Quantifying the resolution level where the GRACE satellites can separate Greenland's glacial mass balance from surface mass balance

J. A. Bonin[1] and D. P. Chambers[1]

Due to the comments of the reviewers, I have made a number of major changes to the paper:

1.) Increased the number of simulations from 6 to 50, to increase the statistical robustness of the results.

2.) Updated the RACMO2 SMB data to the newest release.

3.) Calculated and used the actual spatial correlations and 1-month-lag correlations for the creation of the SMB simulations.

4.) Altered figure 3 (and removed figure 4) to show the above correlation changes.

5.) Added a new figure (9) specifically showing the noise-only statistics in the same way as the SMB-only and DMB-only statistics are shown.

6.) Rewrote or rearranged a large fraction of the manuscript, in hopes of making things more clear and easier to read. I specifically focused on making our motivation for this clear, as well as being more upright about exactly what we were doing (and how we were doing it) in each section. Hopefully it helps.

While recalculating the results, I found a major mistake in my SMB error calculations (Figure 7a). I had originally accidentally differenced the gridded inverted signal from the gridded truth signal, and then taken the average over the SMB basins. This is incorrect in SMB basins which overlap with the glacier basins. What I should have done (and have corrected to, in this version) was compute the average of the truth grids and subtract that directly from the inverted SMB basin amplitudes. Doing so prevents the glacial signal from being recombined in the inversion results, which was not the intent. The error calculations are now correct in Figure 7a, as are all the later results that depended upon those numbers. This led to a slightly different emphasis in the final results, and some wording changes in the document. (The DMB-only and noise-only computations were not affected by this.)

Thank you once again for your help. I really appreciate the extension on the deadline. Let me know if there is anything else I can do to make things easier on you.

Jennifer Bonin

Reply to Reviewer #1:

Thank you for your helpful review. As I understand it, you had several general concerns, regarding the overall clarity of the paper. We hope we have improved this via the following methods:

1.) Including the basic math surrounding the inversion technique, as you suggest.

2.) A major rewrite of sections 3 (simulation definition) and 4 (analysis of results), focusing on a clearer overview of the "SMB" versus "GMB" simulations, the differences between the two, and the rationale behind them. We have explicitly divided section 4 into separate SMB-misfit and GMB-misfit sections, which should also eliminate potential confusion. This should clarify the differences between figures 7 and 8 as well. We have endeavored to make things more clear in the text and apologize for the confusion. (The typo you mentioned at the beginning of section 4.1 only made the confusion worse, and has since been corrected.)

As to your specific comments:

1.) Page 1317, Line 22: I am sure you are aware, but perhaps it is worth mentioning that some GRACE solutions extend beyond degree 60, but these degrees are mostly contaminated by noise.

Agreed. I have added the line "However, this benefit must be balanaced with the cost of greater satellite errors at higher degrees."

2.) Page 1318, Line 25: You state that you use the RMS from the RACMO2 ice model. I C406 believe referring to this as a regional climate model is more appropriate.

Thank you. I have made this correction.

3.) Also, please include additional description of what you mean by the RMS. Is this the RMS of SMB anomalies about some mean time period, or are they absolute SMB values? What time period are you computing the RMS for?

I have altered this section to read: "We sum the RACMO2 regional climate model's [Ettema et al., 2009b] surface mass balance over time, from 2002-2012. This gives grids of cumulative SMB. We remove the mean to create grids relative to the mean mass of 2002-2012 at each location, similar to GRACE monthly mass anomalies." I hope the above phrasing, including the more accurate term "cumulative SMB" rather than just "SMB" makes things more clear.

4.) I can imagine that in locations for which the mass balance is dominated by dynamics, rather than SMB (such as Northwest Greenland and Southeast Greenland - see Velicogna, 2014), that this regional-dependent weighting scheme is insufficient and introduces errors which are unaccounted for in your process. Could you comment on this?

Yes, I am aware that when using SMB only to define the basins, we will not create the "space" to hold mass change via glacier dynamics. That is a large part of the goal of this paper: to see how large errors will be, if we only use the typical technique of estimating basins via SMB. We added this section to make that clear: "While these additional three basins obviously do not include many other areas of active glacier dynamics, the very large signal size of these three glaciers made them a good test case for determining if the effect of glacier dynamics could be backed out using GRACE and an inversion technique. Additional glacial basins could be added as desired in the future."

5.) Page 1322: Why did you choose to make only 6 simulated data sets? This does not seem like enough to achieve statistical significance in your results. Are you confident that you have done so, and can you explain this choice?

We chose a small number of simulations because of the time commitment required. The time needed to run these cases is not too long for the 60x60 cases, but gets very lengthy for 120x120 and 180x180. (For the record, the creation of 250 SMB and 250 GMB simulations at 5 maximum spherical harmonic degrees is still continuing as I type this seven days later. It's not hard to do, just time-consuming.) However, since all of the reviewers felt this was a major concern, we are currently recreating the cases to have 50 simulated runs.

6.) Page 1323, Line 5: The use of GMB and SMB is perhaps a bit careless throughout the manuscript, and it shows very clearly here. In Figure 5c, you have the GMB of a glacier going positive. In fact, the GMB is always negative; glaciers are always discharging. I believe what you are showing in Figure 5 are anomalies with respect to a background discharge rate? Same comment with respect to SMB, for instance on Line 8, you state that the this discharge signal is much larger than the SMB signal. However, the full magnitude of the SMB is generally very large and very positive - I believe you mean "SMB anomaly" rather than "SMB signal", where the SMB is an anomaly with respect to some mean timeframe?

I have clarified by using the more exact term "cumulative SMB". Additionally, due to the suggestion of another reviewer, the glacial dynamic mass balance effects are now named as "cumulative DMB" . Sorry for the confusion due to the short-hand version of the correct term.

7.) Page 1327, Line 7: Please explain what you mean by "relative strength of the SMBmisfit errors over the GMB-misfit errors". Even though there are clumps of 6 in Figure 9, it is difficult to see this, and the reader does not know which clump of 6 belongs to which run?

Because I am now running 50 cases for each simulation set, figure 9 is likely to change entirely. However, when I do finally have the simulations complete and the inversions done, I will keep this in mind and revise the line appropriately.

8.) Figure 9: Here, you show the simulated mass balance for the glacier basins. I assume you could also show this for the other basins (where only SMB was modeled)? Is it possible to do this, or perhaps show just a couple of these, so to elucidate the reader C407 on both your processes as well as your results?

Unfortunately, because the cumulative SMB signal varies with each simulation (unlike the summed GMB signal), such plots are almost impossible to read. I can create plots like this showing the SMB-only inversion results minus their "truth" simulations, but that would really only show each run's RMS error on top of each other, which is already measured in Figures 7a and 8a. When I did so, the plots were very messy confusing, since the cumulative SMB signal is so much more complex than the simplified GMB signal. I would not recommend it, for that reason.

9.) Page 1330, Line 22: It is stated that a stripe reduction could allow for separation between SMB and GMB. However, this separation is only possible for annual timescales, since you must apply a yearly smoothing to the data, is this correct?

That is correct. I added the clarification as: "Significant stripe reduction could potentially allow for cumulative SMB and GMB to be separated using the least squares inversion method, particularly if errors are reduced via temporal smoothing." In my experience, it would take a much larger error reduction to sufficiently remove the month-to-month stripes, and that's tough to do without also removing the month-to-month signal. Hypothetically it's possible, but it's a far tougher problem.

10.) Also, can you please address the issue of having other smaller outlet glaciers within your "SMB" basin? That is you are trying to separate SMB from the three largest outlet glaciers. However, inherently, there are other glacier dynamics that you are capturing in your SMB because of smaller outlet glaciers that you are not modeling. Is this correct? Could you comment on this in the manuscript?

I have added the following paragraph to the introduction, to clarify our motives and methods, and also explain why we picked only the three "big" glaciers that we did: "We expand this technique to include regions designed to contain the mass signal of the largest of Greenland's glaciers:

Kangerdlugssuaq, Helheim, and Jakobshavn. These glacial regions experience two different physical processes atop each other: the localized DMB signal and the broader-scale SMB signal. Unlike most places in Greenland, the DMB signals in Kangerdlugssuaq, Helheim, and Jakobshavn glaciers are expected to be larger than the local SMB signal. That fact allows us to potentially separate the dynamical effects from the SMB effects in these regions, by making a pair of assumptions. First, since SMB is correlated over fairly large regions, we assume that the SMB signal across each of the large glaciers is similar to the SMB just outside the glacier. Second, we assume that any local signal which is not defined by the broader SMB signal is caused by glacial dynamics. The latter is a reasonable assumption in the case of these three glaciers, due to the relatively large size of the expected DMB signal compared to discrepancies in local SMB relative to nearby SMB. This allows us to use two overlapping basins to separate the two independent signals: first, a large SMB basin, similar to those used in previous studies, and second, a small basin covering only the area just around the glacier. The smaller basin is designed to trap the localized signal, which we know to be largely caused by the DMB, while the larger basin will trap the underlying larger-scale signal, which we know to be largely caused by the SMB."

Thank you again for your help,

Jennifer Bonin

Reply to Reviewer #2:

Thank you for your helpful review. As I understand it, your main concern about our paper is that, even assuming ideal, noiseless data, the method may not really separate SMB from dynamic effects. We understand your concern and appreciate you pointing out this confusion to us. To clarify our motivation and also to better explain exactly what we're doing, we have added the following paragraph in the introduction section:

"We expand this technique to include regions designed to contain the mass signal of the largest of Greenland's glaciers: Kangerdlugssuaq, Helheim, and Jakobshavn. These glacial regions experience two different physical processes atop each other: the localized DMB signal and the broader-scale SMB signal. Unlike most places in Greenland, the DMB signals in Kangerdlugssuaq, Helheim, and Jakobshavn glaciers are expected to be larger than the local SMB signal. That fact allows us to potentially separate the dynamical effects from the SMB effects in these regions, by making a pair of assumptions. First, since SMB is correlated over fairly large regions, we assume that the SMB signal across each of the large glaciers is similar to the SMB just outside the glacier. Second, we assume that any local signal which is not defined by the broader SMB signal is caused by glacial dynamics. The latter is a reasonable assumption in the case of these three glaciers, due to the relatively large size of the expected DMB signal compared to discrepancies in local SMB relative to nearby SMB. This allows us to use two overlapping basins to separate the two independent signals: first, a large SMB basin, similar to those used in previous studies, and second, a small basin covering only the area just around the glacier. The smaller basin is designed to trap the localized signal, which we know to be largely caused by the DMB, while the larger basin will trap the underlying larger-scale signal, which we know to be largely caused by the SMB."

