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Effects of Ice Melting on GRACE Observations of Ocean Mass Trends

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Effects of ice melting on GRACE observations of ocean mass trends

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[1] The Gravity Recovery and Climate Experiment (GRACE) was designed to measure variations in the Earth's gravity field from space at monthly intervals. Researchers have used these data to measure changes in water mass over various regions, including the global oceans and continental ice sheets covering Greenland and Antarctica. However, GRACE data must be smoothed in these analyses and the effects of geocenter motions are not included. In this study, we examine what effect each of these has in the computation of ocean mass trends using a simulation of ice melting on Greenland, Antarctica, and mountain glaciers. We find that the recovered sea level change is systematically lower when coefficients are smoothed and geocenter terms are not included. Assuming current estimates of ice melting, the combined error can be as large as 30–50% of the simulated sea level rise. This is a significant portion of the long-term sea level change signal, and needs to be considered in any application of GRACE data to estimating long-term trends in sea level due to gain of water mass from melting ice. **Citation:** Chambers, D. P., M. E. Tamisiea, R. S. Nerem, and J. C. Ries (2007), Effects of ice melting on GRACE observations of ocean mass trends, *Geophys. Res. Lett.*, *34*, L05610, doi:10.1029/2006GL029171.

1. Introduction

[2] The primary science goal of the Gravity Recovery and Climate Experiment (GRACE) is to determine variations in the Earth's gravity field at monthly intervals and at a spatial resolution of several hundred km in order to study the movement of water mass from one location on the Earth's surface to another [e.g., *Wahr et al.*, 1998]. The GRACE project has produced a set of global spherical harmonic gravity coefficients approximately every month since launch in March 2002. After calculating time-variable gravity coefficients by removing a suitable temporal average, one can compute monthly maps of surface mass density change ($\Delta\sigma$) as

$$\Delta\sigma(\phi,\lambda,t) = \frac{a_E\rho_E}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{(2l+1)}{(1+k_l)}P_{lm}(\sin\phi) \cdot \left\{\Delta C_{lm}^{g}(t)\cos m\lambda + \Delta S_{lm}^{g}(t)\sin m\lambda\right\} \quad (1)$$

where $\Delta\sigma$ are in units of kg m^{-2}, a_E is the mean equatorial radius of the Earth (in m), ρ_E is the average density of the Earth (5517 kg m^{-3}), k_l are load Love numbers of degree l, $P_{lm}(\sin\varphi)$ are the fully-normalized Associated Legendre Polynomials of degree l and order m, φ is the geographic latitude, λ is longitude, and (ΔC_{lm}^{g}, ΔS_{lm}^{g}) are fully-normalized, dimensionless spherical harmonic geopotential coefficients.

[3] The gravity field coefficients from GRACE are more accurate at long-wavelengths than at short and they are only estimated up to degree/order 120 (wavelength of 300 km). Numerous studies [e.g., *Wahr et al.*, 1998; *Swenson and Wahr*, 2002] have demonstrated that smoothing of the spherical harmonic coefficients (or equivalently surface mass density) is necessary in order to reduce the increasing error in the GRACE coefficients as a function of degree. Such smoothing is necessary even when computing averages over very large areas. The mean change in mass density over any arbitrary basin ($\Delta\sigma_{basin}$) can be computed directly from the gravity coefficients by

$$\Delta\sigma_{ba\sin} = \frac{a_E\rho_E}{3\Omega_{ba\sin}}\sum_{l=0}^{120}\sum_{m=0}^{l}\frac{(2l+1)}{(1+k_l)}\left\{W_{lm}^{C}\Delta C_{lm}^{g} + W_{lm}^{S}\Delta S_{lm}^{g}\right\} \quad (2)$$

