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Alaskan Mountain Glacial Melting Observed by Satellite Gravimetry

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Abstract

We use satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) as an indication of mass change to study potential long-term mountain glacial melting in southern Alaska and West Canada. The first 3.5 years of GRACE monthly gravity data, spanning April 2002 – November 2005, show a prominent glacial melting trend in the mountain regions around the Gulf of Alaska (GOA). GRACE-observed surface mass changes correlate remarkably well with available mass balance data at Gulkana and Wolverine, two benchmark glaciers of the U.S. Geological Survey (USGS), although the GRACE signals are smaller in magnitude. In addition, terrestrial water storage (TWS) changes estimated from an advanced land surface model show significant mass loss in this region during the same period. After correcting for the leakage errors and removing TWS contributions using model estimates, we conclude that GRACE-observed glacial melting in the GOA mountain region is equivalent to ~ – 101 ± 22 km^3/year, which agrees quite well with the assessment of ~ – 96 ± 35 km^3/year based on airborne laser altimetry data, and is consistent with an earlier estimate based on the first 2 years of GRACE data. This study demonstrates the significant potentials of satellite gravity measurements for monitoring mountain glacial melting and regional climate change.

Keywords: Glacial Melting, Gulf of Alaska, Satellite Gravimetry, GRACE, Gravity Change.

1. Introduction

The global mean sea level rise is mainly driven by two phenomena, the heating of the oceans and snow/ice melting from polar ice sheets and mountain glaciers. Both of these are directly affected by the global warming. Although mountain glaciers only cover a small portion (~ 3%) of the glacierized area of the Earth [1], their contributions to the sea level rise can be significant, as there is growing evidence that, since the mid-1990's, mountain glaciers are melting rapidly [1-3]. Field measurements indicate that the summer warming in high latitudes, especially in arctic Alaska and west Canada, has shown major acceleration in the latest decade [4]. This will likely contribute to accelerated glacier melting in the Gulf of Alaska (GOA) region, and have a significant effect on global sea level rise.

Excluding polar ice sheets over Antarctica and Greenland, the mountains around the GOA coast contain some of the largest glaciers on the Earth. Despite their potentially large impact on sea level rise, the quantification of glacial melting has been a challenge, limited by (temporarily and spatially) sparse measurements. Consistent records of mass balance data are only available for a few small benchmark glaciers in this region. There are great variations in terms of glacial melting rate from region to region, and among glaciers located in the same region [1]. Based on repeated airborne laser altimeter measurements of 28 glaciers in the GOA region from mid-1990s to 2000-2001, a recent study [1] suggests an averaged thinning rate of ~ – 1.8 m/year, and the total long-term glacial melting rate (through extrapolation and interpolation of the data at the 28 glaciers) in the GOA region is ~ – 96 ± 35 km^3/year, which corresponds to a contribution to the sea level rise of ~ 0.27 ± 0.10 mm/year. This can be compared with ~ 0.25 mm/year for the IPCC2001 assessment of the global glacial melting contribution to the mean sea level rise [5]. These numbers suggest that the glacial melting in the GOA region is a major contributor to the global sea level rise.

The Gravity Recovery And Climate Experiment (GRACE), jointly sponsored by NASA and the German Aerospace Center (DLR), was launched in March 2002, as the first dedicated satellite gravity mission [6]. The main goal of GRACE is to measure the Earth gravity field and its variations, at roughly 30-day intervals. The recently approved extension of the GRACE mission (by NASA) to at least early 2010 enables GRACE to provide continuous accurate measurements of Earth gravity change for at least 8 years (2002 through 2010). These time-variable gravity observations can be used to infer mass redistribution on the Earth's surface with an accuracy of ~ 1.5 cm of equivalent water thickness change at about 800 - 1000 km spatial scale [7,8], which include (but are not limited to) terrestrial water storage change (e.g., [7-9]), snow/ice sheet mass variation in polar regions (e.g., [10-12]), and oceanic mass change (e.g., [13,14]).

A recent investigation [11] uses the first two years of GRACE data, covering the period April 2002 to July 2004, to estimate possible glacial melting in the GOA region, and shows encouraging results. The GRACE-estimated total glacial melting rate in the GOA region is ~ – 115 ± 20 km^3/year, very consistent with the estimate from airborne laser altimeter [1]. The methodology used in the study [11] is based on extrapolation of the magnitudes of GRACE-estimated annual variations in the GOA region as a function of the spatial radii used in the Gaussian smoothing, in order to get an estimate of the 'true' magnitude when no smoothing is applied (or when the spatial radius equals to 0). This scaling method may have limited application in the case when seasonal signals are dominated by noise or non-seasonal variability.

A major factor that may affect GRACE-estimated glacial melting is that because of the special spatial features of mountain glacial melting (i.e., very large magnitude of ice mass change occurs in a very small area, compared to GRACE spatial resolution), leakage and attenuation effects due to spatial smoothing should be exceptionally large. How to correctly estimate leakage effects, and restore the total glacial melting rate within a given region is a challenge. The spatial smoothing techniques used in GRACE data may also affect the effective recovery of surface mass change, especially for spatially small variations. The commonly used Gaussian smoothing [15,16] appears not very effective in suppressing the stripping noise in GRACE data (e.g., [17]).