As to your specific comments:

1.) *The authors distinguish between glacial mass balance (GMB) and surface mass balance (SMB). I'm not sure if glacial mass balance is the right word to use here, this is usually used to describe the total mass balance of a glacier (dynamic + SMB). Dynamic mass balance (DMB) might be a better choice*

We have made this alteration.

2.) *section 3.1: The authors designed a rather involved method to generate random SMB maps. I'm wondering if it wouldn't be an option from an independent model, such as MAR (freely available on the internet), to estimate the effect of SMB variability. Considering that you're only using data from 2002-2012, you could even consider to use RACMO data from different time intervals (although a scaling trend might be required). This would arguably produce more realistic maps … and would be much easier to understand for the reader.*

We did originally try using the difference with the 1993-2003 RACMO2 data as a way to measure errors. But the trends and long-term effects are really what we want to measure most, and those change so much between the 1990s and the 2000s that we found it was really not an appropriate of errors. That was what led us originally to creating a randomized version of the slopes and climatology, and the residual followed naturally from there. You are right that we could have (and possibly should have) used the MAR model instead. However, when we started, we frankly did not know about it. Even now, we have no feel for how many correlated errors there would be between MAR and RACMO2, which subtracting the two series would not reveal. Given how large the GRACE errors prove to be relative to any possible errors in the model, we decided not to download and learn to use a totally new (to us) data set, since the general results (that GRACE errors are too large to separate SMB from DMB) would surely not change. I hope that is acceptable. We have downloaded the MAR dataset for similar use in the future, so we thank you for the suggestion.

3.) *The current 3 degree-smoothing approach doesn't take into account that the SMB length scales are variable across the ice sheet*

You are correct. To fix this, we have used the RACMO2 data to create a map of localized length scales. As you expected, they vary significantly over the area, from low near the coasts to +/-5 degrees in central Greenland. We have altered our code to use these variable length scales, rather than a single 3-degree one.

4.) *Only six random simulations are used in the current set-up. This seems to be too low to base any robust conclusions on. The computational costs of the simulations appears to be low, so I would suggest to increase the number of simulations.*

We chose a small number of simulations because of the time commitment required. The time needed to run these cases is not long for the 60x60 cases, but gets very lengthy for 120x120 and 180x180, since it increases as maxdeg^2. (For the record, the creation of 250 SMB and 250 GMB simulations at 5 maximum spherical harmonic degrees is still continuing as I type this seven days later. It's not hard to do, just time-consuming.) However, since all of the reviewers felt this was a major concern, we are currently recreating the cases to have 50 simulated runs.

5.) *page 1316, line 3: remove 'precipitation-based'. As you mention later on, SMB consists of much more than just precipitation.*

Done.

6.) *page 1318, line 11: Here you say that you don't use any constraints or regularization. But wasn't the conclusion of Bonin and Chambers that regularization is required to stabilize the solutions (see eq. 4 in Bonin 2013)? Please include a discussion of why you chose not to use regularization.*

We have done so, briefly: "Although in Bonin and Chambers [2013] we determined that a diagonal constraint matrix assisted in the optimization, experimentation since has demonstrated that when using non-uniform basin weights, such "process noise" does not improve accuracy. As such, our least squares inversion technique computes the set of optimal basin multipliers using no additional constraints or regularization."

7.) *page 1318, line 25: - RACMO2 does not include ice dynamics, it's a regional climate model*

Corrected.

8.) *What time period did you use to compute the RMS, the GRACE period?*

2002-2012. We have now added this information in the paper.

9.) I assume you use cumulative SMB anomalies (which is what GRACE would measure), not the monthly SMB as output by the model? The same applies for the GMB signals, as in fig. 5.

Correct. We have updated the term in the paper to "cumulative SMB" rather than just "SMB".

10.) page 1319, line 22: I don't understand what you mean by 'the external signal is kept constant'. Did you represent ocean and hydrology using a random month from the models and kept this constant? Ocean and hydrology loading vary in time, and so does the effect on the mass inversion. If you pick a random month, you may under/overestimate the effect (same applies to using the average, which will underestimate the effect). Using time-varying model data appears to be more correct.

I apologize for the confusion in this line. All that was meant is that the same (time-varying) external signal, meaning the hydrology and oceanography everywhere outside of Greenland, is used in all simulations. I have removed this line and slightly altered the remaining lines to make that clearer.

11.) page 1320, line 16-17: How did you compute these numbers (83 and 95%). Did you use cumulative SMB anomalies (running sum of monthly SMB minus long-term mean SMB) or just cumulative SMB? The numbers seem high, I suspect that the numbers would be lower for cumulative SMB anomalies.

Yes, these are actually the values for the cumulative SMB anomalies, from RACMO2. To compute them, I separated the trend and climatology from the residual, then computed the RMS of that and compared to the RMS of the full signal in each grid cell. Especially over the coast, a climatology (not a pure sinusoid, though) and a trend really do capture almost all of the mass signal. I was surprised, too.

12.) page 1321, formula 1: I suggest to use a different symbol for r^(3 deg). When I first glanced at the formula, I assumed this means a local 3 degree smoothing radius.

I have totally altered this section, both for clarity and to include the variable length scales you suggested earlier. Hopefully things will now be more clear.

13.) page 1322, line 10: what is the beta-value (.85) based on. This actual value will vary from location to location. Instead of using a fixed value, it would make more sense toestimate the local value from the RACMO data, using the lag-1 autocorrelation value.

Agreed. We have now done that.

14.) page 1329: square root missing in denominator?

Oops! Corrected.

Thank you so much for your suggestions,

Jennifer Bonin

Reply to Reviewer #3:

Thank you for your review. As I understand it, you had several general concerns regarding the overall point of the paper and whether it is worthy of publication in The Cryosphere. While that decision is, obviously, up to the editor, I would point out that many of the people reading this journal are precisely those people who might wonder if GRACE could be used in this way to learn something about the mass variability of large glaciers. Put another way, if this method had worked, an additional section would have been added giving the mass variability of the glaciers, as opposed to the broad-scale "SMB" which most GRACE papers using similar techniques solve for. Had that been the case, I suspect most editors would not argue against this paper being entered into this journal. That being so, I would argue that it is as important to tell the same audience that such a technique DOESN'T work, as it would be to demonstrate that it DID work.

You also note that it "should not be surprising" that the small glacier basins I chose cannot be resolved satisfactorily. I do not think this is at all obvious. Many people (including ourselves and Schrama and Wouters) have successfully used inversion methods to solve for basins as small as our basin #7. Similar mascon methods have been created to at least 2-degree resolution. That being the case, I would argue that it was reasonable to test if these tiny basins could be solved for. I, also, am not shocked that GRACE errors are too large – but nor would I have been shocked if it the method had worked. How can people know what does work and what doesn't, if the failed cases AND the successful ones aren't published?

As to your larger comments:

(a) I apologize for the typo at the start of Section 4.1. You are correct; that should have been refering to the SMB, not the GMB. That has been fixed. In addition, I have done a major rewrite to the entire simulation description and a large section of the analysis, in an attempt to make things more clear.

(b) I did, of course, double-check the code before accepting this surprising result. When I checked, I found that the inverted results, when smoothed into spherical harmonics, really DO match the input simulation well. That is, the math in the least squares process works: it produces what appears to be an optimum fit to the data given it. As for a physical meaning behind why the errors increase with maximum degree, the math doesn't care. This is one of the problems with least squares in general: that the output, while mathematically optimal, may not be the "best" answer in terms of what makes physical sense. I don't like that, and in fact, such problems are a large part of the reason I wanted to run a simulation to test this technique. Right now, people are using similar methods to this one and getting answers which look okay, but which may really be just as inaccurate as this, just because the least squares math is blind.

So I think it's important to both compute the error and admit that it does not make physical sense. I suppose I could fudge some excuse "explaining" it away, or else dodge and avoid the topic at all. But doing the first would both be dishonest and the second unhelpful to others using this technique. Besides, perhaps this way, someone else will be able to figure out why it happens, if I admit the oddity. I will leave it up to the editor to decide whether a physical explanation must be had for every detail of every error in order to publish a paper on a technique. What I do know is that the mathematics support the statistics I listed.

(c) Yes, I realize that the same dynamic processes that I'm focusing on at these three glaciers exist at a lot of other places in Greenland. However, I am pragmatic enough to realize that I can't possibly use GRACE in this way to solve for relatively small dynamical effects over many, many small regions. It is, however, reasonable to ask if those dynamical effects can be seen in the few places where the signal is very large – hopefully larger than the errors. I realize that all other dynamical signal will be inaccurately lumped in to the "SMB" basins. However, that is the standard technique right now. Surely it is better to try and separate out the difference in a few places, even if we can't do it everywhere, than not even attempt to separate out the physical causes anywhere.

I have explained some of this rationale, as well as adding a better description of what we are doing, in the following new introductory paragraph (due to another author's suggestion, the cumulative dynamic glacial mass balance is called "DMB".): "We expand this technique to include regions designed to contain the mass signal of the largest of Greenland's glaciers: Kangerdlugssuaq, Helheim, and Jakobshavn. These glacial regions experience two different physical processes atop each other: the localized DMB signal and the broader-scale SMB signal. Unlike most places in Greenland, the DMB signals in Kangerdlugssuaq, Helheim, and Jakobshavn glaciers are expected to be larger than the local SMB signal. That fact allows us to potentially separate the dynamical effects from the SMB effects in these regions, by making a pair of assumptions. First, since SMB is correlated over fairly large regions, we assume that the SMB signal across each of the large glaciers is similar to the SMB just outside the glacier. Second, we assume that any local signal which is not defined by the broader SMB signal is caused by glacial dynamics. The latter is a reasonable assumption in the case of these three glaciers, due to the relatively large size of the expected DMB signal compared to discrepancies in local SMB relative to nearby SMB. This allows us to use two overlapping basins to separate the two independent signals: first, a large SMB basin, similar to those used in previous studies, and second, a small basin covering only the area just around the glacier. The smaller basin is designed to trap the localized signal, which we know to be largely caused by the DMB, while the larger basin will trap the underlying larger-scale signal, which we know to be largely caused by the SMB."

