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Evaluation of high-frequency oceanographic signal in GRACE data: Implications for de-aliasing

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[1] The sub-monthly portion of a recent daily-resolution GRACE data set (ITG-Grace2010) is evaluated over the ocean by comparing with the high-frequency component of sea level variability measured by satellite altimetry. The current Atmosphere and Ocean De-aliasing (AOD) model used to remove the high-frequency non-tidal ocean mass variations in GRACE data processing is also assessed. We demonstrate that the OMCT-based AOD model does not adequately represent the true sub-monthly variability in non-tidal ocean mass variability, but that ITG-Grace2010 does. The differences are not small, and indicate that a new model, or a data set derived from sub-monthly GRACE information, should be considered for de-aliasing in future GRACE processing. **Citation:** Bonin, J. A., and D. P. Chambers (2011), Evaluation of high-frequency oceanographic signal in GRACE data: Implications for de-aliasing, *Geophys. Res. Lett.*, 38, L17608, doi:10.1029/2011GL048881.

1. Introduction

[2] Data from the Gravity Recovery And Climate Experiment (GRACE) have generally been output as monthly averages [Bettadpur, 2007]. As a consequence, researchers have focused either on the Earth's long-term mean gravity field or variability at annual or longer periods. In order to measure accurate gravity variations at monthly scales and longer, however, high-frequency ocean and non-tidal mass variations in the atmosphere and oceans must be modeled [Flechtner, 2007]. A recent study by Quinn and Ponte [2011] examined the problem in modeling non-tidal ocean mass variations by comparing two different baroclinic ocean models and both to bottom pressure gauges. They found very large differences in the high-frequency band that may cause significant aliased errors in monthly GRACE fields.

[3] In the past few years, several processing centers have experimented with producing GRACE data with sub-monthly sampling resolution [e.g., Rowlands et al., 2005; Kurtenbach et al., 2009; J. A. Bonin et al., High-frequency signal and noise estimates of CSR GRACE RL04, submitted to *Journal of Geodesy*, 2011]. ITG-Grace2010, from the Universität Bonn's Institut für Geodäsie und Geoinformation [Kurtenbach et al., 2009], is one of the more promising of these high-frequency solutions sets. Kurtenbach et al. [2009] have demonstrated that the daily-sampled ITG-Grace2010 series is capable of seeing the smoothly-changing seasonal-scale variability within a month, suggesting that ITG-Grace2010 acts

as an extremely effective daily interpolator of the seasonal signal of hydrology. This has the potential to reduce some of the aliasing caused by currently unmodeled hydrology in monthly gravity solutions, as the ITG group is already trying (<http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010>).

[4] However, we are aware of no study that has evaluated the higher-frequency sub-monthly signal in ITG-Grace2010 – the part that is not a portion of a longer-term signal – especially over the ocean. If ITG-Grace2010 can recover high-frequency sub-monthly variability, this has significant implications for reducing aliasing in the GRACE data. In this study, we will evaluate the accuracy of the high-frequency variability of the ITG-Grace2010 data and the Atmosphere and Ocean De-aliasing (AOD) model used with GRACE data. To do this, we will compare the ITG-Grace2010 and AOD equivalent sea level data with along-track sea level anomalies (SLAs) from satellite radar altimeters. A significant fraction of sea level change in high latitudes has been shown to be related to high-frequency mass variations [e.g., Stammer et al., 2000; Tierney et al., 2000]. If ITG-Grace2010 has a more realistic high-frequency signal than the output of AOD, the variance of the SLAs after subtracting ITG-Grace2010 should be less than the variance of the original SLAs, and also less than the variance of the residuals after removing AOD. The variance of the residual after removing either the GRACE or AOD data will never be zero. For one thing, sea level anomalies are affected by both mass changes and steric (heating/salinity) effects. Altimetry also has different temporal and spatial sampling than GRACE. Finally, large signals on land may leak into GRACE's estimates of ocean mass change. However, these effects will be similar for both calculations (except for land signal leakage), so comparing the AOD and ITG-Grace2010 residuals will give information as to which is closer to the altimetry. We will show, after appropriate filtering, that ITG-Grace2010 reduces the variance in sea level significantly more than AOD at high-frequencies, especially poleward of 30° latitude.