In this study, we reassess the current glacial melting in the GOA region, using a different approach to quantify leakage and attenuation effects in GRACE measurements through numerical simulations. This method, as proved later in this study, is only sensitive to the total amount of ice melting in the GOA region, but not the real magnitude of the signal or spatial distribution of the given amount of mass change, and, therefore, can better quantify the leakage effects and more accurately recover the total glacial melting rate in the GOA region. In addition, we apply an optimized smoothing technique that can more effectively suppress the stripping noise in GRACE data to improve the signal to noise ratio in GRACE-estimated long-term mass change. We use a longer record of GRACE data covering a 3.5-year period from April 2002 through November 2005, and examine possible long-term (or interannual) terrestrial water storage (TWS) changes in the GOA region using estimates from the NASA Global Land Data Assimilation (GLDAS) modeling system. The long-term TWS contribution, if significant enough, needs to be removed from GRACE estimates, in order to get a more accurate assessment of the long-term glacial melting. We also compare GRACE estimates with available mass balance data at two USGS benchmark glaciers, the Gulkana and Wolverine glaciers to see if there is any meaningful agreement or correlation.

2. GRACE Gravity Measurements and Data Processing

We use 40 (approximately) monthly averaged GRACE gravity solutions, in the form of fully normalized spherical harmonics up to degree and order 120. These solutions are constrained by an empirical power law (a scaled version of the Kaula's rule for the mean gravity field [18,19]), in an effort to suppress the noise in the very high degrees and orders. The reference gravity field is the GRACE GGM01 [6] gravity model, derived from the first 111 days of GRACE data. Tidal effects, including ocean, solid Earth, and solid Earth pole tides (rotational deformation) have been removed in the level-2 GRACE data processing [20]. To simplify the computation, we truncate the GRACE solutions at degree and order 60. Owning to their large uncertainties (in the release 1 GRACE solutions), the degree-2 zonal harmonics (C20) are excluded in the computation. The mean of the 40 solutions is removed from all time series in this study.

To minimize spatial noise in GRACE-inferred surface mass changes, we apply a 2-step optimal smoothing to GRACE gravity data, which involves an optimized order-dependent anisotropic smoothing [17] and a 500 km Gaussian smoothing. The optimized anisotropic smoothing is a revised version of the formal error dependent smoothing method developed in an earlier study [17]. As formal error estimates are not provided in the GRACE constrained gravity solutions, we define a proxy 'formal error' for each Stokes coefficient as the uncertainty level of the linear trend fitted to the 40 GRACE solutions. For each Stokes coefficient, we first removed annual and semiannual variations using unweighted least squares fit, and then fit a linear trend to the residual time series (also using an unweighted least squares fit) to get the rate and uncertainty (or sigma) level. Therefore, the optimal weightings (W_{lm}^C and W_{lm}^S) for each Stokes coefficient (C_{lm} and S_{lm}) are defined as,

$$W_{lm}^C = \frac{Rate(C_{lm})^2}{Rate(C_{lm})^2 + (SIG(C_{lm})*k)^2}$$
$$W_{lm}^S = \frac{Rate(S_{lm})^2}{Rate(S_{lm})^2 + (SIG(S_{lm})*k)^2} \quad (1)$$

in which, $Rate(C_{lm},\ S_{lm})$ and $SIG(C_{lm},\ S_{lm})$ are the long-term rate and uncertainty level of the rate of given Stokes coefficient (degree *l* and order *m*). $k = 2.65$ is the optimal solution, and in this case the above weighting, when combined with the 500 km Gaussian smoothing will produce the highest signal-to-noise ratios, following the optimization procedures used in the earlier study [17].

3. GRACE Observed Long-Term Mass Change

3.1 Global Mass Change Rates From GRACE

Monthly surface mass changes are computed from these 40 GRACE gravity solutions on 1° x 1° grids on global basis. As non-tidal atmospheric and barotropic oceanic mass change contributions are removed in the level-2 de-aliasing process [20], these surface mass changes represent mainly terrestrial water storage changes over land, snow/ice mass changes of mountain glaciers and polar ice sheets, and unmodeled baroclinic oceanic mass changes plus errors in GRACE measurements and uncertainties in the background geophysical models used in GRACE data processing. At each grid point, we compute the trend using unweighted least squares fit (with seasonal signals removed first also using unweighted least squares fit), and construct a global rate map of 1° x 1° (Figure 1, in units of cm/year of equivalent water thickness change).

Obviously, many of these 'long-term' signals can be simply from interannual variations (as only 3.5 years of GRACE data are available to this study). However, these 'long-term' anomalies are not randomly located, and many of them bear clear geophysical features. The most prominent positive anomaly is in the Hudson Bay area in the northeast part of the North America continent, coinciding with the region with large anticipated post-glacial rebound (PGR) signals (e.g., [21,22]). GRACE has observed an evident mass loss along the coast in the GOA region, which is consistent with that from previous study [11]. However, our calculations (Fig. 1) suggest less noise in the GOA region, especially over the oceans. This can be attributed to a combination of 1) the extended data record (3.5 vs. 2 years) and the associated improvement of data quality and 2) the different smoothing (2-step optimized vs. 500 km Gaussian) method used in this study. GRACE has also observed several other interesting long-term mass change features, including the prominent mass loss along the coast of West Antarctica, the large accumulation in East Antarctica, and the significant mass loss over East Greenland, which are not discussed in this study.

