Reply to Reviewer #1 (Henryk Dobslaw):

Thank you, Henryk, for your very helpful review. We've altered the text in several places because of it. Here are our more detailed replies. Please let us know if there's anything else you'd suggest changed.

-- Jenni and Himanshu

1.) It is stated at numerous places in the paper that the ITSG series are governed by external geophysical models whereas the swath solutions are free of a priori model information. I believe that both claims are not entirely correct and should be relaxed in the sense that both solutions utilize some external "information" (in certainly distinctly different ways). Note that such information might also include the assumptions that variability over oceans and land is uncorrelated, and that ocean bottom pressure variability in the tropics is very small. The inverse problem with just a 24-hour subset of GRACE data is ill-posed and needs to be stabilized in some way to obtain a reliable solution.

We have tried to be more careful in our wording. You are correct that some sort of stabilization is obviously required, and we now mention that in the paper. What we intended to say with regards to the CSR swath solution, was that there is no external geophysical model used to inform any constraints. The constraints are purely driven by GRACE information. The only external information used to define the constraints is the land and ocean boundary. Our information concerning your understandable question about "the variability over the oceans in the tropics is very small" is also derived purely from GRACE. While the inverse problem with just 24 hr subset of the GRACE data is ill-posed, the stabilization is helped by the fact that only the mascons under the ground tracks are estimated for the day. This inverse problem not as illposed as a global inversion from a 24 hr data. We have attempted to make this more clear in the paper:

"The global mascon solutions and regularization are purely driven by GRACE without any influence from external models. The only external information used to inform the constraints is the land/ocean boundary mask. All the other information for constraints comes from expected signals in GRACE for that month from regularized spherical harmonic solutions (Save et. al. 2016) and the GRACE groundtrack. Since the daily constraints are derived from the respective monthly expected signals from GRACE, the regularization also allows for adjustment of unexpected signals that are captured the monthly solutions. The only submontly signals that will get constrained to zero in the swath solutions are the signals that may have a zero mean over 30 days throughout the mission but do have submonthly variability. The implementation of the swath estimation assumes that such locations are very rare. Thus, the time-variable regularization process used does not bias or attenuate future regional signals based on statistics from models or past GRACE months, but is intentionally designed to encourage no land/ocean correlation in order to reduce leakage. Further details of the data processing for producing the daily GRACE swath solutions is available in Save et. al. 2018 (in-preparation/in-review)."

There isn't a lot of detailed information about how the ITSG series are regularized, but everything we've read/heard suggests that they do it based on signals (RMS, etc) from apriori models. We sent an email to Torsten/Andreas asking for information, and this is what Andreas replied:

> The big picture of the daily processing has not changed much since Enrico's paper in 2012 (https://doi.org/10.1016/j.jog.2012.02.006). We still use daily GRACE normals (in spherical harmonics) and constrain them using a stochastic model derived from geophysical model output, so most of the conclusions from back then can still be applied today. What became more sophisticated over the years is the way how the constraints are computed. We put a lot of thought into how the covariance function of a high-dimensional stationary process can be robustly estimated. This mainly involves exploiting geophysical properties, for example, land/ocean masks.

We've updated the text to make this more clear, as well as adding the reference into it for those who want more information.

2.) It is nice to see that swath solutions show less noise in the tropics than ITSG, but it should be acknowledged at some point in the paper that reducing noise in regions where geophysical signals are expected to be non-existant can be very easily achieved by regularizing the solution towards zero. In case of an unexpected event at some later date (say, an earthquake), regularized solutions tend to underestimate or even miss that signal. Maybe the authors could elaborate a little further about the utilization of regularization (or related techniques) in the swath solutions when discussing the tropical oceans for the pleasure of their geodetic audience?

There is a main swath paper ready to be submitted for review shortly that will discuss all the details of the constraints, etc. We have now included a few details about the regularization in this paper, as well as adding a citation toward the in-progress work for further information in the future. The regularization matrix for the swath solutions are essentially an extension of the monthly regularization matrix design process (as described in Save et. al. 2016) but also includes information for the ground track.

As for your concerns about the tropics, you are correct that it's easy to "regulate away" errors by just driving them the full signal+error to zero. We see no indications that this is what's happening in the swath solutions, though, as said in above. The only way signal (or noise) in the tropics could be artificially driven to zero is if the monthly mean signal was zero, but the submonthly non-noise signal wasn't. That's unlikely to be commonplace, so if the tropics show low sub-monthly noise, it's because there's also low monthly-scale signal there within that particular month.

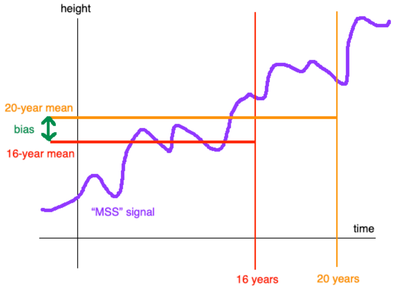
3.) The Low-degree Stokes coefficients not accessible from GRACE alone can be assumed to vary rather slowly in time so that linear interpolation from monthly to daily sampling might be feasible. Have you tried this in some way? Would you expect any consequences for your conclusions? Which regions might be affected most?

If you're talking about the geocenter and J2 terms, we toyed with interpolating them, by fitting a trend/annual and interpolating based on that model. We chose not to add that complication in this paper, however, since we're looking at the sub-monthly signal. As you say, low degrees like the geocenter aren't likely to change rapidly, even assuming we had good daily geocenter data to represent reality with. And if we simply interpolated the change linearly between months, the change in the sub-monthly frequency band would be zero. Thus the omission. We've added a comment about this in section 3.2.

4.) The impact of change in the MSS model might be explored a little further. What is the difference between the 16y and 20y MSS? Is that effect perfectly linear, or do you see larger biases in regions where the MSS models differ most?

At some point in the future, I (Jenni) really would like to dig up my own MSS model and reprocess all my altimetry series correctly. But I haven't done that yet and it's no doubt going to be a pain. I've tried to look into the two MSS models used by Jason, but getting information about them has also proved unexpectedly difficult. The sum total of all the info I can find is from the AVISO website here:
https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/mss.html
As you'll note, it's not extensive, nor does it link to any more useful papers. So I don't actually know the answer to your first question.

But I'm less concerned about short-term, mostly-regional differences where the two different models see slightly different signals, than I am about the bias difference. As best Don and I can figure, the main reason our Figure 1a sees such a huge signal isn't because the models are necessarily very different, but simply because they're centered at a different time. I'm attaching a little sketch I drew to show you what I mean. Even assuming the two MSS models were perfectly identical, because of the 16-year vs. 20-year time span, they're going to see different MEAN values. That's where the bias jump between missions (or rather, between MSS models) is coming from. It's way too big to simply be from real model improvements. They just didn't recenter the bias to the same timespan as the old MSS model. And also didn't tell anyone, which is even more frustrating – and why I wanted to explicitly mention it in this paper, so at least the information is out there someplace.



(I rather doubt that the journal would appreciate publishing my hand-drawn picture, alas.)

5.) The discussion of the signal in the Zapiola Gyre is interesting and deserves more attention. There has been previous work about the dynamics seen from both altimetry and gravimetry (see 10.1029/2018JC014189 and references therein), and it would fit well into the scope of the journal if some further discussion is added based on the swath data.

We absolutely agree that this is a fascinating area. There are some interesting results from the Gyre being included in the main swath paper. The summary is that GRACE swath solutions can clearly observe rotation in the gyre at a sub-monthly frequency that has been previously seen in the altimeter data. We're hoping to do more work in this region in the future – possibly with both ITSG2018 and CSR swath, since they both seem to give plausible localized results. That's a bit outside the scope of this paper, however – and probably shouldn't be published until after Himanshu's swath paper, anyhow.

Also, thank you for the link. That was an excellent paper.

6.) The assessment of the anomaly present in AOD1B RL06 in the South Pacific appears to be sound and forms valuable feedback for the development of general ocean circulation models. Our present-day understanding is that an overly simplyfied Ross Sea bathymetry in the MPIOM model run (i.e., all ocean areas covered by shelf-ice are treated as land) distorts the dominant eigenmodes in the larger region at periods around 3 to 8 days. I expect to see this problem reduced to a large extent in the next release of AOD1B.

