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Journal

Geophysical Research Letters, 31(11)

ISSN

0094-8276

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Publication Date

2004

DOI

10.1029/2004GL019779

Copyright Information

Peer reviewed

Time-variable gravity from GRACE: First results

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[1] Eleven monthly GRACE gravity field solutions are now available for analyses. We show those fields can be used to recover monthly changes in water storage, both on land and in the ocean, to accuracies of 1.5 cm of water thickness when smoothed over 1000 km. The amplitude of the annually varying signal can be determined to 1.0 cm. Results are 30% better for a 1500 km smoothing radius, and 40% worse for a 750 km radius. We estimate the annually varying component of water storage for three large drainage basins (the Mississippi, the Amazon, and a region draining into the Bay of Bengal), to accuracies of 1.0–1.5 cm.   INDEX TERMS: 1243 Geodesy and Gravity: Space geodetic surveys; 1836 Hydrology: Hydrologic budget (1655); 1640 Global Change: Remote sensing. **Citation:** Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, *31*, L11501, doi:10.1029/2004GL019779.

1. Introduction

[2] The objective of the NASA/DLR satellite mission GRACE, launched in March 2002, is to map the Earth's gravity field to high accuracy at ∼30-day intervals. Changes in the gravity field can be used to study processes involving changes in the Earth's mass distribution. *Tapley et al.* [2004] describe the present status of GRACE.

[3] The GRACE Project has now released gravity field solutions for 11 ∼30-day time periods, corresponding roughly to April/May, August, November, 2002, and February, March, April, April/May, July, August, September, October, 2003; where the April/May fields include days from both months. Each solution consists of a set of Stokes coefficients, C_{lm} and S_{lm}, complete to degree and order ≤120. These are the coefficients in a spherical harmonic expansion of the geoid [see, e.g., *Wahr et al.*, 1998]. The subscripts l and m are the degree and order of the spherical harmonic; the horizontal scale is ∼20,000/l km.

[4] We assess the accuracy with which these fields can be used to recover monthly changes in water storage on land and in the ocean. Because GRACE is sensitive to changes in water integrated vertically through the water column and extending over hundreds to thousands of km, there are no relevant data with which to compare. Instead we obtain an initial evaluation of the data by visually comparing with data-constrained numerical models. A quantitative assessment is then obtained from an analysis based on the scatter

about a simple, geophysically plausible time-dependence: a constant plus an annual variation.

2. Degree Amplitudes

[5] The accuracy of a gravity model can be described with degree amplitudes of the geoid error

$$\delta N_l = a \sqrt{\sum_{m=0}^{l} \left(\delta C_{lm}^2 + \delta S_{lm}^2 \right)}, \qquad (1)$$

where δC_{lm} and δS_{lm} are the errors in the Stokes coefficients. δN_l^2 is the contribution to the geoid error variance from all terms of degree l.

[6] Figure 1 shows, in orange, our estimate of the upper bound of the degree amplitudes of the GRACE errors. (We define "GRACE error" as the total error in the monthly gravity solutions, caused by a combination of measurement errors, processing errors, and errors in the geophysical models used to de-alias the GRACE measurements prior to constructing gravity fields.) These degree amplitudes are determined from the 11 GRACE fields by fitting and removing a constant and an annually varying term from each C_{lm} and S_{lm}. We make the conservative assumption that the residual C_{lm}'s and S_{lm}'s consist entirely of error, and we use those residuals in equation (1). We do not include C_{20} when estimating of δN_2, because the GRACE C_{20} results exhibit anomalously large variability in the first few months. We do not estimate δN_0 or δN_1 since 1 = 0, 1 terms are not included in the GRACE solutions. We multiply the δN_l results by 1.1 to obtain the degree amplitudes shown in Figure 1, because the process of fitting and removing constant and annual terms to 11 months of normally distributed random numbers reduces the rms by 0.9. If there are non-annual geophysical signals in the GRACE data, this method will over-estimate the true error. Conversely, if the GRACE errors include annual components, those components will be removed in the fit and so the error will be underestimated. At present, the errors are believed to be largely free of these components (S. Bettadpur, personal communication, 2004) (though see below).