3.2 GRACE-Observed Mass Loss in the GOA Region

Figure 2 gives an enhanced view of the GRACE-estimated long-term mass changes in the GOA region. The locations of the Gulkana and Wolverine glaciers, two USGS benchmark glaciers, are marked by white triangles. These are two relatively small glaciers (of ~ 20 and 19 km^2 in area, respectively). The locations of five largest glaciers (with area over 1000 km^2) [1] in the GOA region are marked by white dots. The first observation of Fig. 2 is that GRACE-observed mass loss (the negative anomaly in the GOA region) spreads to an extensively large area, from Arctic down to the Pacific Ocean, and is close to a rounded shape (with some distortion). The second observation is that the magnitude of the anomaly (along the coast) is about ~ - 4 - 5 cm/year, which is significantly smaller than the laser altimetry estimates (e.g., of ~ -1.8 m/year [1]). However, the geographical center of this large mass anomaly is near the complexes of the glaciers, and slightly to the north. This is a strong indication that this negative anomaly is likely due to a much larger (than the ~ 4 cm/year) mass loss confined to a small area along the coast, plus some contribution from inland areas.

An approximate approach to compute the total original mass loss rate is to sum up all the anomalies within an appropriately defined region, e.g., the region circled by the white lines. This integration will not fully restore the original mass loss rate, as the leakages spreading into the areas outside the defined region may not be negligible. However, it is possible to approximately estimate those leakages (into the regions outside the white box) through numerical simulations. If we assume all the negative anomalies in the GOA region (within the white box) are from leakages of glacial melting and other long-term mass changes in the GOA region during the spatial smoothing, then this mass loss is equivalent to ~ -124 ± 15 km^3/year. The uncertainty level is computed from sigma level at each grid point.

We compare GRACE-observed surface mass changes with USGS seasonal mass balance data (available at http://ak.water.usgs.gov/glaciology/Default.htm) at the Gulkana and Wolverine glaciers, respectively (Figures 3a,b). GRACE time series are determined from the pixel closest to the centers of the two glaciers (marked as white triangles in Fig. 2). The observation data at Gulkana has been extended up to the winter of 2005, while the last measurement (winter 2005) at Wolverine is not available yet. The units of GRACE measurements are cm of equivalent water thickness change (marked on left axis), and the units of the USGS mass balance data are m of equivalent water thickness change (marked on right axis). Although GRACE-observed variations are much smaller than the USGS mass balance measurements, the seasonal changes of the two time series match remarkably well for both glaciers. Both measurements show a steady secular mass loss with clear seasonal variations superimposed.

3.3 Contributions From Long-Term TWS Changes

To quantify possible TWS contributions to GRACE-observed long-term mass loss in the GOA region, we use GLDAS model-estimated TWS changes [23] covering the period January 2002 – June 2005. GLDAS is an advanced land surface modeling system jointly developed by the NASA Goddard Space Flight Center and the NOAA National Centers for Environmental Prediction [23]. GLDAS parameterizes, forces, and constrains sophisticated land surface models with ground and satellite products with the goal of estimating land surface states (e.g., soil moisture and temperature) and fluxes (e.g., evapotranspiration). In this particular simulation, GLDAS was used as input to the Noah land surface model [24] Version 2.7.1, with observed precipitation and solar radiation included as inputs. GLDAS TWS estimates are the sum of soil moisture (2 m column depth) and snow water equivalent. Greenland and Antarctica are excluded because the Noah model does not include ice sheet physics. The GLDAS data are provided on 1° x 1° grids and at 3-hourly intervals.

To be consistent with GRACE measurements, GLDAS TWS changes are expanded into fully normalized Stokes coefficients, up to degree and order 100, and then processed using the same procedures (e.g., truncation at degree 60, and no C20) as GRACE data to get GLDAS-estimated surface mass changes. The degree-0 term (C_{00}), representing total water mass change, and degree-1 terms (C_{11}, S_{11}, C_{10}), representing geocenter motion [9], are excluded in GLDAS, as these terms are not included in GRACE solutions. The 3-hourly GLDAS TWS change data are averaged into the same GRACE 'monthly' intervals, covering the period April 2002 and June 2005 (slightly shorter than the GRACE time series).

We estimate the total TWS changes from GLDAS (Figure 4a) in the Alaska and west Canada region within the white box on Fig. 2. No smoothing is applied in GLDAS data when we compute the TWS time series, as we try to estimate the 'true' TWS contribution. During the 3 years period, the GLDAS data show a significant 'long-term' mass loss on top of some seasonal variations in this region. The straight line in Fig. 4a represents the unweighted least squares linear fit of the time series (when seasonal signals are removed), and gives a secular mass loss of ~ – 88 ± 4 km^3/year. In addition, we estimate the long-term GLDAS trend at each grid point in the GOA region and show the GLDAS trend map in Figure 4b. When computing the GLDAS trend map, the same 2-step optimized smoothing is applied to demonstrate the leakage as GRACE would observe. For a clearer view of the trends, the color scale is set to be half of that used for GRACE results (Figs. 1 & 2). Apparently, TWS variations in the GOA region may contribute to a significant portion of the mass loss observed by GRACE. For comparison, the non-smoothed GLDAS trend map is shown in Figure 4c (which will be used in the simulation in 3.4).

3.4 Numerical Simulation of Leakage Effects

If the signal observed by GRACE is due to the contribution of glacial melting and 'long-term' (more likely interannual or decadal) TWS changes, the spatial smoothing applied to the GRACE data should have greatly reduced the magnitudes of the signals (from ~ – 1 m/year to ~ – 4 cm/year), resulted from very large leakage effects. In order to demonstrate the likelihood of this scenario, we design numerical simulations to assess the glacial melting required to generate similar leakages and similar point-wise magnitudes as GRACE has observed, and to evaluate the leakages into the areas outside the selected regions.