As to your specific comments:

1.) *"Glacial mass balance" is not the right term to denote mass changes due to changingice flow dynamics. Why should SMB be "non-glacial"??*

I have altered this term to the more accurate "cumulative dynamic mass balance".

2.) *A more intricate point about the SMB-versus-dynamic separation: While the authors oppose dynamic signals to atmospherically forced signals (p. 1316, line 19), dynamic signals are partly triggered by SMB (and hence by the atmosphere)through complex feedbacks. [e.g., Murray et al., doi:10.1029/2009JF001522, Zwallyet al.,10.1126/science.1072708]*

Yes, we agree that there are complicated correlations between the two. However, as the two types of signals are often separated in the literature, we have gone with a simplified description, mostly as a memory aid for those less familiar with the terms. (In reality, this method doesn't separate the physical reasons for the signals anyhow, just their strength and spatial extent.)

3.) *Line 2 of the abstract: "precipitation based SMB" sounds odd. Both precipitation and ablation determine SMB.*

Agreed. We have removed this phrase.

4.) *Line page 1318, line 13: "roughly based off the island's drainage": not clear to me what this means.*

We have altered the line to be more explicit: "We use 13 SMB basins covering Greenland (Fig. 2). These are relatively large-scale drainage basins of the area, with the coastal regions separated from the interior."

5.) *Line 25. RACMO2 is not an ice model.*

We have corrected this to “regional climate model”.

6.) page 1324 line 8: You removed the JPL_ECCO ocean model? This sounds like you didn’t account for the fact that an ocean model has been already removed during GRACE processing?

Sorry. I am so used to adding back the monthly-averaged OMCT ocean model, that I forgot to mention it here. We did add it back, then chose to remove a different ocean model, which we believe is more accurate in some regions, as well as a hydrology model, in order to focus on the ice signal. I have altered the text at the start of section 3.3 to say as much: “The GRACE data we use is the standard RL05 solutions from the Center for Space Research (CSR), with the AOD1B ocean dealiasing monthly averages added back.”

7.) *page 1325, line 15 computed -> compared? page 1326, line 10: areas -> errors?*

Sorry, yes. Because of the general alterations to this section, the first phrase is no longer around. The second has been corrected.

8.) page 1327, line 12: "certainly a plausible achievement...": Make clear here that you know about the n_max=96 solutions by CSR. There are, by the way, n_max=120 solutions by ITSG (TU Graz). As long as you disregard errors (as you do in this section) you may think about solutions at any resolution, anyway. You should incorporate a bit more GRACE insights here.

We have altered the wording on this section. And yes, I agree that it’s interesting to think about how even higher-resolutions would affect things. That is why the 120 and even 180 simulations were run.

9.) page 1328, line 11: "quadrature summed" sounds odd to me.

This is a statistics term for taking the square root of the sum of squares (ie: the standard method of combining two or more error estimates). Often you run across the phrase “combined in quadrature” instead, so I altered the phrase to that in the paper, in an attempt to be clearer. I am not sure what else to call it, otherwise.

10.) Line 15 "SNR increases everywhere". Incorrect, as far as the figure shows for basin 2.

I have added this technicality into the document.

10.) page 1329, line 19-21: The argumentation is not convincing. Large north-south elongated SMB basins are as well prone to absorb stripes.

That is true, but all of the Greenland SMB basins I use are significantly wider than the glacier basins (see Fig 2). However, to be more precise, I have added the term “wider” into the phrase in question.

11.) page 1330, line 10: The sentence about the 90 x 90 resolution has limited sense, given the existence of such solutions.

Good point. I have altered the line to say simply: “A 90x90 spatial resolution is achievable for GRACE or for a future satellite gravity mission.”

12.) Fig. 13) looks like the signal consists of two grid cells, contrary to the explanation in the main text.

There is no figure 13. I’m sorry, but I don’t know what you refer to. If you mean Fig 1, the text reads: “The glacial basins are each dominated by a single 1°x1° grid cell, with 1-3 non-zero neighboring cells whose weights are defined by modeled ice loss rates.” This shows the basin with one central cell and one smaller neighboring cell.

13.) Fig. 10b: wrong ordinate axis label

Oops. Thanks.

I appreciate your time,

Jennifer Bonin

Quantifying the resolution level where the GRACE satellites can separate Greenland's glacial mass balance from surface mass balance

J. A. Bonin[1] and D. P. Chambers[1]

[1]{College of Marine Science, University of South Florida, Tampa, Florida}

Correspondence to: J. A. Bonin (jbonin@mail.usf.edu)

Abstract

Mass change over Greenland can be caused by either changes in the glacial dynamic mass balance (DMB) or the surface mass balance (SMB). The GRACE satellite gravity mission cannot directly separate the two physical causes because it measures the sum of the entire mass column with limited spatial resolution. We demonstrate one theoretical way to indirectly separate cumulative SMB from DMB with GRACE, using a least squares inversion technique with knowledge of the location of the glaciers. However, we find that the limited 60x60 spherical harmonic representation of current GRACE data does not provide sufficient resolution to adequately accomplish the task. We determine that at a maximum degree/order of 90x90 or above, a noise-free gravity measurement could theoretically separate the SMB from DMB signals. However, current GRACE satellite errors are too large at present to separate the signals. A noise reduction of a factor of 10 at a resolution of 90x90 would provide the accuracy needed for the interannual cumulative SMB and DMB to be accurately separated.

1 Introduction

Mass change occurring over the ice sheets can be divided into two parts: changes due to dynamical responses of glaciers (thinning and calving), and changes due to large-scale patterns in surface melting, runoff, sublimation, and precipitation. The glacial response is known as dynamic

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mass balance (DMB), while the atmospherically forced signal is the surface mass balance (SMB). These two types of mass change are typically modeled or measured separately. One exception to this rule is when the ice sheet mass balance is measured by satellite gravity, such as the Gravity Recovery And Climate Experiment (GRACE); these measurements are sensitive to the sum of all mass changes, without the direct ability to separate one cause from another. In this paper, we demonstrate one theoretical way to separate cumulative SMB from DMB using GRACE, based on a priori knowledge of glacier locations on the ice sheet. Using simulations, we determine the GRACE spatial resolution needed to separate cumulative DMB and SMB around large glaciers within acceptable error limits.

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In recent years, inverse least squares estimation techniques have been used to localize the smoothed signal observed by GRACE into more precise, geophysically-relevant regions [Schrama and Wouters, 2011; Jacob et al., 2012; Sasgen et al., 2012; Bonin and Chambers, 2013; Luthcke et al., 2013; Wouters et al., 2013]. Most often, these techniques have focused on the mass change over all of Greenland, or else within 8-16 large drainage basins covering the island. We expand this technique to include regions designed to contain the mass signal of the largest of Greenland's glaciers: Kangerdlugssuaq, Helheim, and Jakobshavn. These glacial regions experience two different physical processes atop each other: the localized DMB signal and the broader-scale SMB signal. Unlike most places in Greenland, the DMB signals in Kangerdlugssuaq, Helheim, and Jakobshavn glaciers are expected to be larger than the local SMB signal. That fact allows us to potentially separate the dynamical effects from the SMB effects in these regions, by making a pair of assumptions. First, since SMB is correlated over fairly large regions, we assume that the SMB signal across each of the large glaciers is similar to the SMB just outside the glacier. Second, we assume that any local signal within the glacier region which is not defined by the broader SMB signal is caused by glacial dynamics. The latter is a reasonable assumption in the case of these three glaciers, due to the relatively large size of the expected DMB signal compared to discrepancies in local SMB relative to nearby SMB. This allows us to use two overlapping basins to separate the two independent signals: first, a large SMB basin, similar to those used in previous studies, and second, a small glacial basin covering only the area just around the glacier. The smaller basin is designed to trap the localized signal, which we know to be mostly caused by the DMB, while the larger basin will trap the underlying larger-scale signal, which we know to be mostly caused by the SMB.

From a purely mathematical perspective, the least squares approach should be able to separate a localized signal (DMB) from a wider-spread signal (SMB). However, Bonin and Chambers [2013] found out via simulation that estimating mass change via an inversion modeling method, even over relatively large SMB basins, can result in trend errors of ~20% of the long-term trend signal in basins losing the most mass and approaching 100% of the trend signal in more stable basins. All else equal, the smaller the area, the greater the uncertainty in the inversion results. Because of the relatively small spatial scale of even the largest glaciers, the DMB has not previously been computed using this technique.

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A significant reason inversion techniques give weak results in very small areas is due to the innate limited spatial resolution of the GRACE Release-05 (RL05) data. At GRACE's typical maximum degree/order of only 60, a strong spatially-localized signal is effectively indistinguishable from a weaker, more spread-out signal. However, at higher maximum degrees, such signals become distinct (Fig. 1) – and thus, should become separable by the least squares inversion process. However, this benefit must be balanced with the cost of greater satellite errors at higher degrees. We thus aim to answer two questions. First, how high of a maximum degree/order of gravity coefficients is needed to separate the localized, large-magnitude DMB from the broader-scale, smaller-magnitude SMB? Second, what level of satellite errors is required for current or future satellite gravity missions to separate the signals with reasonable uncertainty? In this paper, we design a series of GRACE-like simulation sets with known "truth" values to test this.

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2 Description of Inversion Method

Throughout this paper, we use a modified version of the least squares inversion method described mathematically in Bonin and Chambers [2013]. This technique uses a set of pre-defined "basin" shapes on a 1°x1° grid, including all of Greenland as well as the surrounding land and ocean area.