where Ω_{basin} is the angular area of the basin. The factors (W_{lm}^{C}, W_{lm}^{S}) represent a smoothed averaging kernel in spherical harmonics, so that the when summed the kernel is approximately 1 over the entire region to be averaged over (such as the ocean), and approximately 0 for other regions [*Swenson and Wahr*, 2002]. The smoothed kernel is derived from a map that is exactly 1 over the area of interest and zero over all other areas that is then decomposed into spherical harmonics to for an exact averaging kernel. In the case of the ocean kernel, the exact kernel is typically defined using a transition from ocean to land defined by a land/ocean database. The exact kernel coefficients are then smoothed using either a Gaussian function or an optimization method to minimize the sum of the variance from GRACE errors and the variance of signals outside the region of interest [*Swenson and Wahr*, 2002]. In this study, as in that of *Chambers et al.* [2004], we have used a smoothing at a Gaussian radius of 300 km, which was found to minimize the errors based on the calculation by *Swenson and Wahr* [2002]. We also computed an "optimal" kernel based on the Lagrange multiplier method of *Swenson and Wahr* [2002], and found that it gave nearly identical results as the Gaussian smoothed kernel. Since the Gaussian smoothed kernel is conceptually easier to understand, we use it in these calculations.

[4] Smoothing of the kernel in this manner means that around ocean/land boundaries the weighting factors transition from 1 over water to 0 over land over a distance equal to approximately 600 km. Because of this, variability from water mass variations on the land unrelated to the ocean mass variations can "leak" into the estimate and imply a variation that may be significantly different from the true

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signal. *Swenson and Wahr* [2002] have shown how to quantify the statistical properties of the leakage based on the variance of the hydrology signal in the farfield and assumptions about the covariance shape. However, this type of analysis only gives the standard deviation of the leaked signal and does not provide insight into the systematic nature of the error. By systematic we mean any error that is not random in nature, but is a bias, a drift, or a coherently varying signal. For instance, we estimate the 1-sigma errors for monthly ocean mass from a combination of GRACE errors and hydrology leakage (from the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004]) to be about 1.8 mm of sea level, with about 1 mm of that due to the leaked hydrology signal. However, this is just the standard deviation of the error and we cannot say whether it has a systematic signal associated with it, such as an error with a seasonal period or a trend. Note that a leakage error with a regular annual variation of amplitude 1.6 mm has a standard deviation of about 1 mm; similarly, a systematic drift of 1 mm yr^{-1} over 4 years will also have a standard deviation of 1 mm. In order to quantify these types of systematic leakage errors, one must analyze the kernel in the presence of modeled hydrology, ice melting, and ocean variations. Since hydrology models do not currently model glacier or ice-sheet melting, we must simulate the possible melting scenarios based on our present knowledge and estimate the potential drift error that may leak into the ocean mass estimate using a particular ocean kernel. This simulation is limited to only the effects of shifting mass uniformly from one area to another at a consistent rate year-to year. It does not address the elastic or viscoelastic response of the solid Earth to the mass change, nor does it address any variations that are not secular.

[5] Another problem with using GRACE for estimating trends in ocean mass is our lack of estimates of the degree 1 terms of the gravity field, or geocenter, from GRACE. As has been explained by both *Chambers et al.* [2004] and *Chambers* [2006], the terms in equation (1) with $l = 1$ are proportional to the instantaneous position of the Earth's mass center relative to an Earth-fixed reference frame [e.g., *Kar*, 1997; *Crétaux et al.*, 2002]

$$\begin{aligned} \Delta C_{10}(t) &= \frac{\Delta z(t)}{a_E\sqrt{3}} \\ \Delta C_{11}(t) &= \frac{\Delta x(t)}{a_E\sqrt{3}} \\ \Delta S_{11}(t) &= \frac{\Delta y(t)}{a_E\sqrt{3}} \end{aligned} \quad (3)$$

where ($\Delta x(t)$, $\Delta y(t)$, $\Delta z(t)$) represent the position of the instantaneous mass center relative to the origin of the terrestrial reference frame attached to the Earth's crust (which is ideally coincident with the long-term mean center of mass). This translational motion, on the order of a few mm, is caused primarily by the movement of planetary fluids and has tidal, non-tidal and secular components. However, it is extremely difficult to measure geocenter motion and separate it from errors in determining the terrestrial reference frame.

