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Short term mass variability in Greenland, from GRACE

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[1] We use twenty-two monthly GRACE (Gravity Recovery and Climate Experiment) gravity fields to recover nonsecular mass change in Greenland. The results show large seasonal variability. We compare with modeled precipitation, evaporation, and runoff derived from ERA40 (the 40-year ECMWF Re-Analysis of the global atmosphere). The model's seasonal amplitude is controlled by runoff and agrees reasonably well with GRACE. Both GRACE and the model show an April/May maximum. But the GRACE results show a delayed minimum relative to the model. This difference is probably associated with omissions in the runoff model, ice discharge, subglacial hydrology, mass loss by blowing-snow, and hydrology in ice-free regions. The discrepancy is smaller, but still significant, for south Greenland alone. When we include a proxy for ice discharge the agreement is improved. **Citation:** Velicogna, I., J. Wahr, E. Hanna, and P. Huybrechts (2005), Short term mass variability in Greenland, from GRACE, *Geophys. Res. Lett.*, *32*, L05501, doi:10.1029/2004GL021948.

1. Introduction

[2] Greenland is one of the largest reservoirs of fresh water on Earth. Its sea level rise contribution in the 1990s may have been 0.13 mm/yr or larger [*Krabill et al.*, 2000]. Changes in Greenland mass are caused mainly by differences between precipitation (P), which adds mass, and evaporation + runoff + discharge ($E + R + D$), which removes mass. Runoff is meltwater that flows from land to the ocean. It can come from melting snow or ice anywhere on the ice sheet, and can flow over or through the ice, perhaps even collecting in reservoirs under the ice. Discharge is the flow of ice across the grounding line, where it displaces an equal mass of ocean water and begins floating. Our mass estimates refer to mass averaged over all Greenland without discriminating between the ice sheet and ice-free regions.

[3] P, E, R, and D vary seasonally. The precipitation rate is largest during winter. Evaporation and melting are larger when the temperature is high, with maxima in mid- to late-summer. Discharge is indirectly linked to temperature. High temperatures cause increased meltwater, some of which reaches the bottom of the ice, lubricating the bed and increasing ice flow. This effect has been seen in alpine glaciers, and has been observed in Greenland away from glaciers [*Zwally et al.*, 2002].

[4] Understanding nonsecular mass variability is useful for three reasons. (1) It provides information about the ice sheet's response to temperature change. (2) It can improve the interpretation of campaign-style mass balance observations that are complicated by the problem of separating steady motions from nonsecular variability. (3) To use altimeter measurements of ice sheet elevations to study mass imbalance, it is important to understand the effects of firn compaction. Those effects can be better assessed if the time variable mass change is better known.

[5] We use gravity field solutions from the NASA/DLR satellite mission GRACE, launched in March, 2002 [*Tapley et al.*, 2004], to estimate changes in the total mass of water, snow, and ice stored on Greenland at monthly intervals. The change in mass between times t_1 and t_2 is

$$M|_{t_1}^{t_2} = \int_{t_1}^{t_2} (P - E - R - D - Q_s - X)dt \qquad (1)$$

We use (1) to compare our GRACE results for M, with mass variations computed using ERA-related model estimates of $P - E - R$. The comparison provides an estimate of the sum of seasonal mass discharge (D), blowing-snow sublimation (Q_s), and hydrology from ice-free regions (X). We do not interpret the secular (long-term) mass trend inferred from GRACE, which is complicated by solid Earth effects.

2. Data

2.1. GRACE Data

[6] The GRACE Project has released gravity field solutions for 22 near-monthly time periods, corresponding to Apr/May, Aug, Sep, Oct, Nov, 2002; Feb, Mar, Apr, May, Jul, Aug, Sep, Oct, Nov, Dec, 2003; and Jan, Feb, Mar, Apr, May, Jun, Jul, 2004. Each solution consists of a set of gravity (Stokes) coefficients, C_{lm} and S_{lm}. We correct for the ocean pole tide. Also, these solutions have had equilibrium annual and semi-annual ocean tides removed, but only at degrees $l \leq 10$; we further remove degrees >10. These corrections have no significant impact on our results.