2. Data Products and Filtering

[5] Sea level anomalies are calculated from the Jason-1 and Jason-2 Geophysical Data Records, version C [CNES, 2008, 2009]. All standard corrections were applied, including the inverted barometer correction, since local atmospheric pressure variations will cause sea level fluctuations but not a change in the total mass observed by GRACE. The new high-frequency, non-tidal de-aliasing correction, based on another ocean model [CNES, 2009, Section 4.2.2], is not applied, as this is the signal we want to observe. We utilize Jason-1 data through the end of 2008 and start using Jason-2 data on January 1, 2009. The Jason-2 data are referenced to the Jason-1 data by removing local biases using the method

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Figure 1. One day (1 Jan 2006) of un-windowed data from (a) altimetry, unsmoothed; (b) Altimetry, 300 km-smoothed; (c) AOD; (d) ITG-Grace2010.

of along-track SLA residuals during their calibration phase as described by *Chambers et al.* [2003].

[6] Since we want to observe daily-scale variations, the 1-Hz along-track altimetry data is averaged into daily files and averaged over $1^\circ \times 1^\circ$ bins. Values at crossover points occurring within the same day are the average of both ascending and descending tracks (Figure 1a). The pattern of groundtracks changes each day until repeating after 10-days due to the satellite repeat period. Since neither GRACE nor AOD is capable of resolving variability at 1° resolution, we apply a 300 km Gaussian smoother to the averaged along-track altimetry data (Figure 1b). The smoother allows observations from crossing tracks to impact each other and additionally reduces the impact of mesoscale eddies. Finally, we apply a temporal high-pass filter to the daily Gaussian-smoothed grids, by removing the low-pass filtered data based on a Gaussian window with a window length of 47 days and a full-width-at-half-maxima (FWHM) of 23 days. Such a window is most similar to a uniform window that is 30 days long, but with a cleaner high-frequency cutoff (Bonin et al., submitted manuscript, 2011). The windowing separates the sub-monthly part of the altimetry signal from the longer-period components.

[7] The model used for de-aliasing ITG-Grace2010 and other GRACE products is a combination of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric forecast system and the Ocean Model for Circulation and Tides (OMCT) [Thomas, 2002; Flechtner, 2007]. The ITG-Grace2010 team has released the daily-averaged, degree/order 40 version of this Atmosphere-Ocean De-aliasing level 1B, release 04 (AOD1B RL04) model. The spatial resolution of a 40×40 spherical harmonic representation ranges from zero at the poles to 565 km at the equator, so no additional spatial smoothing

has been applied. To make the AOD output directly comparable to our altimetry grids, we first transform the spherical harmonics into $1^\circ \times 1^\circ$ gridded data of ocean bottom pressure (OBP), expressed in terms of equivalent sea level (SL) variation, then restrict the grids to those bins covered by the altimetry data on any particular day (Figure 1c), and then apply the same Gaussian 47/23-day high-pass windowing.

[8] The ITG-Grace2010 data cover a seven-year period (August 2002–2009) and are distributed as gravity coefficients up to degree/order 40 [Kurtenbach et al., 2009]. They are constrained so that the north/south stripes which have plagued unconstrained GRACE fields [e.g., Swenson and Wahr, 2006] are drastically reduced, such that no post-processing is required. ITG-Grace2010 solutions are released every day, even when the GRACE satellites are not in science mode and returning data. However, daily solutions made with fewer than half the average number of data points are eliminated from the series used here. Since the coefficients are computed relative to the background de-aliasing model, the AOD1B RL04 daily averages are restored in order to observe the full ocean bottom pressure signal and not the anomalous OBP relative to the background model [e.g., Chambers and Willis, 2009]. Additional processing is identical to the treatment of the AOD model: data are limited to the altimetry $1^\circ \times 1^\circ$ grids (Figure 1d) and then high-pass filtered to isolate the sub-monthly signal.

3. Analysis and Discussion

[9] Figure 2 shows the RMS of sub-monthly variability for altimetry (Figure 2a), AOD (Figure 2b), and ITG-Grace2010 (Figure 2c). The RMS of altimetry SLAs clearly shows the residual mesoscale (mainly steric) energy of the Gulf Stream, Kuroshio extension, and other areas, which

Figure 2. Sub-monthly RMS across the globe between 2003 and 2009 for (a) altimetry, 300 km-smoothed; (b) AOD; (c) ITG-Grace2010. Units: cm of water height.

neither AOD nor ITG-Grace2010 can see. Much of the variability poleward of 30° latitude at sub-monthly scales is clearly related to mass fluctuations, however, as similar variability appears in both the AOD and ITG-Grace2010 data. The variance of ITG-Grace2010 is significantly smaller than that of the AOD model throughout the Southern Ocean (SO), and qualitatively more similar to the altimetry, which suggests that the model is overestimating high-frequency ocean bottom pressure at high latitudes.

