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Impact of short period, non-tidal, temporal mass variability on GRACE gravity estimates

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Abstract. Using orbital simulations of the Gravity Recovery and Climate Experiment (GRACE) spacecraft, we examined the effects on gravity recovery due to short period, non-tidal temporal mass variability in the atmosphere, ocean, and continental hydrology. We found that the magnitude of the aliasing error was strongly correlated with the power of the high-frequency variability of the models. Degree error relative to measurement error increased by a factor of ~20 due to atmospheric aliasing (corresponding to geoid anomalies of approximately 1 mm at 500 km wavelengths), by a factor of ~10 due to the ocean model, and by a factor of ~3 due to the continental hydrology model. De-aliasing done with approximate models gave the greatest reduction in aliasing error for the mid-degrees and higher. For the atmosphere, the residual error was ~1/5 times that of the aliasing error. A barotropic ocean model reduced the aliasing error due to a baroclinic model to nearly the level of measurement noise.

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) launched in March of 2002 is designed to recover the Earth's gravity field at approximately monthly intervals with a spatial resolution of a few hundred kilometers. The nominal product is a piecewise constant series of

gravity solutions tied to monthly epochs. As a consequence of unmodeled variability in the geopotential taking place during the solution time span, the GRACE mission samples the variability in such a way that the gravity field it recovers will differ from the average geopotential during that time span. Preliminary estimates of the GRACE error budget did not specifically address temporal aliasing due to mass re-distribution [e.g., *Kim*, 2000; *Kim and Tapley*, 2002; *Wahr et al.*, 1998].

Orbital simulations by *Thompson et al.* [2000] show that the impact of short period variability in hydrologic systems produces aliasing error comparable to the instrument measurement noise, though partial modeling of the variability could reduce this error significantly. While relatively slow variations are captured by the estimation process, the gravity estimates are corrupted by aliasing of short period mass variability into other spatial and temporal scales. Herein, we discuss the aliasing error that resulted from mass variability models of the atmosphere, ocean, and continental hydrology used in the presence of instrument noise comparable to what had been assumed in previous studies. This aliasing error is characterized relative to the error floor due to instrument noise-only, the benefits of using alternative models of the short period mass variability are quantified (i.e., de-aliasing), and processing guidelines for GRACE are established.

2. Geophysical Models

We selected a collection of different geophysical models that are representative of variability in three different hydrologic systems of the Earth. It was not the purpose of this study to test every available model; rather it was to highlight the impact of different spectrums of mass variability on the GRACE gravity solutions along with the benefits of attempting to reduce this

error with alternative models. We note here that we used the convention for representing and fully normalizing the geopotential coefficients as in *Kaula* [1966].

We analyzed atmospheric pressure grids available at six-hour intervals from the European Center for Medium-range Weather Forecasts (ECMWF) and the National Center for Environmental Prediction (NCEP) Reanalysis Project [*Kalnay et al.*, 1996] for the month of January, 1990. There are notable differences between these models at relatively short time scales [e.g., *Velicogna et al.*, 2001] and in regions where there is a sparsity of meteorological data, for example, Antarctica. An inverted barometer correction (IB) was applied (effectively removing their contribution over the oceans), and the yearly means were removed. In the simulation procedure described later, the ECMWF atmosphere was used as the 'true' model and NCEP as the 'nominal' model.

A variant of the Parallel Ocean Program (POP) developed at Los Alamos National Laboratory [*Dukowicz and Smith*, 1994] and as discussed by *Wahr et al.* [1998] was used to compute two different time series of ocean mass variability. The model chosen to represent the 'true' model was generated by using the fully baroclinic capability of the POP (i.e., vertical density variations were allowed). Barotropic conditions were applied in the POP run (i.e., constant density) to generate the model used to de-alias the baroclinic ocean variability.

For the contribution of continental water mass variations we used a series of geopotential coefficients computed from a global grid of soil moisture and snow mass data generated by NCEP [*Kalnay et al.*, 1996]. *Chen et al.* [1999] describe the details of the computations to generate geopotential coefficients from this data set. It is important to note that this model does not include water storage variations below a depth of two meters; furthermore, variability over the Antarctic continent and Greenland was specifically excluded.

