

# GRACE Measurements of Mass Variability in the Earth System

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Monthly gravity field estimates made by the twin Gravity Recovery and Climate Experiment (GRACE) satellites have a geoid height accuracy of 2 to 3 millimeters at a spatial resolution as small as 400 kilometers. The annual cycle in the geoid variations, up to 10 millimeters in some regions, peaked predominantly in the spring and fall seasons. Geoid variations observed over South America that can be largely attributed to surface water and groundwater changes show a clear separation between the large Amazon watershed and the smaller watersheds to the north. Such observations will help hydrologists to connect processes at traditional length scales (tens of kilometers or less) to those at regional and global scales.

Little is known about a large class of seasonal, climate-related variations in the distribution of water on Earth's surface (1). A major motivation behind the development of the GRACE satellites (2) was the global, synoptic measurement of the associated mass distribution and mass flux of this water through its effects on Earth gravity. Ultimately, accurate and ongoing measurements of gravity variation will aid in developing a new understanding of ocean heat storage (3), deep ocean currents (4), eustatic sea level rise, polar ice mass accumulation (5, 6), groundwater storage (7), and surface water (8).

Earth's gravity field reflects the composition and structure of the planet, including the distribution of the atmosphere and water mass on and below its surface. Observations of seasonal variations in Earth's gravity field place important constraints on models of global mass variability and temporal exchange among the land, ocean, and atmosphere. This is particularly important for subsystems that might otherwise be extremely difficult to detect and monitor (e.g., deep ocean currents and deep aquifers).

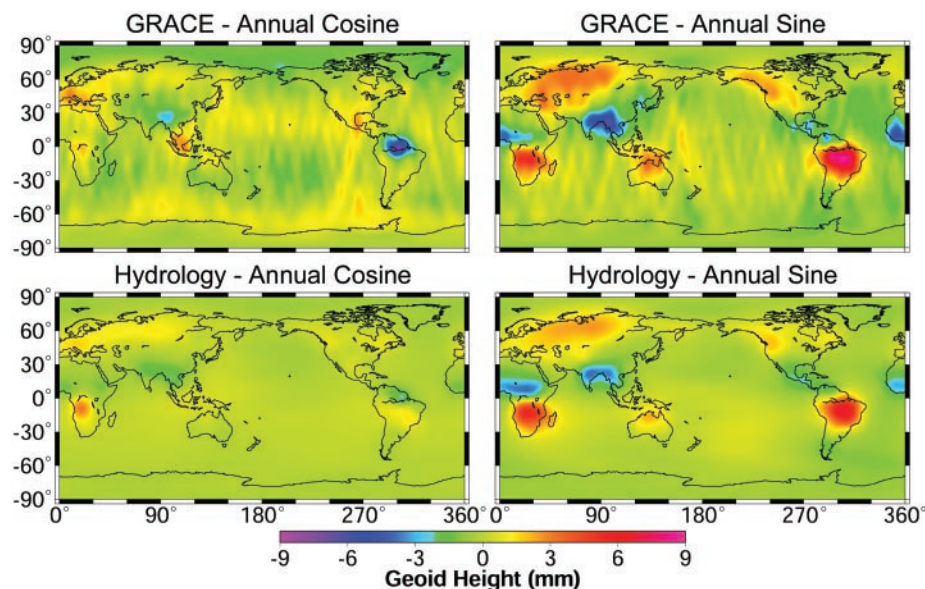
Temporal variations of Earth's gravity field range in size from 10 to 100 parts per million (variation from the mean) and occur on a variety of time scales. In the past, satellite laser ranging (SLR) has been used to determine the very long wavelength seasonal gravitational changes due to mass exchange among the atmosphere, ocean, and continental water sources (9–13). Additionally, the postglacial rebound of the mantle has also been estimated from multidecadal SLR data (14). These measurements have been limited in resolution because of the geographic dis-

tribution of the tracking data and the high altitude of the satellites. The GRACE mission was implemented to provide global measurements of these same phenomena, but with a much finer spatial resolution and greater accuracy than previously possible (15–17).

A sequence of 14 monthly gravity field estimates has been determined from GRACE data collected between April 2002 and December 2003. The monthly gravity estimates were obtained as variations relative to a well-defined a priori gravity model. It is advantageous to adopt models for

the time-variable geophysical processes that are better determined from techniques other than GRACE, particularly if they involve variability at submonthly periods (18). The modeled geophysical variations included the solid Earth and oceanic tides, selected secular variations, pole-tide effects, and a combination of atmospheric pressure variations and the response of a barotropic ocean model driven by ECMWF (European Centre for Medium-Range Weather Forecasts) models of atmospheric pressure and winds (19). Consequently, the GRACE gravity estimates contain information about mass variability due to the signal introduced by geophysical phenomena not already modeled and the residual signal, on average, from omissions in the a priori models (20).