Each basin, i, has a pre-defined internal mass distribution assumed; using those weights, its smoothed appearance at a particular spherical harmonic resolution, $w_i(\phi,\lambda)$, is computed. The goal is to determine the appropriate multiplier, a_i, for each basin, such that when converted to spherical harmonics, the set of multipliers times the shape and weight of the smoothed basins results in as close a match as possible to the simulated GRACE observations.

Mathematically, this can be written as a set of models for each latitude and longitude (ϕ,λ):

$$model(\phi,\lambda) = \sum_{i=1}^{N\,basins} a_i * w_i(\phi,\lambda) \qquad (1)$$

Or, in matrix form, using n basins:

$$model(\phi,\lambda) = \begin{bmatrix} w_1(\phi,\lambda) & w_2(\phi,\lambda) & \ldots & w_n(\phi,\lambda) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \ldots \\ a_n \end{bmatrix} = H(\phi,\lambda)\mathbf{a} \qquad (2)$$

We can then stack the matrices $H(\phi,\lambda)$ for all m grid cells to form an mxn matrix $\mathbf{H}$, containing all the smoothed weight information. Given the array, $\mathbf{y}$, of simulated GRACE observations, we can estimate the array of optimal amplitudes, $\mathbf{a}$, using the least squares normal equations:

$$\mathbf{a} = (\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{y} \qquad (3)$$

We use 13 SMB basins covering Greenland (Fig. 2). These are relatively large-scale drainage basins of the area, with the coastal regions separated from the interior. To this we add 13 external basins: 4 local ocean regions and 9 nearby land regions. The latter specifically include nearby Iceland, Ellesmere Island, and Baffin Island, all of which are known to have large ice mass imbalances themselves. Unlike in Bonin and Chambers [2013], we add to this a set of three glacial basins, which overlap the SMB territory. These define three of the most significant glaciers in Greenland: Kangerdlugssuaq, Helheim, and Jakobshavn. The former two glaciers lay entirely atop SMB basin 4, while Jakobshavn is atop basin 7. While these additional three basins

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do not include many other areas of active glacier dynamics, the very large signal size of these three glaciers makes them a good test case for determining if the effect of glacier dynamics could be backed out using GRACE and an inversion technique. Additional glacial basins can be added, as desired, in the future.

In Bonin and Chambers [2013], we assumed that mass was distributed evenly within each individual basin. However, that assumption was only accurate to first order, since the SMB is dominated by higher losses near the coast. Here, we instead weight the 8 external Greenland SMB basins (1-8), Iceland, Ellesmere Island, and Baffin Island to accentuate coastal mass change. We compute the weights using data from the RACMO2 regional climate model [Ettema et al., 2009b]. By summing RACMO2's SMB data from 2002-2012, then removing the mean at each location, we get grids of cumulative SMB anomaly, similar to GRACE's monthly mass anomalies. We use the RMS of this RACMO2 cumulative SMB data as the weights for our external Greenland basins. The internal Greenland SMB basins and other external basins are still assumed to have uniform mass distribution. The glacial basins are each dominated by a single 1°x1° grid cell, with 1-3 non-zero neighboring cells whose weights are defined by modeled ice loss rates (see Fig. 4a) [Price et al., 2011]. We do not assume that the actual modeled time series of glacial mass loss is correct, but merely use the model to determine the relative likely distribution of mass loss in neighboring grid cells, compared to loss within the central cell.

Although in Bonin and Chambers [2013] we determined that a diagonal constraint matrix assisted in the optimization, experimentation since has demonstrated that when using non-uniform basin weights, such "process noise" does not improve accuracy. As such, our least squares inversion technique computes the set of optimal basin multipliers using no additional constraints or regularization.

3 Definition of the simulation sets

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Our primary goal is to quantify the accuracy of the least squares inversion method, given a fixed set of pre-defined basins and basin weights. We do this by creating multiple 1°x1°-gridded "truth" simulations, converting them to (smoother) spherical harmonics, and then running them through the inversion process. The difference between the inverted basin amplitudes and the basin averages of the 1°x1° "truth" input gives the solution accuracy. We create multiple simulations to prevent coincidental similarities between the input spatial distribution and the basin weights definition from affecting the results in a way which might not occur regularly in reality.

Each simulation contains three parts: a cumulative SMB signal (Sect. 3.1), a cumulative DMB signal (Sect. 3.2), and an estimate of GRACE stripe errors (Sect. 3.3). The combination of these three pieces results in as full a simulation to the truth as we can create. By varying the SMB and DMB signals in the next two sections, we can determine the impact that misfits in the spatial distribution of the basin weights and the two ice mass signals have on the least squares results. The variation in satellite errors allows us a better statistical handle on the likely effect of the GRACE stripes. Summed together, we can determine if the combined errors are small enough to create a meaningful estimate of the truth signal – and therefore learn if this inversion technique can be used to correctly separate the SMB from DMB signals in this region.

3.1 SMB-Only simulation definition

The "SMB-only" simulations actually include the land hydrology and oceanography signals as well as the SMB. (We call them SMB-"only" since, over Greenland, the signal is "only" SMB, not DMB or stripes.) The hydrology model used is the average of the GLDAS-Noah [Rodell et al., 2004] and WGHM [Döll et al., 2003] models. Over the oceans, we use the JPL_ECCO ocean model, run at the Jet Propulsion Laboratory (JPL) as a contribution to the Estimating the Circulation and Climate of the Ocean (ECCO), and available at http://grace.jpl.nasa.gov. It is a baroclinic model based on the MIT general circulation model [Marshall et al., 2007], forced by

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winds, heat flux, and freshwater fluxes from the National Center for Environmental Prediction (NCEP) operational analyses products and also assimilates satellite altimetry and other in situ observations [Fukumori, 2002; Kim et al., 2007].

To this, we add a SMB simulation. Since we had already used RACMO2 to compute the SMB basin weights, we could not directly use it to test the errors caused by misfits of those weights. So we chose to simulate plausible cumulative SMB signals, using RACMO2 as a baseline. We separated the actual 2002-2012 RACMO2 signal into a long-term trend, a 12-month climatology, and the remaining residual. The long-term trend and monthly climatology together make up 83% of the RACMO2 cumulative SMB variability across Greenland, including over 95% of the coastal signal, making them the dominant terms in need of careful reproduction. The residual part contains both sub-annual variability and interannual variability, the latter of which is especially important in mass estimates over Greenland due to its connection with long-term climate change. For the SMB part of our simulations, we sought to mimic the trend, monthly climatology, and residual parts of the cumulative SMB signal by creating semi-randomized "truth" simulations which vary realistically but randomly from the mass distribution used in our basin weights, using the following two-part method.

3.1.1 SMB simulation: trends and monthly climatology

We created altered versions of the trends and monthly climatology maps, by varying the cumulative SMB signals away from the RACMO2 trends and climatology in a random but physically-meaningful manner. To do so, we began by estimated typical correlative length scales, $n(\phi,\lambda)$, at each grid point from the RACMO2 cumulative SMB data. This defines the square of grid cells ($\pm n°$ in each direction) where the average difference from the target grid cell is at least 60% the target value itself. We computed length scales from the trend and monthly climatology maps, then averaged those 13 estimates and used that "typical" value for $n(\phi,\lambda)$. Length scales are generally larger among mass signals in interior Greenland than near the more highly-variable coasts (Fig 3a).

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We then created generic randomized maps, $r(\phi,\lambda)$, with correlative length scales similar to those of RACMO2's trend and climatology. We first filled each map with purely random values in each 1°x1° land grid cell, then replaced each grid cell with the average value within its local length scale. The smoothed grid was normalized to a mean of 0 and standard deviation of 1 across all grid cells (Fig. 3b).

We then took each actual RACMO2 trend/climatology map, $x^{RACMO}(\phi,\lambda)$, and perturbed it by a constant, α, times one of the spatially-correlated random maps, $r(\phi,\lambda)$:

$$x^{SIM}(\phi,\lambda) = x^{RACMO2}(\phi,\lambda) + \alpha * r(\phi,\lambda) * \left| x^{RACMO2}(\phi,\lambda) \right| \quad (4)$$

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We chose α=0.5, or a variability of 50% away from the original signal in any 1°x1° bin. Fig. 3c shows an example of this technique on the trends, after subtracting off the original RACMO2 trends for visibility's sake. This technique means the high-signal coastal areas contain most of the variation, while the quieter interior of Greenland is adjusted with smaller variations away from the expected trends. The signals are not identical to RACMO2, but their differences are spatially correlated, as would be expected from physical processes such as changes in regional temperature and melting, or in precipitation. Fifty different 1°x1° gridded simulations of trends and climatology were created over Greenland, Iceland, and the ice-covered parts of Ellesmere and Baffin Islands.

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For both trends and climatology, we are probably creating a conservative estimate, since RACMO2 has been determined to have much less than 50% error [Ettema et al., 2009a]. However, error estimates in such studies have focused on the errors in the total mass change over all of Greenland, not the mass change in a far smaller area like a single grid cell. Since positive and negative errors will tend to average out over large areas, we presume that local 1°x1°

RACMO2 errors will be significantly larger than global ones. Since we have no information on how much larger the local errors really are, we choose to err on the side of caution and create differences away from our basin weights larger than what we are likely to encounter in reality.

3.1.2 SMB simulation: sub-annual and interannual variability

While the trends and climatology describe the strongest parts of the RACMO2 cumulative SMB estimate, 17% of its variance is driven at other frequencies, including significant interannual variability. To simulate both higher- and lower-frequency variability in the simulated data, we used a random walk process. We first created a series of the random, locally-correlated maps described previously, one for each desired month of simulated data. We then used an autoregressive process such that the simulation at month i+1, x_{i+1}^{SIM}, is a weighted combination of that month's random map, $r(\phi,\lambda)$, and the final map of the previous month, x_i^{SIM}:

$$x_{i+1}^{SIM}(\lambda,\phi)=\beta*x_i^{SIM}(\lambda,\phi)+\left[1-\beta\right]*r(\lambda,\phi) \qquad (5)$$

For β, we used the local autocorrelation of the RACMO2 residuals at a one-month lag (Fig. 3d), which is typically over 0.9. Once the entire randomized time series was created, we removed the mean and multiplied each grid cell by the standard deviation of the RACMO residual (excluding trend and climatology) in each grid cell. This gives the coastlines more variability, as they have in reality, while retaining spatial correlations with the nearby grid cells and temporal correlations with neighboring months.

