Response to Reviewer #1 (Matt King):

Thank you so much for your helpful review. Sorry it's taken me so long to get back to you on it. Let me see if I can respond to each of your main points.

1.) "Given the duplication of the C2,0 term, should not it be excluded from the comparison to GRACE?"

I think this is a really good point, since the influence of C20 is so large at the poles. You're right that using very similar C20 terms for GRACE and the Cheng SLR series might bias them toward each other for reasons that have nothing to do with GRACE itself. However, because the C20 terms are such a big part of the final signal, I didn't really want to produce this paper by totally excluding it. Instead, to answer your question, I decided to test what the impact of removing it was, to see if it was reducing the divergence I see between GRACE and the Cheng SLR series.

So I recreated each of the three main series (GRACE, Cheng 5x5 SLR and Sosnica 10x10 SLR) and totally omitted the C20 terms, then inverted each and took a look at the time series. If the C20 term was causing falsely alignment with GRACE, I would see a larger divergence between GRACE and the Cheng series, in which case, my paper would require revising.

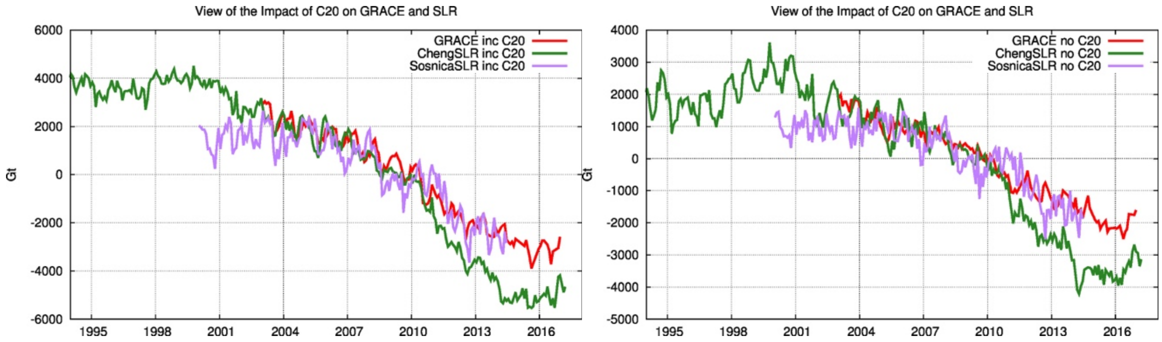


Figure 1: Left-hand image is the inversion with C20 included. Right-hand image is the inversion with C20 totally removed.

However, I see no notable changes in terms of divergence. There are three main effects of removing the C20 terms. First, the overall trend of all three of the series dropped like a rock. (No surprise, given the geometry of the situation.) Second, the month-to-month jitter in all three of the series changed. Third, most oddly, removing the C20 term from the Cheng series produced a large, visible annual signal before about 2007. The other series (including GRACE, using a similar C20) didn't show this impact. So that's bizarre. I assume that the C20 term in the Cheng series is coupled with some other term, to produce this (which wouldn't especially surprise its creators, since they're aware of the general coupling between harmonics caused by a barely solvable problem).

In any case, there was not any significant change in the interannual signal divergence. So in practice, the replacement of the GRACE C20 should bias GRACE towards the Cheng SLR series doesn't seem to have any major effect on the part of the spectrum that I'm worried about. That's a relief.

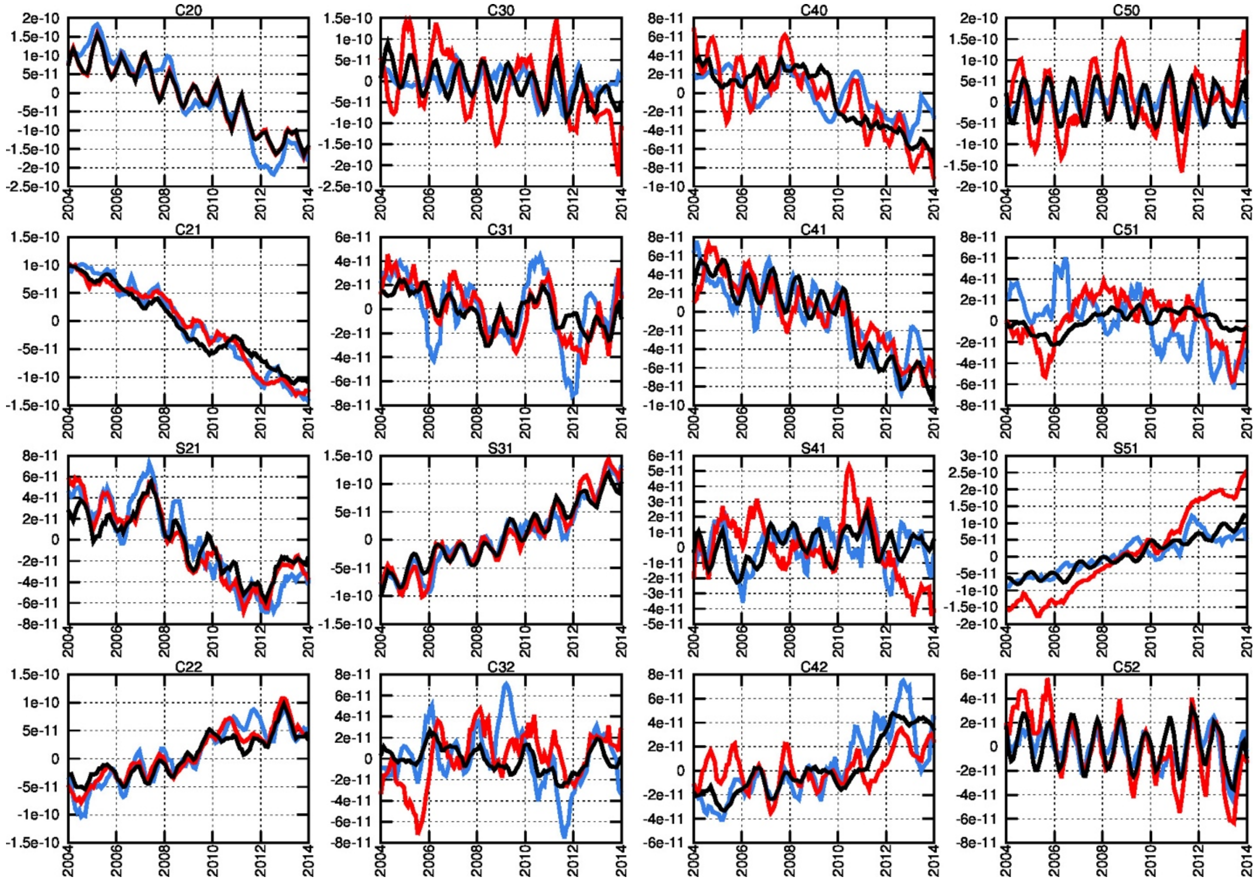
I have created the following commentary for the final version of the paper, briefly discussing this:

> We did consider the impact of replacing the GRACE C_{20} term with that from a series related to the Cheng 5x5 SLR data. To test whether this unfairly biased the Cheng 5x5 SLR results toward GRACE, we removed the C_{20} terms completely from all of the GRACE and SLR series, then inverted each of them again. Removing the impact of the equatorial bulge did greatly reduce the trend of each Greenland+Antarctica inverted series, but it did not significantly impact the interannual differences between GRACE and any SLR series. We thus conclude that the replacement of GRACE's C_{20} values is not a large contributing factor to these results.

Again, I want to thank you for this idea, since it was certainly a troublesome possibility.

2.) "It would be good to see in the supplement (degree, order)-specific time series comparisons for GRACE and SLR to see where the differences occur."

I have created this visual comparison (up to deg/ord 5) and will add it in the appendix for the final paper. For your immediate edification, here they are:


C20
2e-10
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
-2e-10
-2.5e-10
C30
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
-2e-10
-2.5e-10
C40
8e-11
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
-1e-10
C50
2e-10
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
-2e-10
C21
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
C31
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
C41
8e-11
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
-1e-10
C51
8e-11
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
S21
8e-11
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
S31
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
S41
6e-11
5e-11
4e-11
3e-11
2e-11
1e-11
0
-1e-11
-2e-11
-3e-11
-4e-11
-5e-11
S51
3e-10
2.5e-10
2e-10
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
-2e-10
C22
1.5e-10
1e-10
5e-11
0
-5e-11
-1e-10
-1.5e-10
C32
8e-11
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
C42
8e-11
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
C52
6e-11
4e-11
2e-11
0
-2e-11
-4e-11
-6e-11
-8e-11
2004
2006
2008
2010
2012
2014

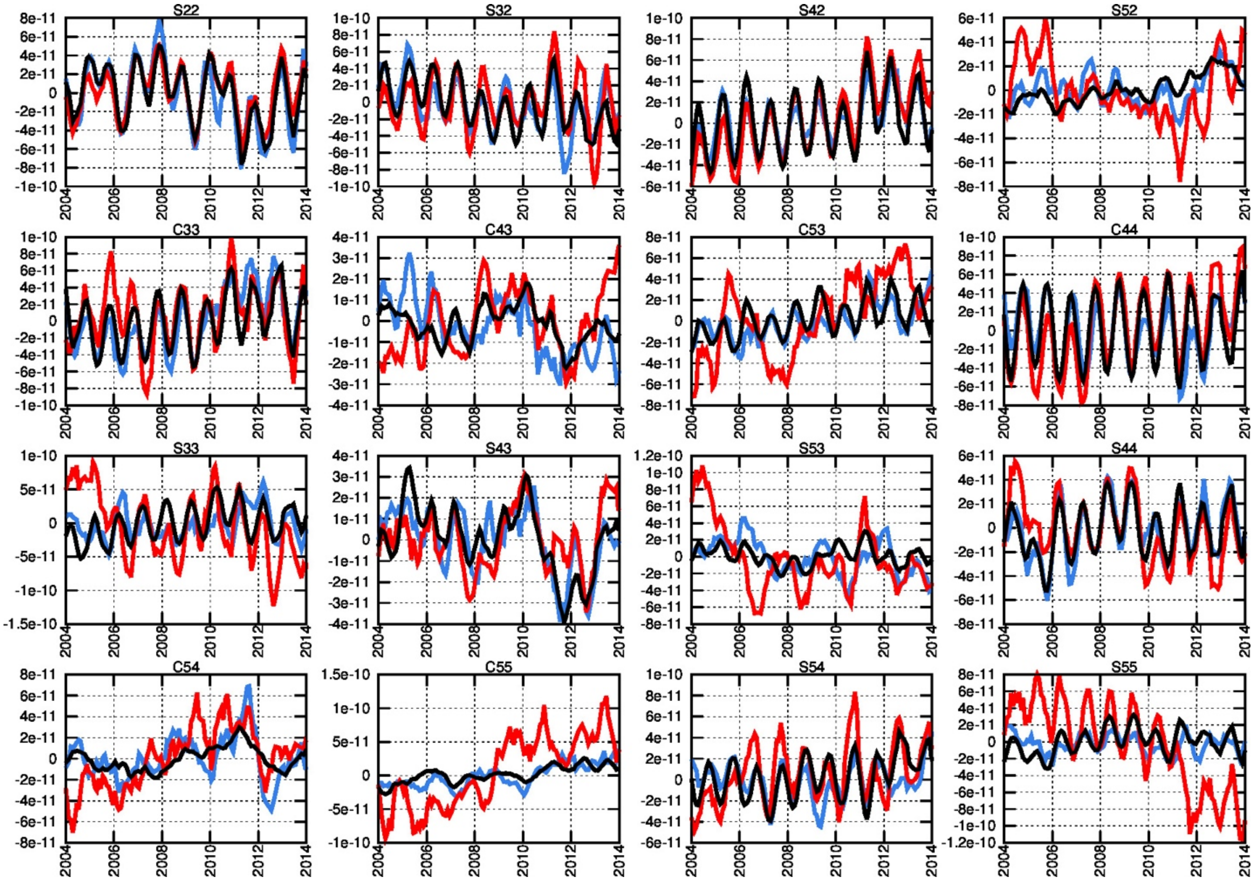


Figure 2: GRACE is in black, Cheng's SLR is in red, Sosnica's SLR is in blue.

3.) You are correct that Figure 1 in the main document (the percent variance explained) was given in terms of the proportion of the signal from 0 to 1, not as a real percentage. That's been changed, so the values in the figure go from 0 to 100%. I'll update for the final version of the paper. Thanks.

4.) "I wasn't sure if autocorrelation was really treated correctly - the authors assume it is diminished by 13-month averages and reduce the degrees-of-freedom appropriately but I think the assumption the series is white noise after this averaging (ie, uncorrelated). Exploration of the noise model by examining the spectra and fit of various noise models could be worth considering although I see an argument here that an exact specification of uncertainty is not the key message but the bias magnitudes…"

The error statistics given for our own solutions (ie: table 1) contain the assumption that the residual solution (after the mean, trend, annual, and semiannual terms are fit and removed) still contains a correlating signal. We assume an AR-1 method and estimate the errors based on that assumption. Based on the paper you recommended, this seems to be a reasonable assumption for Antarctica, and presumably Greenland as well.

I think, though, that maybe the statistic you were really worrying about was the comparison with the IMBIE data? Referring to that, we wrote: "The uncertainty here is based on the variance of the smoothed residuals about the fit, but also accounts for temporal correlation due to the 13-month smoothing already applied to the IMBIE data. This reduces degrees of freedom from 186 to 14, so inflates the error from the least squares fit by sqrt(186/14)."