The differences between the models' spectrums of variability at sub-monthly periods (Figure 1) will result in different sampling by GRACE and different aliasing error characteristics. The atmospheric variability has considerable power at the diurnal and semi-diurnal periods as well as significant power at other periods. Variability in the ocean models is significantly less in terms of spatial extent and magnitude. While the magnitude of the variability in the NCEP continental hydrology model seems to be comparable regionally to that of the ocean or atmosphere models, the monthly variability is nearly secular and contains little power at sub-monthly periods.

3. Simulation Procedure

Here we summarize the method used to generate simulated GRACE observations and to estimate the resulting geopotential field in the presence of these simulated observations. Extensive details of the simulation method and software employed are in *Kim* [2000]. In brief, the MSODP program (developed at UT-CSR to process and simulate GRACE observations) was used to create noisy measurements of both double-differenced GPS range and KBR range-rate for 30 consecutive one-day arcs. The background models used in this procedure represent the 'truth model' in the simulation universe; in particular, we specify the time variable geopotential models used to represent the short period temporal mass variations. The simulated observations along with an alternative 'nominal model' for geopotential variations were used to obtain an estimate of the 'true' gravity. The best estimate of the gravity field was found by minimizing the measurement residuals in the least-squares sense. Models and estimates were limited to geopotential fields of degree and order 2-60.

4. Aliasing Error Definition

The definition of aliasing error used follows that given in *Thompson et al.* [2000]; however, further discussion is required. The nominal GRACE processing provides piecewise constant gravity solutions at approximately monthly intervals. The combination of the static geopotential and the time-variable geopotential used in generating the simulated observations represents the total 'true' geopotential, while the estimated geopotential and the time-variable geopotential used to compute the estimate represented a 'nominal' best fit to the observations. The differences between these two characterizations of the geopotential, on average, provided a measure of the solution accuracy.

The geopotential coefficients for the truth model as a function of time, t, were specified as:

$$G_{true}(t) = G + \delta G_{true}(t) \tag{1}$$

where G is a static field, and $\delta G_{true}(t)$ is the perturbation due to the 'true' time variable potential. The computation of the estimate assumed a nominal field different from the truth model represented by

$$G_{nom}(t) = G + \delta G_{nom}(t) \tag{2}$$

where $\delta G_{nom}(t)$ is the nominal perturbing time variable model relative to the same static field.

An update to the nominal background gravity model was found such that the measurement residuals were minimized. This update is a set of constant corrections to the spherical harmonic geopotential coefficients during the data span, T_s, and represents the gravity information contributed by GRACE:

$$\delta\hat{G}(T_s) = L\{Y_i - f(G_{nom}(t_i)), i = 1,\ldots,m\} \tag{3}$$

where L represents the linearized least-squares problem over m time steps, Y_i are the observations, and $f(G_{nom}(t_i))$ are the predicted measurements. However, there are errors introduced due to aliasing, measurement noise, averaging, as well as the estimation procedure and the update can only be approximated as

$$\delta\hat{G}(T_s) \approx < G_{true}(t) > - < G_{nom}(t) > \tag{4}$$

where < > denotes a time average. By introducing an error term, ε, to make this an equality and combining with equations (1) and (2), we defined total error in the simulations as

$$\varepsilon \equiv \delta\hat{G}(T_s) - \left(< \delta G_{true}(t) > - < \delta G_{nom}(t) > \right). \tag{5}$$

In this study $\delta G_{true}(t)$ was non-zero for all of the simulations. The full aliasing impact due to a completely unmodeled system was realized by setting $\delta G_{nom}(t)=0$. The impact of partially modeling the true variability (i.e., de-aliasing) was found using a non-zero $\delta G_{nom}(t) \neq \delta G_{true}(t)$.