[7] The assumption that the residuals are dominated by errors is likely to be valid at degrees $l \geq 15$. We deduce this by comparing with degree amplitudes predicted from a hydrology model and an ocean model, averaged over nearly the same time periods as the GRACE fields. The CPC hydrology model [*Fan and van den Dool*, 2004] uses observed precipitation and temperature to calculate soil moisture, evaporation, and runoff. The model does not include water variability beneath the soil layer, and does not fully account for the latent heat of fusion of snow, thereby causing the model to remove snow loads prematurely. The model does not include snow variability in the polar

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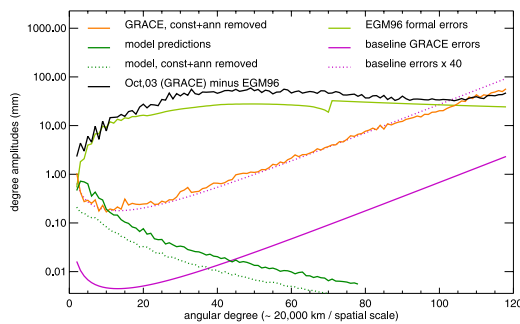
Figure 1. The degree amplitudes of the GRACE fields are shown in orange, computed after removing constant + annual terms. Also shown are degree amplitudes computed for the hydrology + ocean model (before and after removing constant + annual terms); for two estimates of the error in the EGM96 gravity field model; and for the baseline GRACE error estimates.

ice sheets. The ocean model is a JPL version of the ECCO general circulation model [*Lee et al.*, 2002], forced with NCEP reanalysis winds and thermal and salinity fluxes; it assimilates sea surface heights from TOPEX, and temperature profiles from XBT, TAO array and WOCE cruises. To mimic the process used by the GRACE Project to de-alias the raw data, we remove the output of a barotropic ocean model [*Ali and Zlotnicki*, 2003] from the ECCO results. We do not include atmospheric mass variations in our model, because they were removed from the GRACE data (using ECMWF fields) prior to constructing the monthly fields.

[8] The degree amplitudes of the model (solid green line in Figure F1) are larger than our GRACE error estimates at degrees of about $l \leq 10$. The model results after removing constant and annual terms (dashed green line) are smaller than the estimated GRACE errors for all l. This is not surprising, because our error estimates are actually the sum of errors and the non-annual signal. It does not imply that GRACE is incapable of recovering non-annual signals. Geophysical signals tend to be concentrated in specific locations. A large signal in a small region would not contribute much to the degree amplitudes, since those are determined globally. But that signal could rise above the GRACE errors when the Stokes coefficients are combined to form regional averages. Finally, there is considerable uncertainty in the model results. The hydrology signal is especially difficult to model. Large-scale water storage will be an initial target of GRACE analyses, since it causes a large gravity signal and is poorly constrained by other observations.

[9] For $l > 15$ the GRACE degree amplitudes are far larger than the degree amplitudes of the model residuals. At those degrees the GRACE results in Figure 1 are clearly dominated by errors. These errors are considerably smaller than the errors in previous gravity field models. Figure 1 shows the degree amplitudes of the difference between the October, 2003 GRACE solution, and the static gravity field EGM96 [*Lemoine et al.*, 1998] - considered to be among the best global gravity models. The EGM96 formal errors are also shown. Because those formal errors are much larger than our estimated GRACE errors, the difference between EGM96 and the GRACE solution is probably a better estimate of the EGM96 errors than the formal errors. GRACE appears to be more accurate than EGM96 by about a factor of 100 at

degrees between 10 and 40 - corresponding to scales of between 2000 and 500 km. It is notable that a 1-month GRACE solution has lower errors than EGM96 both at low degrees, where EGM96 is constrained by decades of satellite tracking, and at degrees as high as 90 or 100, where EGM96 is constrained by surface gravity and altimetry.

[10] GRACE has not yet achieved its baseline performance level. Figure 1 shows the degree amplitudes of the baseline target (solid purple line), as defined in the GRACE Science and Mission Requirements Document [*Jet Propulsion Laboratory*, 2001]. Our estimate of the present error level coincides closely with 40 × this baseline error estimate (dashed purple line).