Each cumulative SMB simulation series is made from the summation of trend, climatology, and random-walk pieces, for each month. We created 50 simulations of 11 years of cumulative SMB simulation, designed to represent the GRACE years 2002-2012. To these, we added the modeled hydrology and oceanography series, to form the final "SMB-only" simulation "truth" series. We transformed these into spherical harmonic representations of maximum degree/order 60, 75, 90,

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120, and 180 for use in the least squares inversion process. The difference between the inverted results of the SMB-only simulations will estimate the sensitivity of the least squares process to imperfect SMB basin definition and weights.

3.2 DMB-Only simulation definition

In comparison, the set of simulated cumulative DMB signal is artificially simple. We considered using a random walk process, similar to that used in the residual SMB simulation, but decided to avoid such unnecessary complexity. Firstly, we did not have access to good, monthly measurements of the mass signal in any of the three glaciers we were looking at, so we had no clear estimate of the expected variability, particularly at sub-annual frequencies. Secondly, the glacial basins are only 2-4 grid cells in size, and are each dominated by a single central grid cell, so there is minimal concern about signal overlap from nearby glacial bins with vastly different temporal signals. Instead, we kept things simple and manufactured a piecewise linear "truth" signal for each glacial basin (Fig. 4c). The simulated DMB signal is of roughly comparable magnitude to modeled estimates [Howat et al., 2011] and is thus much larger than the cumulative SMB signal is, though across a far smaller area. Everything outside the near-glacier regions in Fig. 4a is set to zero (since the signals there are already included in the "SMB-only" simulations).

We expect misfit errors from the cumulative DMB to arise from the imperfect basin weightings we gave to the non-central glacier cells. To test how large an effect that has, we created an ensemble of 50 simulated cumulative DMB series, each to maximum degree/order 60, 75, 90, 120, and 180. Each run has the same total DMB signal per glacier, but we altered the spatial distribution of that signal slightly each time (for example, Fig. 4b vs. Fig. 4a), via the following method.

We first computed the average weight originally given to the non-central grid cells (W_{sides}) during the definition of the glacier basins. We then altered the glacier's original grid cells (including the central cell) by adding half of W_{sides} times a random value (computed with a mean of 0 and

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variance of 1). Those neighboring grid cells which originally had zero weights were shifted away from zero by randomized weights a tenth as large as W_{sides}. The new weights around the glacier were then summed and normalized by the original sum of weights. This results in the total DMB signal strength distributed differently spatially among the 50 DMB simulations, and always non-identically to the glacier basin weights. The difference between the inverted results of the DMB-only simulations will estimate the sensitivity of the least squares process to imperfect glacier basin weights.

3.3 Stripe-Only simulation definition

Since north-south stripe errors dominate any individual map made from unconstrained, unsmoothed GRACE data, we have created a series of simulated stripes to approximate their impact on the least squares inversion results. The stripe simulation technique is based on an observation by Swenson and Wahr [2006] that due to the north-south stripes, same-order odd-degree harmonics tend to correlate, as do same-order even-degree harmonics. Bonin and Chambers [2013] demonstrated that, given the real GRACE variances at each spherical harmonic as well as correlations with other harmonics, one can make randomized sets of simulated "GRACE-like" stripes.

We use the variances and correlations from the standard RL05 GRACE solutions from the Center for Space Research (CSR), with the AOD1B ocean dealiasing monthly averages added back. We create stripe-only simulations from harmonic cases 60x60, 96x96, and 120x120. The first two series are freely available on the Physical Oceanography Distributed Active Archive Center (PODAAC) website (ftp://podaac.jpl.nasa.gov/allData/grace/L2), while the latter is an experimental case run in the same manner and kindly provided by Himanshu Save at CSR. Despite the slight mismatch in maximum degree, we represent the errors for the 90x90 simulation cases with the 96x96 stripes.

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To best simulate stripe errors, we remove as much of the geophysical signal as possible, to end with what we hope is mostly errors in GRACE. Thus, we removed the ocean and hydrology models used previously, as well as the RACMO2 model over Greenland and Antarctica. None of these models are perfect, so we fit a mean, trend, annual, and semiannual signal to what remained. We know that much of the remaining trend and annual signal is important geophysical signal, but some stripes also fall into those categories. To further separate that, we pulled aside only the trend/annual components of the harmonics which explained at least 50% of that harmonic's full variability. That fraction is added to the "model" and removed from the "residual". The result is a set of "model" maps that do not visibly show stripes, and a set of "residual" maps that are heavily dominated by stripes (Fig. 5a and 5b).

We calculated the actual variance and harmonic cross-correlations from these residual GRACE series, then used the technique in Bonin and Chambers [2013] to make randomized sets of north-south stripes with approximately the same spatial distribution as what is actually seen in GRACE (Fig. 5c). We created 50 randomized variations of the stripes for each GRACE series (degrees 60, 96, and 120). The stripe simulation technique begins to break down at high degrees/orders, overweighting the stripe amplitude within ~5° of the poles at maximum degree 96 and ~10° of the poles at maximum degree 120. To reduce this false effect, we were forced to apply a latitude-based normalization scheme for the 96x96 and especially the 120x120 simulated stripes. This reduced the simulations' bin-based RMS to levels matching the original stripe RMS for each maximum degree.

We chose to create simulated stripes, rather than directly use the residual signal as the GRACE errors because a close look at the residuals reveals that some probably-real interannual signal remains in several of the coastal Greenland basins, even after the trend/annual fit and removal. This is caused by an imperfect SMB/glacial model and the fact that not all remaining signal is perfectly linear or annual. In terms of the simulated stripes, it implies that our stripe estimates will tend to somewhat overstate the true north-south stripes, since the variance of the remaining

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interannual signal will go into simulated stripes. This makes our stripe simulation a slightly conservative estimate of the expected GRACE errors.

Numerous techniques exist to reduce these stripe errors, including a variety of spatial smoothings, correlation-based destriping methods, and spatial and temporal constraints; however each necessarily impacts the signal along with the error. More critical to our interest here, they effectively reduce the spatial resolution of the GRACE data, by damping both error and signal at higher degrees/orders. To use any such post-processing method would undo the benefits of inverting a high-resolution series, making it more difficult to reach the needed resolution to separate SMB from DMB signals. As such, we choose to use no spatially-based stripe-reduction method.

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However, we do use one simple technique to reduce the errors at no spatial cost: applying a year-long temporal moving window to the data. This is useful since a majority of the stripe RMS occurs at periods of less than one year. For example, in the 120x120 case, removing the high-frequency temporal signal reduces the bin-by-bin stripe RMS to 15% or less their original size around the globe. Due to the way basin-scale analysis averages through stripes, this results in yearly-averaged stripe basin RMS values of only about one-third the size of the full stripe basin RMS. And while this will remove or dampen any high frequency "truth" signal, it is the longer-period Greenland ice mass signal we are most interested in for climate change, which means there is only a limited cost to removing some stripes in this way. All of the analysis in the following section uses yearly-smoothed data.

4 Analysis and Discussion

We thus have three sets of simulations, to test the three likely types of error in the least squares inversion process. The SMB-only simulation set will be used to test the impact that imperfect definitions of SMB basins and basin weights will have on the inverted results. The DMB-only

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simulation set will be used to test the impact that imperfect glacial basin weights will have on the inverted results. And lastly, the stripe-only simulation set will be used to test the impact that satellite errors have on the inverted results. Since our least squares inversion routine is perfectly linear, the errors of the inversion of a summed version of the three simulation pieces are the same as the sum of the inverted errors of the three individual pieces. However, by separating the simulation into three known pieces, we can determine from which part different errors arise, and thus learn which is the most limiting factor to getting accurate results using the least squares inversion technique over Greenland.

To do so, we used the least squares inversion method on each of the 50 SMB-only, 50 DMB-only, and 50 stripe-only simulation sets, for smoothed versions of maximum degrees 60, 75, 90, 120, and 180 each. For each inversion, we fit to the full set of SMB, glacial, and external basins. We then difference each simulation's estimated inverted basin amplitudes (a_i) from the original "truth" simulation averaged over each basin. To create easily-comparable statistics out of all this data, we compute the RMS of this difference for each simulation, then take the ensemble mean of that RMS difference for each group of 50 randomized simulations. We call this the "average basin error" in each location, for each simulation set.

In Sect. 4.1, we compare each SMB "truth" input to its inverted response, to determine the errors caused by using imperfect SMB basins in the least squares method. Sect. 4.2 similarly calculates the errors due to the imperfect glacier basins, and Sect. 4.3 shows a visualization of the sum of both types of basin misfit errors. In Sect. 4.4, we determine how large the satellite errors can be, when combined with the total basin misfit errors, to allow for a signal-to-noise ratio of 2. We then compute the RMS of GRACE's satellite errors, to determine if either the current GRACE or a future probable satellite gravity mission might be able to accurately separate the glacier signal from the SMB signal.

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4.1 Misfit errors due to imperfect SMB basin weights

Fig. 6 shows the average basin error from the SMB-only simulation set, for each of the 13 SMB basins and the 3 glacial basins, using yearly-averaged data. The effect of spatial resolution is seen clearly: with increasing maximum degree/order, the errors decrease. This demonstrates the ability of the least squares inversion technique to correctly partition SMB signal, so long as the basins it is trying to fit to are sufficiently resolvable by the limited set of spherical harmonics.