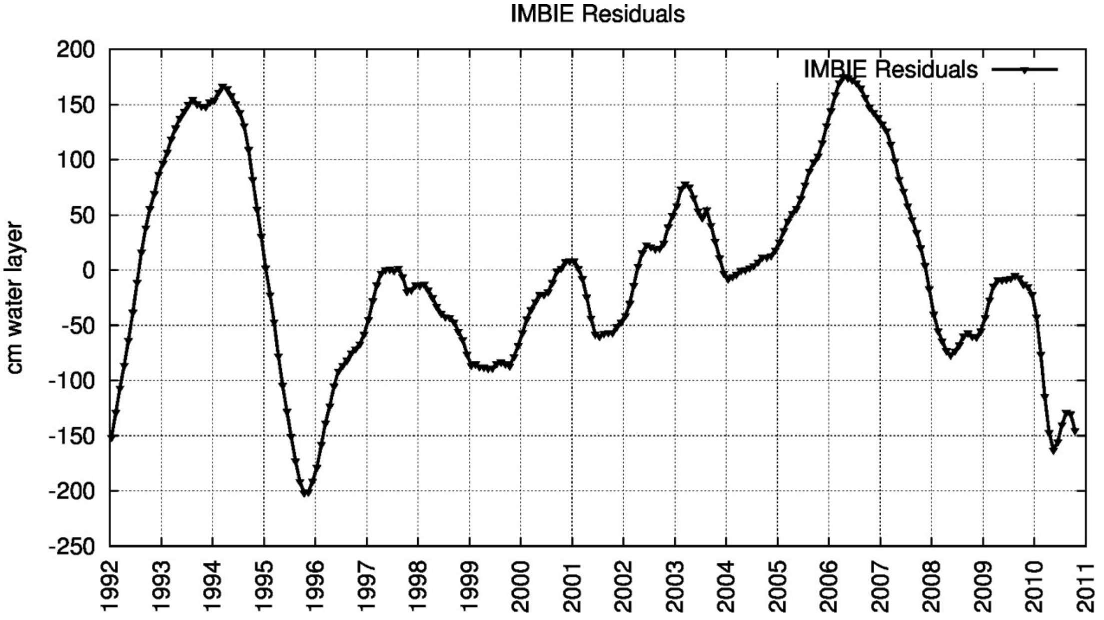


Figure 3: IMBIE inversion over GL+Ant, after removing a seven-parameter fit.

The sqrt(186/14) assumption described here only refers to the treatment of the IMBIE data, and is based on their claims of a 13-month temporal smoothing. A quick look at the IMBIE data after removing the acceleration, trend, annual, etc (above) shows a 3-4-year quasi-periodicity remaining, so I definitely agree that the signal left isn't actually white noise. To test whether the degrees-of-freedom reduction we used (based on a 13-month averaging) is "close enough", I computed the autocorrelation of the monthly IMBIE data (black line below). At a 13-month lag, the autocorrelation is 0.2. It actually crosses zero at about 16 months. I also checked to be sure that decoupling the "monthly" data points from the neighboring ones by using only every 12th point (colored lines) doesn't impact the autocorrelation significantly – and it doesn't.

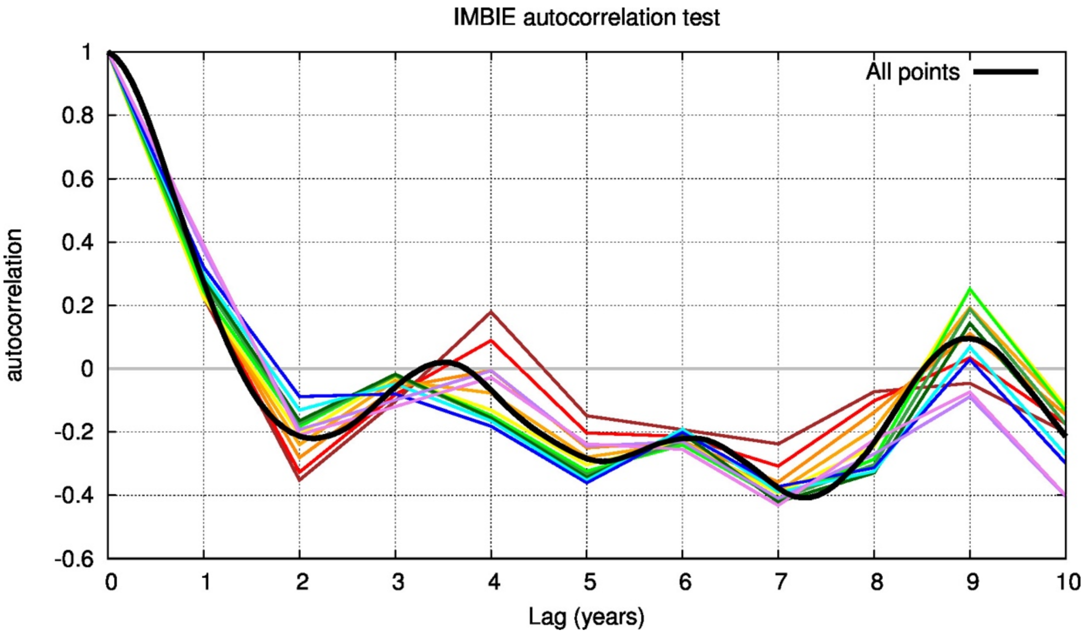


Figure 4: The colored lines are the autocorrelation using only every 12th point, which should not have been made dependent on each other due to the temporal smoothing. The black line is the autocorrelation using all the points.

So, technically, we should probably use a ratio of sqrt(186/11.6), leading to a weighting of the errors of 4.0 rather than 3.6. But since increasing the IMBIE errors won't impact the overall results of the paper, I doubt the detail is worth explaining the added complexity to readers (as you noted). If you feel strongly about this, though, we can change it.

(Overall, by the way, I agree with the paper you recommended: we too often assume that everything other than the mean, trend, annual, semiannual, and tidal aliases is "noise". Some sort of assumption for a low-frequency correlation seems more logical to me. Thanks for the link to the paper. I found it pleasantly clear to read, for a stats paper. Nice work.)

Thank you again for your excellent review. We appreciate the help!

-- Jennifer Bonin

Response to Reviewer #2 (Anonymous)

It has to be said that a related piece of work has recently appeared (Talpe et al. 2017)…

Yes. I also recently read this paper (and talked to the author), and put a brief note in the methods section of my appendix about the differences of method and similarities of general results that we found.

Replacement of C20 by SLR derived estimates This issue has already been mentioned by Matt King in his short comment. So this is to reconfirm that this issue also stroke me as somewhat tricky. By replacing C20 by an SLR-estimate a dependency is introduced which may be favorable for the CSR-SLR solution in the comparison. To clear this up, maybe the authors could show how much C20 contributes to the estimated time series.

As I also said to Matt, I think this is a good point, since the influence of C20 is so large at the poles. You're both right that using very similar C20 terms for GRACE and the Cheng SLR series might bias them toward each other for reasons that have nothing to do with GRACE itself. However, because the C20 terms are such a big part of the final signal, I didn't really want to produce this paper by totally excluding it. Instead, to answer your question, I decided to test what the impact of removing it was, to see if it was reducing the divergence I see between GRACE and the Cheng SLR series.

So I recreated each of the three main series (GRACE, Cheng 5x5 SLR and Sosnica 10x10 SLR) and totally omitted the C20 terms, then inverted each and took a look at the time series. If the C20 term was causing falsely alignment with GRACE, I would see a larger divergence between GRACE and the Cheng series, in which case, my paper would require revising.

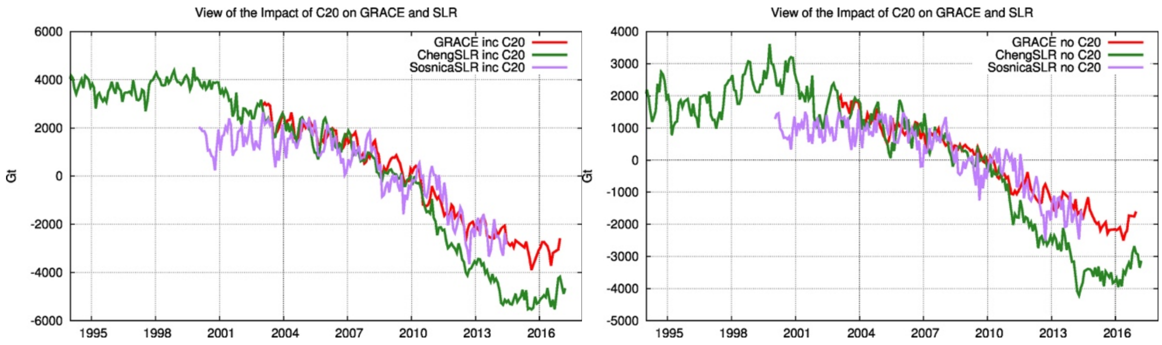


Figure 5: Left-hand image is the inversion with C20 included. Right-hand image is the inversion with C20 totally removed.

However, I see no notable changes in terms of divergence. There are three main effects of removing the C20 terms. First, the overall trend of all three of the series dropped like a rock. (No surprise, given the geometry of the situation.) Second, the month-to-month jitter in all three of the series changed. Third, most oddly, removing the C20 term from the Cheng series produced a large, visible annual signal before about 2007. The other series (including GRACE, using a similar C20) didn't show this impact. So that's bizarre. I assume that the C20 term in the Cheng series is coupled with some other term to produce this (which wouldn't especially surprise its creators, since they're aware of the general coupling between harmonics caused by a barely solvable problem).

In any case, there was not any significant change in the interannual signal divergence. So in practice, the replacement of the GRACE C20 should bias GRACE towards the Cheng SLR series doesn't seem to have any major effect on the part of the spectrum that I'm worried about. That's a relief.

I have created the following commentary for the final version of the paper, briefly discussing this:

> We did consider the impact of replacing the GRACE C$_{20}$ term with that from a series related to the Cheng 5x5 SLR data. To test whether this unfairly biased the Cheng 5x5 SLR results toward GRACE, we removed the C$_{20}$ terms completely from all of the GRACE and SLR series, then inverted each of them again. Removing the impact of the equatorial bulge did greatly reduce the trend of each Greenland+Antarctica inverted series, but it did not significantly impact the interannual differences between GRACE and any SLR series. We thus conclude that the replacement of GRACE's C$_{20}$ values is not a large contributing factor to these results.

---

* Neglecting degree 1 contributions I understand the decision of the authors to not account for the degree 1 signal, based on remaining errors in the SLR data. However, the potential influence of degree 1 neglection may be too large to ignore. As an alternative, maybe the authors can treat the degree 1 signal as noise and assess its influence on the results by producing an ensemble of realistic variations and propagating this through the inversion?

I previously ran a comparison of the Cheng SLR geocenter terms compared to those computed over the GRACE time-period with the technique of Swenson et al. I was surprised to find that the difference between the two geocenter estimates (in terms of their impact on the inverted timeseries) was about the same size as the difference between not using any geocenter and using the Swenson version. According to my coauthor Minkang Cheng and his colleague John Ries, much of this difference is likely to be an error in the SLR C$_{10}$ term caused by the uneven distribution of the ground station network. Also, the difference (after inversion) was small over the combination of Greenland and Antarctica. Certainly, the geocenter term is not what is causing the divergence of SLR from GRACE after 2010, for example (I checked).

I do agree that if one was actually trying to measure the total mass loss of Greenland/Antarctica with this method, so as to compare to other similar estimates, a geocenter would be required. However, in this case, the discrepencies between SLR and GRACE are so large that the main point of the article is actually that one should NOT use 5x5 monthly SLR to push the estimate of mass change back in time. That being the case, the comparison can be run without geocenter being added (in either GRACE or SLR, to keep things equal).

**The supplement has a *.zip ending but actually is in *tgz format*

Sorry; I'll fix that.

** abstract: maybe add some numbers in the abstract to quantify things a bit more*

Which particular details would the reviewer care to have quantified?

** Does the average TC reader knows what is meant by 5x5, 10x10?*

Good point. I'll make sure that's defined initially.

** eq 1 shouldn't the '1-' be outside of the fraction?*

Corrected.

** " indicative of a systematic interannual-scale error in the SLR inversion" What is meant by this? Maybe add a reference, which illustrates the problem at hand?*

What I mean is that, while the GRACE-ChengSLR trend difference is 40% the size of the total trend for 2003-2014, I do not believe this really represents an inability of SLR to represent the long-term trend. Rather, I believe this to be a symptom of SLR's tendency to veer away from the GRACE "truth" for multiple years in a row, then correct itself and come back into alignment (as it seems to be doing in 2017, and as it also may have done back in 2002). Neither I nor Minkang Cheng know of no reference which discusses this, since the accuracy of SLR's interannual variability is very hard to quantify, particularly pre-GRACE. The 15-year record since GRACE started may not be long enough to quantify deviations which take 5+ years to resolve.

This line now reads: “So instead of representing a true, long-term error in trend, the large interannual differences between GRACE and the Cheng 5x5 SLR series are probably indicative of a systematic interannual-scale error in the SLR inversion, which cannot be well quantified given the relatively short length of the GRACE record.” I hope that’s clearer.

** "451 + 28 Gt/yr" I assume this is for Antarctica and Greenland? Maybe explicitly mention this again*

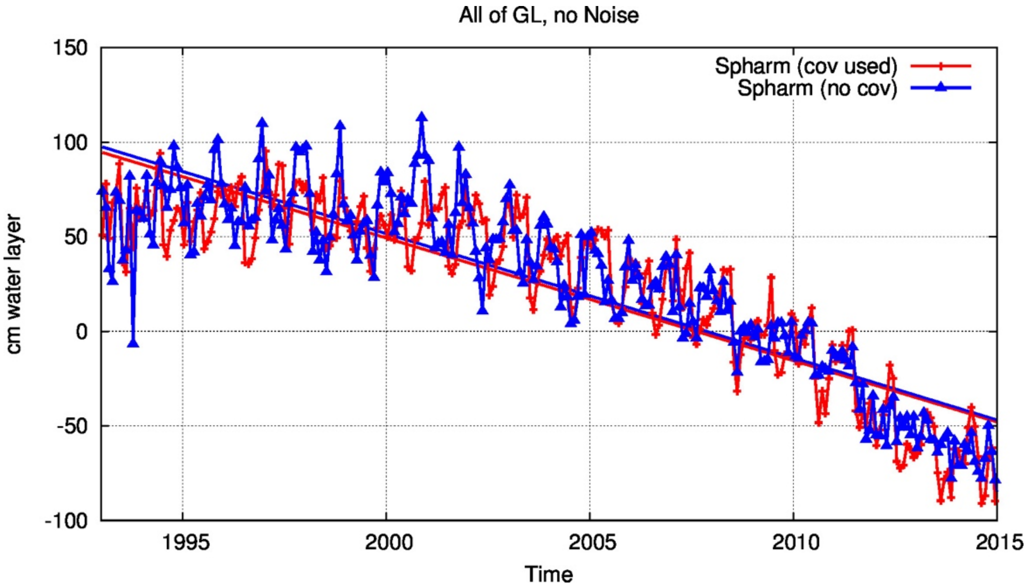
Yes, and done.

