Terrestrial water mass load changes from Gravity Recovery and Climate Experiment (GRACE)

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[1] Recent studies show that data from the Gravity Recovery and Climate Experiment (GRACE) is promising for basin- to global-scale water cycle research. This study provides varied assessments of errors associated with GRACE water storage estimates. Thirteen monthly GRACE gravity solutions from August 2002 to December 2004 are examined, along with synthesized GRACE gravity fields for the same period that incorporate simulated errors. The synthetic GRACE fields are calculated using numerical climate models and GRACE internal error estimates. We consider the influence of measurement noise, spatial leakage error, and atmospheric and ocean dealiasing (AOD) model error as the major contributors to the error budget. Leakage error arises from the limited range of GRACE spherical harmonics not corrupted by noise. AOD model error is due to imperfect correction for atmosphere and ocean mass redistribution applied during GRACE processing. Four methods of forming water storage estimates from GRACE spherical harmonics (four different basin filters) are applied to both GRACE and synthetic data. Two basin filters use Gaussian smoothing, and the other two are dynamic basin filters which use knowledge of geographical locations where water storage variations are expected. Global maps of measurement noise, leakage error, and AOD model errors are estimated for each basin filter. Dynamic basin filters yield the smallest errors and highest signal-to-noise ratio. Within 12 selected basins, GRACE and synthetic data show similar amplitudes of water storage change. Using 53 river basins, covering most of Earth's land surface excluding Antarctica and Greenland, we document how error changes with basin size, latitude, and shape. Leakage error is most affected by basin size and latitude, and AOD model error is most dependent on basin latitude.

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1. Introduction

[2] The NASA/Deutsches Zentrum fur Luft und Raumfahrt (DLR) Gravity Recovery and Climate Experiment (GRACE) satellite mission was launched in March 2002. It consists of two identical satellites at about 500 km altitude, separated by about 220 km, in identical near-polar orbits. GRACE measures Earth's gravity field and its changes over time using range-rate perturbations between the two satellites sensed with a microwave interferometer. Each satellite is also tracked with an onboard GPS receiver. Perturbations due to nongravitational forces (such as atmospheric drag) are removed using an accelerometer mounted at the mass center of each satellite. GRACE detects spatial and temporal variations of Earth's gravity field with astonishing sensitivity. Published results have demonstrated that GRACE is able to detect changes in mass corresponding to surface water loads of 1 cm, with horizontal dimensions of hundreds of km and larger [*Wahr et al.*, 2004].

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[3] Recent studies [e.g., *Chambers et al.*, 2004; *Tapley et al.*, 2004; *Wahr et al.*, 2004; *Ramillien et al.*, 2005; *Schmidt et al.*, 2006] show that GRACE can be used to estimate changes in terrestrial water storage at basin scales. Evapotranspiration, a critical but difficult to constrain component of the water cycle, can be estimated by combining GRACE and other observations [*Rodell et al.*, 2004b]. *Swenson et al.* [2003] estimated GRACE error over North American basins from simulated GRACE data, but error estimates were based on prelaunch satellite measurement error predictions, approximately 40 to 50 times smaller than current error levels [*Wahr et al.*, 2004]. In this study, we assess realistic GRACE errors globally and provide a comprehensive global comparison between climate model predictions and GRACE estimates.

[4] There are few direct observations to compare with GRACE products, so we must rely on indirect methods to quantify errors, using four resources: internal error measures reported with GRACE products; temporal (monthly) variations in GRACE spherical harmonic (SH) coefficients and related water storage estimates; independent water storage estimates from numerical models of land surface processes; and atmospheric and ocean model results used in GRACE processing and reported with GRACE data products. An additional complication is that there is no unique way to compute water storage changes from GRACE spherical harmonics. We use four different methods of combining harmonics, called basin filters, including one new method, described in section 2.2.

Table 1. Summary of the Data

Type	Data
Monthly GRACE SH coefficients	GRACE data
GRACE internal error	GRACE measurement noise
Numerical models	synthetic GRACE data (GLDAS+ECCO+NCEP-AOD model)

[5] Accuracy of water storage estimates from GRACE is limited by precision of the GRACE measurement system, which we estimate from internal error measures reported with GRACE products. We refer to this as measurement noise. A second error source is inaccuracies in atmospheric and ocean fields used to remove effects of ocean and atmosphere mass redistribution from GRACE observations. We refer to this as atmosphere-ocean dealiasing error (AOD). A third error source, leakage error, arises from a limited range of spherical harmonics used to represent gravity field variations. Leakage error is estimated from water storage fields taken from climate models by using the same finite range of SH coefficients available from GRACE. We examine these three error sources individually, and in combination, for river basins with diverse sizes, shapes, hydrologic regimes, and geographic locations.