As the maximum degree is lowered, the biggest degradations are seen in basin 7 (which overlaps with Jakobshavn Glacier) and basin 4 (which overlaps with the other two glaciers), with particularly big changes seen as the maximum degree drops from 90 to 75 to 60. In the case of basin 7 and Jakobshavn Glacier, the two overlapping basins have large and consistently anti-correlated error time series, particularly in the 60x60 case. At low spatial resolution, the inversion technique cannot appropriately separate the spatial maps of basins 7 and Jakobshavn, and it tends to place some of the signal that belongs in one basin into the other. Similarly, basin 4's response reflects the errors from Helheim and Kangerdlugssuaq glaciers. We hypothesize that basin 7 sees a significantly stronger signal than basin 4 because it is the smallest of the SMB basins, and because a large percentage of its high-signal coastline is also covered by the Jakobshavn basin. In comparison, the SMB signal in basin 4 is more widely distributed than the nearby glacial DMB signals, it has a significant amount of area not also covered by the glacial basins, and its two glaciers are not losing mass at identical times and rates and may counter each other's effects at times.

Even near Jakobshavn, however, the strength of this error is highly sensitive to the spatial resolution used. For example, the basin 7 and Jakobshavn SMB-misfit errors are cut in half merely by increasing the spatial resolution from 60x60 to 75x75, and to a sixth by maximum degree/order 120. In practice, the worst of the errors caused by inexact SMB basin definitions could be avoided via an accurate higher-resolution GRACE series.

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4.2 Misfit errors due to imperfect Glacial basin weights

Fig. 7 shows the average basin errors from the DMB-only simulation set, for each of the 13 SMB basins and the 3 glacial basins, using yearly-averaged data. In most basins, increasing the maximum degree/order from 60 to 90 (or above) reduces the errors. However, in the critical basins 4 and 7 and the glaciers themselves, the situation is less simple. Basin 4 shows highest errors for the 75x75 cases, as do overlapping Helheim and Kangerdlugssuaq Glaciers. In basin 7, the errors are inverted to what we had expected, with larger errors occurring at higher spatial resolution. There is no physical explanation for this, though we have verified that the mathematics work: the least squares results do create a smoothed pattern which closely mimics the input DMB-only signal. We view this as an example of why simulations like this one are important: just because the least squares inversion gives an answer does not mean that answer is right! In any case, the size of these glacial basin weight misfits is an order of magnitude smaller than the SMB basin misfits, making this result of secondary impact.

4.3 Combined method errors due to imperfect SMB and Glacial basin weights

To visualize the relative size of the above misfit errors compared to the "truth" geophysical signals, we have plotted the inverted glacial signals from the 50 combinations of SMB and DMB simulations in Fig. 8. In the dark solid lines, we show the "truth" signal from each glacier basin, for comparison. The majority of the errors are driven by misfits between the SMB data and the pre-defined SMB basins, with only a small effect due to the misfit between the DMB data and the pre-defined glacial basins.

Fig. 8 demonstrates that the two types of basin weight misfit errors do not cause an insurmountable hurdle to our ability to separate the cumulative SMB from DMB signal. Error-free 60x60 solutions may not provide sufficient spatial resolution to clearly resolve interannual changes in glacial and non-glacial Greenland series, particularly in the Jakobshavn area, due to imperfections in basin definitions. However, 90x90 solutions would allow relatively small changes in inflection to be seen, if those solutions contained no satellite errors.

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4.4 Allowable vs. actual GRACE stripe errors

Unfortunately, GRACE observations do contain satellite errors. The RMS errors caused by inverting the stripe-only simulations, after yearly-smoothing, can be in Fig. 9. As expected, the errors increase as the maximum degree increases. The errors in the glacier basins are significant, and the errors in the SMB basins overlapping those glaciers grow very large, in comparison to the basin misfit errors (Figs. 6 and 7).

Fig. 10a shows the SMB-misfit and glacial-basin-misfit errors from the previous sections combined in quadrature. If GRACE had no satellite errors, Fig. 10b would be the signal-to-noise ratio (SNR) of the inversion technique, computed by dividing the basin RMS of the ideal "truth" SMB+DMB signal by these combined basin-misfit RMS errors. In this noise-free case, the SNR increases almost everywhere as spatial resolution improves. The SNR is below 1.0 (errors are larger than the signal) for most of the interior basins (9-13) at a maximum degree of 60, and improves slightly at higher resolutions.

Most of the coastal basins have SNRs greater than 5 at all maximum degrees. However, basin 7 has the lowest SNR of the coastal basins: 0.7 at maximum degree and only 2.3 by degree 90. Basin 4 gives nearly as poor a showing, with noise-free SNRs of 1.2 at 60x60 to 2.4 at 90x90 resolution. Even by maximum degree 180, the SMB basins which overlap the glaciers have expected noise-free SNRs of only a bit above 5. This is concerning since the basins nearest to the glaciers are in most need of accurate separation.

Now we consider the situation if GRACE satellite stripe errors are also included. To call the cumulative SMB from DMB signals separable, we require a minimum desired stripe-inclusive SNR of 2.0 – that is, the signal RMS must be at least twice the total error RMS of the stripes and basin misfit errors combined. In Fig. 10c, we show the maximum stripe errors which meet this SNR>2 goal, given the known basin misfit errors and "truth" signals. We compute this using:

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$$SNR = \frac{RMS_{truth}}{\sqrt{\left(RMS_{SMB}^2 + RMS_{DMB}^2\right) + RMS_{stripes}^2}} \geq 2 \qquad (6)$$

which gives:

$$RMS_{stripes} \leq \sqrt{0.25 RMS_{truth}^2 - \left(RMS_{SMB}^2 + RMS_{GMB}^2\right)} \qquad (7)$$

The maximum level of allowable stripes is largely independent of maximum degree/order, except in SMB basins 4 and 7. In those critical basins, it is impossible to get stripe-inclusive SNRs of 2.0 at a maximum degree of 75 or below, and at 90x90 the basins remain particularly sensitive to stripe errors. As Fig. 8 previously suggested, a spatial resolution of at least 90x90 is needed to correctly separate the SMB and DMB signals into their correct basins.

Unfortunately, the actual yearly-windowed inverted errors from the stripe-only simulations are large and grow larger quickly with increasing maximum degree/order (Fig. 9). Fig. 11 shows a direct comparison of the possible ranges of stripe errors which allow a stripe-inclusive SNR of at least 2 (green bars), relative to the actual RMS errors found from the stripes-only simulation. The non-glacier-overlapping SMB coastal basins of the 60x60 case all have stripe errors within the acceptable SNR>2 ranges, but by 120x120, the actual errors in all basins are much larger than needed to reach that target. In the critical glacier-overlapping basins, 4 and 7, a 60x60 solution cannot reach a SNR of 2, the 90x90 stripes are up to 10 times larger than the maximum allowable, and the 120x120 stripes are about 30 times too large. The trouble is two-fold: first, the GRACE stripe errors increase rapidly with degree, and second, the inversion technique preferentially dumps narrow signals, like stripes, into small basins, like the glacial basins, while "averaging through" more of the stripes over larger (and especially wider) basins. The allocation of stripe signal into glacier basins results in inverse signals allocated to SMB basins 4 and 7. This counters much of the local effect and best represents the short-wavelength stripe signals, but it also badly pollutes estimates of SMB and DMB there. The negative impact of the stripes is stronger than if the inversion was done using only SMB basins and had no places specifically allocated to catch the glacial DMB signal.

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5 Conclusions

A basin-based least squares inversion technique can theoretically be used to separate the cumulative SMB signal from the cumulative DMB signal in Greenland, assuming sufficient spatial resolution of the input data. We found that a maximum degree of 60x60 is insufficient for this task, particularly near Jakobshavn Glacier, but that a maximum degree of 90x90 can accomplish it with expected signal-to-noise ratios greater than 2 in all coastal SMB basins. Internal basins have smaller SNRs and may need to be combined into broader basins, if their far smaller mass distribution is to be correctly measured. The expected errors due to misfitting basin weights are small enough to clearly discern fairly small interannual changes in glacial signals, though we would expect weaker results for the SMB basins overlapping those glaciers. A 90x90 spatial resolution has already been achieved by today's GRACE and is plausible out of future satellite gravity missions as well.

Unfortunately, this is true in theory only. Realistically, when current GRACE noise estimates are included, a SNR > 2 is never achievable for the SMB basins where the three targeted glaciers are located. Since GRACE errors increase far faster with degree than the inversion method's basin-misfit errors decline, this problem becomes worse as the maximum degree of GRACE increases. There is no point where the misfit errors in the inversion method (highest at low degrees) balance with the satellite errors (lowest at low degrees) to allow a good SNR. If higher SNR levels than 2 are desired, the GRACE errors would need to be brought down even further, as they depend on the inverse square of the target SNR.

Significant stripe reduction could potentially allow for cumulative SMB and DMB to be separated using the least squares inversion method, particularly if errors are also reduced via temporal smoothing, as we have done here. Taking into account yearly averaging, the GRACE noises would need to be reduced by approximately a factor of 10 at 90x90 or 30 at 120x120. This noise reduction would need to be accomplished without altering or removing the high-spatial-resolution signal. We suspect that no post-processing scheme alone can currently

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accomplish this task, so the separation of the DMB from SMB using this method must await a new GRACE release or a future mission with smaller stripe errors.

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Acknowledgements

The authors want to express great thanks to Himanshu Save at the Center for Space Research in Austin, TX, for the use of his 120x120 solutions and error estimates, as well as his helpful commentary on the research.

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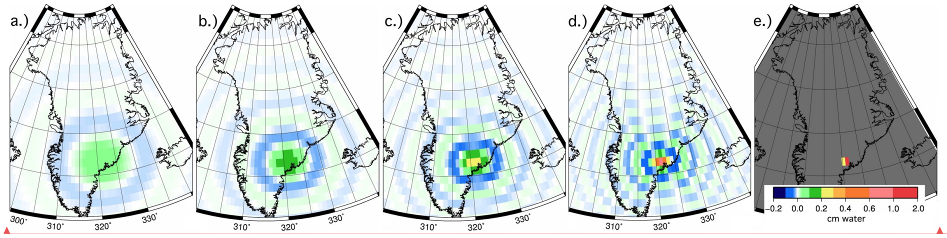

Figure 1: Impact of spatial resolution on the apparent shape and amplitude of a 1 cm signal over Helheim Glacier, given the apriori weight distribution in (e). Maximum degrees/orders are limited to (a) 60x60, (b) 90x90, (c) 120x120, (d) 180x180, and (e) the original 1x1 grid cells.