Figure 5 illustrates the two simulated regions, the GOA region (red box) and the Hudson Bay area (blue box). As the PGR effects are so dominant, it's necessary to include them in the simulation to reduce leakage errors into the nearby GOA region. In the GOA region, we construct long-term mass changes by placing a certain amount of long-term glacial melting within a predefined area (filled with blue, ~ 90,957 km^2) along the coast. This is approximately the total glacierized area in the GOA coastal region [1]. Model-estimated TWS trends are used for other land area within the red box (adopted from the non-smoothed GLDAS trend map shown in Fig. 4c). However, TWS changes within the green box, or slightly extended 'glacierized' area are excluded. In the mean time, we place a certain amount of mass increase around the Hudson Bay area (filled with blue, 4.6980e+06 km^2). The purpose is not to correctly model or interpret the PGR signal, but rather to approximate the leakage into the GOA region (the neglect of the ocean area in the Hudson Bay appears to have negligible effects on the leakage estimates in the GOA region). Long-term mass changes outside the two selected boxes are set to 0. We expanded the constructed mass change field into fully normalized Stokes coefficients up to degree and order 100, and then process the results with exactly the same procedures (e.g., 2-step optimized smoothing, truncation at degree 60, no C20, and no degree-1 terms) as used for the GRACE data to simulate what GRACE would observe.

The total glacial melting and apparent 'PGR' mass signal are determined through numerical experiments so that the simulated total mass loss in the GOA region can best match GRACE observations, in the sense of that the simulated results show roughly the same amount of total integrated mass loss (~ – 124 km^3/year) as the GRACE data within the same selected area (white or red box on Fig. 2 or 5). At the same time, the simulated 'PGR' effects can also best match GRACE observations to generate the same amount of mass increase (~ + 237

km^3/year) with the same selected area (blue box on Fig. 5). This is equivalent to solving a multi variables ‘equation’. We use two criteria in searching for an optimal solution that can best resemble GRACE measurements. First, the magnitude of simulated mass change in the GOA region is similar to GRACE observation, which, in some sense, is similar to the scaling method used in the previous study [11] (but specifically for long-term period here). Second, the simulated total mass change in the predefined area is the same as GRACE measurements, which enables a more accurate estimate of the total leakage from the spatial smoothing(s).

Using the above two criteria, in the final simulated results (Figure 6a), we place a total glacial melting of – 101 km^3/year evenly distributed within the selected areas, along the GOA coast (filled with blue in Fig. 5), which is equivalent to averaged melting of ~ – 1.1 m/year in the simulated area (about the same melting rates at the two benchmark glaciers shown in Figs. 3a,b), and a + 443 km^3/year ‘PGR’ mass increase in the Hudson Bay area (also filled with blue in Fig. 5). The simulated results show similar geographical distribution of leakages and similar point-wise magnitudes in the two simulated regions, when compared with GRACE measurements (Fig. 6b). Therefore, the spatial smoothing (and truncation) significantly reduces the magnitudes of the signals (~ – 1.1 m/year vs. ~ – 4 - 5 cm/year) when the changes occur within small areas (~ 90,957 km^2 in this case). Considering the total original mass loss placed in the GOA region is ~ – 180 km^3/year (glacial melting + GLDAS TWS change, which is ~ – 79 km^3/year when the extended ‘glacierized’ area is excluded) and the simulated mass loss (within the white box region on Fig. 6a) is ~ – 124 km^3/year, a significant portion (~ – 56 km^3/year) appears leaked into areas outside the selected region.

We carry out another experiment to test the sensitivity of GRACE-recovered long-term mass changes to the spatial distribution of the original signal. We place the same amount of glacial melting (– 101 km^3/year) evenly distributed within a larger area of ~ 150,340 km^2 along the GOA coast (extended from the original area), equivalent to averaged melting of ~ – 0.67 m/year, and keep everything else the same as in the experiment shown on Fig. 6a. In this case, GRACE-recovered glacial melting within the same selected area (white box on Figs. 6a,b), is virtually unchanged, when compared to the results shown on Fig. 6a (~ – 123.7 vs. – 124.3 km^3/year) where the original change is distributed over a much smaller area (~ 90,760 km^2), with significantly larger (1.1 vs. 0.67 m/year) point-wise annual melting. This indicates that the mass changes integrated from leakages within the selected region is closely tied to the possible total glacial melting (plus other long-term changes) within the selected region, and is not sensitive to the actual spatial distribution of the changes (as long as they are centered in roughly the same locations). This is also something we would hope for, by using the large averaging region, as our main interest and focus are to assess the potential total mountain glacial melting along the vast GOA coast region. The integrating region is determined to be large enough to cover as much of the leakage from the GOA region as possible, but, in the mean time, to stay away from other major signal and leakage in surrounding regions.

4. Discussions

Despite of the improved recovering methods, our GRACE-estimated glacial melting rate in the GOA region (~ – 101 ± 22 km^3/year) can be affected by many error sources that are not quantified and neglected in this study. GLDAS TWS estimates show significant long-term (or interannual) variability. However, how to correctly quantify long-term TWS change is still big challenge. Different hydrological models could show significantly large discrepancy (even at seasonal time scales). Another major error source is the uncertainty in PGR estimates in the GOA region. Although the ICE-5G PGR signals in the GOA region are relatively small [22], GPS measurements do indicate evident surface uplift along the coast in southeast Alaska, which is likely caused by post-Little Ice Age glacial retreat [25]. If the uplift can be confirmed as PGR signal, it would suggest that current GRACE-based assessments should have underestimated the true glacial melting rate in the GOA region [12]. However, the GPS observed surface uplift (in the GOA region) is also possibly caused by the present-day glacial melting. The comparison between GRACE-observed present-day ice load change and GPS observed uplift would help to understand and interpret each other (further discussion is beyond the scope of this study).