Taking into account the average difference between the truth and nominal background models (Figure 2) is critical because this difference can be erroneously described as aliasing error. This is not error in the gravity recovery, but un-modeled gravity signal that is correctly adjusted for by the estimation process. The accuracy of background models on average will limit the ability to directly interpret the gravity field estimates as mass changes in continental hydrology [*Wahr et al.*, 1998; *Velicogna et al.*, 2001]. Fortunately, the differences in background models for periods on the order of the solution time span or longer are something that can be corrected for after the gravity estimation process is complete.

5. Results

A representative error floor was established by assuming no time-variable geopotential model for either the truth or nominal models. Depending upon the particular parameterization used, the error in this static gravity case can vary. The resulting error was obtained when only measurement error was considered and is a result that the aliasing simulations may approach but can never exceed. It is included as a reference in all the degree error plots shown in Figure 3.

The atmospheric model simulations indicated that the aliasing error due to ignoring the short-period variability of the ECMWF atmosphere increased the degree error by an order of magnitude once other errors have been reduced to the level of the simulated measurement noise (Figure 3). Using the NCEP atmosphere as a nominal model in an attempt to de-alias the estimate was particularly successful at reducing error at the middle to high degrees. It is important to note that degree error curves do not give an indication of the spatial structure of error that can exist, even in regions that did not contain any variability (Figure 4).

Results of the ocean model aliasing and de-aliasing simulations (Figure 3) reflected the reduced magnitude and relatively weaker short period variability of the ocean models. The error had a very similar structure to the results of the atmospheric simulations, though significantly reduced in overall magnitude. These simulations did not address the overall question of aliasing caused by differences between the POP ocean model and other competing ocean models. The key result was that a barotropic ocean model can be used to successfully de-alias the baroclinic model, nearly reducing the error to the limit of the measurement noise.

Though large at seasonal periods [e.g., *Wahr et al.*, 1998], the NCEP continental hydrology model contains little variability at sub-monthly periods that would allow for aliasing in the gravity estimates. The simulation results with this model produced a significantly smaller

amount of error relative to the atmosphere and ocean simulations (Figure 3), even below the level of error found for the partially de-aliased atmosphere. This simulation result illustrated that the relatively large mean in the hydrology model (Figure 2) omitted in the 'nominal model' was recovered by the gravity estimate procedure.

The error upturn at the lowest degrees (~2-5) that appeared in a similar manner in all of the simulation results is not a feature unique to aliasing. There was no correlation between the unique characteristics of the input models (Figures 1 and 2) and the features observed at the lowest degrees (Figures 3 and 4). The low degree error was found to be dominated by the fact that the GRACE system solution methods for those degrees are particularly sensitive to systematic errors.

6. Discussion

The benefits of de-aliasing were most evident at the middle to higher degrees while the error at the lowest degrees (~2-5) was dominated by other aspects of the GRACE processing methods. Qualitatively, we found that the level of aliasing error was strongly correlated to the high-frequency power present in the models. It is important that the background time variable models used in GRACE processing contain a reasonably accurate representation of the high-frequency content in the Earth's systems. Accurate estimates of the uncertainty in these models are needed for predicting the level of aliasing error that may be present from using these models. For example, the atmospheric de-aliasing error predictions may be an underestimate and the de-aliasing conclusions optimistic because the errors in the two fields used (ECMWF and NCEP) are partially correlated [*Wahr et al.*, 1998; *Velicogna et al.*, 2001].

We did not test competitive models sufficiently different from the POP model to assess the inherent accuracy of ocean models in general. The de-aliasing simulations with the ocean models primarily tested the assumption that a barotropic model was sufficient for describing high-frequency ocean behavior. The slowly varying baroclinic ocean response was captured by the estimate and did not result in significant aliasing. A barotropic model is currently used to model the shorter period variability for the production of GRACE gravity estimates [*Ali and Zlotnicki*, 2003].

Aliasing error predictions based on an NCEP-class continental hydrology are limited by the lack of reasonable short-period variability. Our results indicated that the aliasing error due to a model with such a temporal spectrum was below the level of even an optimistic estimate of the residual error present after partially de-aliasing the atmospheric effects. An NCEP-class model may even be of limited value in assessing variability at the monthly time scales, requiring models with higher spatial and temporal resolutions in order to compare with expected GRACE gravity recovery [e.g. *Rodell and Famiglietti*, 1999]. Even if using this type of model in GRACE processing resulted in a more precise gravity estimate, it may introduce significant errors in interpreting monthly gravity solution changes as continental hydrological mass variability.