[10] To test whether ITG-Grace2010 is more (or less) similar to altimetry SLA than AOD is, we calculate a residual for each day. The RMS of the sub-monthly filtered altimetry-AOD residuals and altimetry-ITG residuals are shown in Figure 3. Although there is still common high variance in regions of the western boundary currents and the Antarctic Circumpolar Current (ACC) due to steric fluctuations in the altimetry, it appears that the altimetry-ITG residuals have significantly smaller variance throughout the Southern Ocean. To better quantify the difference, we compute the percentage of the altimetry SLA variance that is explained by AOD (Figure 4a) and by ITG-Grace2010 (Figure 4b). Positive values mean that the OBP (AOD or ITG-Grace2010) reduces variance in the altimetry SLAs, which indicates the OBP variation is consistent with the high-frequency sea level. Negative values mean that subtracting OBP increased the variance in SLA, which points to an error in that estimate of OBP.

Figure 3. RMS of daily differences between (a) altimetry – AOD; (b) altimetry – ITG-Grace2010, for sub-monthly frequencies only. Units: cm of water height.

[11] In the equatorial region, neither AOD nor ITG-Grace2010 explain a significant amount of the SLA variance. The average variance explained by either series in the within $\pm 30^\circ$ latitude is less than 3%, which is hardly a surprise, given the small OBP variability in the region (Figure 2). Additionally, there is some indication from models that the equatorial regions may contain more steric than mass-driven signal [Vinogradova *et al.*, 2007], which will reduce the subtractive effect of either GRACE or AOD on altimetry.

Figure 4. Percentage of SLA variance explained by (a) AOD; (b) ITG-Grace2010, for sub-monthly frequencies only.

[12] Poleward of 30°, both AOD and ITG-Grace2010 reduce the variance significantly in many places. However, particularly in the Southern Ocean, there are quite a few areas where the residual altimetry-AOD variance is higher than that of the original SLAs (negative values in Figure 4a), indicating the model is in error. Removing the AOD signal from altimetry results in a variance reduction in only 40% of the grid cells south of 30°S, while using ITG-Grace2010 reduces the variance in 80% of the grid cells. There is a smaller distinction between the grid cells with a positive variance reduction in the Northern Hemisphere (45% for AOD vs. 49% ITG-Grace2010), but ITG-Grace2010 better explains the high-frequency signal seen by altimetry there as well.

[13] The results are even better if one considers only regions with high OBP variability at high frequencies. In regions where the RMS of the high-pass filtered ITG-Grace2010 data (Figure 2c) is greater than 2 cm, using ITG-Grace2010 reduces the SLA variance in 67% of the grid cells poleward of 30°N and 91% of the grid cells poleward of 30°S. AOD reduces the variance in only 47% of the northern high-variability areas and 50% of the southern region. Globally, the average variance reduction in high-frequency SLA in regions where OBP variability is greater than 2 cm is 87% for ITG-Grace2010, but only 47% in AOD. If we limit the comparison further to those (mostly southern) regions where the GRACE RMS is above 3 cm, 98% of the high-signal grid cells show a reduced variance using ITG-Grace2010, but only 64% using AOD. As these are the regions where the largest high-frequency signal occurs, improvements here are proportionately more important.

4. Conclusions

[14] This analysis indicates two findings of value. The first is rather troubling: the high-frequency content of the de-aliasing model used in GRACE processing (based on the OMCT ocean model) does not accurately represent sub-monthly OBP variability. Quinn and Ponte [2011] suggested this might be a problem based on comparison with another ocean model and bottom pressure gauges, but this is the first direct evidence using altimetric observations of high-frequency sea level as comparison. While other studies have indicated problems at longer-periods [e.g., Chambers and Willis, 2010], this is less of an issue, since the monthly GRACE data can correct the model at these time-scales. However, errors at sub-monthly time-scales will potentially be aliased into long-period errors in the GRACE monthly solutions, which cannot be corrected in a straightforward manner.

[15] The second conclusion is more optimistic: based on this analysis, it appears that with appropriate processing, GRACE data can resolve sub-monthly variability over the ocean, and that it can do so more accurately than the OMCT-based AOD model can model it. The ITG-Grace2010 methodology may not prove the optimal way to do this, but further work is needed to begin using GRACE data itself to improve the de-aliasing model for future GRACE data releases. We suggest testing whether ITG-Grace2010 data can be used to constrain the ocean models used for GRACE de-aliasing,

whether the data can differentiate between different models to use for GRACE de-aliasing, and optimally, whether ITG-Grace2010 can be assimilated into ocean models. At the very least, the differences between the OMCT-based AOD model and ITG-Grace2010 need to be evaluated in terms of the aliasing effects likely present in the current monthly GRACE data.

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