Congrats on figuring out the bug! I'm glad to hear it. What a bizarrely localized issue. Is this just for our own information, or would you like us to quote you in here so everyone knows? We assume the latter and have altered the manuscript accordingly, but if you'd prefer for us not to do so, that's also fine. Let us know what you'd like and we'll see it done.

Section 4: In terms of the language, I suggest to clearly separate between observations, which might "see" or "observe" signals; and on the other hand numerical models, which rather "predict" variations. I suggest to modify this throughout the whole manuscript, but in particular adapt the wording in Section 4.

Sorry. That's my bad. Srinivas has only been yelling at me about this imprecision since 2002, now. :) You'd think I'd know better. I've gone through and corrected it, as you suggest.

l. 135: The products used here have higher resolution in time but not in space, right?

Correct. We altered the line to make this more clear.

l. 137: The desire of labelling the CSR swath data as the "main" GRACE product is understandable, but not fully justified. Maybe just call it "your" GRACE product?

Agreed, this is definitely not the "main" GRACE series. We meant the main series used by THIS paper, not overall. We have altered the text to make that clear.

l. 159: ... results shown here represent the full non-tidal mass signal.

We have added a line confirming that the ocean tide model was removed and has not been restored.

l. 174: Who, in fact, is Norbert?

I am so sorry. I use Mendeley to organize my citations and somehow, in the submitted version of the document, the second half of the bibliography disappeared, including all authors with last names later than "M", and the ITSG citations shifted from the first author (Mayer-Gurr) to the last (Norbert). I have no idea how, but that has been corrected. Sorry again.

Reply to Reviewer #2:

Thank you very much for your helpful review. We'll respond to each point in kind:

0. Another major item is: "Half the References section is missing!" (Perhaps a problem with the OS website?).

> This error was noted by the first reviewer and has been corrected. We honestly have no idea how the second half of the references vanished, but it's been fixed. Oops. Sorry.

1. My major complaint is not with the GRACE processing, but with the altimetry – and more specifically it is with Figure 1, which reports a large "bias offset" between Jason-1 and Jason-2. This certainly will be a surprise to the altimeter community, and it contradicts what has been previously published – see, for example, papers by Ablain et al. (doi: 10.1080/01490419.2010.487805) and Beckley et al. (doi: 1.1080/01490419.2010.491029).

The Jason project teams and most users would be very concerned to see Figure 1 published as is, and for good reason. In fact, this "bias" is merely caused by use of inconsistent versions of Jason GDRs. One cannot blindly combine different GDRs, based on different corrections and possibly other things (retracking?), and expect consistency. The authors should not rely on the "experienced aid of Don Chambers," but should carefully examine user handbooks and other documentation. They will find that there are other differences, too, not just the MSS model. After I did some digging, I can add one thing in the authors' defense, which is a point about better data documentation. For some reason, the CLS group uses a naming (or non-naming) convention that is confusing. Their MSS evidently comes with a rate, and by changing the "reference time period" the MSS obtains different values, even though the fundamental MSS model is the "same" and retains the same name. (It is not a matter of the time span of data going into the determination of the MSS.) It would be much better if CLS didn't confuse users in this way, but that's the way matters stand. The GDR attributes give no hint of this problem, but the data handbooks do.

What the authors should have done, and should have written, is something like the following:

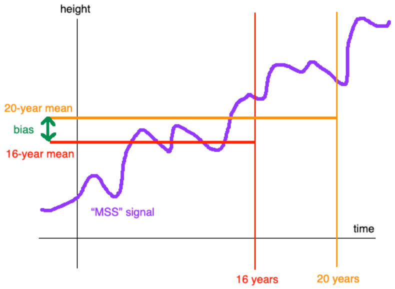
"We have used the best available Geophysical Data Records (GDRs) from Jason-1 and Jason-2, and applied consistent geophysical models to ensure a self-consistent time series of sea surface height anomalies across the missions. The source data are from Jason-1 version "E" and Jason-2 version "D" GDRs. Documentation for these different version numbers indicate the use of different processing standards, in particular ancillary geophysical models in the two sets of products. Most important for our investigation, we have used a consistent mean sea surface and ocean tide model. We have also used the ECMWF Reanalysis for the dry troposphere and inverse barometer corrections, as provided on the Jason-1 GDR-E, to mitigate any changes to the ECMWF operational analysis during our period of interest."

This does require some data processing. An alternative approach is not to use the GDRs at all, but instead use DUACS(Aviso) or MEASURES products, which are reprocessed data with consistent data handling since 1993.

We entirely agree as to what the problem is, and the ideal way to fix it. Unfortunately, as you say, the issue is not well-documented at all, even in the handbooks, much less on the AVISO website – which means we will not be the only people to run into this problem and be baffled by it. Anyone downloading modern GDR data will run into it, because the older versions of the data are no longer available. We cannot find a copy of the old MSS model anywhere, though the most recent MSS model data can be downloaded from the AVISO website after some contortions. Similarly, the GDR-D data for Jason1 simply isn't online anymore at either PODAAC or AVISO. GDR-E only exists for Jason2 and Jason3, not Jason1. Which makes using matching GDR versions or official MSS models effectively impossible.

We chose to make a point of this in this paper largely to make others aware of the potential problem. It's very easy to miss, because it's natural to assume that since the GDR versions out there are the only ones available, they can be strung together safely. People have read the papers you suggested, and are thus using codes which assume the mission-to-mission offset is spatially-uniform (as it otherwise would be). But with the jump between GDR-D and GDR-E, it's not.

The big problem is not that the SSH model changed between versions (that's expected), but that they didn't level it so that the (arbitrary) time-means were the same between versions. I hand-drew a cartoon of the issue below, in case that better helps explain what I'm describing. Even assuming the two MSS models were perfectly identical, because of the 16-year vs. 20-year time span, they're going to see different MEAN values. That's where the bias jump between missions (or rather, between MSS models) is coming from. It's way too big to simply be from real model improvements. They just didn't recenter the bias to the same timespan as the old MSS model, or provide a way for others to do so afterwards.



The resulting bias will result in incorrect results on the order of +/- 4cm heights in some areas, so it's important that others know that it needs to be handled. Ideally, of course, the producers of the GDRs would update all the Jason satellites together, or use MSS models with identical global means, to avoid this issue altogether. But they haven't, so GDR users have to deal with the issue on their own. Which they certainly can't do, if they aren't told there's an issue to begin with!

Now, as you say, the best method to handle this would be to reprocess with my own, consistent MSS model, not the differing versions inside the GDR files. Most likely we'll end up doing that for future work, if the Jason2 and 3 GDR products don't come out with a version E soon (as we keep hoping they will!). But that's going to take a lot of time and effort to code up from scratch and run, and the mean-bias correction we've already made corrects for the worst of the problem – the bias jump between missions – already. (The E-version MSS may also be more accurate on a point-by-point basis, but that just means a possible quality degradation between missions – and we already have a degradation over time with GRACE anyhow, so that's tolerable.)

As you say, DUACS is another option, but we would prefer to avoid using a premade gridded product. While that would fix this MSS issue, we have no idea how the optimal interpolation used in the combination of multiple satellites will alter the high-frequency data, particularly in areas with less good coverage. That seems to us a harder to handle problem than the change in MSS model (once the jump between missions is handled).

Because of the confusion both reviewers showed for this subject, we have lengthened and clarified this section in the text. Hopefully the details will make more sense now.

2. The reference "Eumetsat,... (2016) for Jason-1 products isn't right, as Eumetsat had nothing to do with Jason-1.

You're right. But actually, when altering this section of text, we realized that the Jason-1 handbook has not been correctly updated to list the current MSS information, so we instead pointed to the AVISO website, which we presume has the most up-to-date information.