2.2. ERA40 Estimates of $P - E - R$

[7] P − E is estimated using two-meter surface air temperature, snowfall, and surface latent heat flux, from April, 2002–March, 2004 ECMWF operational analyses on a 0.5° grid (E. Hanna et al. Observed and modelled Greenland Ice Sheet snow accumulation, 1958–2003, and links with regional climate forcing, manuscript in preparation, 2005). Model runoff is non-zero only during May–September, and is calculated using the *Janssens and Huybrechts* [2000] runoff/retention model which incorporates *Pfeffer et al.*'s [1991] meltwater retention scheme. The model does not

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include the time it takes meltwater to travel across or through the ice sheet to the ocean.

2.3. Other Datasets

[8] Gravity signals caused by mass variations outside Greenland can contaminate the GRACE estimates. We evaluate several sources of this leakage. To estimate contamination from hydrology outside Greenland, we use global water storage output from the model of Y. Fan and H. van den Dool (The CPC global monthly soil moisture data set at 1/2 degree resolution for 1948 to present, submitted to *Journal of Geophysical Research*, 2004). Ocean contamination is estimated using a JPL version of the ECCO (Estimating the Circulation and Climate of the Ocean) general circulation model [*Lee et al.*, 2002]. To mimic the de-aliasing process used by the GRACE Project, we remove a barotropic ocean model [*Ali and Zlotnicki*, 2003] from the ECCO results.

[9] The Arctic Ocean is not included in these models. We estimate its leakage by using the GRACE fields, with a 750-km Gaussian averaging function, to calculate mass variations at individual Arctic Ocean points; identifying the place where the signal is maximum (so that our estimate is an upper bound); and assigning that signal to every Arctic Ocean point.

3. Greenland Mass Variations From GRACE

[10] Virtually all nonsecular variability in the gravity field comes from redistribution of mass in the atmosphere, the oceans, and the water, snow, and ice stored on land. Surface mass variability can be estimated from GRACE Stokes coefficients using equation (2) of *Swenson et al.* [2003]. We extract the change in mass averaged over Greenland using an averaging function that minimizes the combined measurement error and signal leakage, and is constructed assuming the GRACE measurement errors are 40 $\times$ the pre-launch estimates. We scale this function so that when it is applied to a uniform mass change of 1 cm water equivalent (w.e.) over all Greenland, it returns a value of 1 cm. GRACE does not recover degree l = 1 terms, and the GRACE C_{20} coefficient shows large variability. We have thus removed C_{20} and $l = 1$ harmonics from the averaging function, which is equivalent to ignoring those terms when computing Greenland mass from GRACE and all fields used to compare with GRACE. Removing these terms broadens the averaging function so that it becomes weakly sensitive to mass variations around the globe.

[11] To recover the nonsecular component of the Greenland signal, we simultaneously fit secular and annually varying terms to the GRACE averages, and subtract the secular term from those averages. The residuals are shown in Figure 1a. A pronounced seasonal cycle is evident, with the same general features during the first (pre-2003.5) and second (post-2003.5) years. The mass decreases in early spring, reaches a minimum soon after the start of the year, and increases rapidly to a maximum in April/May. This cycle is particularly evident in the second year. It is less easy to distinguish a seasonal cycle in the first year, presumably due to missing GRACE months. But the monthly values that do exist are consistent with this same general description.