Terrestrial water variations are the largest omitted phenomena and are thus the dominant unmodeled signal that should be evident in the monthly gravity estimates. Estimates of terrestrial water storage can have important political and economic implications, as they are critical for understanding and predicting climate change, weather, agriculture productivity, flooding, and other natural hazards (1, 21). Soil moisture in particular is an important component in the analysis of climate change and the performance of general circulation models (22, 23). The difficulty with models of global terrestrial water storage is



**Fig. 1.** Comparison of annual variation in the geoid height from GRACE and the GLDAS hydrology model (smoothing radius 400 km; degree-2 coefficients not included). The cosine (i.e., winter-summer, left) and sine (i.e., spring-fall, right) components determined from GRACE (top) and from the GLDAS hydrology model (bottom) are shown as a function of geographic location. The cosine component from GRACE ranged from  $-7.2$  mm to  $+3.0$  mm with a global root mean square (RMS) of 0.9 mm (a negative value represents a variation that is opposite in phase, i.e., peaking in summer rather than winter); the sine component ranged from  $-6.4$  mm to  $+8.9$  mm with a global RMS of 1.3 mm (a negative value indicates a variation that peaks in fall rather than spring). The cosine component from the GLDAS model ranged from  $-2.3$  mm to  $+3.2$  mm with a global RMS of 0.4 mm; the sine component ranged from  $-4.0$  mm to  $+6.7$  mm with a global RMS of 1.0 mm. Most of the annual peak values were concentrated in the sine (spring-fall) component.

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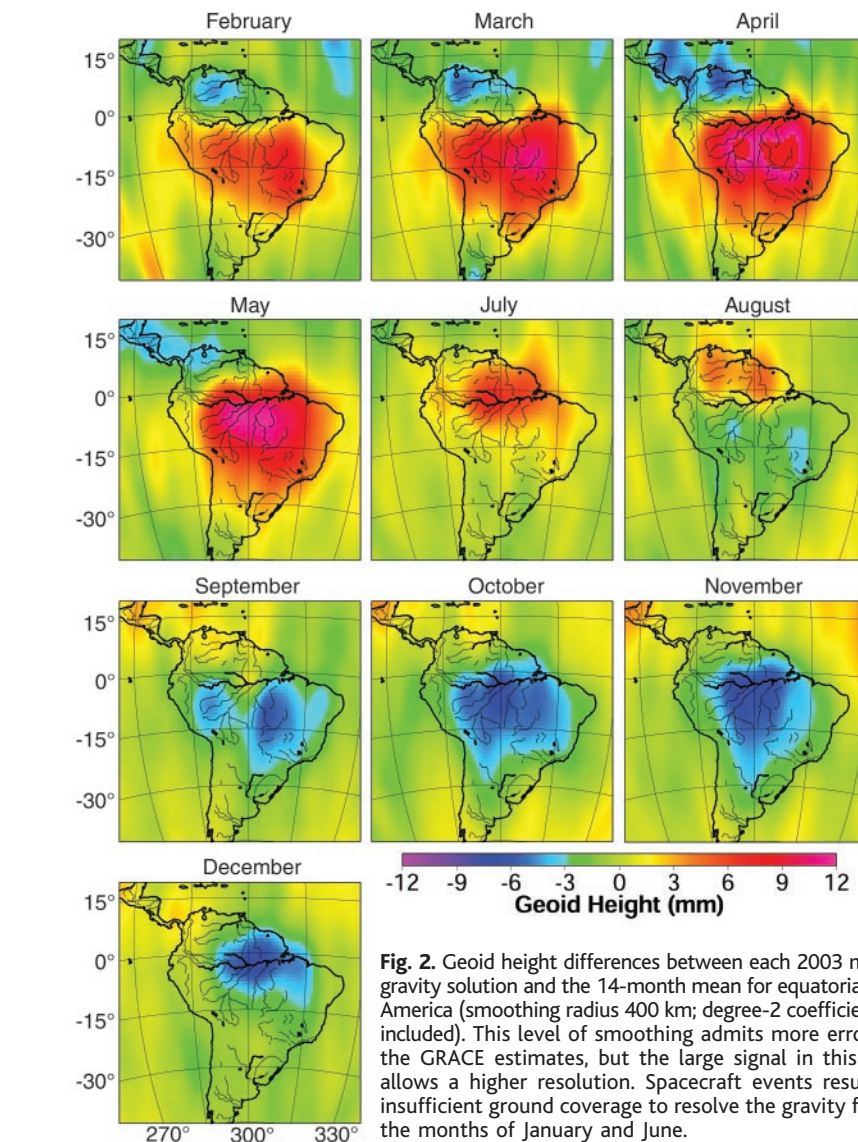
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that they are often poorly constrained by direct observations. This can result in some models being heavily constrained by a prescribed climatology (24). Furthermore, competing models often differ considerably in magnitude from one another and from independent in situ observations (7, 25, 26).