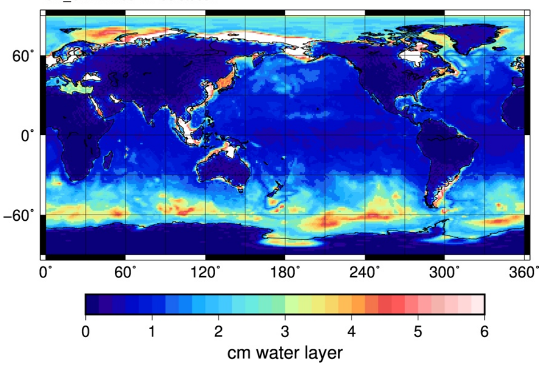
3. Line 21: "as large as" -> "even larger than"

Corrected

4. Line 23: How do you know the ocean models are poor in the Southern Ocean? If data assimilation has been used in their development, then I'd agree, but I thought OMCT and MPIOM had no assimilation. Is there another reason to think models are poor there?

It's true that neither OMCT nor MPIOM use data assimilation, but at the same time, their creators do test them (or maybe even "tune" them?) by checking against whatever data exists. So in areas where data is limited, it's hard for them to determine if the models go amiss in some way, and correct for it. Thanks to its depth and difficulty to get to, the southern ocean is one of those places which is not well observed (few bottom pressure recorders, limited XBT drops, etc). And thanks to its uneven topography and global zonal circulation, its physics is complex. All of which make errors more likely than elsewhere.

The easiest way for me to demonstrate the heightened uncertainty in this area is simply to show you the standard deviation of the submonthly differences between AOD1B RL05 (OMCT) and AOD1B RL06 (MPIOM):



Notice that some of the biggest submonthly differences – up to 5cm in equivalent water height – are in the Southern Ocean. The larger uncertainties in this area are confirmed by the AOD1B modelers (ie: Dobslaw et al 2017; doi:10.1093/gji/ggx302) who similarly see large differences in their models and improved GRACE KBRR residuals in the area. Other modelers recognize the area as similarly less well-known.

The usual assumption is that a newer model is generally better – and in fact, we've proved that in this paper, in terms of AOD1B. But, as we also showed here, there are remaining submonthly errors in the model. It's hard to say exactly how large those errors are (I couldn't find any good paper on it for any of the models used here), due to the paucity of observed data in the region, but it's telling that neither the OMCT nor MPIOM modelers were surprised to hear about potential weaknesses in their models in this area.

5. Line 27: "predicated" is the wrong word to use here.

Corrected

6. Line 163: "signal" -> "signal was"

Corrected

7. Line 170: The authors here might wish to cite published work that has examined the barotropic circulation in this region. For example, work by Chris Hughes: doi:10.1029/2006JC003679

Yes, thank you, done. That was, in fact, the paper that got me (Jennifer) interested in this region.

8. Line 210: Is MPIOM also forced by pressure? If not, how does this affect the C3 comparisons? Line 203 already notes that OMCT uses pressure forcing.

Yes, both models use comparable types of forcing, including pressure. We've altered the text to make this more explicit.

9. Line 214: The Lynch-Gray reference should be augmented (or even replaced by) Carrere et al.: doi:10.1029/2002GL016473

Done, thanks.

10. Caption to Figure 3. It would be useful to give the time intervals over which these standard deviations were computed. (In fact, I don't think I saw this in the main text anywhere either, but I may have missed it.)

Oops. You're right. That's now fixed, both in Fig 3 and in the main text. The span used was April 2002 to January 2016 (the periods when we had data for all the series). Sorry.

11. Line 247. I would add "except for the middle and North Atlantic". It seems GRACE is not improving the prior model there.

Agreed, corrected. It's interesting that there's such a neutral response in the Atlantic, actually.

12. Lines 280, 288: Are Figures 6a and 6b reversed?

Yes, thanks. Corrected.

13. Line 308: Could slightly more explanation be added here, or at least a reference? It is not obvious to me how Gaussian temporal windows are being used to form a band-pass filter.

Done. Basically, you can use two windows of different lengths to create a band-pass filter. For example, if you process the same series with first a 30-day boxcar sliding window and (separately) a 20-day boxcar, then you can difference the 20-day series from the 30-day one to get a bandpass filter between 20-30 days. It's the old game where windowing in the time domain is equivalent to filtering in the frequency domain. We're using Gaussian windows to avoid ringing due to sharp cutoffs, but the same principle applies. (Yes, we've checked this with an FFT in the past.) The benefit of using windows rather than frequency-based techniques is that it allows you to work with gappy data.

14. Line 345: I would again suggest that it is mentioned that the Middle and North Atlantic are problem areas.

Done.

15. Section 7. Since this section already lists long URL addresses for data used, those things could be eliminated in the main text.

Good idea. Done.

16. I much appreciate the color scales in (for example) Figure 5, where arrows point which way which model is superior. Very useful. Some of the figures are a bit hard to read, however, and a bit cramped. The fonts/resolution of Figure 2 seems especially fuzzy – a Word feature?

Yes, it annoys us, too, and yes, Word makes it worse than the file is on its own. Figure 2 is a combination of a line plot (made in gnuplot) and a map (made in GMT). We can't find a "pretty" way of joining the two, except doing so manually in a graphics program, which reduces the resolution – and forces us to save in PNG format (since the journal won't accept jpgs). Word, apparently, doesn't like PNG format. We've redone Figure 2 with a clearer-looking font to match the others, which makes it less obvious. The final plot should look better, since it won't have the issue with Word on top of the limited resolution.

Marked-up Manuscript Version:

Evaluation of Sub-Monthly Oceanographic Signal in GRACE "Daily" Swath Series Using Altimetry

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Abstract. Bottom pressure estimates from three different GRACE gravity series (an experimental CSR swath series, ITSG2016, and ITSG2018) and two global ocean models (OMCT and MPIOM) are compared to Jason altimetry sea level anomaly estimates, in order to determine the accuracy of the GRACE and model data at sub-monthly time scales. We find that the GRACE series are capable of explaining 25-75% of the sub-monthly altimetric variability over most of those ocean regions which have high signal strength. All three GRACE series explain more of the sub-monthly variability than the de-aliasing products they were created with do. Upon examination over finer frequency bands, the GRACE series prove superior at explaining that altimetric signal for signals with periods as short as 10 days.

1 Introduction

Many Earth-observing satellite missions utilize high-frequency oceanographic models to prevent quick-moving geophysical signals from aliasing into longer-period errors under the effect of a relatively long orbital repeat pattern. Both the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004; Wouters et al., 2014) and the Jason family of radar altimeters (Lambin et al., 2010; Ménard et al., 2003) use such ocean de-aliasing models. For such de-aliasing to be successful, the models must naturally be close to reality, else the errors in using them might be even larger than not de-aliasing at all. Over the past two decades, the sub-monthly global de-aliasing models have improved substantially. Yet they remain imperfect, particularly in hard-to-observe areas such as the distant and deep southern ocean. In this work, we utilize Jason satellite altimetry data to demonstrate that sub-monthly GRACE data can improve upon the existing GRACE de-aliasing model in several high-signal regions. We then attempt to measure over which frequency bands GRACE is more like altimetry than the existing model is, and thus where and when it might add value over the current de-aliasing model.

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The work in this paper was preceded by Bonin and Chambers (2011), called BC11 henceforth. BC11 used older altimetry, model, and GRACE data, but was still able to demonstrate that the then-modern daily ITG-GRACE2010 series could explain 10-30% more of altimetry's variance than the de-aliasing model of the day could, across large bands of the southern ocean and northern Pacific. The theory which both that paper and this one are based upon is straight-forward. If GRACE is observing real sub-monthly ocean bottom pressure signals, then the variability of the difference between GRACE and altimetry (along the altimetry groundtracks) ought to be smaller than the variability within altimetry alone. Or, put in a more mathematical form, if GRACE is seeing real signal, then:

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$$\text{var(Altimetry – GRACE)} < \text{var(Altimetry)} \quad (1)$$

In this case, the percent of altimetry's variance explained by GRACE will be greater than zero. Similarly, if GRACE is more accurate than the de-aliasing model, then a double-difference of the variances will show that:

$$\text{var(Altimetry – GRACE)} < \text{var(Altimetry - Model)} \quad (2)$$

Or in terms of relative percent variance explained:

$$\text{pervar(Alt. explained by GRACE) - pervar(Alt. explained by Model)} > 0 \quad (3)$$

We do not expect this method of comparison to work well in places with large short-wavelength signals, which neither GRACE nor the models resolve well, nor where altimetry is measuring ocean height changes caused primarily by temperature or salinity differences, which GRACE cannot see at all. However, as we determined in BC11, this restricts us only from regions with strong currents, such as along the western boundaries of the continents and the center of the Antarctic Circumpolar Current, leaving most of the ocean accessible to this analysis.