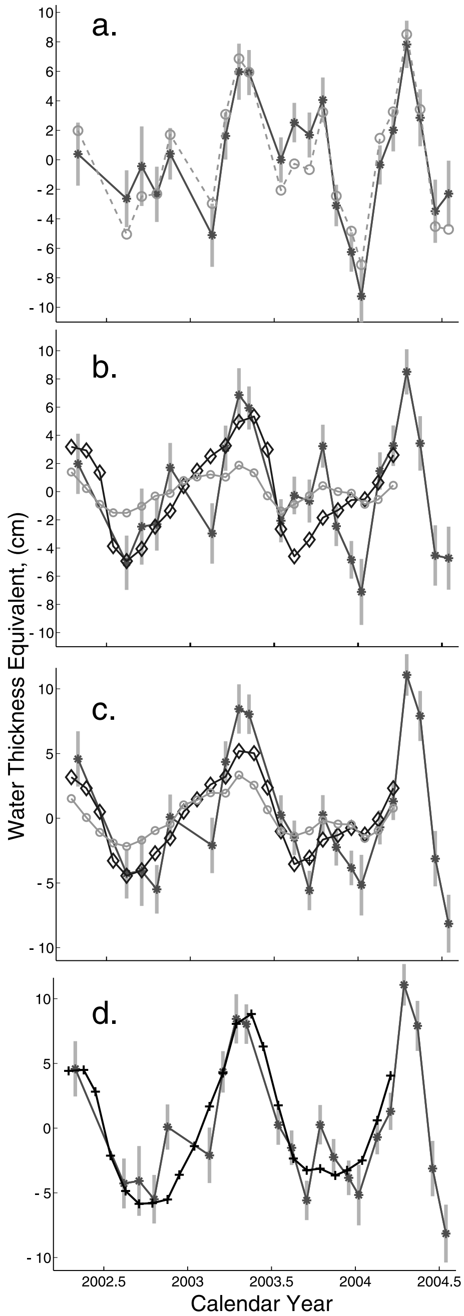

Figure 1. (a) Nonsecular Greenland mass variability from the GRACE (stars). Error bars come from convolving our averaging function with estimates of the gravity coefficient uncertainties. Also shown (circles) are the GRACE results after removing the estimated leakage from external water storage and ocean mass redistribution. 1 cm of water equivalent corresponds to 20 km^3/yr. (b) Nonsecular Greenland mass variability from GRACE (stars) after removing the leakage, compared with ERA40 nonsecular mass variations for $P - E$ (circles) and $P - E - R$ (diamonds). Error bars represent the effects of uncertainties in the GRACE fields, and do not include possible errors in the leakage estimates. (c) The same as b, except for south Greenland. (d) Compares the GRACE results (stars) after removing leakage, with $P - E - R - D$ (plus signs), where D is estimated using observed calving rates from an Alaskan glacier. Results are for south Greenland.

[12] Each estimate in Figure 1a has an error bar, obtained by convolving our Greenland averaging function with uncertainties in the GRACE Stokes coefficients. We estimate those uncertainties as follows.

[13] A constant and an annually varying term are removed from each C_{lm}, S_{lm} time series. We assume the residuals consist entirely of GRACE gravity field errors. This causes us to overestimate the true errors, since the real gravity field is certain to have non-annual components. We use these residual coefficients to construct a set of residual degree amplitudes, $B_l = \sqrt{\sum_m \left(C_{lm}^2 + S_{lm}^2\right)}$, for each month. We increase each B_l by 5%, because removing an annually varying term from 22 random numbers reduces the rms by 5%. We find the B_l have the same degree-dependent shape as the pre-launch error estimates. So we assume the true degree amplitudes errors for each month = $d \times$ (pre-launch degree errors), and we estimate d by fitting the pre-launch errors to the B_l for that month. For every l we distribute these degree amplitude errors among the different C_{lm}, S_{lm}'s so that their relative errors are consistent with the m-dependent calibrated errors provided with the GRACE fields.

[14] Figure 1a shows that the uncertainties of each monthly GRACE value are a significant fraction of the values themselves. But the measurement errors in the GRACE coefficients are believed to be largely uncorrelated from one month to the next (S. Bettadpur, personal communication, 2004). Thus the seasonal trend evident in the GRACE results represents the true seasonal mass cycle during these years.