A weighted least-squares fit was used to estimate the annual cosine (winter-summer) component, the annual sine (spring-fall) component, and a linear trend for the 14 monthly GRACE gravity fields. A similar estimate was based on the terrestrial water storage as determined from the Global Land Data Assimilation System (GLDAS) (21, 27). The estimated cosine and sine components are compared in Fig. 1. To emphasize the wavelengths of interest in continental and basin scale hydrology applications, we have removed the degree-2 coefficients and downweighted the higher degree coefficients (i.e., short-wavelength spatial scales) using a smoothing function with an effective Gaussian radius of 400 km (28). [See (29) and fig. S1 for details of the comparison between GRACE and GLDAS land hydrology and the spatial scales appropriate for that comparison.] Qualitatively, there is general agreement between the annual geoid variability observed by GRACE and that estimated by the GLDAS hydrology model, although GRACE observed significantly larger magnitudes (Fig. 1).

Although GRACE estimates tend to be dominated by the unmodeled hydrological processes, they also contain a variety of other signals (both real and erroneous) that must be considered when interpreting the results. Perfect agreement with models of land hydrology is not necessarily expected. As is common with global continental hydrology models, GLDAS does not model deep subsurface water, snow persistence, or variability on the Antarctic continent. GRACE results of temporal gravity variations are an important additional constraint on the output of hydrological models, as they represent the total vertically integrated effect of mass.

The month-to-month geoid variability for South America during 2003 (Fig. 2) shows that for the Amazon basin, a local maximum of 14.0 mm relative to the mean was observed in April 2003 and a local minimum of  $-7.7$  mm was observed in October 2003. The Amazon observation is particularly important because it is the largest drainage basin [ $>5$  million  $\text{km}^2$  (7)] and has the largest annual signal observed by GRACE (Fig. 1). In fact, an elevation change of a few centimeters of surface water in the Amazon can be equivalent to water flows greater than the average discharge of the Mississippi River (8). Therefore, it is important to be able to accurately measure the variability of surface water and groundwater in this region in both space and time. However, in this region, surface water variability is exceedingly difficult to measure



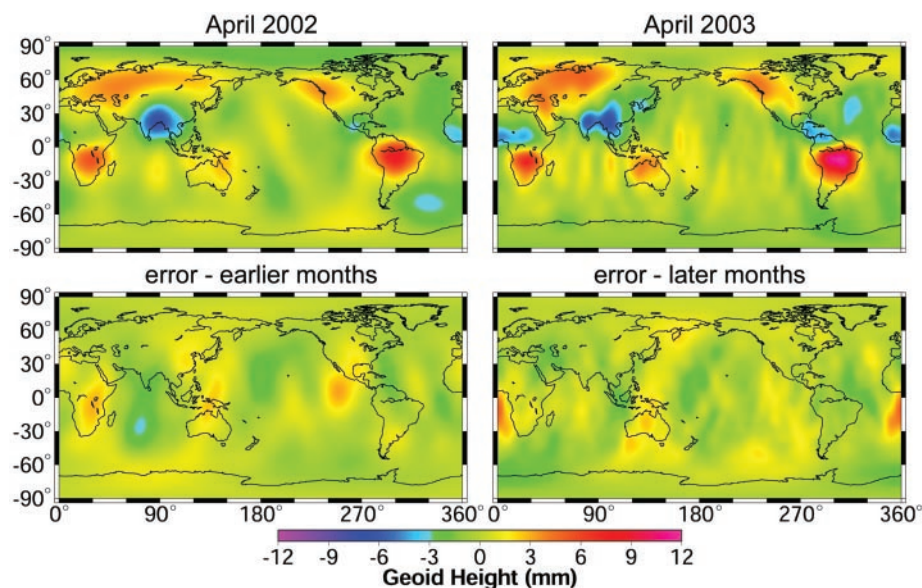
**Fig. 2.** Geoid height differences between each 2003 monthly gravity solution and the 14-month mean for equatorial South America (smoothing radius 400 km; degree-2 coefficients not included). This level of smoothing admits more error from the GRACE estimates, but the large signal in this region allows a higher resolution. Spacecraft events resulted in insufficient ground coverage to resolve the gravity field for the months of January and June.

using traditional methods of runoff and level gauges. Additionally, GRACE observed a clear separation in geoid variability between the large Amazon watershed and the much smaller Orinoco watershed to the north (Fig. 2). There should be a separation in the drainage processes between watersheds, because the Amazon is separated from watersheds bordering to the north topographically (in the form of the Guiana Highlands, known for Angel Falls) as well as meteorologically (due to the equator).