[6] The GRACE inter-satellite ranging measurements are inherently insensitive to geocenter motion, and therefore it is not included in the GRACE estimates of the time-varying gravity field. Effectively then, the GRACE project references the gravity field to the Earth's instantaneous geocenter, so that $\Delta C_{10} = \Delta C_{11} = \Delta S_{11} = 0$ by definition. This means that the GRACE gravity coefficients represent the change in mass relative to a frame whose center moves slightly in time relative to the crust-fixed frame. However, what we really want is to measure water mass variations relative to the crust-fixed frame, which will require both a well-defined reference frame and knowledge or model of the geocenter motion relative to it.

[7] Other satellite geodetic techniques (e.g., SLR, GPS) have been used to measure seasonal motion of the geocenter. *Chambers et al.* [2004] demonstrated that adding a seasonal model of the geocenter variations to the GRACE coefficients produced a better determination of the seasonal ocean mass variation. However, only seasonal geocenter variations are currently considered accurate enough to use for this type of analysis. The secular change of the geocenter due to ice mass redistribution is relatively uncertain, but is estimated to be relatively small. By using a simple simulation of ice mass loss in some areas (e.g., Greenland) with a corresponding gain in the ocean, we can derive gravity coefficients that include the associated geocenter effect of the water mass redistribution. Then, by setting these geocenter terms to zero, we can estimate the size of the error introduced if geocenter is neglected in computing ocean mass trends from GRACE data.

[8] At the same time, we can compare the known ocean mass increase in the simulation with the result determined using a smoothed ocean kernel. This will allow us to assess the possible systematic errors due to leakage. The next section will describe the ice melting simulation and the calculations performed. We will then discuss results in terms of the determination of mean ocean mass trends using the techniques commonly applied to GRACE data.

2. Description of Simulation

[9] We have run three distinct scenarios. For each scenario, we assume that sea level is rising at a uniform rate of 1.0 mm yr^{-1} (1.0 kg m^{-2} in terms of mass density) due only to water mass being added to the ocean from Greenland, Antarctica, or glaciers. No current estimate or model suggests that any of these sources is contributing as much as 1 mm yr^{-1} to sea level rise. By using a value of 1 mm yr^{-1}, it is easy to later scale the result based on an observed rate since we are using a spatially uniform pattern over each land area. We note that a similar scaling argument is valid if the pattern is not uniform but known and unchanging from year to year.

[10] In the Greenland- and Antarctica-melting scenarios, the mean mass density over each appropriate land area was calculated by multiplying the total ocean area by 1.0 kg m^{-2} and then dividing by the appropriate land surface area, based on a 1° global grid and the same land/ocean database use to construct the kernel. The mean mass density was applied uniformly at each grid point over either Greenland or Antarctica. A value of -146.8123 kg m^{-2} was computed for Greenland and -27.2742 kg m^{-2} for Antarctica, where the negative sign indicates mass was being lost to the oceans. It is the relative size of the mass density changes

over Greenland and Antarctica to the change over the ocean that leads to a concern over the leakage. Although the land area where the smoothed ocean kernel transitions from 1 to 0 is relatively small, the mass density loss over the area is some 25 to 150 times larger than the mass density increase over the ocean (i.e., -146 kg m^{-2} compared to 1 kg m^{-2}). Even leakage at the level of 1% can be substantial.

[11] Computing mass density change for the glacier-melting scenario was slightly more complicated. We used a database of glacier locations and surface areas [*National Snow and Ice Data Center*, 2005] (Figure 1). These data were then mapped to the same 1° global grid, and the glacier area within each grid was computed ($A_{glacier}(\varphi, \lambda)$) along with the total area of the worldwide glaciers ($A_{glacier\_total}$). Then the mass density in each grid with a glacier was computed as

$$\Delta\sigma_{glacier}(\phi, \lambda) = -\left[\Delta\sigma_{ocean}\frac{A_{ocean}}{A_{glacier\_total}}\right]\frac{A_{glacier}(\phi, \lambda)}{A_{grid}} \tag{4}$$

This equation computes the change in the mass density for glaciers on a 1° grid so that more glaciated areas (judged by the ratio of the glaciers to the grid box) contribute more to the ocean and also spreads the change out evenly over the 1° grid.