Other contributions may include errors in the atmospheric model (used in GRACE dealiasing [20]) and long-term residual baroclinic signals over the ocean. We assume that the errors in the atmospheric model are negligible. The relatively low variance over the oceans (except for the leakages from land and ice sheet) in GRACE observations (Fig. 1) suggests that long-term oceanic baroclinic signals appear also negligible, which is consistent from the conclusion of the previous study [11]

5. Conclusions

Through the above numerical simulations, we conclude that GRACE-observed long-term mass loss in the GOA region may represent a total mass loss of ~ – 180 ± 22 km^3/year in the GOA region, of which the majority appears to be caused by glacial melting along the coastal areas. Long-term TWS changes may have significant contribution to GRACE-observed mass loss in the GOA region as well. Assuming the GLDAS estimates fairly represent TWS changes in this large area, the difference between GRACE observation and GLDAS estimate would approximate the glacial melting in the GOA region, which is ~ – 101 ± 22 km^3/year.

This estimate agrees remarkably well with the airborne laser altimetry measurement of ~ – 96 ± 35 km^3/year [1]. This agreement may be a coincidence, as the airborne laser altimetry estimate is based on the measurements between mid-1990's to 2000 or 2001 over only 28 glaciers in the GOA region, while GRACE estimate is based on the data from a recent 3.5-

year period (April 2002 – November 2005). There should be many other uncertainties in both estimates. The GRACE measurement errors, other leakage effects (e.g., from baroclinic oceanic signals), and errors in the background geophysical models are not quantitively assessed. The extrapolation of the laser altimetry data and the two-point estimate methodology (i.e., the laser altimetry results are mostly based on two repeated measurements several years apart [1] to get the long-term rates) may also lead to large uncertainties in the laser altimetry estimates.

Our GRACE-estimated glacial melting in the GOA region is consistent with the previous assessment of ~ – 115 ± 20 km^3/year based on the first 2 years of GRACE data [11], reconfirming the significant glacial melting in the GOA region in recent years. Model-estimated TWS changes show significant long-term (or interannual or decadal) variations in the GOA regions during this 3.5-year period, and account for a large portion of GRACE-observed annual mass loss in this region. The simulated averaged glacial melting rate (~ – 1.1 m/year) when using a total glacierized area of ~ 90,957 km^2 (close to published total glacierized area in the GOA region [1]) is consistent with the estimates from the USGS measurements at the two benchmark glaciers (Figs. 3a,b).

The consideration of PGR (and other long-term mass change) contributions in our simulations has significant effects on the simulated mass loss in the GOA region. For the simulation shown in Fig. 6a, if the PGR effects are not considered and everything else remain the same, the simulated total mass loss within the selected region is ~ – 87 km^3/year, as compared with the estimate of ~ – 124 km^3/year when the PGR effects are modeled. The large difference is mainly because the two anomalies are geographically close and are both significant, and the leakages between the two regions are expected to be relatively large. Based on the estimates of the ICE-5G model [22], the PGR effects (themselves, as compared to the PGR leakages) in the GOA region are relatively small and neglected in this study.

The ongoing GRACE data reprocessing is expected to significantly improve the accuracy of GRACE time-variable gravity fields. With a longer record of GRACE data with improved accuracy, GRACE time-variable gravity data will be a more valuable data resource (in addition to remote sensing) to the study of mass balance of mountain glaciers, polar ice sheets, and climate change.

This study further demonstrates the significant potential of using GRACE time-variable gravity measurements for monitoring regional scale glacial melting. Through improving the signal-to-noise ratio (at long-term period), the optimized smoothing technique used in this study can more effectively suppress the stripping noise in GRACE-estimated mass change fields. The numerical simulation experiments designed in this study provide a tool to estimate the exceptionally large leakage effects due to the spatial smoothing used in GRACE data, and enable the quantification of small spatial scale ice mass change signal such as mountain glacial melting. The methods used in this study only rely on the presence of long-term signals in GRACE-estimated mass changes (and are independent on any seasonal variability), and, therefore, are expected to be particularly useful in regions where seasonal signal may be relatively insignificant, such as over Antarctica.

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References:

[1] A.A. Arendt, K.A. Echelmeyer, W.D. Harrison, C.S. Lingle, V.B. Valentine Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level, Science 297 (2002) 382-386, DOI: 10.1126/science.1072497.

[2] M.F. Meier, M.B. Dyurgerov, SEA LEVEL CHANGES: How Alaska Affects the World, Science 297 (2002) 350-351, DOI: 10.1126/science.1073591.