---

* Use of diagonal SLR and GRACE error-covariances , and thus neglecting off-diagonal error-covariance. I think this is the most serious issue I can find in the paper. Since I don’t know whether this is going to have a large impact on the results I’m recommending a major revision to allow the authors to clarify this. I suspect that in particular SLR may have significant off-diagonal components in its error-covariances. The SLR network is very sparse and may not be optimal for the retrieval for ice mass change signals at higher latitudes. To account for this, one would in principle need to propagate the full SLR error-covariance on the 1x1 degree grid used as observations. The associated error-covariance matrix of the gridpoints will consequently be quite unstable (e.g. from 36 SLR ’observations’ one produces 360x180 observations, without adding more information), which potentially could break down the inversion scheme as it is implemented now. In the current setup, the authors ignored error-covariances and by choosing an equidistant 1x1 grid also artificially increased the density of observations at higher latitudes inversely proportional to cosine(lat). In a broad sense, ignoring offdiagonal contributions and artificial increase of observations can be interpreted as a regularization, which the authors should justify. I therefore, propose that the authors either justify their choices for the 1x1 grid in combination with a diagonal error-covariance or better: that the authors replace matrix H (see eq S1) by an operator which directly maps Stokes coefficients to the unknown vector a. When full error-covariances are available these can then also be implemented with hopefully relatively little effort.

** "and thus heavily dependent on the same very low degree spherical harmonics" Maybe quantify this with formal error correlations?*

I tested the impact of the Cheng 5x5 SLR covariance matrices a year or so ago, using the uncorrelated inversion method only (see example for Greenland below). The red line is the inversion with the covariance matrix included, while the blue line uses the identity matrix instead. As you can see, the subannual part changes – but that’s also the least accurate part of the signal. The long-period and interannual signals remain effectively the same. Now, this was done with an older, simpler version of the code, without the correlations between sub-regions included. But I've no reason to believe that results using the modern code would look all that different. (I should add, by the way, that one reason the error covariances make little difference is probably because the Cheng SLR series uses a consistent number of satellites in it: always just the five. So the accuracy of the combined solution doesn't drastically change when a new satellite is added/removed, as is the case in the Talpe paper.)



I just talked to Matt Talpe. Neither he nor I can find any way to take these spherical harmonic covariances and propagating them onto a 1x1 degree grid. The only way to take the error covariance into account would be to switch to a spherical harmonic representation from the top-down. That's simple in concept, but involves a total rewrite of the correlated inversion computer code in practice. Moreover, spherical harmonics naturally force the use of global data, while the gridded technique also allows us to use the same code on limited regions of the world. For 5x5 harmonics like SLR, that isn't useful, but it is valuable for other purposes using 60x60 GRACE data. Given the lack of clear improvement in the inverted results above, we chose to stick with the easier-to-use system already in place.

As I mentioned to the other reviewers, Minkang Cheng has very recently created an SLR series using the exact same input data, but estimating over 6 months rather a single month. When I repeat the inversion process with that data, I find that the divergence after 2010 vanishes (proving that it really was just a numerical instability). Once we tidy up these new results, we will surely write another paper. I feel it would be more meaningful to incorporate the detailed error analyses you mention, in that future paper instead, which will (hopefully) contain a timeseries which we feel is stable and trust-worthy enough for others to use. Given that the conclusion of this current paper is basically “the monthly SLR data is not accurate enough to use for this purpose”, extended error calculations seem noncritical, to me. I hope that a promise to look into the impact of the error covariances for the future will be sufficient for you and the editor.

Thank you very much for your assistance and helpful thoughts,
Jennifer Bonin

Response to Reviewer #3 (Kosuke Heki)

Thank you for your time and effort. I really appreciate the review.

No. 1 Separation of Greenland and Antarctica using external information:
The limited spatial resolution of the SLR 5 x 5 model could not separate ice losses from the two ice sheets. Nevertheless, I think there are external clues to answer the question, how much coming from Greenland and how much from Antarctica. Matsuo et al. (2003) used the quadratic component in the vertical position time series of GNSS stations in Greenland to validate their results. Because of uncertainties in GIA models, it is not straightforward to discuss linear uplift/subsidence rates of the Antarctic GNSS stations. However, because GIA rates do not change in a short time-scale, quadratic (or higher degree) components in vertical position would entirely reflect the elastic response of the lithosphere to the present-day ice melting. Several GNSS station in Antarctica have been operational since 1990s, and the authors at least discuss if the signature of the accelerated ice mass loss ever exists in Antarctica.

You, Matt King and I went back and forth a little on this via email, but to recap for the editor, while I agree that some "guestimation" based on GPS is probably possible on this issue, I don't think I know enough about the subject to do it myself. As Matt mentioned, there would be a lot of questions about mantle viscosity effects, in addition to the question of time-variable modern-day surface loading. More, I worry that any such process would have to assume a continuation of linearity in regions where the signal is linear now, during timespans when the signal might really have been accelerating (etc). So this sort of separation would have to be handled very delicately, I think.

It's a good idea for someone to try to combine these data types, nonetheless, I think. For the time being, I have added a comment in the relevant appendix section suggesting: "While it might be plausibly possible to use external sources (such as ground GPS stations) to separate the two regions, that is likely to be a complex process, particularly as one goes backwards in time to periods when few GPS stations exist. We leave such efforts to a future paper." Perhaps that will inspire someone.

No 2. Reality of the departure of SLR data from GRACE:
Below I compare Figure 4 (left) and a figure drawn by the reviewer using the CSR Level-2 RL05 spherical harmonics data with standard filters (right). It shows the gravity time series at a certain point in southern Greenland (65N 40W), and indicate anomalous changes after 2012, a short-term accelerated mass loss in 2012 and a longer-term stationary behavior until present (reflecting increased precipitation there). I see some similarity between the 5x5 SLR data (rather than GRACE HiRes-Local) and the mass changes in southern Greenland. Is it conceivable that mass signals in southern Greenland leaked into the SLR 5x5 solution?

I noticed this visual similarity, too, initially. Two things convinced me that it's not a case of "overweighting" Greenland somehow. First, because any such signal would be seen by GRACE (as you note), but neither my "highres" case nor the 5x5 or global 60x60 GRACE inversions see the amount of decrease seen by SLR. (They all slow down somewhat in the later years, please note. They just don't show the strong acceleration in 2010-2011, then plateauing that SLR does.) Secondly and more importantly, though, as I mentioned in my email to you, last month I finally cajoled Minkang Cheng into making a new SLR series in which he combines 6 months of data into a single solution (rather than only a month). In that SLR series, the big deviation that his monthly solutions showed away from GRACE after 2010 totally disappears. This proves to me that it was just an artifact of the SLR errors, not a real signal from Greenland or anywhere else. It seems that the monthly SLR solutions are just barely stable, and adding more observations stabilizes them better. So I'd like to put this question on hold for a future paper, until I can write up the results on this brand-new SLR series. I still think it’s important to put the results of the ordinary monthly solutions out there, though, since those are commonly available. Not to mention getting the method clearly down on paper.

Minor comments
Page 9 line 4: “trend errors are statistically indistinguishable from zero.” sounds strange (trends could be indistinguishable from zero but errors should not be indistinguishable from zero).
Page 11 line 9: Please explain the “input-output method”?
Page 12 line 13: “before” what (words missing)?
Page 14 line 19: Nerem and Wahr (2011) missing in the reference list

All these things have been reworded or added.

Thank you again for your helpful thoughts,
Jennifer Bonin

Using Satellite Laser Ranging to measure ice mass change in Greenland and Antarctica (marked-up version)

Jennifer A. Bonin[1], Don P. Chambers[1], Minkang Cheng[2]

[1]College of Marine Science, University of South Florida, Tampa, FL, 33701, USA
[2]Center for Space Research, University of Texas at Austin, Austin, TX, 78759, USA

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

Abstract. A least squares inversion of Satellite Laser Ranging (SLR) data over Greenland and Antarctica could extend gravimetry-based estimates of mass loss back to the early 1990s, and fill any future gap between the current Gravity Recovery and Climate Experiment (GRACE) and the future GRACE Follow-On mission. The results of a simulation suggest that, while separating the mass change between Greenland and Antarctica is not possible at the limited spatial resolution of the SLR data, estimating the total combined mass change of the two areas is feasible. When the method is applied to real SLR and GRACE gravity series, we find significantly different estimates of inverted mass loss. There are large, unpredictable, interannual differences between the two inverted data types, making us conclude that the current 5x5 spherical harmonic SLR series cannot be used to stand in for GRACE. However, a comparison with the longer IMBIE time-series suggests that on a 20-year time-frame, the inverted SLR series' interannual excursions may average out, and the long-term mass loss estimate be reasonable.

1 Introduction

Since the Gravity Recovery and Climate Experiment (GRACE) was launched in 2002 (Tapley et al., 2004), it has provided an excellent time series of mass change integrated over Greenland and Antarctica's ice sheets (Jacob et al., 2012; Luthcke et al., 2013; Schrama and Wouters, 2011; Shepherd et al., 2012; Velicogna and Wahr, 2013). However, GRACE data go back to just mid-2002, and only a few other data series exist before then to study longer-term mass change. These include satellite altimetry (Howat et al., 2008; Johannessen et al., 2005; Shepherd et al., 2012) and the 'input-output' method's combination of surface mass balance models and glacier flow speeds from interferometry (Rignot et al., 2011; Sasgen et al., 2012; Shepherd et al., 2012). Due to the paucity of data and its limited resolution in both space and time, estimates of ice mass change before GRACE are necessarily more uncertain. High-quality Satellite Laser Ranging (SLR) tracking data [*Cheng et al.*, 2011, *Cheng et al.*, 2013] to geodetic satellites is one possible additional data set that could be exploited to compute variability in ice mass before 2002, as it exists for over a decade before GRACE.

Although SLR tracking data can be used to infer time-variable mass change [e.g., *Nerem et al.*, 2000], it can only do so over a much longer wavelength. The resolution of SLR-based gravity fields is 8000 km at the equator (based on 5x5 spherical harmonic Stokes coefficients, or a maximum degree/order of 5), compared to 660 km for GRACE (based on 60x60 spherical harmonics, or a maximum degree/order of 60). This difference in resolution has resulted in few ice mass studies having been completed with SLR data. For example, *Nerem and Wahr* [2011] compared an SLR C_{20} Stokes coefficient time-series with a time-series from GRACE-based estimates of Greenland and Antarctica mass loss. This led them to suggest that the two ice sheets could explain the increase in the rate of change of C_{20} in the late 1990s. However, this analysis is not the same as our goals, as it used GRACE observations to explain SLR signals, rather than determining mass change directly from the SLR data. More recently, *Matsuo et al.* [2013] used a 4x4 SLR-based gravity series to demonstrate the similarities between SLR and GRACE data in a general sense. They noted similar mass loss over the entire Arctic and showed that the center of that mass loss occurred over roughly the same spatial extent. These two examples are promising, and suggestive that SLR and GRACE may be seeing comparable signals. However, as *Matsuo et al.* acknowledged, the low spatial resolution of the SLR data makes it "not feasible to obtain definitive estimates of the total amount of the mass change… even for an area as 'large' as Greenland."

To better resolve the SLR signal and obtain a more definitive estimate than *Matsuo et al.*'s direct method, we will utilize a least squares inversion technique to localize the SLR signal over Greenland and Antarctica. This technique provides us with time-series of interannual variability, as well as decadal-scale trends and accelerations over Greenland and Antarctica. We have two ultimate goals in this. First, to extend the time-series of polar mass change backwards in time, before GRACE. And second, to serve as a gap-filler between GRACE and the future GRACE Follow-On mission. The original GRACE mission's last month of data was June of 2017, after several years of slowly degrading data quality and increasing gaps between monthly solutions. The Follow-On mission will not launch until at least March of 2018, leaving perhaps a year's gap where no science data can be collected. Having a trusted gap-filling series which could also verify the quality of the later-mission GRACE data would be of benefit.

Data and methods are described in sections 2 and 3, and in the supplemental material. In section 4, we compare inversions of the SLR and GRACE data over Greenland and Antarctica during GRACE's 2003-2014 time frame, and compare their trends and interannual signals. The implications of the results of our experiments, as well as the extension of the SLR data back to 1994, are discussed in section 5.

2 Data Sets

The primary data series used here are a set of maximum degree/order 60 ("60x60") monthly-averaged spherical harmonic Stokes coefficients from GRACE (dates: 2003-2016) and a set of 5x5 monthly-averaged spherical harmonic coefficients from SLR to a series of geodetic satellites (dates: 1994-2016). A second, more limited, set of 10x10 SLR coefficients is also tested for comparison (dates: 2000-2014).

The GRACE series used here is the standard CSR Release-05 spherical harmonic version (ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05/) (Bettadpur, 2012), with no constraints applied during processing. We apply the following standard post-processing steps: 1) C_{20} is replaced with the estimate derived from SLR tracking (ftp://podaac.jpl.nasa.gov/allData/grace/docs/TN-07_C20_SLR.txt) due to GRACE's known weakness in resolving that harmonic (Chambers, 2006), 2) a pole-tide correction is applied to harmonics C_{21} and S_{21} (Wahr et al., 2015), and 3) a GIA model is removed. The GIA model is composed of the W12a GIA model (Whitehouse et al., 2012) south of 62°S, and the *A et al.* [2013] model north of 52°S, using a smoothed combination of the two between 52-62°S. No smoothing or destriping [e.g., *Swenson et al*., 2006; *Chambers and Bonin*, 2012] is applied, nor are any geocenter (degree 1) coefficients utilized. In addition to using the full 60x60 GRACE coefficients for 2003-2014, we also truncate down to 5x5 and 10x10 subsets, to compare more directly to the SLR data.