[12] In order to compute gravity coefficients, we produced three global maps with the same mean ocean mass density (+1.0 kg m^{-2}), and different mass densities over land and ice-sheets. For Scenario 1 (Greenland melting), Greenland grids were set to -146.8123 kg m^{-2} and all other land grids were set to zero. For Scenario 2 (Antarctica melting), Antarctica grids were set to -27.2742 kg m^{-2} and all other land grids were set to zero. For Scenario 3 (glaciers melting) grids with glaciers in them were set to a mass density computed from equation (3), while all other land grids (including Greenland and Antarctica) were set to zero. Spherical harmonic coefficients were then computed from the gridded density maps by integrating over the entire spherical area of the Earth (Ω)

$$\begin{aligned}\Delta C^{\sigma}_{lm} &= \int_{\Omega} \Delta\sigma(\phi, \lambda) P_{lm}(\sin\phi)\cos m\lambda d\Omega \\ \Delta S^{\sigma}_{lm} &= \int_{\Omega} \Delta\sigma(\phi, \lambda) P_{lm}(\sin\phi)\sin m\lambda d\Omega\end{aligned}, \tag{5}$$

so that

$$\Delta\sigma(\phi, \lambda, t) = \frac{1}{4\pi}\sum_{l=0}^{\infty}\sum_{m=0}^{l} P_{lm}(\sin\phi) \cdot \left\{\Delta C^{\sigma}_{lm}(t)\cos m\lambda + \Delta S^{\sigma}_{lm}(t)\sin m\lambda\right\}. \tag{6}$$

$P_{lm}(\sin\varphi)$ are the same Legendre Polynomials as in equation (1). The factor of $1/4\pi$ is included to account for the spherical area of the Earth that was introduced in the formulation in equation (5), and the super-script $^{\sigma}$ denotes that the coefficients (ΔC^{σ}_{lm}, ΔS^{σ}_{lm}) have dimensions of mass density. Although equation (6) expands the spherical harmonics to infinite degree, they are truncated in practice. For this experiment, we calculated coefficients to degree and order 120, similar to the expansion used for GRACE.

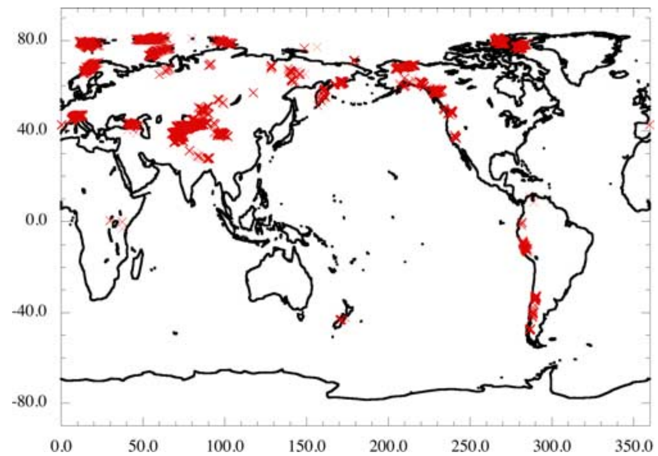

Figure 1. Location of glaciers used in this study. Data from *National Snow and Ice Data Center* [2005].

[13] Thus, given a set of coefficients (ΔC^{σ}_{lm}, ΔS^{σ}_{lm}) determined from simulated mass density maps, it is straightforward to determine the equivalent gravitational coefficients that GRACE would sense by combining equations (1) and (6). The next step is to calculate mean ocean mass from these coefficients using the same smoothing kernel one would use with GRACE coefficients [e.g., *Chambers et al.*, 2004].

[14] We will do the computations with and without geocenter terms and compare the results with the known input (i.e., 1.0 mm yr^{-1} of sea level rise). Any deviations from the input signal indicate a systematic error in the estimate due to the combined effect of smoothing the coefficients (leading to leakage of ice melting rates) and ignoring the geocenter rates.