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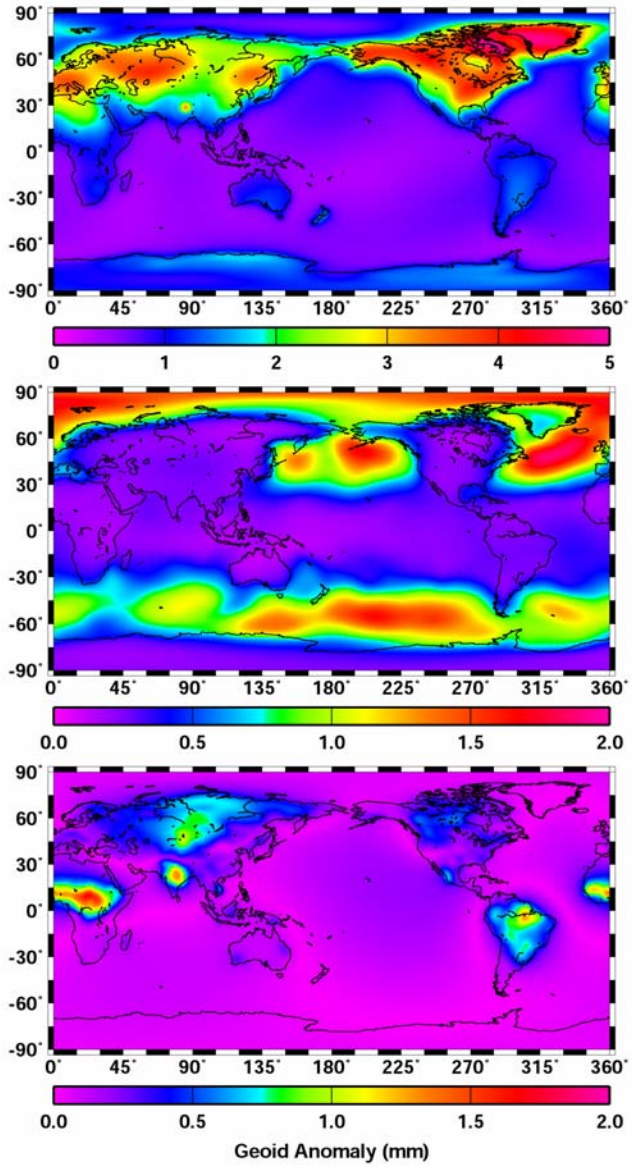

Figure 1. RMS about the monthly mean of the time variable geopotential models used to generate observations: ECMWF atmosphere (top), POP baroclinic ocean (middle), and NCEP continental hydrology (bottom).

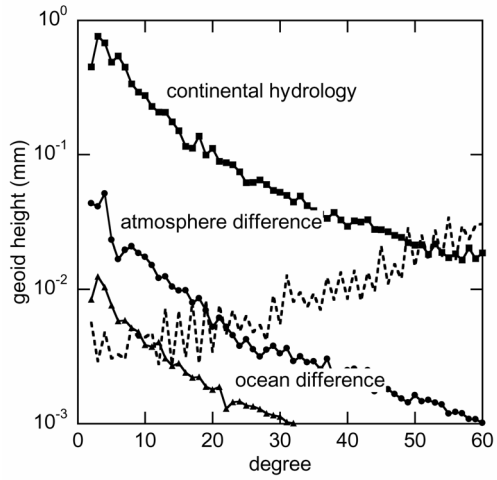

Figure 2. Averages of the 'true' and 'nominal' time variable models used. Degree difference is shown for the atmosphere and ocean models. Degree amplitude is shown for the continental hydrology model since no de-aliasing was attempted with that model type.