The primary SLR series used here (Cheng, 2017; Cheng et al., 2011, 2013) is a variant of the weekly, 5x5 SLR product created at the University of Texas's Center for Space Research (CSR) and released alongside the GRACE series (ftp://podaac.jpl.nasa.gov/allData/tellus/preview/L2/deg_5/CSR.Weekly.5x5.Gravity_Harmonics.txt). We use a version that is averaged monthly, rather than weekly, to make it more directly comparable to the monthly GRACE data. This version contains an estimate of C_{61}/S_{61} (but no other degree-6 harmonics) to avoid skewing the C_{21} harmonic due to a lack of sufficient degrees of freedom during the creation of the SLR gravity product (Cheng and Ries, 2017). The same GIA model is removed as with GRACE. Though the Cheng 5x5 SLR series exists from 1993 onward, prior to November 1993, only four satellites were used in its creation (Starlette, Ajisai, and Lageos 1 and 2), whereas after that point, Stella was added as well. Because this change in satellite geometry could create possible jumps in the time-series, we have only used data from 1994 onwards. The geocenter (degree 1) SLR terms are removed, both for comparison's sake (because GRACE cannot perceive them) and because the SLR C_{10} term is suspected to have an incorrect trend caused by non-uniform ground network coverage (Collilieux et al., 2009; Wu et al., 2012). The geocenter terms commonly added to GRACE (Swenson et al., 2008) are expected to be more accurate, but they cannot be created for months when GRACE does not exist, and thus cannot be used at all before 2002. We found that using no geocenter at all brought our results closer to the results using GRACE-derived geocenter terms than using the original SLR geocenter terms did.

A pair of secondary SLR series (Sośnica et al., 2015), created at the Astronomical Institute at the University of Bern, are also considered for comparison, though they do not extend far back in time before GRACE. Like the primary Cheng 5x5 SLR series, the two Sośnica SLR series were created from the combination of multiple satellites' SLR tracking data – mostly the five used in the Cheng 5x5 series, but also including BLITS, Larets, Beacon-C, and LARES, over the time spans they exist. Monthly solutions for 2000-2014 are available for download (ftp://ftp.unibe.ch/aiub/GRAVITY/SLR). Two versions exist: an unconstrained case to maximum degree/order 6x6, and a constrained case to 10x10. Again, the geocenter terms are not included and the same GIA correction used in the GRACE processing is removed.

Before enacting any inversion in the spatial domain, we wish to understand how similar these three SLR series are to the GRACE series, over the limited spherical harmonics they contain. To demonstrate this, we first smooth all of time-series for each gravity coefficient with a 200-day window, thus removing signals with semi-annual periods and shorter, which are likely to be noisy in both SLR and GRACE. We have plotted the GRACE, Cheng 5x5 SLR, and Sośnica 10x10 SLR series harmonic by harmonic in the supplemental information. We then compute the percent of the smoothed GRACE variance that is explained by each SLR series (Figure 6), via the equation:

$$PVE = 1 - \frac{var(GRACE-SLR)}{var(GRACE)} \qquad (1)$$

where *var* denotes the variance of either the GRACE series or the residual once SLR is subtracted off. A percent variance explained (PVE) of one means perfectly matching signals, a PVE of zero means that removing SLR does not reduce the GRACE variance, and a negative PVE means that the residual actually has more variability than the original GRACE series did. Ideally, we would want our PVEs to be above zero for all harmonics, and near to one for the largest and most important harmonics.

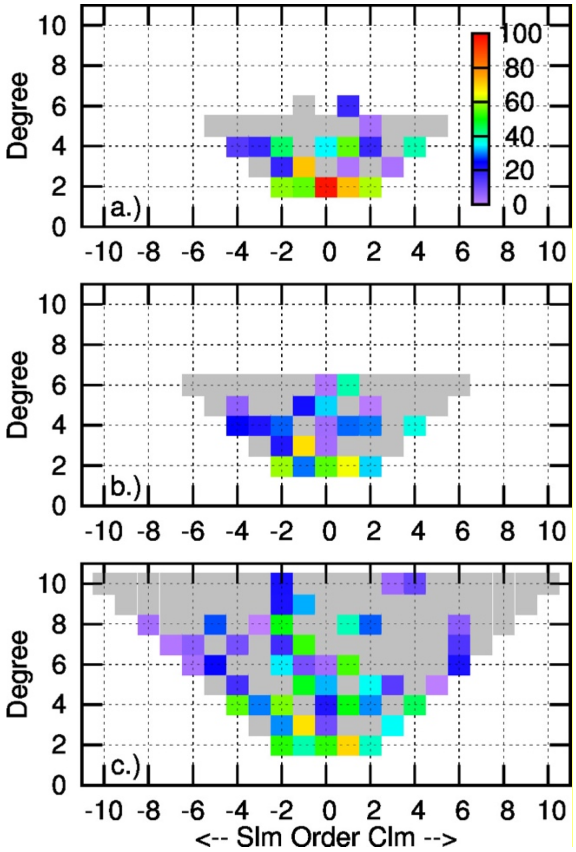


Figure 6: Percent of GRACE variance explained by three SLR time series, after a 200-day smoother has been applied. SLR series are: (a) Cheng et al's 5x5 series, (b) Sośnica et al's 6x6 unconstrained series, and (c) Sośnica et al's 10x10 constrained series. Harmonics with negative percent variance explain are greyed out. The C_{20} term in (a) is a perfect 1.0, because the GRACE C_{20} has been replaced by the SLR value. S harmonics are denoted as negative orders along the x-axis, while C terms are listed as positive ones.

We find that around half of the GRACE signal is explained by SLR for the degree-2 harmonics, but that skill rapidly decreases with wavelength. Above degree 4, none of the three modern SLR series explain a large percentage of the GRACE signal. Many of the harmonics of degrees 3 and above have negative PVEs, demonstrating SLR's known low sensitivity to them. Additionally, while low-degree harmonics from truncated GRACE series are well-separated from the higher-degree coefficients, lower-degree SLR harmonics will inherently contain aliased errors from the unsolved-for higher-degrees.

The Sośnica 10x10 and Cheng 5x5 series have generally comparable PVEs at the lower degrees. While the Sośnica 6x6 data is similar to the Sośnica 10x10 data at degrees 2-3, it explains significantly less of the GRACE variance for degrees 4-6. For that reason, we focus on the other two series in this paper. The Cheng 5x5 series is particularly useful in this study because of its much longer record, but the independent nature of the Sośnica 10x10 makes it valuable for comparison.

3 Methods: Global Inversion

To localize the mass signal from the low-resolution GRACE and SLR series into areas near Greenland and Antarctica, we use a modified version of the inversion technique described in *Bonin and Chambers* [2013]. In that paper, a series of regions are defined ahead of time, and a least squares approach constrained by process noise is used to estimate the amount of mass change arising in each region. We attempted to use the same approach here, but quickly found that what can be done with 60x60 data sets cannot be accomplished with lower-resolution 5x5 data (see supplemental information).

Instead, we use a correlation-based approach to constrain the least squares inversion. We first separate the world into three main areas: Antarctica, the ice-covered area near and including Greenland, and everything else. We divide each large area into multiple sub-regions, then tie those sub-regions loosely together with spatial and temporal constraints. This allows different sub-regions, such as eastern vs. western Antarctica, to vary at different times, while still keeping the number of observations significantly greater than the number of independent parameters solved for, thus giving a stable solution. The constraints are based on the JPL mascon GRACE data (Watkins et al., 2015) from 2003 to 2014, after GIA has been removed. We compute cross-correlations between sub-regions within each area from the mascon data, and use those to constrain the sub-regions to vary in expected spatial patterns. We also use lag-1 auto-correlations of each sub-region to force each month's solution towards the neighboring months'. The derivation of the constrained inversion process is given in the supplemental information.

We first tested the process on a completely simulated data set, similar to the one used in *Bonin and Chambers* [2013]. The details of the simulated data are given in the supplemental material. The results suggest using a correlation-constrained least squares inversion allows for accurate estimates of the Greenland and Antarctic mass change when using 60x60 or even 10x10 simulated data. However, a 5x5 resolution proves insufficient to invert the sub-annual signals correctly (Figure 7a and b). We believe that this inaccuracy comes about because both Greenland and Antarctica are polar areas, and thus heavily dependent upon the same very low-degree spherical harmonics. Without higher-degree harmonics to clarify the situation, the mathematics cannot always determine which region to place which signal in.

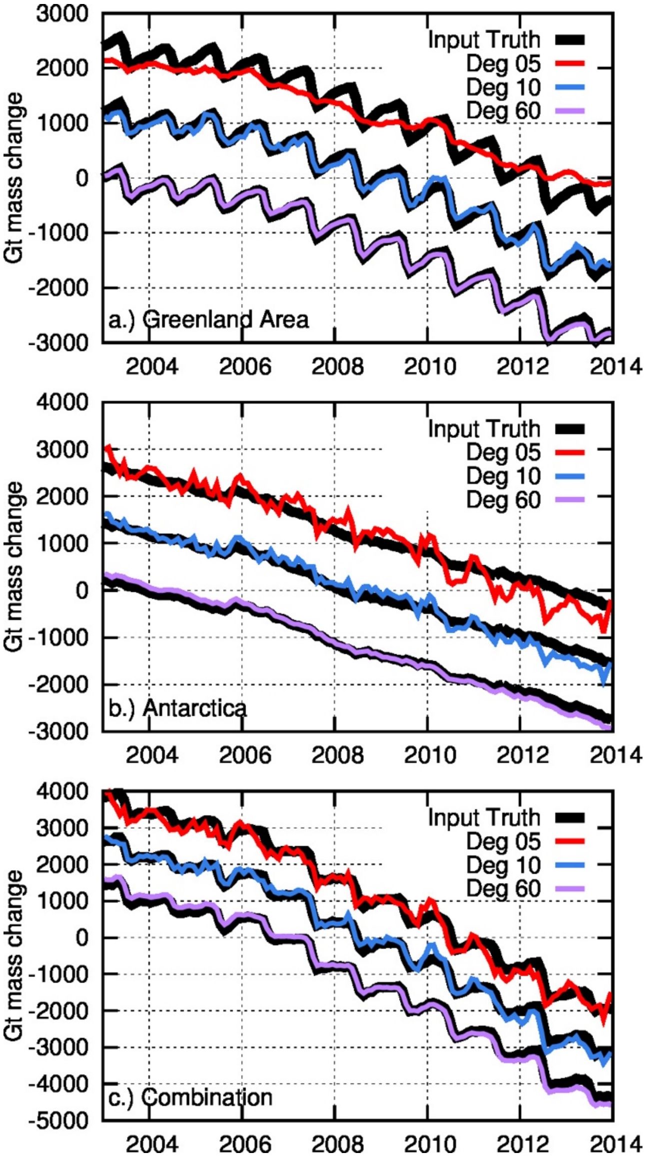


Figure 7: Simulated inversion results by maximum degree/order, relative to input 'truth' signal. Regions considered: (a) Greenland and surrounding islands; (b) Antarctica; (c) the sum of Greenland and Antarctica. Each inversion was run using correlation-based constraints. Time-series are offset for clarity.

We can eliminate this problem by summing the time series of the two areas and looking at the total mass loss over Antarctica and the near-Greenland area combined (Figure 7c). Using SLR-like 5x5 harmonics for the simulation results in a negligible simulated trend error (7 ± 18 Gt/yr). The 60x60 simulated inversion produces a small trend error of 36 ± 8 Gt/yr (6.5% the simulated 'truth' trend). After removing these trends, the remaining RMS error of the correlation-constrained simulation inversion is 202 ± 10 Gt for 5x5 data, 131 ± 10 Gt for 10x10 data, and just 37 ± 5 Gt for 60x60 data, which demonstrates that higher-resolution series are much better able to track the month-to-month variability within the data. (All errors given are 95% confidence levels, based on a Monte Carlo simulation of random noise with a known red spectrum, after fitting for a bias, trend, annual, and semi-annual signals. The Monte Carlo simulation's values are generated using the same RMS and lag-1 autocorrelation as the inverted data.)

4 Analysis: Comparison with GRACE

Based on the results of the simulation, we applied the least squares inversion technique with correlation-based constraints to the real SLR and GRACE data and summed over all of Antarctica and the near-Greenland area. The resulting mass change time-series are shown in Figure 8. For a comparison 'truth' signal, we use a combination of two higher-resolution inversions of the 60x60 GRACE data, which inverts over only Antarctica and Greenland individually, and places each local signal into more, smaller regions. This technique more accurately estimates the mass trends and higher-resolution signals than the larger-region correlated technique can, since its regions and parameters are tuned for the full 60x60 data rather than 5x5 data (see supplemental information). This allows for a more realistic estimate of the SLR errors. Also, since part of our goal is to match up the SLR time-series with a high-quality GRACE one, learning the mismatch between them is important all on its own.

We first consider the errors implicit in reducing the locally-defined, high-resolution GRACE inverted series (black line in Figure 8a) to a 5x5 truncated series (orange line). We find an error of 31.7 Gt/yr in trend (7.0 ± 2.5% of the high-resolution GRACE trend), such that between 2003-2014, the 5x5 GRACE inversion estimates 380 Gt greater total polar mass loss. Over that same time, the remaining RMS difference between the 5x5 and high-resolution GRACE inverted signals after the trends are removed is 220 Gt (63.7%). These numbers are fairly comparable to our 5x5 simulation-based errors of 1.3 ± 1.6% for trend and 75.1% for RMS. We should thus expect to see errors on this level from any SLR series, simply due to the signal truncation effect.