3. Estimates of Surface Mass Variability

[11] Most of the monthly variability in the gravity field is caused by redistribution of mass within the atmosphere, oceans, and water/snow stored on land. If all gravity changes were caused by mass variations within a thin layer at the Earth's surface, and by the deformation of the solid Earth in response to those mass variations, the mass variability could be estimated from the GRACE Stokes coefficients using equations (9) and (13) of *Wahr et al.* [1998]. The mass estimates must be smoothed to obtain accurate results. To construct the figures shown here, we smooth both the GRACE and the model estimates using a Gaussian averaging kernel with a radius (i.e., half-width) of 1000 km [*Wahr et al.*, 1998, equations (30)–(34)]. We omit $C_{2,0}$, as well as all $l = 0$, 1 terms, from all mass calculations, both for GRACE and the model.

[12] For each GRACE field, we construct 1000 km Gaussian averages of surface mass at every point in a 2° × 2° global grid. We model and remove the ocean pole tide using IERS polar motion values. (The luni-solar ocean tides had been removed from the fields prior to their release; but the ocean pole tide had not.) We simultaneously fit
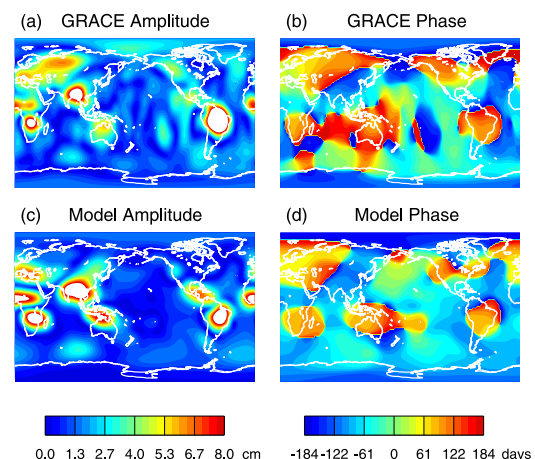

Figure 2. The best-fitting annually varying component of surface mass inferred from the GRACE data ((a) amplitude; (b) phase) and from the hydrology + ocean model ((c) amplitude; (d) phase). The amplitude is expressed in units of water thickness; the phase is defined as the time of maximum amplitude, measured in days past the start of the year. The results are computed for a 1000 km Gaussian averaging radius.

constant and annually varying terms to the results. Figures 2a and 2b show the amplitude and phase of the annual cycle; Figures 2c and 2d show the corresponding model predictions. The GRACE results are dominated by large annual continental mass signals that are in general agreement with the model predictions. Both GRACE and the model show large signals in Central and South America, southeast Asia, Africa, and northern Australia and Indonesia. GRACE shows a larger signal over northern Russia than predicted by the model, which could conceivably be explained by the tendency of the hydrology model to underestimate snow loads. Both sets of phase results show the annual cycle over continents tends to be maximum in Spring or Fall.

[13] Both GRACE and the model give results over the ocean that are much smaller than the maximum features on land, providing additional confidence that the large GRACE results over land are mostly real signal. There are locations in the Southern Ocean where GRACE and the model have similar amplitudes. But there are also substantial differences. In general, the ocean model results tend to show an east-west alignment, whereas the GRACE results are more nearly north-south: the orientation of the satellite ground tracks. This reflects a weakness in the GRACE recovery of the cross-track gravity signal.

[14] The most prominent ocean discrepancy is the $\sim$3.0–3.5 cm GRACE feature near Tahiti in the south-central Pacific, far enough from significant land areas that the results should be insensitive to hydrology signals. Neither the ECCO ocean model nor the non-Boussinesq model used by *Song and Zlotnicki* [2004] show an annual signal greater than 2 cm at latitudes lower than ±40° at the model's full resolution. This upper bound becomes smaller still after applying a 1000 km Gaussian average. The model predictions for the region around Tahiti show an annual amplitude of only 0.7 cm for a 1000 km average.