4. Evaluation of GRACE Mass Errors

[15] The GRACE mass variations shown in Figure 1a contain contributions from several sources, including changes in Greenland mass, errors in atmospheric corrections, leakage from mass variations outside Greenland, and GRACE gravity field errors. The effects of gravity field errors are represented by the error bars. Here, we consider the effects of atmospheric errors and leakage.

[16] The GRACE Project uses ECMWF fields to remove atmospheric contributions to gravity prior to solving for Stokes' coefficients. The atmospheric fields contain errors. We evaluate those errors by comparing the ECMWF pressure fields both with NCEP re-analysis pressure fields, and with observed pressure from meteorological stations in the WMO catalog and Greenland automatic weather stations (K. Steffen, personal communication, 2004). We find the errors in the atmospheric contribution are negligible, contributing less than 3% to the variance of the GRACE results.

[17] To evaluate the leakage from external sources we calculate Greenland averages of the hydrology and ocean models described in section 2.3, using the same averaging function used for GRACE. The largest leakage comes from hydrology, and is related to the broadening of the averaging function caused by the removal of the $l = 1$ and C_{20} terms. The leakage includes a seasonal component, so cannot be treated as uncorrelated errors. Instead, we subtract the leakage estimates from the GRACE averages. The results are shown in Figure 1a. The leakage effects are significant, but do not change the general seasonal characteristics of the results. We have estimated the leakage using other hydrology and ocean models, and obtained similar results.

5. Comparison With ERA40 Fields

[18] The GRACE mass variations include contributions from both the ice sheet and the ice-free coastal regions. For some applications, such as finding Greenland's total seasonal sea level contribution, it is not necessary to separate these contributions. Their relative importance is an issue, however, for understanding the source of the signal. Because of its relatively small area, the ice-free region needs a mass density ~6 times larger than that needed by the ice sheet, to cause the same gravity signal. To explain the 16 cm w.e. peak-to-peak mass variation in Figure 1a, the water/snow variation averaged over the ice-free region would have to be ~115 cm, an unreasonably large value. This suggests the seasonal GRACE signal comes mainly from the ice sheet.

[19] Figure 1b compares the GRACE mass estimates after removing the leakage computed in Section 4, with ice sheet mass estimates computed using ERA40 results for $P - E$ and $P - E - R$ in (1). GRACE and $P - E$ show similar timing, but the GRACE amplitude is about 3 times larger. This suggests the GRACE seasonal mass change is dominated by something besides $P - E$.

[20] The GRACE and $P - E - R$ estimates have similar amplitudes and both have April/May maxima. But the GRACE minima occur several months later than the $P - E - R$ minima, especially in the second year. Since this difference is large relative to the GRACE errors it presumably reflects a combination of mass discharge, the it takes for melt water to reach the ocean, hydrology from the ice-free region, subglacial hydrology, blowing-snow sublimation, and errors in the ERA40 estimates, The mass loss by blowing-snow sublimation, for example, peaks in January and could represent a contribution of up to 2.3 cm w.e. [*Box et al.*, 2004].

[21] Seasonal variability in Greenland is largest in the south, where temperature variability is also greatest. We construct an optimal averaging function for south Greenland, which we define as the region below 73°N (the approximate latitude of Summit). We convolve it with the GRACE fields, the leakage models, and the ERA40 estimates. Figure 1c compares the GRACE results after removing the leakage, with ERA40 predictions. GRACE still shows a January, 2004 minimum - several months later than predicted by ERA40.

[22] To decide whether seasonal discharge could be a factor for south Greenland, we generate ad-hoc discharge estimates by constructing a proxy, C, for the south Greenland calving rate, and assuming $D \approx C$. Discharge, which occurs when ice flows across the grounding line, is not the same as calving, which is the detachment of an iceberg from the floating ice tongue. But there are connections between the two. Both increase with increasing temperature, for example.