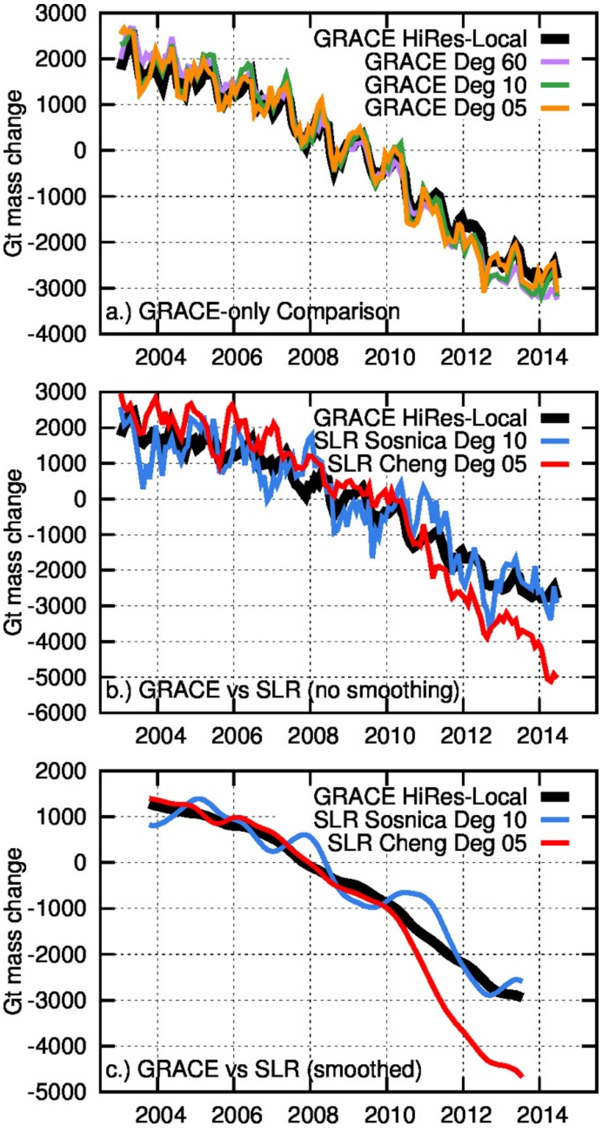


Figure 8: Comparisons of inverted GRACE and SLR mass signals, over Greenland and Antarctica combined. (a) GRACE-only comparison, for different maximum degree/orders, relative to the high-resolution, local GRACE inversion. (b) SLR comparison. (c) Low-pass SLR comparison, after applying a 400-day (13 month) smoother.

Figure 8b shows the inversion of the SLR series compared to GRACE, over only those months where both SLR and GRACE data exist. The trend differences between GRACE and the Cheng 5x5 SLR series are particularly startling (40.9 ± 11.1% error), especially considering that the Sośnica 10x10 time-series has a trend error of similar size to what simple truncation to 5x5 harmonics causes (7.3%). However, when the trend is removed, large and different RMS errors (145-167%) remain in both. We smoothed both the GRACE and SLR time-series with a Gaussian smoother that cuts off periods shorter than 13 months (Figure 8c; final column of Table 1), to remove month-to-month jitter and get a better view of what is causing the differences.

From 2003-2010, the Cheng 5x5 series sees very similar trends to the high-resolution GRACE series; the difference between their trends is statistically indistinguishable from zero. Then, from 2010-2014, the Cheng SLR and GRACE trends diverge suddenly and significantly (106.1 ± 28.6% trend difference). Collectively, this results in the 40.9% error from 2003-2014. The Sośnica 10x10 inversion shows no such sudden change in behavior. This divergence in the Cheng SLR data seems so sudden that we initially believed it might have been caused by the pole-tide error discussed by *Wahr et al.* [2015]. Their correction is a two-piece affair, treating the C_{21} and S_{21} harmonics differently before and after 2010, and its impact is largely linear. However, after applying the correction to our GRACE data, we realized that no pole-tide correction is large enough to explain the differences we see between GRACE and the Cheng SLR series. As *Wahr et al.* noted, the impact of their correction is on the order of 0.5 cm/yr equivalent water thickness in trend throughout the world. Trends in Greenland and Antarctica are two or three orders of magnitude greater than that.

Series to Difference, Relative to GRACE High-Res Series	Trend Error (Gt/yr)	Trend Error (%)	Residual RMS Error	Residual RMS Error (Smoothed)
GRACE 5x5	-31.7 ± 11.5	7.0 ± 2.5	63.7%	46.1%
GRACE 10x10	-45.3 ± 11.3	10.0 ± 2.5	52.6%	39.6%
SLR Cheng 5x5	**-184.8 ± 50.5**	**40.9 ± 11.1**	**145.2%**	**156.1%**
SLR Sośnica 6x6	-182.2 ± 54.5	40.4 ± 12.0	188.9%	165.1%
SLR Sośnica 10x10	**33.1 ± 31.3**	**-7.3 ± 6.9**	**167.3%**	**158.0%**

Table 1: Differences relative to GRACE 60x60 high-resolution, local inversion, over the combined Greenland/Antarctica region during 2003-2014. Residual RMS errors are those after the trend has been removed, relative to the GRACE 60x60 detrended RMS. The final column is the residual RMS error after a 13-month Gaussian filter has been applied to all series. Errors given are purely statistical 95% confidence levels after fitting for a bias, trend, annual, and semi-annual signals, based on a Monte Carlo simulation of random red noise with the given RMS and lag-1 autocorrelations. They do not include the intrinsic errors of the satellites themselves, or the effects of the inversion method. Errors are computed on series including only those months estimated by GRACE.

So instead of representing a true, long-term error in trend, the large interannual differences between GRACE and the Cheng 5x5 SLR series are probably indicative of a systematic interannual-scale error in the SLR inversion, which cannot be well quantified given the relatively short length of the GRACE record. Continuing the series past 2014 (Figure 9) encourages us in this belief, since the SLR series measures effectively zero trend in mass change for 2014-2016, bringing it back towards the GRACE series. The Sośnica 10x10 series also differs significantly from GRACE on the interannual scale, despite the good agreement in trend. Its pattern of difference is more sinusoidal, with 2- to 3-year periods, on top of a small but more-or-less constant trend difference. On an even shorter scale, the Cheng and Sośnica SLR series both resolves large annual-scale and shorter fluctuations that GRACE does not see. Since the SLR series do not see the same changes in either annual or multi-year signals as either each other or GRACE, we presume that the differences are most likely errors in SLR, though it is possible that GRACE contains unsuspected large interannual errors as well.

We did consider the impact of replacing the GRACE C_{20} term with that from a series related to the Cheng 5x5 SLR data. To test whether this unfairly biased the Cheng 5x5 SLR results toward GRACE, we removed the C_{20} terms completely from all of the GRACE and SLR series, then inverted each of them again. Removing the impact of the equatorial bulge did greatly reduce the trend of each Greenland+Antarctica inverted series, but it did not significantly impact the interannual differences between GRACE and any SLR series. We thus conclude that the replacement of GRACE's C_{20} values is not a large contributing factor to these results.

5 Results: 1994-2017 Time-Series

It is disappointing but not a tremendous surprise that the SLR series cannot fully resolve the varying nature of the polar mass signal. GRACE is a rather high-resolution data set, while as Figure 6 demonstrates, only the lowest-degree part of the SLR estimates are likely to be highly accurate. Our simulation showed that we are already pushing at the bounds of our spatial resolution to try localizing 5x5 data into even a single Greenland and Antarctic region, so one presumes that combining that difficulty with incorrect higher-degree values in SLR results in the large interannual errors that we see. Certainly, those errors mean that a 5x5 SLR field cannot be used to fill in gaps in the GRACE/GRACE Follow-On record.

However, in a longer-term sense and bearing in mind the limitations of the data, SLR does a fair job of estimating ice mass change. The Sośnica 10x10 series is not available much before GRACE or after 2014, but we can compute the Cheng 5x5 SLR inversion back to 1994 and through to the beginning of 2017 (Figure 9). The most recent years of data show that the sharp divergence beginning in 2010 is recovering by 2017. (The lack of other satellite or in-situ evidence for an increased mass loss from 2010-2014, and a stable mass state since then, makes us certain that SLR is less accurate than GRACE over this time-span.) If this recovery continues, it will represent not a trend error, but an interannual error with a divergent period of around five years. Given that suggestive evidence, it is possible that the Cheng SLR series might be broadly accurate on the 1994-2017 time-scale, even though any individual year's estimate could be fairly far off.

The Cheng 5x5 SLR series' constant twenty-three-year trend is -451 ± 28 Gt/yr for the combination of Greenland and Antarctica. However, a single line is an extremely poor approximation for this longer, sharply curving data set. If we instead assume that the ice sheets are in a long-term stable state at the beginning of 1994, then we can determine a constantly accelerating curve at an optimal point along the 1994-2017 SLR data (orange line in Figure 9). The best two-piece fit to the data involves a constant (zero mass change) part until December of 1996 (± 5 months) followed by a constant acceleration of -25.8 ± 1.1 Gt/yr^2 thereafter. As Figure 9 shows, even this model exaggerates the amount of mass that SLR sees lost after 2016 – an effect which would not occur if the Cheng SLR series did not diverge from GRACE beginning in 2010.

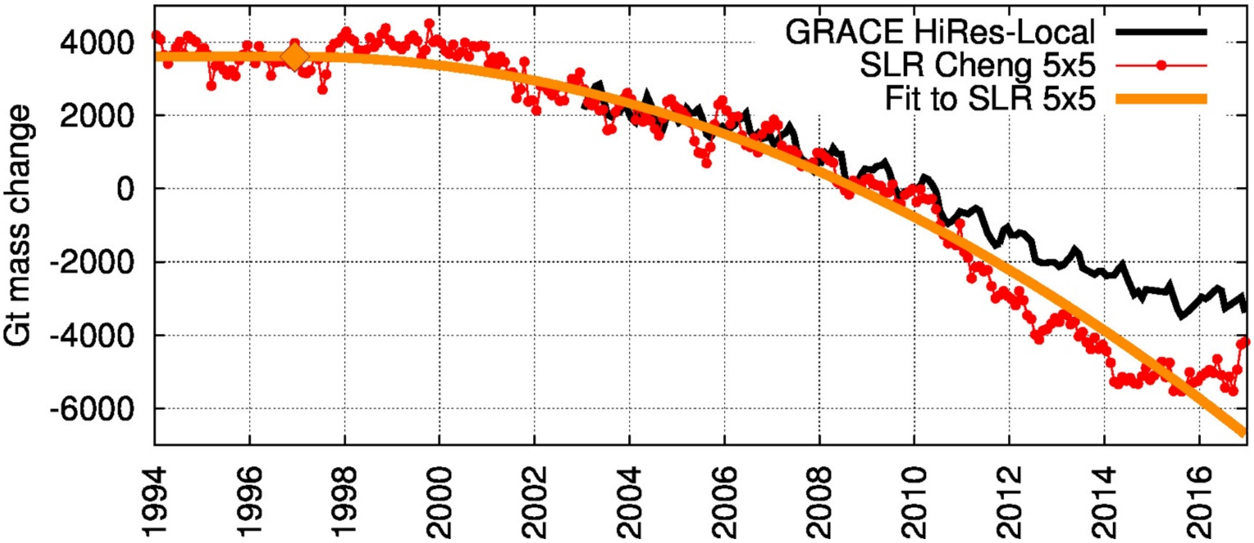


Figure 9: Mass loss over Greenland and Antarctica combined, carried back to 1994, from the Cheng 5x5 SLR inversion. Monthly results are shown as red dots, with the best-fit accelerating curve sketched in orange. The orange diamond represents the point at which acceleration begins. The high-resolution, local GRACE inversion is shown (black) beginning in 2003, for comparison.

The obvious question we need to answer is how often SLR takes such multi-year excursions, and whether it really does get back on track afterwards. One way to get a feel for the pre-GRACE accuracy of the SLR inversion is via a comparison with an additional data set. The Ice-sheet Mass Balance Inter-comparison Exercise (IMBIE) for Greenland and Antarctica (http://imbie.org/data-downloads) (Shepherd et al., 2012) is a time-series of mass change created from a combination of different techniques and data sources. This ensemble average includes radar altimetry over the whole timespan, and laser altimetry and GRACE after 2003. It also includes timeseries made with the model-based input-output method (estimates of precipitation minus runoff, sublimation, and ice discharge). It does not exist over the islands near Greenland which we included in our estimate, principally including Iceland, Svalbard, Ellesmere Island, and Baffin Island. To make a fair comparison, we mask out these neighboring islands from our final gridded solution, so as to compare across the same area, then compute the summed mass change over Antarctica and Greenland. For visual purposes, we also smooth both GRACE and SLR with a 13-month Gaussian smoother to duplicate what was done with IMBIE. One significant difference remaining is that IMBIE naturally includes the impact of the geocenter terms, while we have excluded those from our SLR estimate because of their large expected errors.

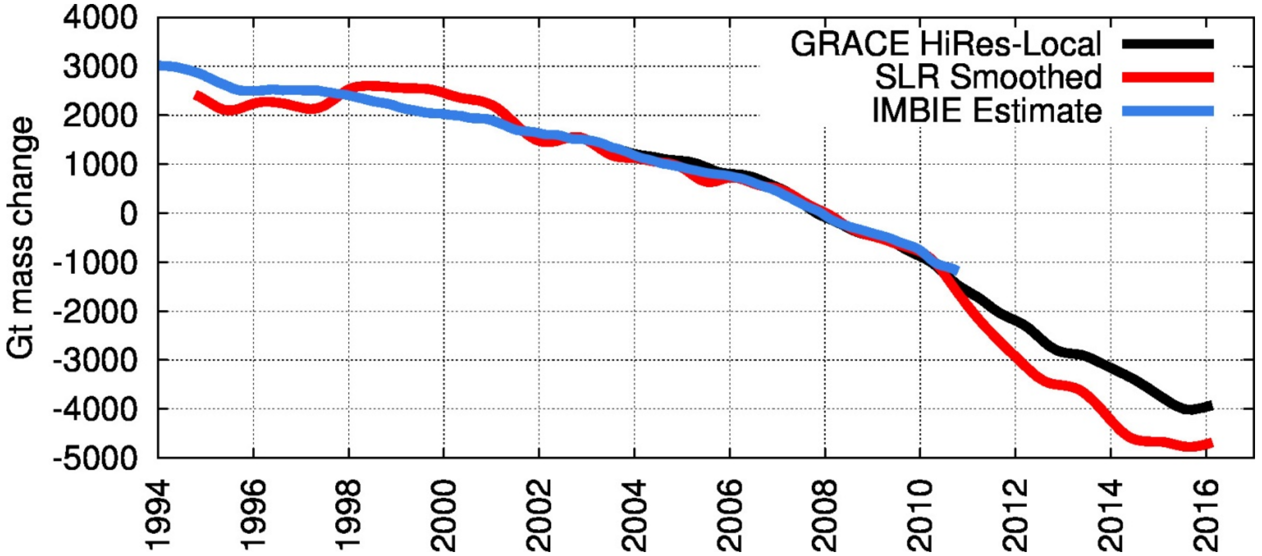


Figure 10: The high-resolution localized GRACE (black), Cheng 5x5 SLR (red), and IMBIE (blue) estimates of Greenland and Antarctica's mass change. A 13-month smoother has been applied to the GRACE and SLR results, and they are scaled to include only the areas of Antarctica and Greenland, not the islands surrounding Greenland, to duplicate the IMBIE approach.