[3] M.B. Dyuregov, M.F. Meier, Twentieth century climate change: Evidence from small glaciers, Proc. Natl. Acad. Sci. U.S.A. 97 (2000), 1406-1441

[4] F.S. Chapin, III, M. Sturm, M.C. Serreze, J.P. McFadden, J.R. Key, A.H. Lloyd, A.D. McGuire, T.S. Rupp, A.H. Lynch, J.P. Schimel, J. Beringer, W.L. Chapman, H.E. Epstein, E.S. Euskirchen, L.D. Hinzman, G. Jia, C.-L. Ping, K.D. Tape, C.D.C. Thompson, D.A. Walker, J.M. Welker, Role of Land-Surface Changes in Arctic Summer Warming, Science 310 (2005) 657-660, DOI: 10.1126/science.1117368

[5] J.A. Church, J.M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin, and P.L. Woodworth, Changes in Sea Level. In Climate Change (2001). The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, JT, Ding Y, Griggs DJ, Noguer M, van der Linden P, Dai X, Maskell K and Johnson CI, eds, Cambridge University Press, 639-694.

[6] B.D. Tapley, S. Bettadpur, M.M. Watkins, C. Reigber, The Gravity Recovery and Climate Experiment; Mission Overview and Early Results, Geophy. Res. Lett., 31 (9) (2004), L09607, 10.1029/2004GL019920.

[7] J. Wahr, S. Swenson, V. Zlotnicki, I. Velicogna (2004), Time-Variable Gravity from GRACE: First Results, Geophy. Res. Lett., 31 (2004), L11501, doi:10.1029/2004GL019779.

[8] J.L. Chen, C.R. Wilson, J. S. Famiglietti, and M. Rodell, Spatial Sensitivity of GRACE Time-Variable Gravity Observations, J. Geophys. Res., 110 (2005), B08408, doi:10.1029 /2004JB003536.

[9] J.L. Chen, M. Rodell, C.R. Wilson, J. S. Famiglietti, Low Degree Spherical Harmonic Influences on GRACE Water Storage Estimates, Geophys. Res. Lett., 32 (14) (2005), L14405 10.1029/2005GL022964.

[10] I. Velicogna, J. Wahr, Greenland mass balance from GRACE, Geophys. Res. Lett., 32 (2005), L18505, doi:10.1029/2005GL023955.

[11] M.E. Tamisiea, E.W. Leuliette, J.L. Davis, and J.X. Mitrovica, Constraining hydrological and cryospheric mass flux in southeastern Alaska using space-based gravity measurements, Geophys. Res. Lett., 32 (2005), L20501, doi:10.1029/ 2005GL023961.

[12] I. Velicogna, J. Wahr, Measurements of Time-Variable Gravity Show Mass Loss in Antarctica, Science, (2006) DOI: 10.1126/science.1123785.

[13] D.P. Chambers, J. Wahr, R. S. Nerem, Preliminary observations of global ocean mass variations with GRACE, Geophys. Res. Lett., 31 (2004), L13310, doi:10.1029/2004GL020461.

[14] J.L. Chen, C.R. Wilson, B.D. Tapley, J. S. Famiglietti, and M. Rodell, Seasonal Global Mean Sea Level Change From Altimeter, GRACE, and Geophysical Models, J. Geodesy DOI 10.1007/s00190-005-0005-9, 79 (9) (2005) 532 - 539.

[15] C. Jekeli, Alternative Methods to Smooth the Earth's Gravity Field, Department of Geodetic Science and Surveying, Ohio State University, Columbus, OH (1981).

[16] J. Wahr, M. Molenaar, and F. Bryan, Time-variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, J. Geophys. Res., 103(B12) (1998), 30,205– 30,230.

[17] J.L. Chen, C.R. Wilson, K.W. Seo, Optimized Smoothing of GRACE Time-Variable Gravity Observations, J. Geophys. Res. (2006) (in press).

[18] W. Kaula, Theory of satellite geodesy, Blaisdale Press, Waltham, Mass (1966).

[19] S. Bettadpur, GRACE Gravity Field Product Description and Mission Profile, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract G31A-03 (2004).

[20] S. Bettadpur, Level-2 Gravity Field Product User Handbook, The GRACE Project (2003).

[21] W.R. Peltier, Deglaciation induced vertical motion of the North American continent and transient lower mantle rheology, J. Geophys. Res., 91 (1986), 909-9123.

[22] W.R. Peltier, GLOBAL GLACIAL ISOSTASY AND THE SURFACE OF THE ICE-AGE EARTH: The ICE-5G (VM2) Model and GRACE, Annual Review of Earth and Planetary Sciences, 32 (2004): 111-149, doi:10.1146/annurev.earth.32.082503.144359.

[23] M. Rodell, P.R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J.K. Entin, J.P. Walker, D. Lohmann, and D. Toll, The Global Land Data Assimilation System, Bull. Amer. Meteor. Soc., 85 (3) (2004), 381–394.

[24] M.B. Ek, K.E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J.D. Tarpley, Implementation of the upgraded Noah land-surface model in the NCEP

operational mesoscale Eta model, J. Geophys. Res., 108 (2003), 8851, doi:10.1029/2002JD003296.

[25] C.F. Larsen, R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer, E.R. Ivins, Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat, Earth and Planetary Science Letters 237 (2005) 548– 560.

Figures:

Figure 1. Global long-term mass change (in units of cm of equivalent water height change per year, cm/yr) estimated from 40 GRACE monthly gravity solutions.

Figure 2. Long-term mass loss observed by GRACE in the Gulf of Alaska (GOA) region. The integrated total mass loss in the white-line circled area is equivalent to ~ –124 ± 15 km^3/year. The 2 white triangles mark the locations of two USGS benchmark glaciers, the Gulkana Glacier (~ 20 km^2 in area) and Wolverine Glacier (~ 19 km^2 in area), while the white dots mark the locations of the 5 largest glaciers in the GOA region (~ 1000 km^2 or above in area).