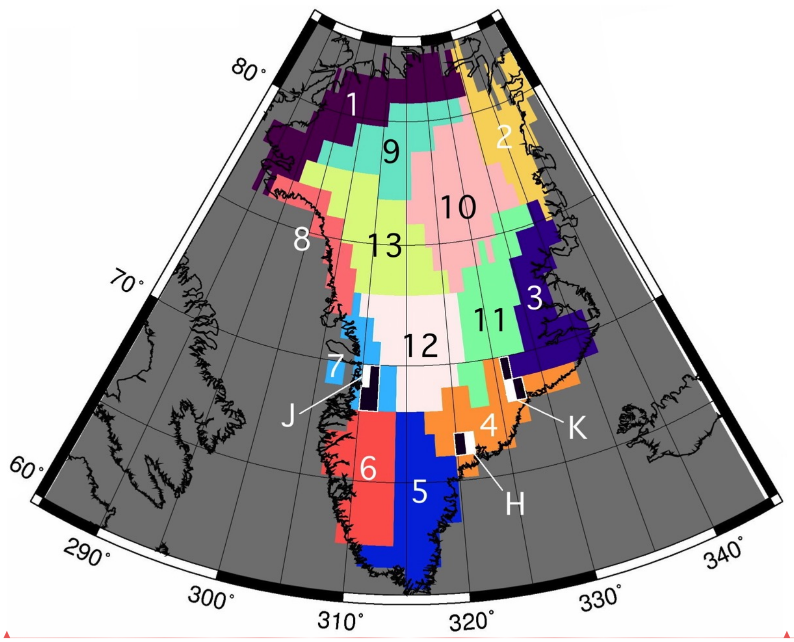

Figure 2: SMB and glacial basins for Greenland. Glacial basin (J)akobshavn overlaps with SMB basin 7, while (H)elheim and (K)angerdlugssuaq overlap basin 4. White grid cells show the central glacier cell, while black are lesser-weight glacier cells.

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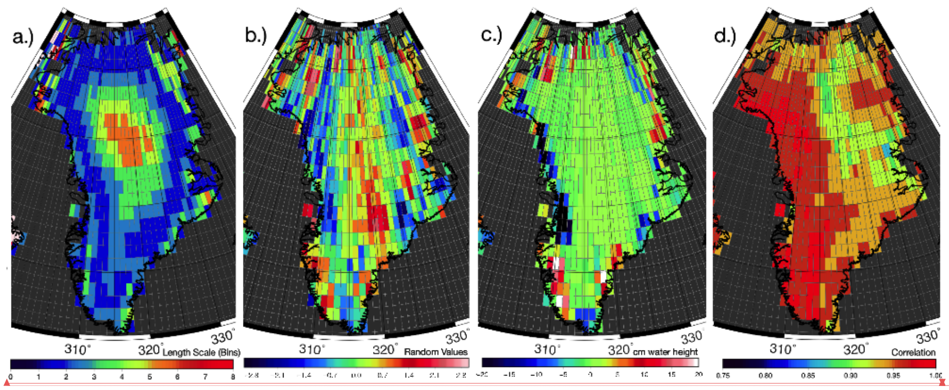


Figure 3: Example components of the simulation-building process: (a) the typical RACMO2 length scales as defined by the trend and climatology; an example of the random part of the trend signal made using this spatially-correlated randomization, before (b) and after (c) applying the RMS-based amplitude weighting; and (d) the one-month-lag autocorrelation of the RACMO2 residuals, used for the time component of the interannual and subannual simulation creation.

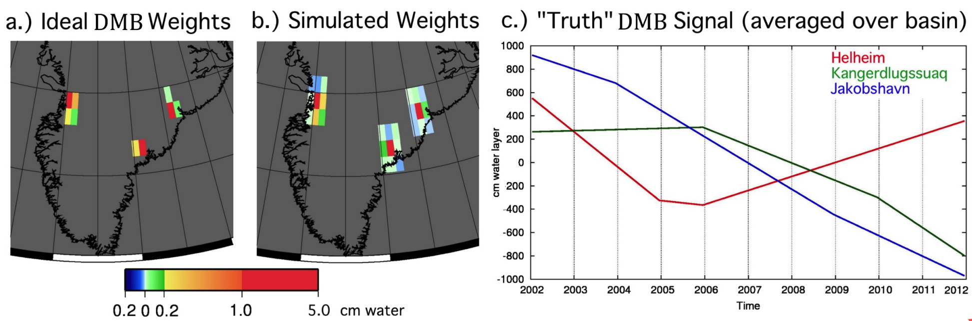
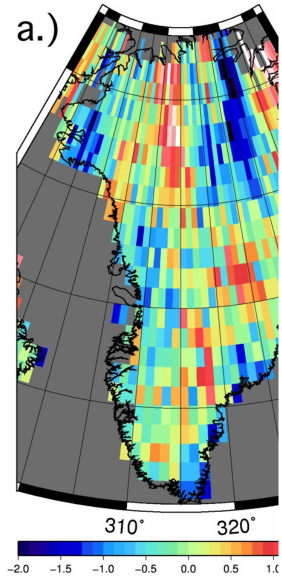


Figure 4: (a) Ideal DMB weights used as basin definitions, (b) an example of the relative weights used in the DMB 'truth' data, and (c) the 'truth' DMB signal for each glacier.



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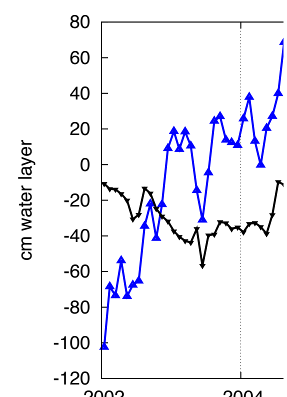

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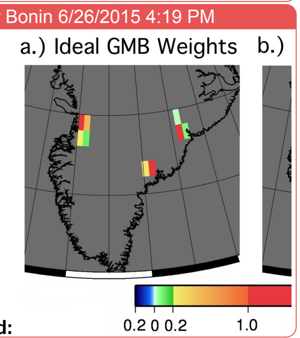

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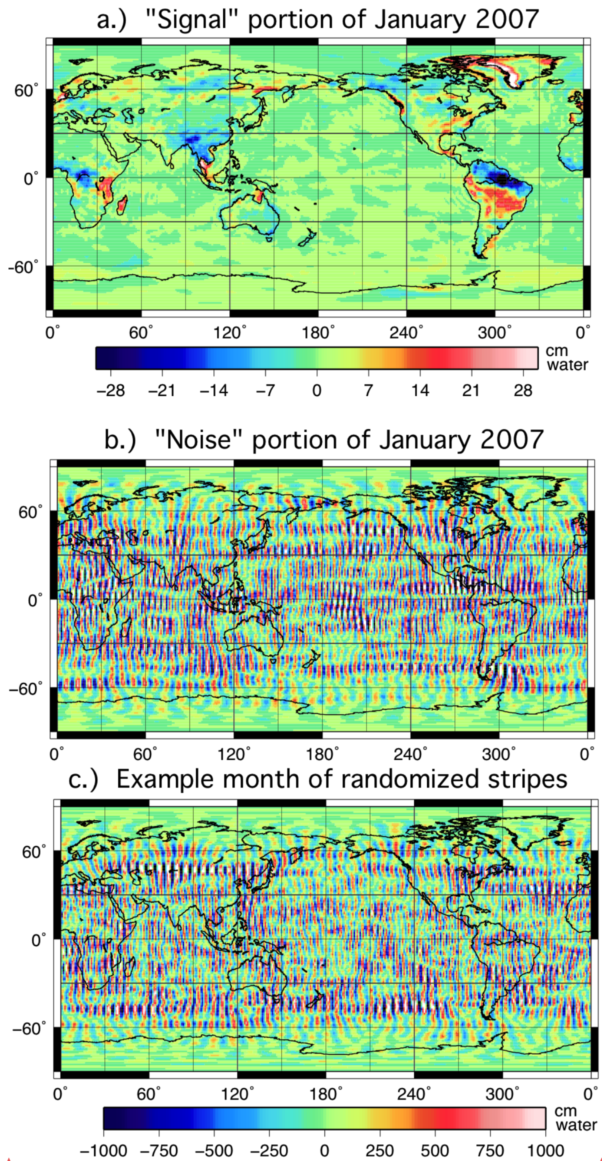

Figure 5: 96x96 (a) 'model' and (b) 'stripe residual' for January 2007, and (c) an example month of simulated 96x96 stripes.

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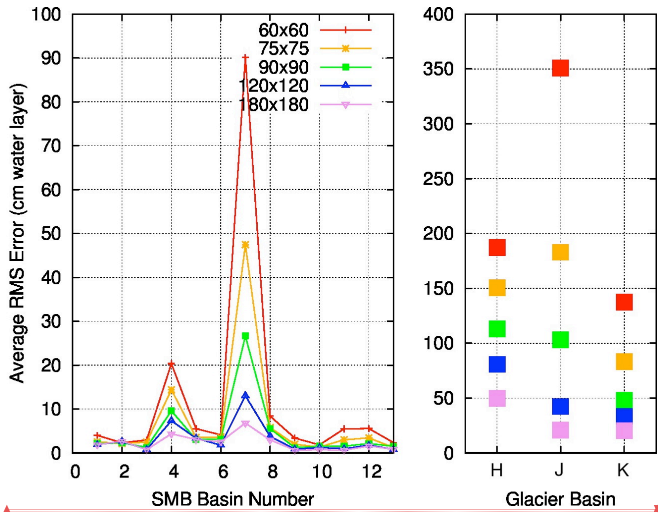


Figure 6: Average RMS difference from 'truth' per basin for the SMB-only simulations, for data of increasing maximum degree, in SMB basins and glacial basins. Yearly-windowing applied.