As Figure 10 demonstrates, IMBIE's mass change estimate aligns neatly with GRACE during its six-year overlapping time-span, but also approximates a similar long-term signal to SLR before GRACE. During the overlapping fifteen-year period (1994-2009), the Cheng 5x5 SLR inversion estimates an average mass loss rate of -197 ± 40 Gt/yr, while IMBIE sees a statistically identical trend of -220 ± 42 Gt/yr. (The IMBIE uncertainty here is based on the variance of the smoothed residuals about the fit, but also accounts for temporal correlation due to the 13-month smoothing already applied to the IMBIE data. This reduces degrees of freedom from 186 to 14, so inflates the error from the least squares fit by sqrt(186/14).) Assuming IMBIE is correct, the SLR inversion sees multi-year errors before 2002, as it does from 2010-2017. However, over the long-term, these errors have averaged out in previous similar cases, as they seem to be in the process of doing now.

6 Conclusion

We compared two unrelated SLR series to the GRACE data, in the hopes that one or the other would prove capable of reliably matching GRACE and estimating mass change over Greenland and Antarctica on its own. The Sośnica 10x10 series contains significant shorter-period discrepencies with GRACE, but estimates the ten-year trend with reasonable accuracy. Unfortunately, the Sośnica series does not exist before 2000 or after 2014, so it cannot currently be tested over longer scales. It would be potentially possible to use the Sośnica method to extend the series – but with a caveat. The creators of this series included not only the five long-running geodedic satellites in their solution, but also BLITS, Larets, Beacon-C, and LARES over the time-spans they have existed. Beacon-C is the only one of those satellites which exist before 2000, and it has been heavily downweighted. Larets first enters into the solution in September of 2003, BLITS in September of 2009, and LARES not until February of 2012. So we expect the signal quality to be degraded prior to 2003, leading to pre-GRACE estimates of mass change which may be of low accuracy. On the other hand, since 2012, the Sośnica technique should produce a solution comparable or better than what is shown in Figure 8 and Table 1. An extended Sośnica-like series might, therefore, be useful for filling the gap between GRACE and GRACE Follow-On.

The Cheng 5x5 series already exists for the full 1994-2017 time period. However, because of the large uncertainty on interannual periods, we do not believe the Cheng 5x5 inverted SLR data series should be used to estimate mass loss over Greenland and Antarctica on its own. Certainly, we cannot use it to fill short-term gaps in the GRACE record, or between GRACE and the future GRACE Follow-On mission. Nonetheless, over longer time spans (~20 years), the inverted Cheng 5x5 SLR series appears to measure real mass change signal, similar to the more extensive IMBIE estimates. It (or an extended Sośnica-like series) thus ought to be considered in combination with other data sources in the future. As an attempt to make SLR more useful for this effort, our future work will include the creation of a new SLR series, created in the same manner as the Cheng 5x5 series, but including a year of data in each estimate, rather than a month. The hope is that by sacrificing the sub-annual signal, we can gain better accuracy at inter-annual periods, thus reducing the variability which stymies us here and creating a more useful pre-GRACE estimate of total mass change over Greenland and Antarctica.

7 Acknowledgments

We would like to deeply thank John Ries at the University of Texas's Center for Space Research for his kind assistance in the preparation of this paper. Thank you so much for sharing your generous SLR background knowledge and advice with us.

This research was conducted under a New (Early Career) Investigator Program in Earth Science NASA grant (NNX14AI45G). We are most appreciative of NASA's funding and support.

8 Data Availability

The monthly Cheng 5x5 SLR data is available as part of the supplemental information, online at doi:10.5281/zenodo.831745. All other data series are publically available at the websites listed in the text. The numerical inversion results or mapped regional definitions are available from the authors upon request.

9 References

A, G., Wahr, J. and Zhong, S.: Computations of the viscoelastic response of a 3-D compressible earth to surface loading: An application to glacial isostatic adjustment in Antarctica and Canada, Geophys. J. Int., 192(2), 557–572, doi:10.1093/gji/ggs030, 2013.

Bettadpur, S.: UTCSR Level-2 Processing Standards Document (for Level-2 Product Release 0005), GRACE 327–742, CSR Publ. GR-12-xx, Rev. 4.0, University of Texas at Austin., 2012.

Bonin, J. and Chambers, D.: Uncertainty estimates of a GRACE inversion modelling technique over Greenland using a simulation, Geophys. J. Int., 194(1), 212–229, doi:10.1093/gji/ggt091, 2013.

Chambers, D. P.: Observing seasonal steric sea level variations with GRACE and satellite altimetry, J. Geophys. Res., 111(C3), C03010, doi:10.1029/2005JC002914, 2006.

Cheng, M.: Laser Ranging in 5x5 Spherical Harmonics, Zenodo, doi:10.5281/zenodo.831745, 2017.

Cheng, M. and Ries, J.: The unexpected signal in GRACE estimates of C20, J. Geod., 1–18, doi:10.1007/s00190-016-0995-5, 2017.

Cheng, M., Ries, J. C. and Tapley, B. D.: Variations of the Earth's figure axis from satellite laser ranging and GRACE, J. Geophys. Res., 116(B1), B01409, doi:10.1029/2010JB000850, 2011.

Cheng, M. K., Ries, J. C. and Tapley, B. D.: Geocenter Variations from Analysis of SLR data, from Reference Frames for Applications in Geosciences, International Association of Geodesy Symposia (Springer-Verlag Berlin Heidelberg), , 138, 19–36, 2013.

Collilieux, X., Altamimi, Z., Ray, J., Van Dam, T. and Wu, X.: Effect of the satellite laser ranging network distribution on geocenter motion estimation, J. Geophys. Res. Solid Earth, 114(4), 1–17, doi:10.1029/2008JB005727, 2009.

Howat, I. M., Smith, B. E., Joughin, I. and Scambos, T. A.: Rates of southeast Greenland ice volume loss from combined ICESat and ASTER observations, Geophys. Res. Lett., 35(17), 1–5, doi:10.1029/2008GL034496, 2008.

Jacob, T., Wahr, J., Pfeffer, W. T. and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise., Nature, 482(7386), 514–8, doi:10.1038/nature10847, 2012.

Johannessen, O. M., Khvorostovsky, K., Miles, M. W. and Bobylev, L. P.: Recent ice-sheet growth in the interior of Greenland., Science, 310(5750), 1013–1016, doi:10.1126/science.1115356, 2005.

Luthcke, S. B., Sabaka, T. J., Loomis, B. D., Arendt, a. a., McCarthy, J. J. and Camp, J.: Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution, J. Glaciol., 59(216), 613–631, doi:10.3189/2013JoG12J147, 2013.

Matsuo, K., Chao, B. F., Otsubo, T. and Heki, K.: Accelerated ice mass depletion revealed by low-degree gravity field from satellite laser ranging: Greenland, 1991-2011, Geophys. Res. Lett., 40(August), 4662–4667, doi:10.1002/grl.50900, 2013.

Nerem, R. S. and Wahr, J.: Recent changes in the Earth's oblateness driven by Greenland and Antarctic ice mass loss, Geophys. Res. Lett., 38(13), 1–6, doi:10.1029/2011GL047879, 2011.

Nerem, R. S., Eanes, R. J., Thompson, P. F. and Chen, J. L.: Observations of annual variations of the earth's gravitational field using satellite laser ranging and geophysical models, Geophys. Res. Lett., 27(12), 1783–1786, doi:10.1029/1999GL008440, 2000.

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, a. and Lenaerts, J. T. M.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., 38(5), n/a-n/a, doi:10.1029/2011GL046583, 2011.

Sasgen, I., van den Broeke, M., Bamber, J. L., Rignot, E., Sørensen, L. S., Wouters, B., Martinec, Z., Velicogna, I. and Simonsen, S. B.: Timing and origin of recent regional ice-mass loss in Greenland, Earth Planet. Sci. Lett., 333–334, 293–303, doi:10.1016/j.epsl.2012.03.033, 2012.

Schrama, E. J. O. and Wouters, B.: Revisiting Greenland ice sheet mass loss observed by GRACE, J. Geophys. Res., 116(B2), B02407, doi:10.1029/2009JB006847, 2011.

Shepherd, A., Ivins, E. R., A, G., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. a, Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sørensen, L. S., Scambos, T. a, Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V, van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D. and Zwally, H. J.: A reconciled estimate of ice-sheet mass balance., Science (80-.)., 338(6111), 1183–9, doi:10.1126/science.1228102, 2012.

Sośnica, K., Jäggi, A., Meyer, U., Thaller, D., Beutler, G., Arnold, D. and Dach, R.: Time variable Earth's gravity field from SLR satellites, J. Geod., 1–16, doi:10.1007/s00190-015-0825-1, 2015.

Swenson, S., Chambers, D. and Wahr, J.: Estimating geocenter variations from a combination of GRACE and ocean model output, J. Geophys. Res., 113(B8), B08410, doi:10.1029/2007JB005338, 2008.

Talpe, M. J., Nerem, R. S., Forootan, E., Schmidt, M., Lemoine, F. G., Enderlin, E. M. and Landerer, F. W.: Ice mass change in Greenland and Antarctica between 1993 and 2013 from satellite gravity measurements, J. Geod., 1–16, doi:10.1007/s00190-017-1025-y, 2017.

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F. and Watkins, M. M.: GRACE measurements of mass variability in the Earth system., Science, 305, 503–5, doi:10.1126/science.1099192, 2004.

Velicogna, I. and Wahr, J.: Time-variable gravity observations of ice sheet mass balance: precision and limitations of the GRACE satellite data, Geophys. Res. Lett., 40(April), n/a-n/a, doi:10.1002/grl.50527, 2013.

Wahr, J., Nerem, R. S. and Bettadpur, S. V: The pole tide and its effect on GRACE time-variable gravity measurements: Implications for estimates of surface mass variations, J. Geophys. Res. Solid Earth, 120(6), 4597–4615, doi:10.1002/2015JB011986, 2015.

Watkins, M. M., Wiese, D. N., Yuan, D., Boening, C. and Landerer, F. W.: Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons, J. Geophys. Res. Solid Earth, 120, 1–24, doi:10.1002/2014JB011547.Received, 2015.

Whitehouse, P. L., Bentley, M. J., Milne, G. A., King, M. A. and Thomas, I. D.: A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates, Geophys. J. Int., 190(3), 1464–1482, doi:10.1111/j.1365-246X.2012.05557.x, 2012.

Wu, X., Ray, J. and van Dam, T.: Geocenter motion and its geodetic and geophysical implications, J. Geodyn., 58, 44–61, doi:10.1016/j.jog.2012.01.007, 2012.

Using Satellite Laser Ranging to measure ice mass change in Greenland and Antarctica (supplemental; marked-up version)

Jennifer A. Bonin[1], Don P. Chambers[1], Minkang Cheng[2]

[1]College of Marine Science, University of South Florida, Tampa, FL, 33701, USA
[2]Center for Space Research, University of Texas at Austin, Austin, TX, 78759, USA

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

Supplemental Information: Inversion Mathematics

We considered two related inversion methods for this work. The first is the technique described in *Bonin and Chambers* [2013], which constrains the solution using a simple diagonal matrix of process noise. The second, which we ultimately determined to work better for the low-resolution 5x5 data, uses a more complicated constraint, based on the auto- and cross-correlations of modeled data within nearby sub-regions. In this section, we will mathematically define both, as well as giving some basic statistics of each, based on a simulation.

Our simulated 'truth' data is a combination of three sets of model output. Over the non-ice land, we use the Global Land Data Assimilation System (GLDAS) model with the Noah land surface model to estimate hydrological mass change (Rodell et al., 2004) (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings). Over the oceans, the simulation consists of the 'cube 92' version of the ECCO2 model's bottom pressure estimates, which are created at daily resolution on a regular ¼°x¼° grid (Menemenlis et al., 2008) (ftp://ecco2.jpl.nasa.gov/data1/cube/cube92/lat_lon/quart_90S_90N/PHIBOT.nc/). The monthly version of the Regional Atmospheric Climate Model version 2.3 (RACMO2) (van Meijgaard et al., 2008) is used to simulate the ice mass change over Greenland and Antarctica. All three series are resampled to a 1°x1° equirectangular projection. Because RACMO2 only estimates the effects of surface mass balance, but does not include information about glacier melting, it drastically underestimates mass loss in some areas, especially over western Antarctica. To better approximate the true shape of the mass loss, we replace only the RACMO2 trends with the trends of a 100-km Gaussian-smoothed version of the JPL mascon GRACE data (Watkins et al., 2015). The non-linear interannual, annual, and sub-annual portions all remain the original RACMO2 estimates. After combining the ocean, land, and ice portions of the simulation, we add or subtract a uniform-depth layer of water across the oceans at each time, so as to conserve mass over the entire planet. This simulated 'truth' series is known to 1°x1° accuracy, and is transformed to limited 5x5 and 60x60 spherical harmonics, to represent the simulated SLR-like and GRACE-like visions of the 'truth'. These harmonics are re-converted back into grid form for the least squares inversion.

That inversion technique reads in such spatially-limited grids – simulated, GRACE, or SLR – as its observation array, **y**, where each element in that array refers to a different latitude/longitude grid point. The other needed input is a series of pre-determined regions or spatial kernels, covering the entire world. We tested numerous combinations of regions, but the two we found most effective for this problem are a large-region case for use with the simple process-noise constraint technique (Figure S1a), and a smaller-region case for use with the more complex correlated constraint technique (Figure S1b, d, and f). The goal of the inversion is to determine how much mass goes into each region, in order to result in a 5x5 or 60x60 view comparable to the input data.