Figure 3. Comparison between GRACE observations (blue curves with square markers) and the USGS archived mass balance time series for the Gulkana and Wolverine Glaciers (red curves with triangle markers). The GRACE time series are point-wise estimates after the 800 km Gaussian smoothing, in units of cm of equivalent water thickness change (marked on left axis). The USGS results are in units of m of equivalent water thickness change (marked on right axis). The two strait lines represent the linear trends from unweighted least squares fit.

Figure 4. (a) GLDAS-estimated total soil moisture and snow water changes (in units of km^3/year of equivalent water mass change) in non-glaciered regions in Alaska and West Canada within the same area circled by white line as in Fig. 2. No smoothing is applied to GLDAS data, and other treatments are consistent with GRACE data (e.g., truncation, no C20, and no degree-1 terms). (b) GLDAS-estimated 'long-term' water storage change in the Gulf of Alaska region with same smoothings and other data treatments as GRACE data (in cm/year of water thickness change). (c) GLDAS-estimated 'long-term' water storage change in the Gulf of Alaska region without smoothing (in cm/year of water thickness change). GLDAS data covers the period April 2002 to June 2005. The color scales are different in (b) and (c), and also different from that used for GRACE results (in Figs. 1 & 2), for clarity of presentation.

Figure 5. Illustration of the two simulated areas, the GOA region (red box) and the Hudson Bay area (blue box). The filled areas (with blue color) are where the original glacial melting and PGR mass change are distributed.

Figure 6. a) Simulated glacial melting and TWS change in the GOA region (in units of cm/year of equivalent water thickness change), as would be observed by GRACE after the same data processing.

Figure 6. b) GRACE-observed long-term mass changes in the same area (in units of cm/year of equivalent water thickness change).

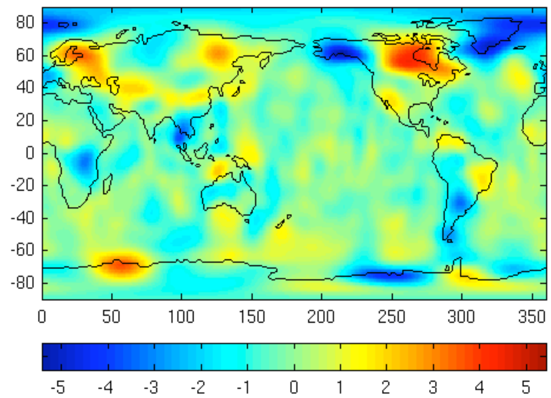

Figure 1

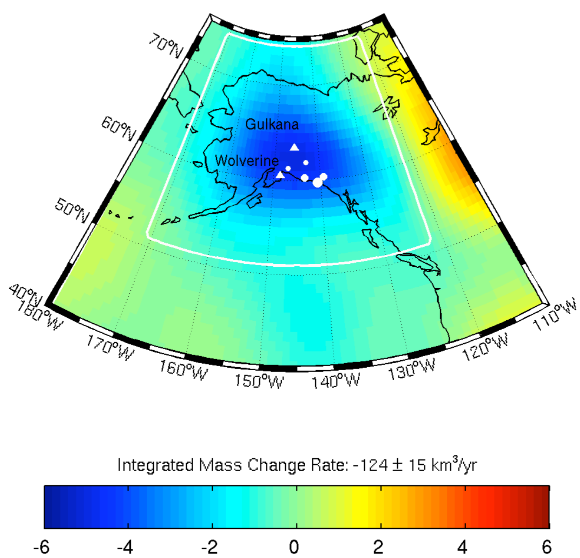

Figure 2

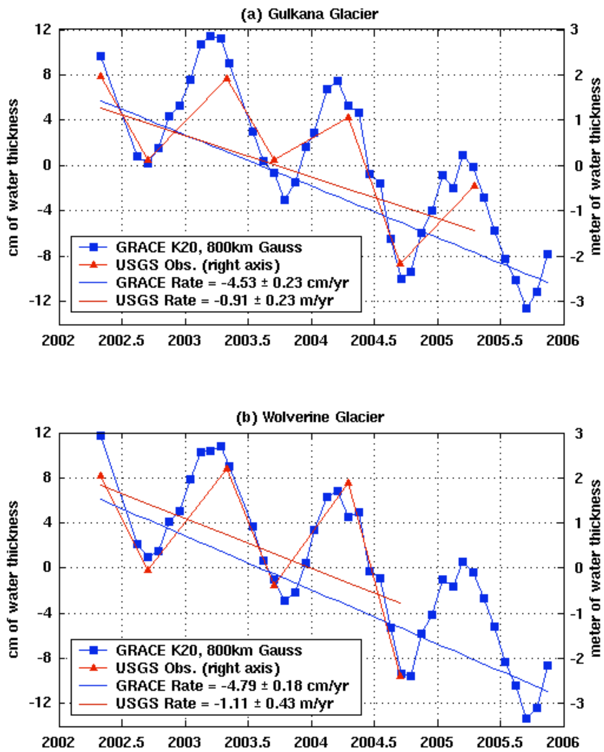
(a) Gulkana Glacier
cm of water thickness
meter of water thickness
GRACE K20, 800km Gauss
USGS Obs. (right axis)
GRACE Rate = -4.53 ± 0.23 cm/yr
USGS Rate = -0.91 ± 0.23 m/yr
2002
2002.5
2003
2003.5
2004
2004.5
2005
2005.5
2006
(b) Wolverine Glacier
cm of water thickness
meter of water thickness
GRACE K20, 800km Gauss
USGS Obs. (right axis)
GRACE Rate = -4.79 ± 0.18 cm/yr
USGS Rate = -1.11 ± 0.43 m/yr