[23] Little is known about Greenland calving, other than it is more intense in summer than winter [*Sohn et al.*, 1998]. Instead, to estimate $D(=C)$ we use observed calving rates for the Columbia glacier in Alaska [*Tangborn*, 1997], scaled so the amplitude of the annual cycle averaged over south Greenland is the same as that for the difference between GRACE (with leakage removed) and P − E − R. This amplitude is about the same as the peak-to-peak amplitude of the modeled runoff. Although the Columbia glacier is at a lower latitude

(about 61°N) than most of Greenland, the largest Greenland iceberg producers are the tidewater glaciers in the south.

[24] Figure 1d compares the GRACE results with our estimates of $P - E - R - D$. The inclusion of D has improved the agreement in both amplitude and phase. The differences between GRACE and $P - E - R - D$ are not notably outside the GRACE errors. Our estimated D is based on too many ad hoc assumptions for us to claim the discrepancy between GRACE and $P - E - R$ is due mainly to discharge. But the results do show that ice discharge could help resolve this discrepancy.

6. Summary and Discussion

[25] We have used GRACE data to recover nonsecular changes in the temporally integrated $P - E - R - D - Q_s - X$ (equation (1)) averaged over Greenland. As far as we know, these are the first measurements of any kind that lead to estimates of monthly variations in total Greenland mass. We find evidence of a strong seasonal cycle, with a well-defined April/May maximum and a broad minimum that, at least in the 2003/2004 winter, occurs near the beginning of the year. The peak-to-peak variation is about 16 cm w.e., consistent with estimates from *Reeh et al.* [1999]. The amplitudes and dates of the yearly maxima are similar to those predicted from ERA40-derived estimates of $P - E - R$. But the timing and overall shape of the GRACE and ERA40 minima disagree. The discrepancy is somewhat reduced when we compare results over south Greenland, where the largest seasonal mass variability occurs.

[26] Some of the discrepancy could be caused by errors in the $P - E - R$ results. Also, despite current thinking to the contrary, we cannot categorically rule out the possibility that the GRACE measurement errors might have a non-negligible seasonal component. Our leading hypothesis, though, is that the discrepancy reflects a combination of ice discharge, blowing-snow sublimation, and delayed runoff caused by such things as temporary storage in sub-ice reservoirs [e.g., *Joughin et al.*, 1996].

[27] The only one of these effects we have considered quantitatively is discharge (D), and even then we only use an ad hoc proxy based on aerial photos of Alaskan glacier calving. Our resulting $P - E - R - D$ estimates over south Greenland show reasonable agreement with GRACE. But our model of D is tentative enough that we hesitate to claim that discharge is the most important missing component.

[28] Suppose, however, that the difference between the GRACE and $P - E - R$ results were due to discharge. Since this difference has about the same amplitude as our model results for R, it would imply that D and R have similar amplitudes. This is perhaps surprising, though we know of no seasonal Greenland discharge observations that address this.

[29] An argument possibly working against the discharge hypothesis comes from *Zwally et al.*'s [2002] continuous GPS measurements of ice flow rates at a location near the equilibrium line in west-central Greenland. The GPS rates show a pronounced ice velocity maximum in early August, about the same time as the Alaskan calving rate maximum. But, unlike the calving rates which steadily decline during the fall, the GPS rates decrease abruptly after their August maximum. This would not produce the broadened, delayed minimum needed to improve the agreement with GRACE. On the other hand, the GPS measurements were made to the north of the main outlet glacier and at 1175 m elevation. The actual glacial discharge, which occurs at sea level, could conceivably have different seasonal characteristics.

[30] The signal from blowing-snow sublimation could contribute significantly to the mass change, with an amplitude and timing that suggest it might reduce the discrepancy between GRACE and ERA40. Also, our runoff model assumes $R \neq 0$ only during May–September, and does not include a delay between the time of melting and the time of flux into the ocean. For example, the temporary storage and subsequent discharge of water from subglacial reservoirs has been ignored. Little is known about this process. Relatively high winter temperatures recorded in South Greenland of just a few degrees below zero in January (WMO catalog) suggest that delayed runoff from subglacial reservoirs may be possible even in the early months of the year.

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