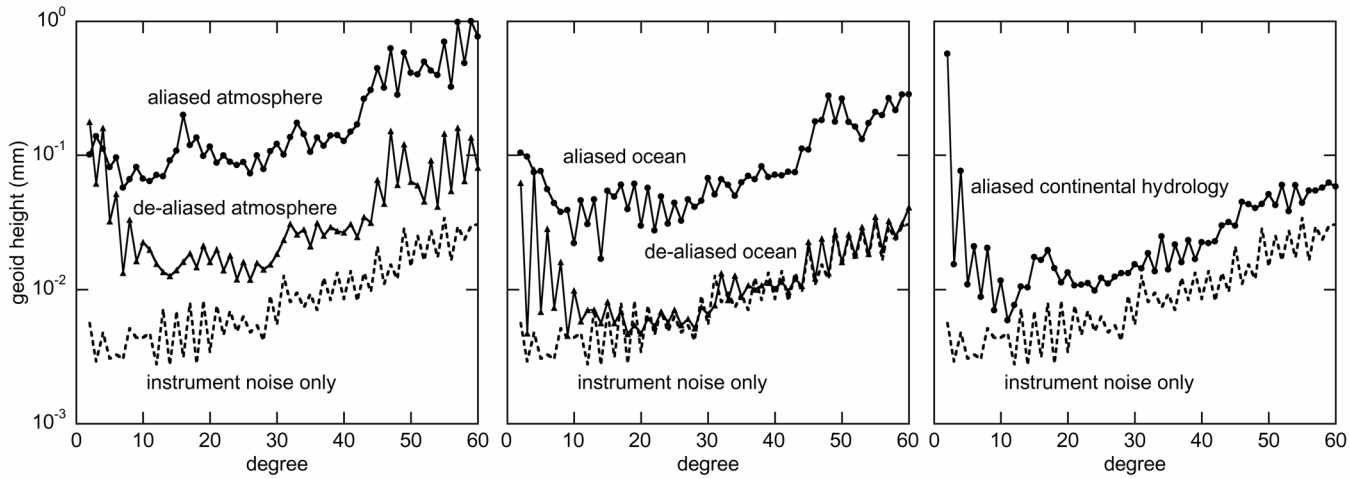

Figure 3. Degree error as defined in equation (5). Atmosphere results (left) are for error due to ECMWF along with residual error after de-aliasing with NCEP. Ocean results (middle) are for error due to the baroclinic model along with residual error after de-aliasing with the barotropic model. Continental hydrology results (right) are only for the error due to NCEP; no de-aliasing was attempted.

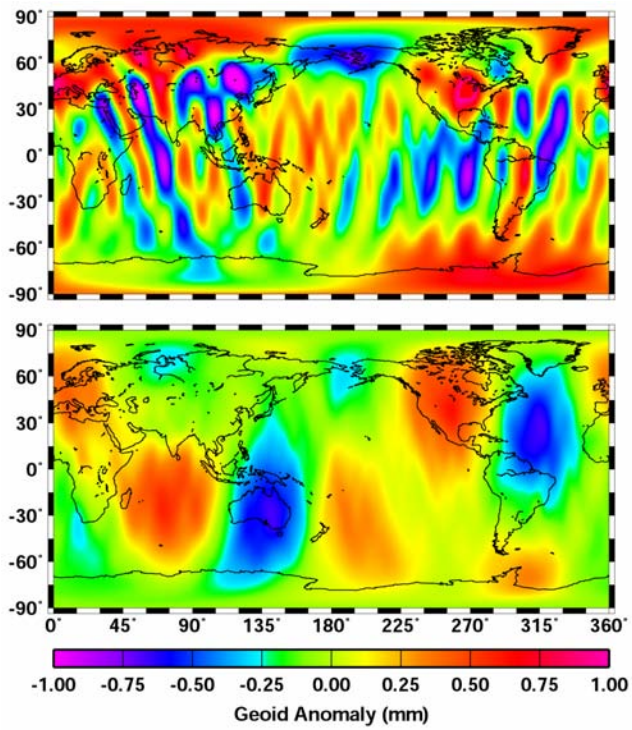

Figure 4. Atmospheric model simulation results. Error due to ECMWF (top) and error after de-aliasing with NCEP model (bottom). Geoid anomaly, Gaussian smoothed with a 500 km radius.