Our ultimate goals in this work are two-fold. First, we wish to demonstrate conclusively that the modern "daily" GRACE series we consider are truly measuring real sub-monthly signal, and that not all of that signal is coming from their apriori ocean de-aliasing models. Second, unlike in BC11, we wish to place more specific bounds on which frequency bands GRACE is able to measure better than its de-aliasing model does. The ultimate goal which we aspire to in future work is to create a combined sub-monthly ocean de-aliasing model, where the highest frequencies and shortest wavelengths remain purely model-based, but the longer frequencies and larger spatial scales are blended with those pieces of information from GRACE which are statistically likely to be more accurate.

2 Methods

The procedures followed in this work are largely those laid out in BC11. In broad form:

1.) Ocean bottom pressure data from GRACE and sea-level anomaly data from Jason-1 and Jason-2 are collected and processed in the standard manner. Bottom pressure estimates from the ocean de-aliasing models used with GRACE are also prepared. Details on this step are given in the following section.

2.) Since the altimetry data exists only in those places and times which Jason overflies, the GRACE and model data are masked to cover only those same groundtracks. On days where either GRACE or altimetry data does not exist, no data of any type is utilized. All data types are averaged into daily files at 3° resolution. The altimetry and model data are smoothed using a 300km Gaussian spatial filter, in order to better match them with the native GRACE resolution. This also reduces the impacts of eddies and other short-wavelength phenomena.

3.) All data types are band-pass filtered, to recover information within three frequency regimes: signals with periods shorter than 10 days, between 10 and 20 days, and between 20 and 30 days. Gaussian temporal windows are used to segment these regimes so as to avoid incorporating unwanted frequencies due to side-lobes. In addition to these three frequency bands, the sub-monthly variability is considered as a whole, as in BC11.

4.) The differences between GRACE and altimetry, and also between the models and altimetry, are computed over each frequency band. The variances of each differenced series are measured. The percentage of altimetry's variance which is explained by GRACE or the models is computed for each frequency band. A double-difference estimate of this percent variance explained (Eq. 3) demonstrates visually and statistically which GRACE or model estimate explains more of the altimetry signal in the various areas and frequency bands.

In addition to the updated GRACE, model, and altimetry data series, the main difference between this work's techniques and those in BC11 is the use of more frequency bands, so that the type of sub-monthly variability can be more closely analyzed. The 10-day altimetry orbital repeat period necessitates the use of larger (3°) grid cells, such that sufficient data is retained within most grids over the shortest frequency band.

3 Data Products

3.1 Jason Altimetry

The estimates of sea level anomaly considered here come from the most modern Jason-1 and Jason-2 Geophysical Data Records (GDR) at this time. We use Jason-1 GDR version E from 2002-2008, and Jason-2 GDR version D from 2009-2016. These products are freely available from PODAAC and NOAA (see Data Availability). All standard corrections are applied, including the inverted barometer correction. However, the non-tidal ocean de-aliasing model contained within the dynamic atmospheric correction (DAC) is *not* removed, as that is what we are attempting to observe.

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While computing the sea level anomaly values, we stumbled across one surprise difficulty which we would like to make particular note of, for the benefit of other Jason GDR data users. When we went to reference the Jason-2 data to the Jason-1 data, we determined that there is a large, geographically-correlated bias between the most modern data releases of the two missions (Fig. 1a). To provide a historical backdrop, Jason-1 produced solo data from January 2002 through July 2008, at which point it was joined by Jason-2. The two satellites flew in the same orbit, one shortly behind the other, until the start of 2009, at which point Jason-1 was moved into an interleaved complementary orbit. The last of the Jason-1 data was captured in March 2012, after which Jason-2 flew alone for four years. In February of 2016 (after GRACE finished) Jason-3 was added in an identical orbit for eight months, until Jason-2 was moved to the complimentary orbit through its demise in May 2017. The common way of aligning the two missions is to take the data during the overlap periods and compute a bias from that. Historically these mission biases have pointed out several complex error types, but those are now understood, so that the Jason-1 GDR-D to Jason-2 GDR-D biases were constant across the ocean. When we compute the Jason-2 GDR-D to Jason-3 GDR-D biases (Fig. 1b), that is still what we see.

Thus our surprise upon finding a large, non-uniform Jason-1 GDR-E to Jason-2 GDR-D bias! We have determined that this bias pattern comes from a change in the mean sea surface (MSS) model used between the D and E versions of the GDR output. In version D, a 16-year MSS correction (MSS_CNES-CLS-2011) was created by averaging satellite altimetry data over the years 1993-2008. In version E, a different dynamic topography model (MSS_CNES-CLS-2015) was created over the longer 1993-2012 timespan instead. (For details on the Jason-1 GDR-E MSS, see the AVISO website: https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/mss/mss-description.html. For details on the Jason-2 GDR-D MSS, see the Jason-2 Handbook: CNES et al., 2011.)

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The change of MSS model results in two types of differences during the Jason-1 to Jason-2 leveling process. First, the newer GDR-E MSS model has a finer resolution and is averaged over differing years, which will result in slightly different values in some areas. We are currently assuming that any such differences will be small and will tend to cancel out when looking at data over the entire globe. The second, much more concerning issue is that of the mean bias. The MSS model used in GDR-E is referenced to a center date of 2003, while the GDR-D is referenced to a center date of 2001 – and no bias correction has been applied (or provided) to align the two averages to an identical time stamp. In areas where the sea surface height is experiencing a trend, this will introduce an artificial jump between the two averages. Averages made from even identical input data would be offset from each other by a time-constant, but spatially-variable, bias of approximately the size shown in Figure 1a.

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To correct for this properly, one would ideally need to reprocess both (or all three) sets of Jason data with a consistent MSS model. This being a lengthy process, however, we used the following approximate technique instead. We computed the average overlap bias (Fig. 1a) along the ground-tracks, then smoothed it with a 100km Gaussian smoother to remove very short-wavelength features, and used the value of that at each point as the Jason-2 bias correction. We note that it is very important to compute the value at each point, as there would be a ±4 cm spread in water heights otherwise, depending on where in the ocean you are looking. Using the mean bias over this map would result in a constant -0.785 cm correction, which would not be accurate in most places. (As a comparison, we found the Jason-2D to Jason-3D bias to be a larger but very stable -2.871 cm.)

3.2 GRACE Gravity

While most Gravity Recovery and Climate Experiment (GRACE) series have been released at monthly intervals in spherical harmonic form with a maximum spatial resolution of 300-500 km, over the past decade there have been several attempts at resolving the GRACE data into higher temporal frequencies. We consider three different modern GRACE "daily" series here.

The main GRACE series used in this paper, called "CSR swath" throughout, is an experimental mascon (mass-concentration) product created at the Center for Space Research (CSR) at the University of Texas at Austin (Save et al., 2018). The CSR GRACE swath solutions used here are an extension of the CSR RL05 GRACE monthly mascon solutions (Save et al., 2016) but computed daily for those mascons observed by a particular day's ground track. Though the full extent of this data is not currently available for public release, a subset consisting of only the ocean grid cells between 66°S and 66°N has been created and released (see Data Availability). This will allow for replication of this paper's techniques, as desired.