3. Results and Analysis

[15] Table 1 gives the estimated mean ocean mass change in terms of sea level rise for each of the scenarios when the smoothed ocean kernel used by *Chambers et al.* [2004] is used to process the data. Results are given using both the geocenter terms and ignoring them, which is currently done in processing GRACE data. In all cases the estimates are systematically lower than the input of 1.0 mm yr^{-1}. This represents the error introduced from leakage of large trends outside the ocean due to the smoothed kernel. The error is largest for Greenland and glaciers, being approximately 35–40% of the simulated sea level rise. Antarctica, because it has a larger surface area and hence a lower equivalent mass loss in the simulation, differs from the input by only 17%. In all cases, though, the estimated ocean mass is systematically lower than the simulated signal, although the magnitude is dependent on both the amount of ice melting and its source.

[16] The effect of ignoring geocenter rates is interesting. Because the movements of mass from Greenland, glaciers, or Antarctica to the oceans cause geocenter motion of the opposite sign in the z direction, the systematic error will be either negative or positive. Thus, for the Greenland- and glacier-melting scenarios, ignoring the associated geocenter rates causes a further systematic error of about 26%, so that the overall error is about 60% of input sea level rise.

Table 1. Recovered Trends in Ocean Mass Using Gravity Coefficients to Degree 120 and a Smoothing Function Used by *Chambers et al.* [2004][a]

Scenario	Using Geocenter	Not Using Geocenter
Greenland	0.64	0.38
Antarctica	0.83	0.98
Glaciers	0.61	0.38

[a]The input was exactly 1.0 mm yr^{-1}. Units are mm yr^{-1}.

Ignoring geocenter for the Antarctica-melting scenario actually reduces the systematic error to only 2%. The only way this can happen is if the geocenter rate error is very nearly the same size but opposite sign as the trend error from leakage. Note that the tests without including the geocenter terms also include the systematic leakage error.

[17] We must re-iterate that all these results are dependent on knowing the amount of ice melting each year from each source and assuming the loss is uniform over Greenland and Antarctica and over each glacier grid. If the geometry of the melting is constant, though, the results are linearly scaleable if one knows the amount of mean melting and are addable to obtain the full effect of all sources. Most recent observations of mass loss from Greenland and Antarctica estimate the contribution of each to be closer to 0.4 mm yr^{-1} [e.g., *Velicogna and Wahr*, 2005, 2006] while the estimated contribution from glaciers over the last decade is closer to 0.8 mm yr^{-1} [*Dyurgerov and Meir*, 2005]. Table 2 gives the systematic error in ocean mass based on these levels of melting.

[18] The total systematic error is about -0.5 mm yr^{-1} (30% of the input sea level rise) if geocenter is used. If geocenter is ignored, the error increases to -0.76 mm yr^{-1} (50%) due mainly to the large contribution from glaciers. Thus, the effect of having to use both a smoothed kernel and neglecting geocenter terms in GRACE processing may potentially introduce a systematic error in the calculation of sea level change of up to -0.76 mm yr^{-1}, assuming ice sheets and glaciers are melting at the estimated rates and using the smoothed ocean kernel used by *Chambers et al.* [2004].

[19] Recall that the smoothed ocean kernel used in these calculations is derived from an exact kernel that transitions from 1 to 0 at exactly the ocean/land interface. How will the results change if we derive a smoothed kernel based on an exact kernel that transitioned from 1 to 0 some distance from the land? Although GRACE errors would increase (because of a smaller averaging area), land leakage errors should be significantly reduced, as very little data over land is included in the average. Such a kernel would tend to underweight contributions to mean ocean mass from coastal regions, but this is arguably a significantly smaller error than leakage from the much larger land variations.