The inherent spatial-temporal resolution of the variability, and hence the smoothing needed to resolve the signal relative to the errors in the GRACE data, will depend on the region of interest (global versus regional) as well as the time scale (monthly versus annual). Extracting mass variability for specific watersheds requires specialized methods of spatial weighting that take into account the unique features of a region (30). The magni-

tude of the errors in the GRACE estimates varies from month to month because of a combination of factors—ground-track coverage, temporal coverage (i.e., missing days), mismodeled short-period variability, and spacecraft events. Although a 400-km smoothing radius was selected to illustrate annual variability (Fig. 1) and large-amplitude regional signals (Fig. 2), this is not necessarily the level of smoothing that is appropriate for the entire globe for all monthly solutions (29) (fig. S2). There is a clear difference between the 2002 and 2003 monthly solutions; improvement was observed in the 2003 solutions soon after improvements to the onboard satellite software were implemented. This does not make the earlier solutions from 2002 inadequate for analysis, but a higher level of smoothing is required when comparing these earlier monthly solutions.

With the current level of precision obtained



**Fig. 3.** Observed geoid height differences relative to a mean geoid (top) and a representation of the expected errors at the same levels of smoothing (bottom) for the April 2002 (left) and April 2003 (right) solutions (smoothing radius 1000 km for 2002, 600 km for 2003; degree-2 coefficients not included). The predicted errors are generated as a random realization of the calibrated error covariance, which will exhibit broad-scale patterns at the level of a few millimeters. Real gravity variations at this level cannot be confidently observed, but variations with larger amplitude (e.g., Amazon basin) or at larger spatial scales (e.g., Africa and Asia) will be clearly determined.

in GRACE processing, our analysis suggests that on a global level, the 2002 solutions can resolve spatial scales of  $\sim 1000$  km and the 2003 solutions can resolve features down to  $\sim 400$  to 600 km. As an illustration, solutions from April 2002 and from April 2003 are shown together in Fig. 3. These show that the annual cycle is closely, but not exactly, repeated. For example, the region just to the north of Africa's tropical rainforest region was observed to be drier in 2003. Several additional factors might influence this observation. Whereas the April 2003 solution uses days entirely within the calendar month, the 2002 solution required a mix of days in April and May. Furthermore, the larger smoothing radius used for the April 2002 solution removes more of the shorter wavelength features, thereby minimizing the overall amplitude of the features observed. With these caveats in mind, the two classes of solutions show similar features with subtle interannual differences.

As an additional aid to analysis, a sample realization of the possible geographical distribution of errors is also shown in Fig. 3. The error maps are a randomly generated realization of the geoid error based on the calibrated covariance for these monthly solutions (29) (fig. S3). These maps are not intended to be an exact spatial representation of the error for any particular solution; they are intended to illustrate how random error in the GRACE gravity field solution can result in geoid features that may appear similar to geophysical processes. We found

that the level of error in the 2003 solutions was on the order of 2 to 3 mm for spatial features of  $\sim 600$  km; the same level of error was possible in the 2002 solutions only after smoothing to  $\sim 1000$  km.

GRACE is able to resolve variations in the gravity field for a range of spatial scales down to 400 km for particular times and regions with large signals. Data acquisition at this level or better is expected to continue for several more years. Future reprocessing of the current data with improved methods is expected to increase both the resolution and the accuracy. Although reprocessing will improve the accuracy of the GRACE solutions, final interpretation requires an understanding of the interaction among atmosphere, ocean, and land hydrology.

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- GRACE is a dedicated satellite mission whose objective is to map the global gravity field every 30 days for 5 years with unprecedented accuracy and with a spatial resolution of 400 km. Jointly implemented by NASA and DLR (Deutsches Zentrum für Luft- und Raumfahrt) under the NASA Earth System Science Pathfinder Program in 1997, GRACE was launched on 17 March 2002 from Plesetsk, Russia, onboard a Rockot launch vehicle. The GRACE mission consists of two identical satellites in near-circular orbits at  $\sim 500$  km altitude, separated from each other by  $\sim 220$  km along-track and linked by a highly accurate intersatellite K-band microwave ranging system. Each satellite carries Global Positioning System (GPS) receivers and attitude sensors and high-precision accelerometers to measure the surface forces. Through the dynamical evolution of the orbits, the intersatellite distance change (which is extracted from phase measurements of the K-band signal transmitted between the two satellites) contains implicitly the influence of the globally integrated mass distribution and its movements within the Earth system.
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#### Supporting Online Material

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SOM Text  
Figs. S1 to S3  
References

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