The CSR swath series is a near-daily solution, with the world divided into 40962 equal-area geodesic mascon blocks with an average distance of 120 km across. Equivalent water layer (cm) anomalies are computed for each daily orbital pass by estimating the mass change observed in a narrow swath around the GRACE groundtrack. These passes are then accumulated over consecutive days to give an estimate of the global mass anomaly at shorter temporal resolution. The mass estimate of each mascon is only directly updated when GRACE satellites overfly the mascons within 250 km from the center of the mascon. The mascons at high latitudes are observed every 1-2 days while a few mascons near the equator are observed only once every 4-5 days depending on how the groundtracks lay out over time. Typical ocean mascons at mid-latitudes are observed once every 2-4 days. A statistical combination of older data and newer neighboring data fills in the gaps. The global mascon solutions and regularization are purely driven by GRACE without any influence from external models. The only external information used to inform the constraints is the land/ocean boundary mask. All the other information for constraints comes from expected signals in GRACE for that month from regularized spherical harmonic solutions (Save et. al. 2016) and the GRACE groundtrack. Since the daily constraints are derived from the respective monthly expected signals from GRACE, the regularization also allows for adjustment of unexpected signals that are captured in the monthly solutions. The only submontly signals that will get constrained to zero in the swath solutions are the signals that may have a zero mean over 30 days throughout the mission but do have sub-monthly variability. The implementation of the swath estimation assumes that such locations are very rare. Thus, the time-variable regularization process used does not bias or attenuate future regional signals based on statistics from models or past GRACE months, but is intentionally designed to encourage no land/ocean correlation in order to reduce leakage.

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Further details of the data processing for producing the daily GRACE swath solutions will be available in Save et. al. 2019 (in-preparation/in-review).

During processing, the sub-monthly release-5 GRACE de-aliasing model ("AOD5", see next section) was removed as one of the standard apriori background models. The GRACE swath series thus estimates the ocean mass change relative to this AOD5 model. We have restored the daily average of the non-tidal ocean model, such that the results shown here are the updated combination. (A model of ocean tides was similarly removed during GRACE processing, but was not restored.) The CSR swath series has also had a GIA model removed (A et al., 2013), though at sub-monthly scale that is noncritical. No geocenter information is included, because GRACE cannot measure it. We chose not to insert an external geocenter estimate, since geocenter series with daily output are rare, and the accuracy on the weekly and sub-weekly scale is highly uncertain and likely to be poor (for example: *Männel and Rothacher*, 2017). Interpolating linearly between monthly geocenter values would not add information to the sub-monthly frequencies we are interested in. Similarly, the GRACE C_{20} signal was not replaced and thus assumed to be correct.

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The result is a smoothly-varying series with the ability to pinpoint signals very well spatially (Fig. 2a). The CSR swath technique (like most other mascon methods) has the ability to separate ocean and land signals reasonably well, thus decreasing leakage from land and ice-covered areas into the ocean. The swath series also tends not to show the classic north-south "stripe" errors which are customary with GRACE spherical harmonic solutions. The practical combination of temporal and spatial accuracy can be examined by looking at the average signal at each time over relatively small areas of the world. Consider the average across the Argentine ocean basin, off the coast of Brazil (Fig. 2b). While it is likely that many of the spikes seen there are error-driven, there are significant sub-monthly-scale features picked up which are hoped to be real (for example: Hughes et al., 2007). The GRACE swath solutions show higher amplitude in the sub-monthly frequencies that are not observed by the background OMCT model in that region. Studies are ongoing to identify the period(s) of these sub-monthly signals and are a topic of discussion in Save et. al. 2019 (in preparation/review).

We also consider a pair of additional GRACE series, ITSG2016 and ITSG2018, created by the Technische Universität Graz (TU Graz, see Data Availability). The older of the two, ITSG2016 (Mayer-Gürr et al., 2016), is being superceded by the newer and still somewhat experimental ITSG2018 (Mayer-Gürr et al., 2018). Both series are created in spherical harmonic form to maximum degree/order 40, using Kalman filtering. In order to resolve the daily global gravity field, the solutions are stabilized using a stochastic model derived from geophysical models, along with apriori land/ocean masks (Kurtenbach et al., 2012). ITSG data exists even when GRACE does not augment it, but it tends toward the models used, so we omit all days when the CSR swath data denotes a gap. The two ITSG versions differ in the background models used and the details in how instrumental processing steps were handled (see the above websites for details). Significantly, ITSG2016 uses the release 5 ocean de-aliasing model (AOD5), while ITSG2018 uses the newer release 6 version (AOD6, see next section).

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3.3 De-aliasing Ocean Models

It is critically important for the production of monthly GRACE gravity products that sub-monthly changes within the ocean which could cause gravitational anomalies are estimated and removed from the GRACE data before processing. Doing so prevents sub-monthly signals from aliasing incorrectly into the monthly estimates. Even the higher-frequency GRACE series remove these modelled estimates from their input before processing the gravity fields, and then restore them later. This means the CSR swath and ITSG solutions considered here actually solve for the residual gravitational signal between the reality and the ocean model. In this paper, we look for evidence that GRACE can see not merely the reproduced apriori model, but additional high-frequency ocean signal above and beyond that.

We will consider the oceanic bottom pressure signals ("GAD" products) of the two most recent GRACE Atmosphere and Ocean De-aliasing (AOD) models, AOD release 5 (Dobslaw et al., 2013; Flechtner et al., 2014) and AOD release 6 (Dobslaw et al., 2017). These ocean bottom pressure products are the output of high-resolution baroclinic ocean models and do not measure the influence of tides.

AOD5's ocean bottom pressure estimates come from the Ocean Model for Circulation and Tides (OMCT) (Thomas, 2002), a baroclinic ocean model which estimates the state along 1° horizontal grids with 20 vertical layers and time-steps of 20 minutes. OMCT is forced every six hours with the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric pressures, wind stresses, temperatures, and freshwater fluxes. Its bottom pressure output is made available for GRACE processing every six hours with spatial resolution given by maximum spherical harmonic degree/order 100 (~200km). The CSR swath and ITSG2016 GRACE series were both made using AOD5.

The bottom pressure estimates of AOD6, the very newest GRACE generation's de-aliasing product, are instead based on the Max Planck Institute for Meteorology Ocean Model (MPIOM) (Jungclaus et al., 2013), a global general circulation ocean model which is a cousin to OMCT, not a direct descendant. The innate spatial resolution of this model is 1° along the horizontal with 40 vertical layers, and time-steps are given as 90 minutes. It is similarly forced by ECMWF atmospheric pressures, wind stresses, temperatures, and freshwater fluxes, but outputs every 3 hours rather than every 6 and to a maximum spherical harmonic degree/order of 180 (~111km).

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As a comparison, we also briefly consider the high-frequency ocean component of the de-aliasing product used with the Jason altimetry data. A run of the barotropic, non-linear, finite-element model Mog2D (Carrère and Lyard, 2003; Lynch and Gray, 1979) is used for this, representing the impacts of the ECMWF winds and pressure fields at frequencies with periods below 20 days (note: this is different than the ~30-day months used elsewhere in this paper). The full Dynamic Atmospheric Correction (DAC) product is unfortunately released as a combination of Mog2D with the larger inverted barometer model, which contains significant sub-20-day signal as well and thus cannot be easily separated (see Data Availability). However, a separated subset of the high-frequency Mog2D altimetry de-aliasing

Deleted: (https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/atmospheric-corrections/description-atmospheric-corrections.html) ocean model is available, only along the Jason groundtracks, within the GDR records themselves, which is what we use here.

4 Sub-monthly Results

As an example of the statistics we will be computing, we show the point-by-point standard deviation of the full sub-monthly signal from CSR swath, altimetry, and the difference of CSRswath-altimetry in Fig. 3. This plot, like all others, is computed only over dates when all data types exist, between April 2002 to January 2016. Notice how the altimetry sea level anomaly product shows a very large (>5 cm water height) variability within the major current systems. GRACE does not see these signals, either because they are short-wavelength signals (for example, eddies) beneath the ~300-km resolution of GRACE, or because they are sea surface height changes which do not correspond to a mass change (for example, those caused by a change in temperature, not pressure). Additionally, there are several areas of high, short-wavelength ocean activity, such as the Argentine gyre southeast of Brazil, where GRACE registers only a reduced fraction of the full signal, for the aforementioned reasons.