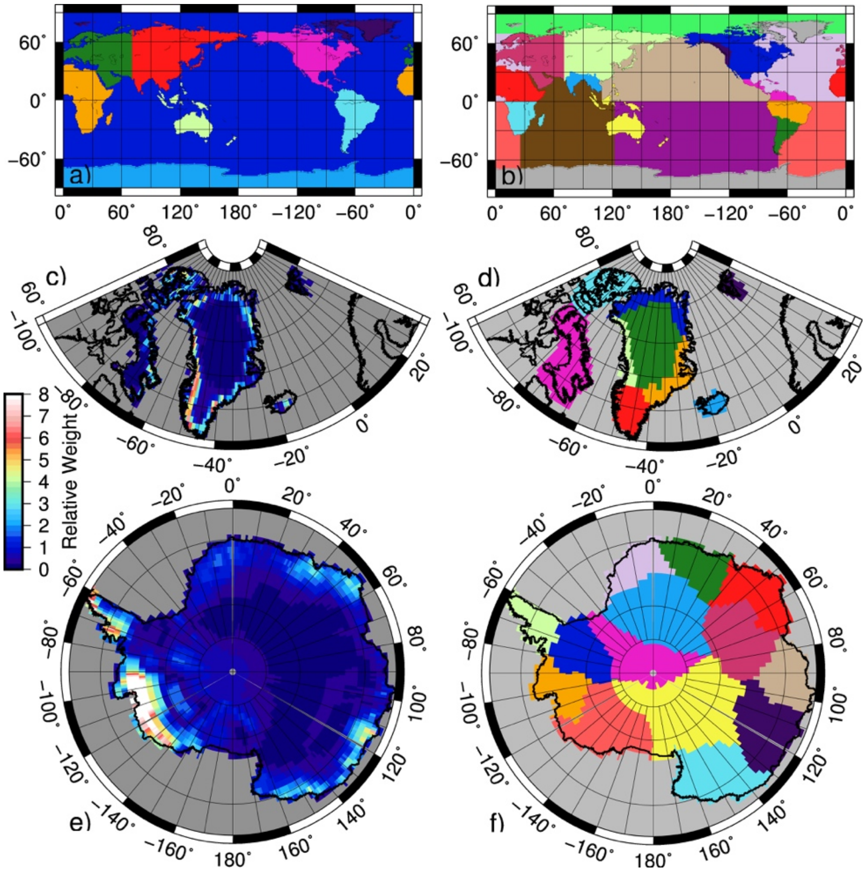


Figure S1: Maps of regions and sub-regions used. (a) shows the large-region layout, while (b), (d), and (f) show the sub-regions of the small-region layout. (c) and (e) are the relative weights applied to the polar regions (which are re-normalized into each smaller sub-region for the small-region cases). The colors in (a), (b), (d) and (f) are arbitrary, merely chosen to visibly separate each area from the others.

In *Bonin and Chambers* [2013], we assumed that the mass was uniformly distributed within each region, but in the large regions we are using here, that proved impractical. In this paper, the distribution of mass within many of the regions is still defined as uniform, but each region near Greenland and in Antarctica is weighted by the standard deviation of the RACMO2 series, such that the coastlines are designed to hold most of the mass change signal (Figure S1c and e, normalized for the large-region case). Similarly, six continental regions with the largest annual hydrologic signals are weighted using GLDAS standard deviations.

We wish to create an estimate of the amplitudes, **a**, which denote the optimal average mass localized into each region at a given time. If $\boldsymbol{\varepsilon}$ is the mismatch between the observations and modeled amplitudes, then what we want to solve can be written as a common least squares observation equation:

$$\mathbf{y} = (\mathbf{Ha} + \boldsymbol{\varepsilon}) \tag{S1}$$

The matrix **H** defines each weighted region's transformation between its 1°x1° gridded shape and a grid limited to the lower-resolution spherical harmonics of the desired maximum degree/order. We can solve for the optimal mass in each region, $\hat{\mathbf{a}}$, by solving the least squares normal equations:

$$\hat{\mathbf{a}} = (\mathbf{H}^{T}\mathbf{H})^{-1}(\mathbf{H}^{T}\mathbf{y}) \tag{S2}$$

However, as both *Schrama and Wouters* [2011] and *Bonin and Chambers* [2013] determined, without a constraint the least squares technique often misplaces the signal, resulting in the correct sum of mass over a large area, but with it distributed incorrectly internally. Most commonly, this shows itself as a large false positive signal in one sub-region, and an equally large false negative signal in a neighboring one, though the sum of those two sub-regions' signals is correct. To remedy this, *Schrama and Wouters* [2011] recommended applying an empirically-determined diagonal matrix of process noise, **N**, as a constraint:

$$\hat{\mathbf{a}} = (\mathbf{H}^{T}\mathbf{H} + \mathbf{N})^{-1}(\mathbf{H}^{T}\mathbf{y}) \tag{S3}$$

This works quite well when using 60x60 GRACE data and relatively small regions, as both of the prior papers show. However, using more limited 5x5 data means using far fewer spherical harmonics as the ultimate input, which prove insufficient for use with large numbers of relatively small regions. In fact, even quite large regions prove too small to solve for accurately. When we tried dividing Antarctica into eastern and western halves, we quickly learned that we could not separate the two correctly, given only 5x5 data. The same proved true about separating the area around Greenland into more than one region. As such, we had no choice but to consider continental-scale regions (as in Figure S1a) instead, when using the simple process-noise constraint technique.

An alternative technique is to separate Antarctica, and separately Greenland, into more pieces, yet tie each of those sub-regions to the others, and to itself during the surrounding months, via a web of constraints. Mathematically, this can be described by equation S4. We created our constraints from the correlations and variances of the JPL GRACE mascon solutions with GIA removed, using data from 2003-2014.

$$\hat{\mathbf{a}}_t = [\mathbf{H}^T\mathbf{H} + \alpha_L^2(\mathbf{L}^T\mathbf{L}) + \alpha_C^2(\mathbf{C}^T\mathbf{C})]^{-1}\,[\mathbf{H}^T\mathbf{y} + \alpha_L^2(\mathbf{L}^T\mathbf{L})\bar{\mathbf{a}}_{t-1}] \qquad \text{(S4)}$$

Here, the lag matrix, **L**, describes the matrix of expected lag-1 auto-correlations for each region, and $\bar{\mathbf{a}}_{t-1}$ is the value in the grid cell during the previously-computed month. The factor $\boldsymbol{\alpha}_\mathbf{L}$ is determined by trial and error; we found a value of approximately 3 produced good 5x5 results with the simulated 'truth' data. We run the data through twice, forwards and then backwards in time, to iterate and avoid lower accuracy during the first few points in the series.

The cross-correlation matrix, **C**, contains the expected cross-correlations between each sub-region and every other in the larger region, weighted by the ratio of their variances. This is done similarly but separately for the Greenland and Antarctic areas. $\boldsymbol{\alpha}_\mathbf{C}$ is also determined empirically; we found that a value of 1 resulted in the best fit to the simulated 'truth' data in the 5x5 case.

Equations S5 and S6 show an example of how to set up the **L** and **C** matrices, for a simple set of three sub-regions (*i*, *j*, and *k*) and the three constraints used to fully connect them. In this example, $xcorr_{i,j}$ denotes the modeled cross-correlation between sub-regions *i* and *j*, while $acorr_i$ is the modeled autocorrelation of sub-region *i*.

$$\mathbf{L} = \begin{bmatrix} 1 & -xcorr_{i,j} & 0 \\ 1 & 0 & -xcorr_{i,k} \\ 0 & 1 & -xcorr_{j,k} \end{bmatrix} \qquad \text{(S5)}$$

$$\mathbf{C} = \begin{bmatrix} acorr_1 & 0 & 0 \\ 0 & acorr_2 & 0 \\ 0 & 0 & acorr_3 \end{bmatrix} \qquad \text{(S6)}$$

Figure S2 demonstrates the relative effectiveness of constraining the inversion via simple process noise, versus constraining it via regional correlations. We computed the average inverted signal over three large regions: all of the Greenland area, all of Antarctica, and the combination of the two. This allows any incorrect internal redistributions of mass from the sub-regions to be ignored, while focusing on the bigger, directly-comparable picture. Table S1 lays out each region's trend errors for the different inversions, relative to the 'truth' simulated input.

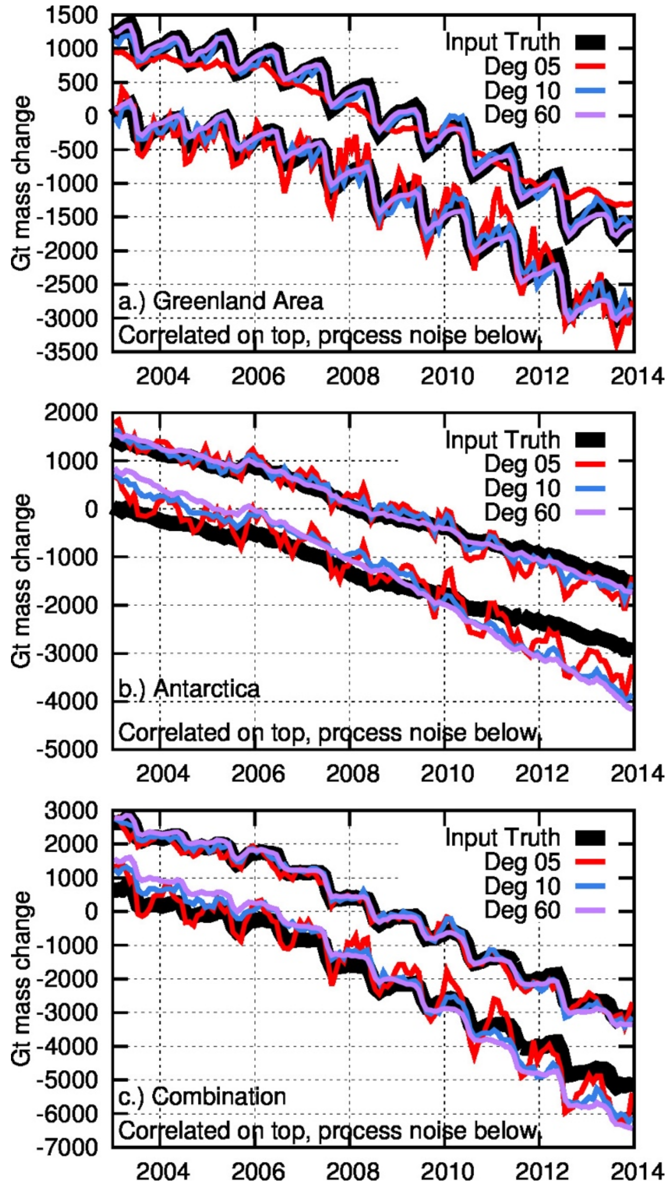


Figure S2: Simulated comparison of the large-region, process-noise constrained inversion (top lines in each plot) vs. the small-region, correlation constrained inversion (bottom lines). Shown are the regional averages over (a) Greenland and the surrounding islands; (b) Antarctica; and (c) the sum of Greenland and Antarctica. The regional average of the input 'truth' is shown in black for comparison.

We found that in Greenland (Figure S2a), the simple process-noise case worked better than the correlated one, for 5x5 data. The 5x5 process-noise constrained inversion results in a lot of jitter, but it recaptures the input simulated seasonal signal and the long-term trend (trend errors are 4.3% of the full 'truth' trend). When we applied the correlation-based constraint, the 5x5 inversion was no longer able to pull out the seasonal signal, and the trend had been significantly reduced (trend errors of 17.4%). Note that this problem is caused solely by the lack of spatial resolution in the data; with 10x10 or 60x60 input data, both problems are be eliminated: the 60x60 trend errors are 2.8% when using correlation-based constraints.

Series to Difference, Relative to Simulated 'Truth'	Greenland Trend Error (%)	Antarctica Trend Error (%)	Combined Trend Error (%)
process noise 5x5	4.3 ± 3.1	-30.4 ± 6.8	-13.0 ± 3.8
process noise 10x10	-0.5 ± 1.5	-51.1 ± 10.3	-25.7 ± 5.5
process noise 60x60	-7.1 ± 1.2	-64.5 ± 6.5	-35.7 ± 3.2
correlated constraint 5x5	17.4 ± 4.1	-15.1 ± 4.7	1.3 ± 1.6
correlated constraint 10x10	4.5 ± 1.6	-9.6 ± 3.1	-2.5 ± 1.6
correlated constraint 60x60	-2.8 ± 0.5	-10.2 ± 1.1	-6.5 ± 0.8
high-resolution 60x60 local	-1.5 ± 0.3	0.6 ± 0.5	0.7 ± 0.5

Table S1: Simulated inversion differences relative to the 'truth' input, over the three regions. Errors given are purely statistical 95% confidence levels after fitting for a bias, trend, annual, and semi-annual signals, based on a Monte Carlo simulation of random red noise with the given RMS and lag-1 autocorrelations.

Antarctica (Figure S2b) shows the opposite results: the simple process-noise constraint results in large trend errors, while the correlation-based constraint does a fair job of recovering the simulated input. At 5x5 resolution, the trend errors increase from 15% for the constraint-correlated technique, to 31% for the process-noise-correlated technique. The situation actually grows worse as resolution improves: for 60x60 data, the errors jump from 10% to 64%. The reason for this is straightforward and concerns the physical meaning of the computed amplitudes, **a**, over such huge areas. The different parts of the greater Greenland region tend to vary contemporaneously with each other, so that using a single number to define all of them (in a weighted fashion) will be close to correct, though not perfect. However, Antarctica does not vary so uniformly. Western Antarctica is expected to have lost mass each year recently, while eastern Antarctica is thought to be close to equilibrium and has had periods where the overall mass has likely increased in recent years (Boening et al., 2012). A single value for **a** cannot represent both situations at once. Either the two sub-regions need to separated – which works for 60x60 data but is unrealistic with only 5x5 data – or we need to limit the two halves of Antarctica in different ways. The correlation constraint technique does the latter, and results in a more reasonable estimate for the Antarctic trend because of it.