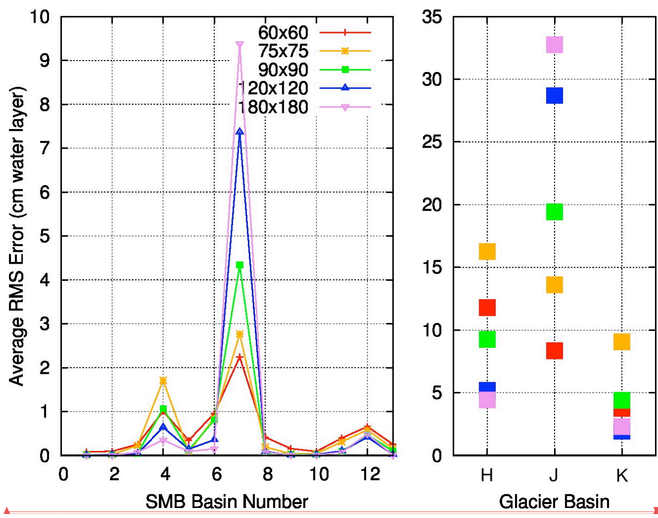
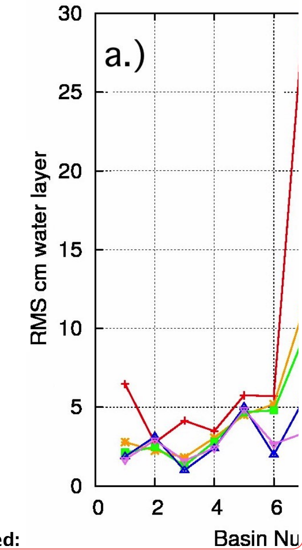


Figure 7: Average RMS difference from truth per basin for the DMB-only simulations, for data of increasing maximum degree, in SMB basins and glacial basins. Yearly-windowing applied.



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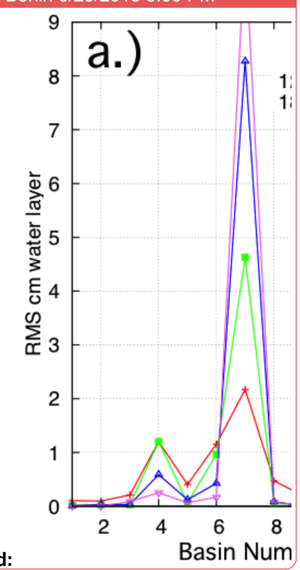

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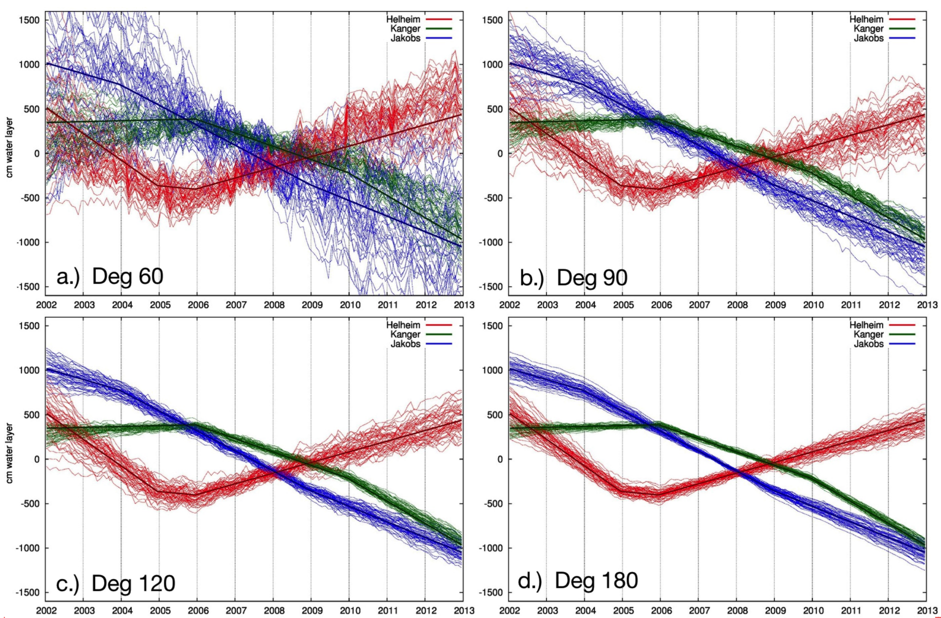

Figure 8: Visualization of the spread caused by the combined SMB and glacial basin misfit errors, at the three glaciers, for maximum degrees (a) 60x60, (b) 90x90, (c) 120x120, and (d) 180x180. Solid black lines denote the 'truth' simulated signal per basin.

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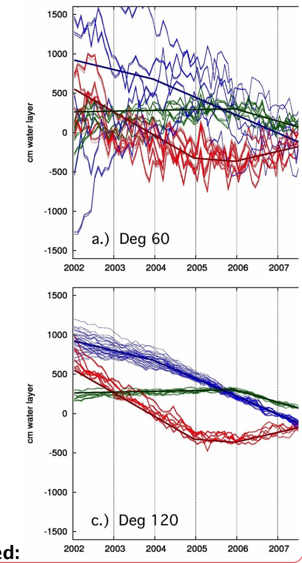

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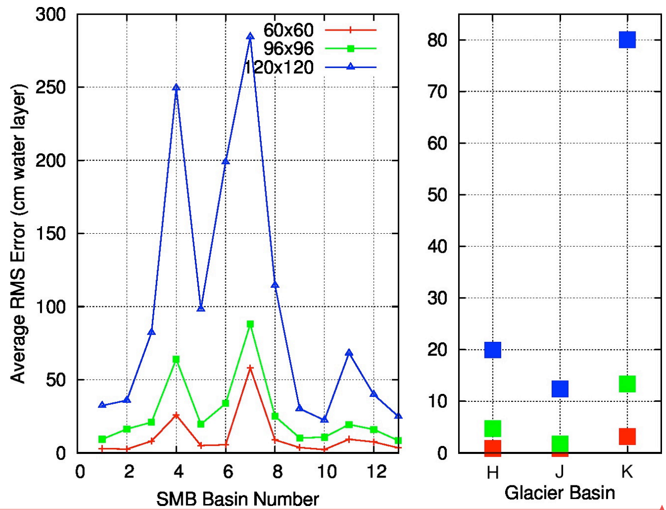

Figure 9: Average RMS error per basin for the noise-only simulations, for data of increasing maximum degree, in SMB basins and glacial basins. Yearly-windowing applied.

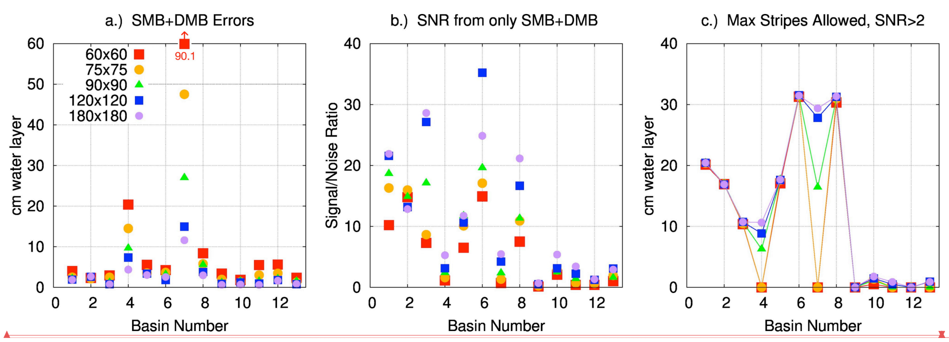

Figure 10: (a) Estimated errors caused by misfits between the SMB and DMB input data and the defined basin weights, (b) Signal-to-Noise Ratio using only the misfit errors, and (c) the maximum stripe level allowable to result in a SNR > 2 when stripes are included. All figures use yearly-windowed data.

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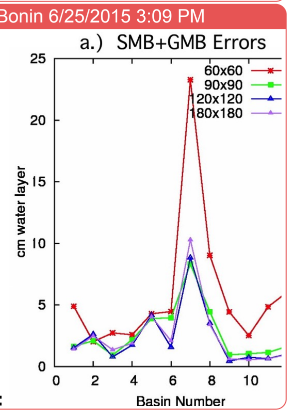

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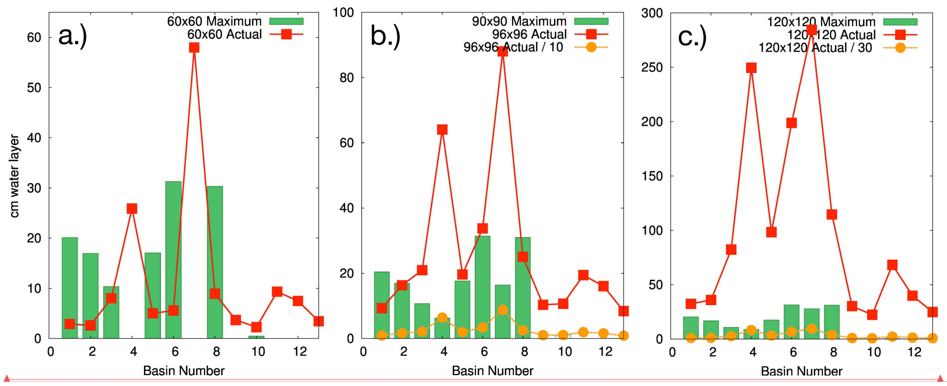

Figure 11: Comparison of maximum allowed stripes (green boxes) based on SNR > 2, and the actual estimated stripes per basin (red lines) for the (a) 60x60, (b) 90x90, and (c) 120x120 cases. For (b), the actual stripe signal is from the 96x96 GRACE runs. The orange dashed lines denote the actual stripes reduced by the factors of 3.5, 9, and 30, as needed to fall within the allowed values. All figures use yearly-windowed data.

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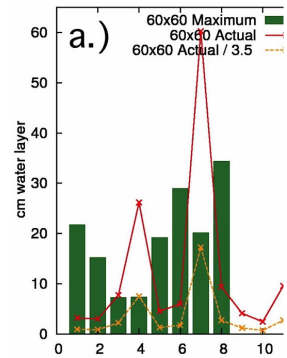

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