It may appear at first glimpse that GRACE does not measure sufficient altimetric signal to allow our technique to work, but that is a trick of the eye. Fig. 4a shows the percent of altimetry's sub-monthly variability explained by the GRACE swath series. This Percent Variance Explained (P.V.E.) is closely related to the normalization of Fig. 3c found by dividing through by Fig. 3b, and can be computed as:

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$$P.V.E. = \left(1 - \frac{var(Alt - GRACE)}{var(Alt)}\right) * 100\% \qquad (4)$$

where obviously signals other than GRACE can be inserted in its place. We see that there are large sections of ocean, particularly the southern ocean, where the CSR swath series explains 25-75% or more of altimetry's sub-monthly variability. It does not explain the variability within the equatorial region simply because there is so little signal there (see Fig. 3) that the signal-to-noise ratio gets very low. The altimetric P.V.E. by ITSG2016 and ITSG2018, and by the de-aliasing models GAD5 and GAD6, are shown in direct comparison in Fig. 4. In each case, the largest P.V.E.s occur in about the same areas as in the CSR swath series, with only the relative amplitude changing. Generally, with the exception of the northern Atlantic, the three high-frequency GRACE series show a higher P.V.E. compared to altimetry than either of the GRACE de-aliasing models.

Table 1 lists the areal percentage of the ocean between 66°S and 66°N in which each series explains at least 25% of altimetry's variance. The first data column shows this statistic for all grid cells, while the last two columns consider only those non-coastal cells where the CSR swath series measures an RMS of at least 2 or 3 cm water height (masks outlined in Fig. 3a). All three of the GRACE series show a large negative P.V.E. (<-25%) near 90°E, 5°N (Fig. 4a, b, c). This solid-Earth signal is the impact of the Andaman-Sumatra earthquake from 2004, which had a large gravitational effect both during and after

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the event. For statistical purposes, we have removed the most affected grids from our analysis in all of the following tables.

The double-difference plots (Fig. 5) obtained by subtracting one map in Fig. 4 from another via Eq. 3, can better show us which data series most closely matches altimetry in the sub-monthly realm. The percentage of negative non-coastal ocean area between 66°S and 66°N is listed in Table 2. These percentages measure the area where each alternative series explains more of altimetry's variance than the CSR swath series does – or, in other words, places where the alternative series is more likely than CSR swath to be correct. The statistics are again given for all grid cells as well as for the low-signal and high-signal areas separately. They again omit the earthquake area as well as coastal regions which might contain ice or hydrological leakage effects.

We use the CSR swath series as our main comparison series here. We immediately note that the CSR swath series is, in nearly all higher-lattitude locations, better than the AOD5 model upon which it was founded. Fig. 5a is clear proof that the CSR swath series is not merely regurgitating the apriori ocean model provided to it, but is altering it in a manner which makes it more like altimetry – a manner very likely to be an improvement.

By comparing Fig. 5b to 5a, we see that in most places, the newer AOD6 model improves upon AOD5, making the differences between it and the GRACE CSR swath series smaller. However, this is surprisingly not true within one region, near 210°E, 60°S. In the bright-pink-colored region there, the AOD6 model is found to be both different from the CSR swath series and measurably worse based on the altimetric P.V.E. To confirm that this difference was not caused by an error in the altimetry product, we also ran the same analysis on the high-frequency ocean de-aliasing model used by Jason altimetry (Fig. 5c). We found that the CSR swath series is roughly equivalent to the Jason ocean de-aliasing model in that spot. This implies that GRACE, AOD5, and the Jason de-aliasing model all estimate one signal, which additionally matches with the altimetry data, while the AOD6 model predicts something very different. Presumably the AOD6 model is wrong, though precisely why was not immediately clear.

We examined whether an error over a limited time period was causing the AOD6 discrepancy, but found that the same patch of poorly-matched data occurred for all years from 2003-2016. Fig. 6b shows the regionally-averaged sub-monthly time series of AOD5, AOD6, and CSR swath over a single year, compared to the sea level anomalies from Jason altimetry. The time-series of all four series are very similar, with altimetry being the most unlike the other three, as might be expected. The correlation between CSR swath and AOD5 time-series is 94.2%, while the correlation between CSR swath and AOD6 is a still-high 91.6%. However, the main difference is not a matter of correlation, but of amplitude: AOD6 is magnified compared to AOD5. The standard deviation of the CSR swath series over 2003-2013 is 3.72 cm, which corresponds well with AOD5's standard deviation of 3.75 cm. The AOD6 time-series has a much higher standard deviation than either: 5.33 cm.

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We then ran a spectral analysis of the four time series over the mostly-continuous 2003-2013 timespan (Fig. 6a), using the least-squares-based Lomb-Scargle method to accommodate the remaining gaps in the data. From this we learned that the AOD6 differences are not caused by a change at a single harmonic, but are rather an amplified signal throughout the entire sub-monthly band, particularly at periods below 10-15 days. The root cause of this difference was initially unknown, though the comparison with altimetry strongly suggested that the AOD6 data was in error in this region. This assessment has since been provided to the developers of AOD1B, who hypothesize that the problem may be caused by a deficit in the MPIOM ocean model configuration around Ross Sea. In AOD6, the model treats all ice shelf areas as land, whereas in fact water several hundreds of meters deep is present underneath the floating ice. In the next release 07 of AOD1B, ice shelf areas will be included into the ocean model domain, which is expected to have a positive effect on the simulation of the region's dominant eigenmodes at 3 to 8 day periods, thus hopefully correcting this problem.

We also compared the CSR swath series to the two ITSG high-frequency GRACE series (Fig. 4d and 4e). The older ITSG2016 series is generally less like altimetry than the CSR swath series, particularly in the equatorial and northern oceans. Only 26.8% of the ocean area shows an improvement relative to altimetry, when switching from CSR swath to ITSG2016. The newer ITSG2018 series is decidedly better, with 45.2% of the grids improving over CSR swath, including 73.7% of the area with more than 2 cm RMS GRACE variability. ITSG2018 is likely an improvement over the CSR swath series in the southern ocean, while CSR swath is probably still better in the equatorial and quieter northern parts of the ocean. Larger differences for both ITSG series along some coasts suggest either worse tidal models or (particularly near Greenland) significantly increased leakage from nearby land, in comparison to the CSR swath series. We would also anticipate the arctic and near-Antarctic oceans to be more poorly measured by ITSG2018 than CSR swath because of the large impact of ice leakage in those areas, but that cannot be tested using the non-polar Jason altimetry data.

5 Band-passed Results

We used a set of Gaussian temporal windows to act as band-pass filters, dividing the above results into three pieces: signals with periods below 10 days, between 10-20 days, and between 20-30 days. To create the band-pass effect, we used three highpass filters, with 10-day, 20-day, and 30-day cutoffs, then subtracted one from the other in subsequent pairings. (For example, the 20-30 day bandpass signal is the 30-day highpass signal minus the 20-day highpass signal.) To provide a baseline, Fig. 7 shows the altimetric P.V.E. by the CSR swath series for each frequency band. For signals with periods of more than 10 days, the CSR swath series perceives at least 25% and often more than 50% of the altimetric variability across most of the southern ocean and the high-signal part of the north Pacific. Conversely, the swath series does a poor job of reproducing the altimetric signal at periods shorter than 10 days.

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Since most of the altimetric signal in this highest temporal frequency band occurs over small spatial scales along the major currents, it is not surprising that GRACE cannot measure it.

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Fig. 8 shows the double-difference P.V.E. comparison for the three frequency bands, with statistics given in Table 3. Its left-hand column depicts the CSR swath series minus AOD5 results, demonstrating that the CSR swath series estimates an improved ocean signal across the entire southern ocean in all three frequency bands, but especially for signals with periods longer than 10 days. In the 10-20 day band, the CSR swath series better explains the altimetric signal than its apriori model can in 83.4% of the high-signal (RMS > 2 cm) part of the southern ocean. In the 20-30 day band, that improves to 87.8%.

