, *Space Sci. Rev.*, *108*, 261–270.

Lefevre, F., T. Letellier, F. Lyard, and E. Schrama (2006), FES99: A tide finite element solution assimilating tide gauge and altimetric information, *J. Atmos. Oceanic Technol.*, *19*(9), 1345–1356.

Luthcke, S. B., D. D. Rowlands, F. G. Lemoine, S. M. Klosko, D. Chinn, and J. J. McCarthy (2006), Monthly spherical harmonic gravity field solutions determined from GRACE inter-satellite range-rate data alone, *Geophys. Res. Lett.*, *33*, L02402, doi:10.1029/2005GL024846.

Ray, R. D. (1999), A global ocean tide model from Topex/Poseidon altimetry: GOT99.2, *NASA Tech. Memo.*, *209478*, 58 pp.

Ray, R. D., and S. B. Luthcke (2006), Tide model errors and GRACE gravimetry: Towards a more realistic assessment, *Geophys. J. Int.*, *167*, 1055–1059, doi:10.1111/j.1365-246X.20006.03229.

Ray, R. D., D. D. Rowlands, and G. D. Egbert (2003), Tidal models in a new era of satellite gravimetry, *Space Sci. Rev.*, *108*, 271–282.

Schrama, E. J. O., and N. A. M. Visser (2006), Accuracy assessment of the monthly GRACE geoids based upon a simulation, *J. Geod.*, *81*, 67–80.

Seo, K.-W., C. R. Wilson, J. L. Chen, and D. E. Waliser (2008), GRACE's spatial aliasing error, *Geophys. J. Int.*, *172*, 41–48, doi:10.1111/j.1365-246X.2007.03611.x.

Swenson, S. C., J. Wahr, and P. C. D. Milly (2003), Estimated accuracies of regional water storage variations inferred from the Gravity Recovery and Climate Experiment (GRACE), *Water Resour. Res.*, *39*(8), 1223, doi:10.1029/2002WR001808.

Tapley, B. D., S. Bettadpur, 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.

Velicogna, I., and J. Wahr (2006), Measurements of time-variable gravity show mass loss in Antarctica, *Science*, *311*, 1754–1756.

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.

Wahr, J., S. Swenson, and I. Velicogna (2006), Accuracy of GRACE mass estimates, *Geophys. Res. Lett.*, *33*, L06401, doi:10.1029/2005GL025305.

S. C. Han, Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (schan@puuoo.gsfc.nasa.gov)

K. W. Seo, Korea Polar Research Institute, 504 Get-Pearl Tower, Incheon, 406–840, Korea. (seo.kiweon@kopri.re.kr)

D. E. Waliser, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. (duane.waliser@jpl.nasa.gov)

C. R. Wilson, Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78712, USA. (crwilson@maestro.geo.utexas.edu)