[15] Because the origin of this GRACE feature is unclear, we will assume it is caused by GRACE errors. This suggests a $\sim$3 cm upper bound for the maximum error of the annual GRACE mass components. This value depends on the averaging radius. The maximum annual component over the ocean is about 2 cm for a 1500 km averaging radius, and 4 cm for a 750 km radius. These values are extreme upper bounds on the annual solution uncertainties. Clearly the signals are much smaller over most of the ocean.

[16] We obtain an estimate of the globally averaged error by using the rms of the GRACE mass values after removing the best-fitting constant and annual terms. Figure 3a shows those rms values, while Figure 3b shows the results of applying this same procedure to the model. The rms results for GRACE reach almost 3 cm at several locations. The corresponding signals in the model are notably weaker. This does not necessarily imply the large GRACE features are errors. In fact, many of them occur in regions where the model predicts significant annual variability (Figure 2c).

[17] Still, we conservatively assume the rms values shown in Figure 3a are caused entirely by GRACE errors. When we square the rms values, average over the globe, and take the square root, we obtain $\sim$1.3 cm. Multiplying by an additional factor of 1.1, to adjust for the rms decrease that occurs when constant and annual terms are fit and removed from random numbers, we conclude that an upper bound for the globally averaged error in the monthly GRACE mass
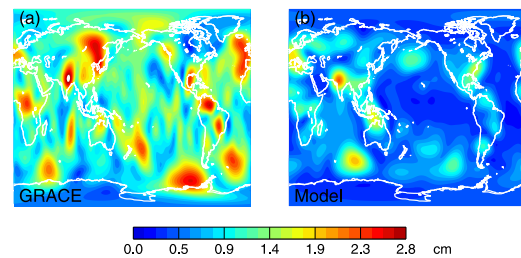

Figure 3. The rms, about the best fitting constant+annual terms, of the mass variability inferred from (a) the GRACE data; and (b) the hydrology + ocean model. The results are computed for a 1000 km Gaussian averaging radius.

solutions is 1.5 cm. This error estimate becomes 1.0 cm for a 1500 km averaging radius and 2.1 cm for a 750 km radius.

[18] We obtain similar error estimates using an alternate method. We simulate errors in the Stokes coefficients by assigning each C_{lm} and S_{lm} a normally distributed random number with an rms value of 40x the baseline error estimate. We use those numbers to generate a large ensemble of Gaussian-averaged surface mass values. The rms of those values is 1.1 cm for a 1500 km radius, 1.5 cm for a 1000 km radius, and 2.0 cm for a 750 km radius; all almost identical to the rms values inferred from Figure 3.

[19] Our estimates of the errors in the monthly GRACE mass solutions can be used to infer the probable size of the errors in the annually varying component. Suppose the 11 GRACE mass estimates at any location are replaced with 11 random numbers, and constant and annual terms are fit to those 11 numbers. We find, after averaging over thousands of random number sets, that the annual solution has an amplitude of 0.7 of the rms of those original 11 numbers. Thus the 1.5 cm upper bound for the rms error in the 1000 km monthly solutions obtained from the results shown in Figure 3, implies an upper bound for the globally averaged error in the annually varying amplitude of 0.7 × 1.5 = 1.0 cm. The errors for other averaging radii are 0.7 cm at 1500 km, and 1.4 cm at 750 km.

[20] If we apply this same scaling between rms values and annual signals to the 3 cm maximum rms value seen in Figure 3, we conclude that the maximum error in the annual component for 1000 km averages should be about 2.3 cm. This is reasonably consistent with our 3 cm upper bound based on the GRACE results for the annual cycle near Tahiti (though there is no large rms signal near Tahiti).

4. Water Storage in Specific Regions

[21] To illustrate an application of the GRACE fields, we use them to estimate water storage variability in three large drainage basins: the Mississippi River basin, the Amazon River basin, and the union of two major drainage systems flowing into the Bay of Bengal. We use a method described by *Swenson and Wahr* [2002] and *Swenson et al.* [2003], that minimizes the sum of satellite errors and leakage errors to construct an optimal averaging kernel for each region. That method requires an estimate of the GRACE errors, for which we use 40 × the baseline errors.