The middle column of Fig. 8 shows the same thing, but for AOD6. For periods shorter than 10 days, the two series are roughly equivalent. For sub-monthly periods longer than 10 days, the AOD6 series better matches altimetry over northern and equatorial regions, while the CSR swath series proves to be 10% or more better than AOD6 in much of the southern ocean. Improvements over its AOD5 predecessor can be seen in all frequency bands. The CSR swath series better explains the 10-20-day altimetric signal than the AOD6 model does in 44.5% of the high-signal southern ocean bins. For the 20-30 day band, CSR swath better explains 58.9% of these bins. Additionally, the small region of poor performance near 210°E, 60°S is confirmed to be a very high frequency issue, mainly visible in the 1-10-day band and not visible in the 20-30-day band.

The right-hand column of Fig. 8 is the ITSG2018 comparison. (ITSG2016 was found to be inferior to its successor in all bands, so we do not depict it here.) There are few frequency-based distinctions between the CSR swath and ITSG2018 series. In the southern ocean, ITSG2018 signals with any sub-monthly period are more likely than CSR swath signals to be like altimetry (ITSG2018 is better in 65.5%, 85.6%, and 79.4% of the grids by area, for the 0-10, 10-20, and 20-30 day bands respectively). The opposite is true in the lower-signal equatorial and northern oceans (similar percentages of 26.0%, 45.2%, and 44.7%). The large positive (>30%) coastal differences near Alaska, Patagonia, the Antarctic Peninsula, and Greenland again suggest that ITSG2018 does not segregate the land ice leakage as well as the CSR swath series does, while the large negative (<-30%) coastal differences north of Australia hint towards a possibly improved tidal or ocean model. CSR swath series' generally higher equatorial P.V.E. could indicate that series has better reduced the GRACE stripe-like errors compared to ITSG2018 in these regions of relatively low oceanographic signal.

6 Conclusions

Using a comparison with Jason altimetry, we have demonstrated that two modern near-daily GRACE series are capable of estimating real sub-monthly oceanographic signal. Both the CSR swath series and ITSG2018 explain a fair proportion of the high-frequency altimetric signal outside of major currents,

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the equatorial region, and the northern Atlantic; more of it than the apriori ocean models they are based upon can. We found that these near-daily GRACE series are particularly sensitive for signals with periods above about 10 days, and less so as the signal length shortens below that.

At the moment, it appears that the CSR swath series is better able to eliminate land-leakage from ice and hydrology from entering the ocean grids, making it distinctly better than ITSG2018 along the coasts and near the large ice sheets. CSR swath also appears probably better at removing the false north-south stripes commonly created during GRACE processing, allowing the quieter equatorial regions to be better estimated. The ITSG2018 series, on the other hand, appears to better observe the sub-monthly state of the southern ocean, particularly in those areas with large amounts of variability. This might be an impact of the different processing scheme, or it might be due to the use of the newer AOD6 model as an ocean de-aliaser. To test the latter, we plan on eventually reproducing the CSR swath data with AOD6 as an apriori model.

Our analysis here demonstrates that, particularly in the poorly-observed southern ocean, sub-monthly GRACE data can be used to improve our knowledge of the ocean bottom pressure. We hope to use this in the future to validate global ocean models, perhaps even merging the GRACE data with modeled results in order to produce a combined de-aliasing product superior to either source alone.

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7 Data Availability

All data required to reproduce this work is freely available online in the following locations:

- The Jason-1 GDR-E records from 2002-2008 are available at ftp://podaac.jpl.nasa.gov/allData/jason1/L2/gdr_netcdf_e/.
- The Jason-2 GDR-D records from 2009-2016 are available at ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason2/gdr/gdr/.
- The GRACE CSR Swath data is not generally available for release yet, but a subset consisting of only the ocean grid cells between 66°S and 66°N has been placed at https://doi.org/10.18738/T8/95ITIK.
- The GRACE ITSG2016 series can be found at https://www.tugraz.at/institutes/ifg/downloads/gravity-field-models/itsg-grace2016/.
- The ITSG2018 is here: https://www.tugraz.at/institutes/ifg/downloads/gravity-field-models/itsg-grace2018/.
- The GRACE de-aliasing AOD5 and AOD6 model data can be downloaded from ftp://rz-vm152.gfz-potsdam.de/grace/Level-1B/GFZ/AOD/.
- The Jason de-aliasing DAC model data can be found either as the "HF" section of the GDR files mentioned above, or else in combination with the IB effect at https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/atmospheric-corrections/description-atmospheric-corrections.html.

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8 Competing Interests

The authors declare that they have no conflicts of interest.

9 Author contribution

Jennifer Bonin processed the altimetry, model, and ITSG GRACE data, and computed the band-passed analysis and its statistics. Himanshu Save designed and created the CSR GRACE Swath series, and assisted on the assessment of the results. Jennifer Bonin prepared the manuscript with additions by Himanshu Save.

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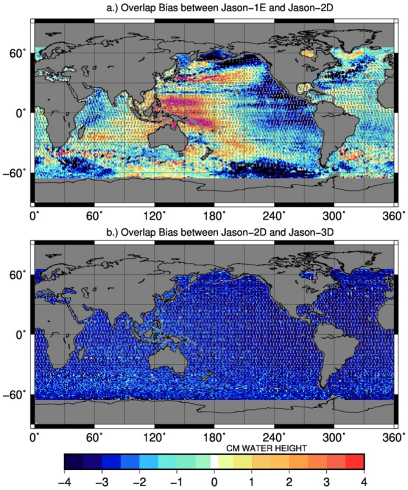
Figures



a.) Overlap Bias between Jason−1E and Jason−2D

b.) Overlap Bias between Jason−2D and Jason−3D

Figure 1: Bias offsets between (a) Jason-1 and Jason-2, and (b) Jason-2 and Jason-3.

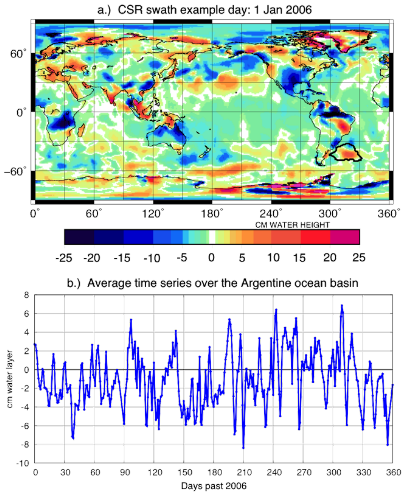
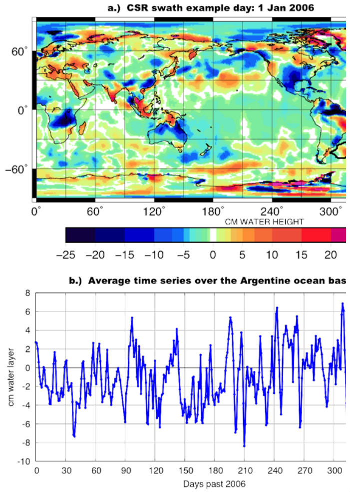


Figure 2: (a) An example day (1 Jan 2006) of the GRACE swath data. (b) An example of the temporal resolution of the GRACE swath series, over the Argentine ocean basin, off the coast of Brazil. The thick line in (a) shows the basin outline used.



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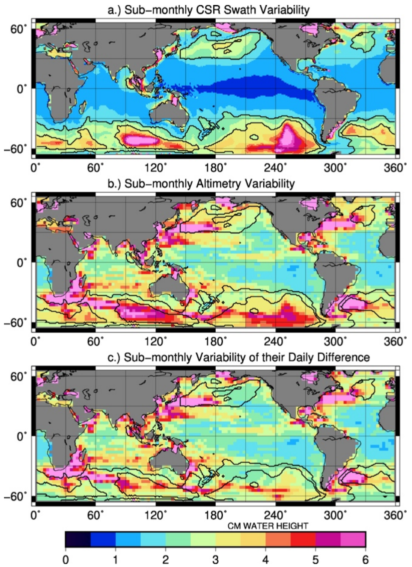

Figure 3: Standard deviation of (a) CSR Swath sub-monthly ocean bottom pressure, (b) Jason altimetry sub-monthly sea surface height anomalies, and (c) the difference between the two series, during 2002-2016. Units are cm of water height in all cases. For comparison's sake, all plots include the 2cm and 3cm contour lines computed from the CSR swath plot (a).