[20] We created such a kernel, using an exact kernel that was based on a land/ocean mask where values within 300 km of land were set to 0 along with the land values. This was then smoothed with the same 300 km radius Gaussian function as before, and the calculations were repeated. Table 3 summarizes the results using the current observations of ice melting listed in Table 2. The new smoothed ocean kernel significantly reduces the error. In the case that the geocenter motions are included, the errors range from only -0.01 mm yr^{-1} for Antarctica-melting to -0.13 mm yr^{-1} for glacier-melting, with a combined error of only -0.17 mm yr^{-1}, or only 11% of the simulated sea level rise. If geocenter is ignored, the error is only 33% of the simulated sea level rise, compared to 48% when the original ocean kernel was used. We find that this change is reflected when we apply the different ocean kernels to the same set of GRACE observations. Using the GFZ_RL03 data from February 2003 to August 2006, we find that the trend in ocean mass increases by 0.35 mm yr^{-1} when the new ocean kernel is utilized, which is nearly what is predicted by this simulation.

4. Conclusions

[21] If mountain glaciers and ice sheets in Greenland and Antarctica are melting at the rates estimated in recent articles [e.g., *Velicogna and Wahr*, 2005, 2006; *Dyurgerov and Meir*, 2005], then any ocean mass trends estimated from GRACE gravity coefficients will be systematically too small. Part of this is from leakage of the large ice-mass rates due to necessary smoothing of the GRACE coefficients, while part of it is due to lack of knowledge of geocenter rates. The leakage portion may be reduced if the smoothing is reduced over land. Based on our simulation and current estimates of melting rates (1.6 mm yr^{-1}), the signal will be underestimated by nearly 0.76 mm yr^{-1} if a kernel based on a smooth transition from ocean to land exactly at the coastline is used. If the transition is changed to occur 300 km offshore, the error due to leakage alone is reduced to about -0.17 mm yr^{-1} based on the assumed rates of melting, while the error increases to -0.53 mm yr^{-1} if possible geocenter rates are also ignored. Thus, the effect of ignoring geocenter rates is nearly twice the size of the leakage error and of the same sign. Any investigation studying mean sea level rise from GRACE must take these effects into account. Note that these errors are in addition to any systematic trend caused by glacial isostatic adjustment. We also remind the reader that this study is based entirely on a simulation and is only meant to analyze potential

Table 2. Estimated Systematic Trend Errors in Ocean Mass[a]

Scenario	Contribution to MSL	Error Using Geocenter	Error Not Using Geocenter
Greenland	0.4	− 0.14	− 0.25
Antarctica	0.4	− 0.07	− 0.01
Glaciers	0.8	− 0.31	− 0.50
Sum	**1.6**	**− 0.52**	**− 0.76**

[a]Based on scaling results in Table 1 with the listed contribution to sea level rise. Negative values mean true ocean mass will be underestimated. Units are mm yr^{-1}.

Table 3. Estimated Systematic Trend Errors in Ocean Mass From Table 2 Using an Updated Ocean Kernel That Goes to Zero 300 Km From Land[a]

Scenario	Contribution to MSL	Error Using Geocenter	Error Not Using Geocenter
Greenland	0.4	− 0.03	− 0.19
Antarctica	0.4	− 0.01	+ 0.08
Glaciers	0.8	− 0.13	−0.42
Sum	**1.6**	**− 0.17**	**− 0.53**

[a]Negative values mean true ocean mass will be underestimated. Units are mm yr^{-1}.

problems in using GRACE data for detection of small, long-term trends in mass change. Corrections for systemic errors introduced by processing and lack of geocenter estimates should explicitly include uncertainties determined from modeling based on the choice of input models and averaging kernels. Variations to the corrections derived in this study would arise from the ignored contamination caused by interannual hydrological changes, non-uniform melting geometries, and uncertainties in the mass loss that are typically as much as 50%. The uncertainty associated with this systematic error estimate from the range of mass loss estimates alone is at least ±0.4 mm yr^{-1}, given the values used in our simulations. The uncertainty may be even higher considering recent observations of larger changes in mass loss from Greenland in the last year and its non-uniform pattern [*Chen et al.*, 2006; *Luthcke et al.*, 2006].

[22] Finally, because different ocean kernels will affect the results significantly, one must test their own kernel using a similar simulation. Additionally, this type of systematic error will occur for estimations of any trend with GRACE data, even for estimates of trends over ice sheets or land. We advise any investigator interested in studying mass trends from GRACE over any region perform a similar simulation for their particular application, in order to address the potential error for their study.

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