[22] GRACE results for the mass variability within each basin, along with contours of the averaging kernels used to
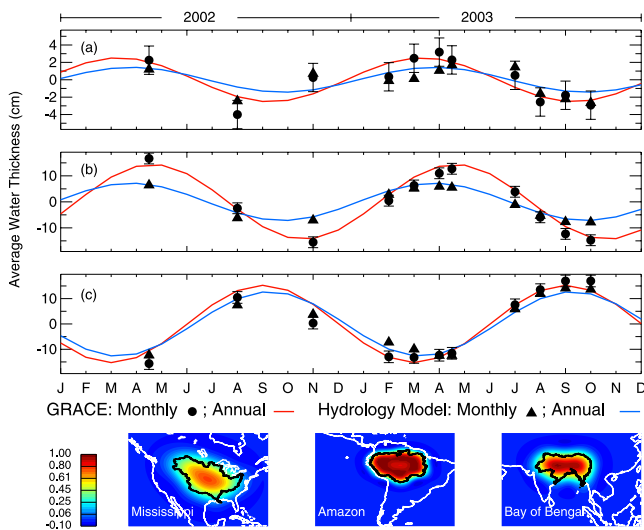
Figure 4. The mass variability within (a) the Mississippi River basin, (b) the Amazon River basin, and (c) a drainage system flowing into the Bay of Bengal, as inferred from the 11 GRACE fields (dots). The GRACE error bars are determined from simulations. Also shown are results inferred from the hydrology model, as well as the best-fitting annual signal for both the GRACE values and the model predictions. The bottom panels show the optimal averaging kernels used to recover this mass variability.

generate those results, are shown in Figure 4. The error bars on the GRACE results are estimated by applying these same averaging kernels to synthetic GRACE data, a method described by *Swenson et al.* [2003]. The synthetic data include contributions from GRACE errors (assumed to be $40 \times$ the baseline error estimate) and from geophysical signals, and include a water storage contribution computed using the CPC hydrology model. A portion of each error bar in Figure 4 is caused by mass signals outside the region leaking into the basin estimates, and includes the effects of omitting C20 and the l = 1 terms when constructing the GRACE results.

[23] Also shown in these figures are predictions from the CPC hydrology model for the same months. The model agrees well with GRACE in the Bengal and Mississippi basins; but predicts a significantly smaller signal, with a somewhat advanced phase, in the Amazon. The differences between the model and GRACE in the Amazon are significantly larger than the GRACE uncertainties.

5. Summary

[24] By comparing GRACE gravity fields for different months, we infer that the accuracy of the available GRACE monthly solutions is about 2 orders of magnitude better than the accuracy of EGM96 - considered to be among the best global gravity models - at scales between 500 km and 2000 km. The accuracy is about 40 times worse than the baseline target. Still, the errors are small enough that when averaged over 1000 km and larger, the mass estimates inferred from the GRACE data clearly show annually varying changes in continental water storage. The amplitudes and phases of those signals are in general agreement

with the predictions of a hydrology model. Furthermore, the inferred mass signals over the ocean are small, again in agreement with model predictions. In fact, although the agreement degrades with decreasing averaging radius, the largest water storage signals are still clearly evident at averaging radii as short as 400 km (not shown). The globally averaged uncertainty in the amplitude of the annually varying mass signal recovered from these GRACE fields is 0.7 cm for a 1500 km averaging radius, 1.0 cm for a 1000 km radius, and 1.4 cm for a 750 km radius. The annual error at any single location could be as large as 2, 3, or 4 cm for 1500 km, 1000 km, and 750 km radii, respectively.

[25] Project personnel continue work to identify the sources of error and to reduce their impact. For example, a month-by-month analysis (not shown) suggests the errors in the recovered mass are 30% smaller for the fields beginning in March 2003, than for the fields prior to that date.

[26] We also compute water storage variability in three large drainage basins: the Mississippi, the Amazon, and the region draining into the Bay of Bengal. We estimate the annually varying amplitude of that variability to accuracies of about $1.0 - 1.5$ cm. These results illustrate the kinds of applications made possible by data from this satellite mission.

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