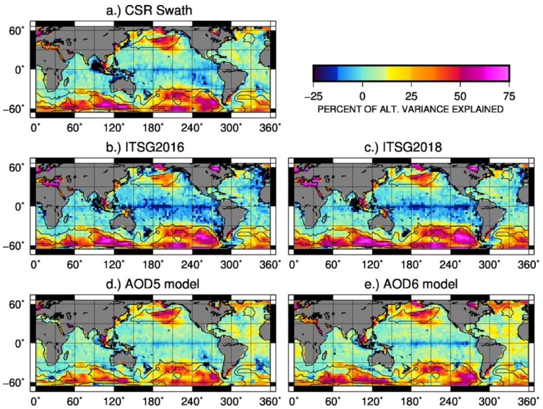

Figure 4: Percent of altimetric variance explained by five different series: (a) CSR swath GRACE data, (b) ITSG2016 GRACE data, (c) ITSG2018 GRACE data, (d) AOD5 ocean de-aliasing model, and (e) AOD6 ocean de-aliasing model.

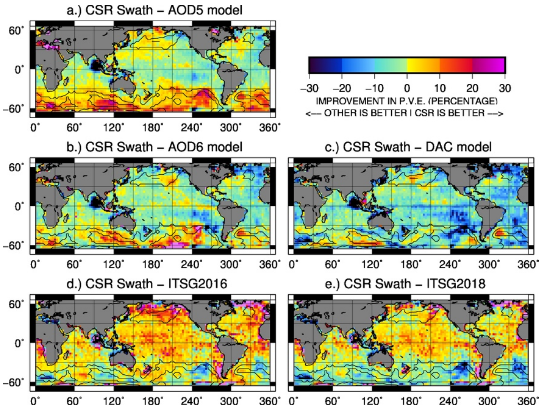

Figure 5: Differences in sub-monthly P.V.E for CSR swath vs. another data type: (a) AOD5 de-aliasing ocean model, (b) AOD6 de-aliasing ocean model, (c) altimetry's DAC de-aliasing ocean model, (d) ITSG2016 GRACE data, and (e) ITSG2018 GRACE data. Values are relative to CSR swath P.V.E.s, so positive numbers (red) denote that CSR swath matchest altimetry better, while negative numbers (blue) denote that the other series matches altimetry better.

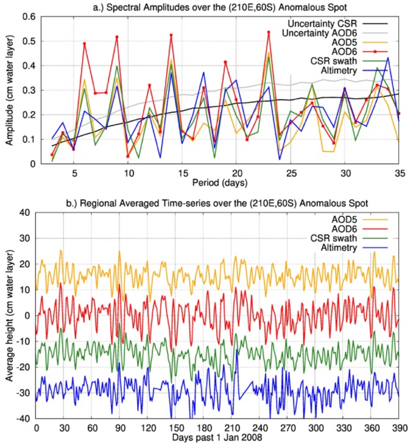

Figure 6: Example timeseries (a) and spectral amplitude plot over AOD6's anomalous spot near (210°E, 60°S), with lines offset for clarity. Spectral analysis (b) was computed for the timespan 2003-2013. The black line shows the uncertainty for the CSR swath series (which is similar to the AOD5 and altimetry uncertainties), and the grey line shows the uncertainty for the AOD6 series. Signals below these lines are not statistically significant.

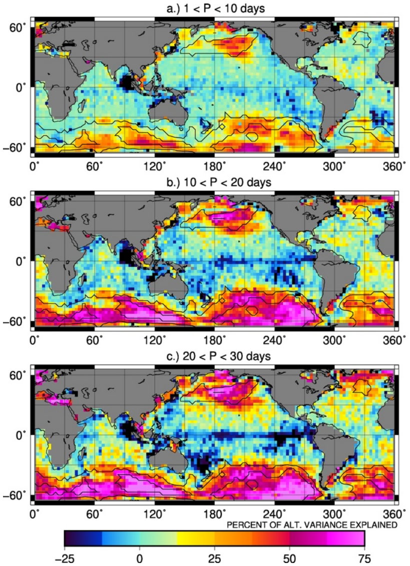

Figure 7: Percent of altimetric variance explained by the CSR swath series at three sub-monthly frequency bands: (a) periods below 10 days, (b) periods between 10-20 days, (c) periods between 20-30 days.

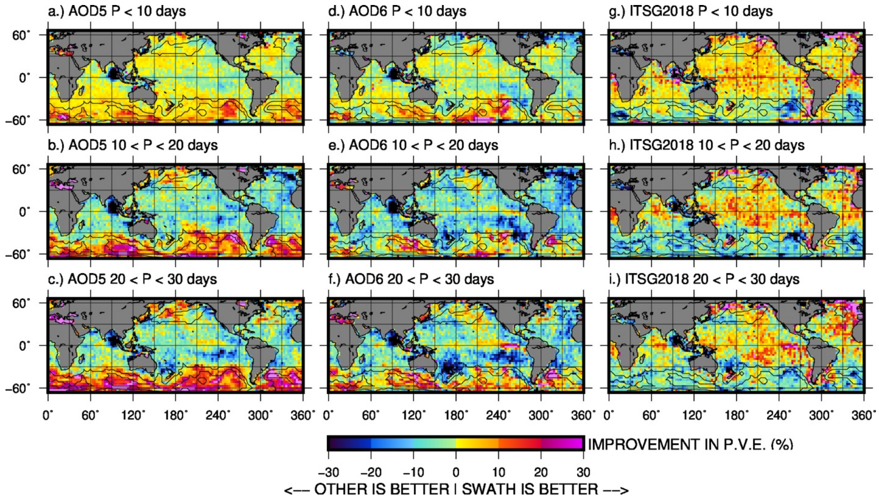

Figure 8: Differences in P.V.E for CSR swath vs. another data type, per frequency band: (a, b, c) AOD5 de-aliasing ocean model, (d, e, f) AOD6 de-aliasing ocean model, and (g, h, i) ITSG2018 GRACE data. The top row gives the highest sub-monthly frequency band, while the bottom gives the lowest sub-monthly frequency band. Values are relative to CSR swath P.V.E.s, so positive numbers (red) denote that CSR swath matchest altimetry better, while negative numbers (blue) denote that the other series matches altimetry better.

Tables

Table 1: Percent of non-coastal ocean area explaining at least 25% of altimetry's sub-monthly variance. 2 cm and 3 cm RMS bounds are defined in Figure 3a.

Data series	All grid cells	RMS > 2 cm	RMS > 3 cm
CSR swath	17.1%	43.1%	66.2%
ITSG2016	16.2%	40.6%	68.7%
ITSG2018	19.4%	48.9%	77.2%
AOD5	13.0%	31.8%	50.1%
AOD6	17.3%	41.3%	58.1%

Table 2: Percent of non-coastal ocean area where the altimetric variance is better explained by the given time-series than by the CSR swath series. 2 cm and 3 cm RMS bounds are defined in Figure 3a.

Data series	All grid cells	RMS < 2 cm	RMS > 2 cm	RMS > 3 cm
ITSG2016	26.8%	20.9%	39.1%	56.7%
ITSG2018	45.2%	31.6%	73.7%	85.3%
AOD5	52.2%	71.1%	12.4%	4.1%
AOD6	70.1%	79.9%	49.4%	33.3%
DAC	87.5%	91.8%	78.5%	70.3%

Table 3: Percent of non-coastal ocean area where the altimetric variance is better explained by the given time-series than by the CSR swath series. 2 cm RMS bounds are defined in Figure 3a. Column 5 estimates only over the part of those regions which are in the southern ocean.

Data series	Frequency Band	All grid cells	RMS > 2 cm	RMS > 2 cm southern
AOD5	1-10 days	39.0%	12.9%	8.6%
	10-20 days	65.1%	25.9%	16.6%
	20-30 days	58.5%	20.2%	12.2%
AOD6	1-10 days	58.7%	43.8%	40.0%
	10-20 days	79.4%	60.0%	55.5%
	20-30 days	68.6%	45.7%	41.1%
ITSG2018	1-10 days	38.0%	61.0%	70.5%
	10-20 days	57.4%	82.1%	87.8%
	20-30 days	54.0%	73.0%	79.5%