Figure 3

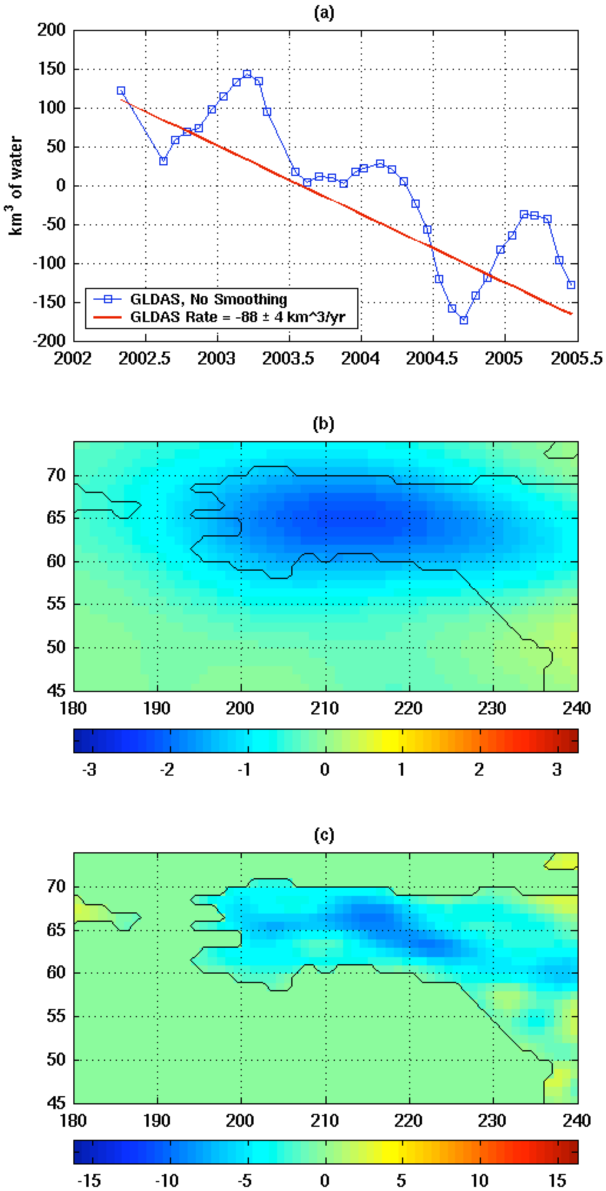
(a)
km^3 of water
GLDAS, No Smoothing
GLDAS Rate = -88 ± 4 km^3/yr
200
150
100
50
0
-50
-100
-150
-200
2002
2002.5
2003
2003.5
2004
2004.5
2005
2005.5
(b)
70
65
60
55
50
45
180
190
200
210
220
230
240
-3
-2
-1
0
1
2
3
(c)
-15
-10
-5
0
5
10
15

Figure 4

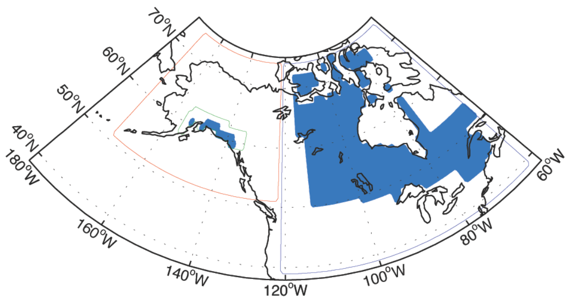

Figure 5

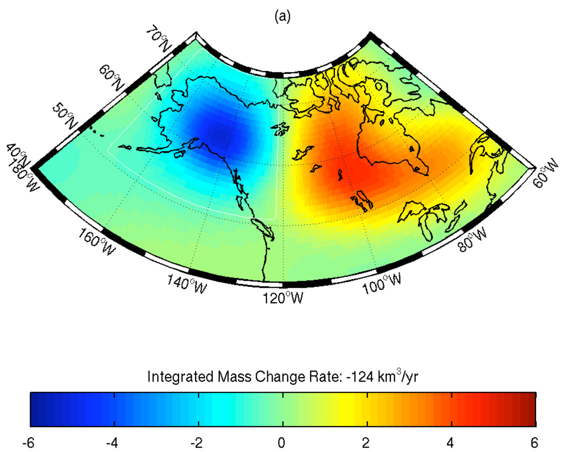

Figure 6a

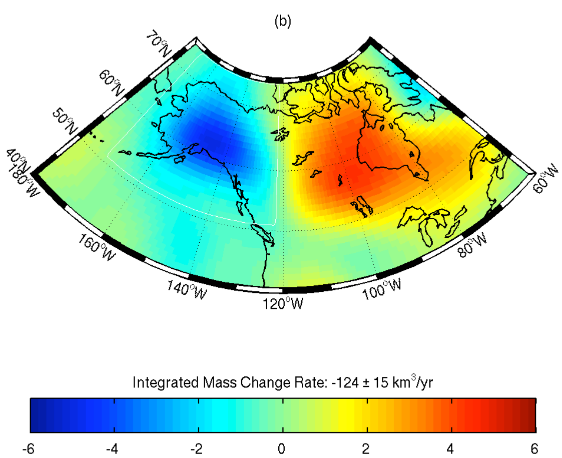

Figure 6b