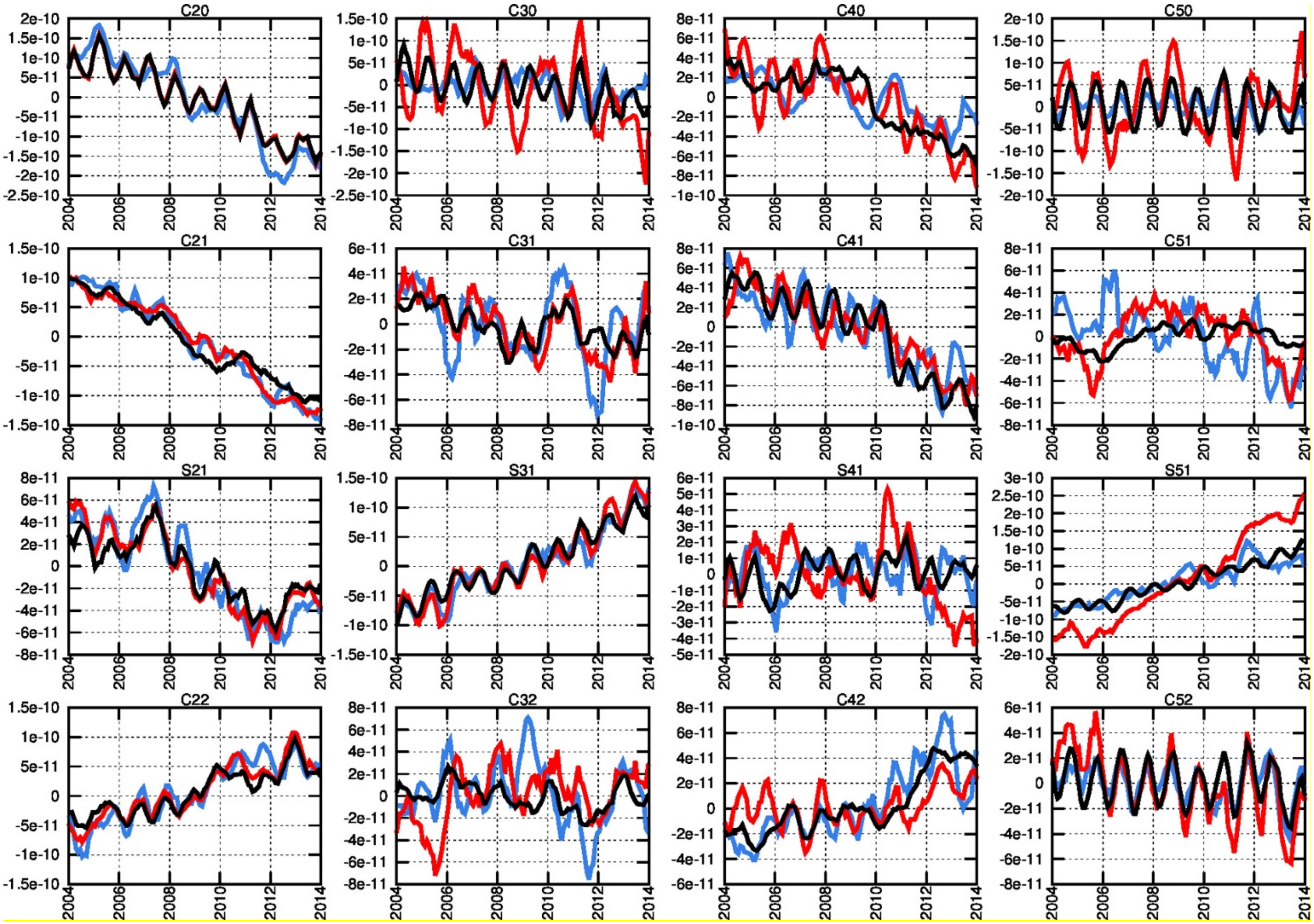
This leaves us with no technique that works well for all parts of the world. We did attempt to combine equations S3 and S4, so that we use the simple process-noise constraint over Greenland, while at the same time using the correlation constraint over Antarctica (not shown). However, we found that the 5x5 results were still less good than using the correlation constraint everywhere. We hypothesize that the reason we cannot get both the process noise technique's good results in Greenland and the correlation constraint technique's good results in Antarctica at the same time is because the two polar areas are inseparable when looking at only the lowest degree spherical harmonics. Changing the results in one area forces changes in the results of the other. While it might be plausibly possible to use external sources (such as ground GPS stations) to separate the two regions, that is likely to be a complex process, particularly as one goes backwards in time to periods when few GPS stations exist. We leave such efforts to a future paper.

Instead, given the inherent connection between Greenland and Antarctica, we choose to sum the two regions and consider the combination as our final answer (Figure S2c). While our simulation demonstrates that we are unable to accurately separate Greenland from Antarctica at a 5x5 resolution, we can at least confirm that the entire polar land ice mass change can be estimated with reasonable accuracy at an SLR-like spatial resolution. Trend errors over the combined polar regions are estimated at 1.3 ± 1.6% of the trend for the correlation-constraint technique, compared to 13 ± 4% for the process-noise-constraint technique. To back out the Greenland area and Antarctic mass changes independently, we would require spherical harmonics which we trust to approximately degree/order 10.

We would note that, very recently, *Talpe et al.* [2017] used a similar method to estimate Greenland and Antarctica's mass change. They used principal component analysis to determine GRACE's dominant long-term spatial pattern of variability (rather than pre-defining weighted regions as we do here), then derived the time-series associated with that pattern from SLR. They only focused on the first mode, which gives the large-scale polar mass loss, since the next three modes were related to the hydrological cycle instead. This alternative technique is thus also unable to truly separate Greenland from Antarctica using SLR data. It additionally assumes stationarity between the GRACE time-frame and the pre-GRACE time-frame, such that the mass change in Greenland and Antarctica is treated as a single entity varying as one, with the relative weight between the two determined not by SLR but by the first EOF mode from GRACE's 2003-2016 data. While this is likely to produce a more accurate spatial pattern than our pre-weighted regions do during the GRACE time-frame, we can not assess how well that pattern reflects the true state of polar ice mass change pre-GRACE. One benefit to the correlation-constrained sub-regions technique used here is that it allows the pre-GRACE SLR data to set the spatial pattern without influence from the melt during the GRACE years.

Our analysis was designed to minimize the errors of a 5x5 inversion. We found that using the same optimization parameters and regional definitions with 60x60 data resulted in an over-estimation of the mass trend of 6.5 ± 0.8%. When using real data, we do not wish this exaggerated trend to appear as part of our comparisons. Instead, when we create 'truth' series for the real-world comparison from the GRACE 60x60 data, we use the simple process-noise technique (equation S3) over each pole separately, and with higher-resolution regions to invert into. Over Greenland, we use the local regions defined in *Bonin* *and Chambers* [2015] (excluding the specialized glacier-only basins used there), which include thirteen separate regions in Greenland itself. Over Antarctica, we use the Antarctic division shown in Figure S1f, but with the southern ocean divided into twelve sectors. By computing the inversion locally rather than globally, we are able to achieve excellent similarity to the simulated 'truth' in each region. In Greenland, the trend error is just -1.5 ± 0.3%, while in Antarctica it is 0.6 ± 0.5%. Directly summing the two inverted time-series to estimate the total polar mass loss results in a trend error of only 0.7 ± 0.5%. This is proof that the inversion technique works very well with higher-resolution data. However, we are not able to accomplish the same separation with 5x5 inputs.

Supplemental Information: Comparison of Input Series by Harmonic Coefficient



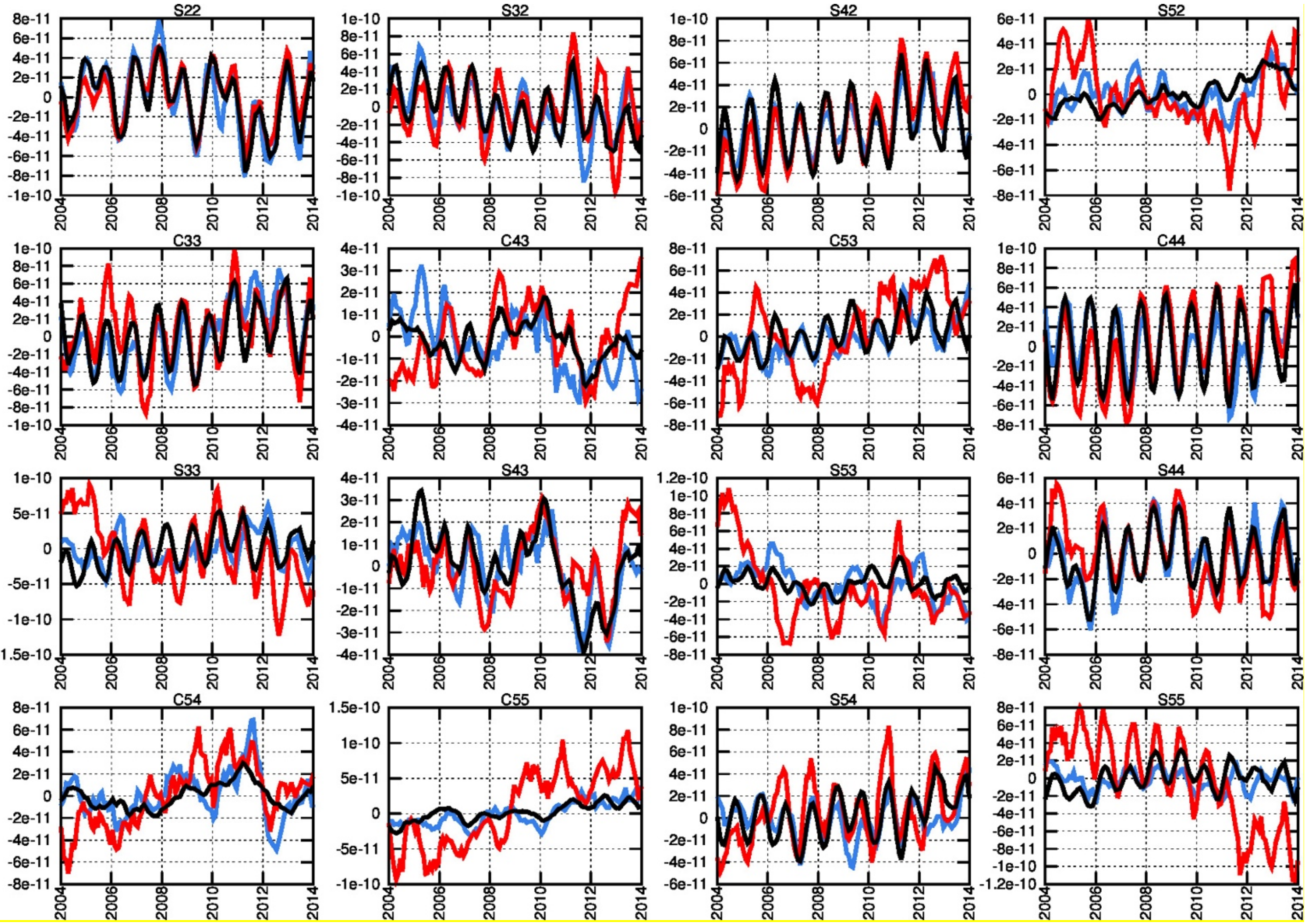


Figure S3: Time-series of the GRACE (black), Cheng 5x5 SLR (red), and Sośnica 10x10 SLR (blue) input data series, by spherical harmonic coefficient. A 200-day smoother has been applied to all series.

References

Boening, C., Lebsock, M., Landerer, F. and Stephens, G.: Snowfall-driven mass change on the East Antarctic ice sheet, Geophys. Res. Lett., 39(21), L21501, doi:10.1029/2012GL053316, 2012.

Bonin, J. and Chambers, D.: Uncertainty estimates of a GRACE inversion modelling technique over Greenland using a simulation, Geophys. J. Int., 194(1), 212–229, doi:10.1093/gji/ggt091, 2013.

Bonin, J. A. and Chambers, D. P.: Quantifying the resolution level where the GRACE satellites can separate Greenland's glacial mass balance from surface mass balance, Cryosph., 9, 1761–1772, doi:10.5194/tc-9-1761-2015, 2015.

van Meijgaard, E., van Ulft, B., van de Berg, W. J., Bosveld, F. C., van den Hurk, B., Lenderink, G. and Siebesma, A. P.: The KNMI regional atmospheric climate model RACMO version 2.1 (KNMI TR-302), Royal Netherlands Meteorological Institute (KNMI), de Bilt, Netherlands., 2008.

Menemenlis, D., J-M. Campin, Heimbach, P., Hill, C., Lee, T., Nguyen, A., Schodlok, M. and Zhang, H.: ECCO2: High resolution global ocean and sea ice data synthesis, Mercat. Ocean Q. Newsl., 31(October), 13–21 [online] Available from: http://www.mercator-ocean.fr/content/download/691/5904/version/1/file/lettre_31_en.pdf#page=13, 2008.

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin*, J. K., Walker, J. P., Lohmann, D. and Toll, D.: The Global Land Data Assimilation System, Bull. Am. Meteorol. Soc., 85(3), 381–394, doi:10.1175/BAMS-85-3-381, 2004.

Schrama, E. J. O. and Wouters, B.: Revisiting Greenland ice sheet mass loss observed by GRACE, J. Geophys. Res., 116(B2), B02407, doi:10.1029/2009JB006847, 2011.

Talpe, M. J., Nerem, R. S., Forootan, E., Schmidt, M., Lemoine, F. G., Enderlin, E. M. and Landerer, F. W.: Ice mass change in Greenland and Antarctica between 1993 and 2013 from satellite gravity measurements, J. Geod., 1–16, doi:10.1007/s00190-017-1025-y, 2017.

Watkins, M. M., Wiese, D. N., Yuan, D., Boening, C. and Landerer, F. W.: Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons, J. Geophys. Res. Solid Earth, 120, 1–24, doi:10.1002/2014JB011547.Received, 2015.