2. Data and Methods

2.1. Data

2.1.1. GRACE Products and Internal Errors

[6] GRACE products and internal errors are available at PO.DAAC (http://podaac.jpl.nasa.gov/grace) and ISDC (http://isdc.gfz-potsdam.de/grace). Near-monthly (13–45 days) solutions are added as they are produced, beginning with April/May 2002. Here we use 13 solutions from August 2002 to December 2003. December 2002, January 2003, May 2003, and June 2003 results are not available. Separate bimonthly solutions for both April and May 2002 and April and May 2003 are not included in our analysis. Since most conclusions are based upon synthetic data constructed to resemble available GRACE fields, these omissions do not affect our results. GRACE products include SH degrees and orders up to 120. We omit coefficients beyond degrees 50 (spatial scales smaller than about 400km) and recognize that SH degrees larger than about 15 suffer from significant errors in current GRACE time-varying fields. Mean SH coefficients are computed from the series of 13 monthly SH coefficients and time variations are given with respect to these mean coefficients. Reported internal error (a standard deviation for each coefficient) is determined from the misfit of GRACE SH coefficients to measured data, and does not fully represent all error sources.

4. Conclusions

[29] With synthetic GRACE data, we examined Gaussian smoothing and dynamic filters. Gaussian smoothing (B_1 and B_2) applies the same weight to all SH orders at each SH degree, producing rounded water storage features. There are trade-offs in choosing the amount of Gaussian smoothing, with additional smoothing reducing signal amplitude. An objective criterion for choosing the amount of smoothing is not clear. Dynamic filters (B_3 and B_4) use a least squares criterion to filter each degree and order differently according to signal and error spectra. Dynamic filter coefficients can be fixed, or changed over time as the error and signal change. To implement the dynamic filters one requires additional information about signal strength, which can be obtained either from numerical models like GLDAS, or from GRACE product themselves. The dynamic filters force variance to be concentrated in regions where there are water storage variations. The dynamic filter concept was superior to Gaussian filtering in all the examples we examined.

[30] Global signal-to-noise ratio maps from the four basin filters are a guide to regions where currently released GRACE products can be useful in water storage studies. In general these are areas where SNR is greater than unity. This excludes many arid regions, but includes a fairly large fraction of the land surface. Water storage changes and associated errors are estimated over 12 basins and compared with GLDAS. For these large basins, the four basin filters perform similarly. When the goal is to produce a gridded water storage map, then spatial resolution is of paramount importance, and dynamic filters (B_3 or B_4) are preferred.

[31] Annual amplitudes for the 12 basins are larger for GRACE than synthetic data (from GLDAS), but nonannual residuals are about the same size. There may be multiple explanations. One is simply that GLDAS underestimates the annual cycle in these basins, but interannual variations are more nearly correct. GLDAS does not include groundwater, a possibly significant element of annual storage changes. The GRACE annual cycle may also be larger than GLDAS because aliasing may contaminate the annual signal more than smaller nonannual residuals of random phase throughout the world. GRACE may also contain annual noise of unknown origin.

Table 3. Coefficients of Linear Polynomials Representing GRACE Errors[a]

	1	x	y	z
Noise (B_1)	45.2888	−0.3586	−0.3275	−0.0855
Leakage (B_1)	30.4823	−0.2819	−0.2018	−0.0526
AOD (B_1)	25.2369	−0.1278	0.2213	0.1299
Noise (B_3)	10.5450	−0.0571	−0.0076	−0.0098
Leakage (B_3)	37.0218	−0.2755	−0.1381	−0.0795
AOD (B_3)	11.6251	−0.1924	0.5037	0.1686

[a]Here x, y, and z are normalized variables for basin size, latitude, and shape, respectively. The detailed descriptions of the normalizations are described in section 5.

[32] For both annual and nonannual components, GRACE variations are less dependent on basin filters than those for synthetic data. This is evident in the smaller vertical scatter in the symbols of Figure 11. We suspect that true GRACE measurement noise is smaller than the noise model used to create synthetic data. This is suggested by Figure 1.

[33] Using 53 basins, we estimate measurement, leakage, and AOD model errors, and graph their dependence on basin size, latitude, and shape. These are the main variables anticipated to be important for a given basin. Linear polynomials fit by least squares provide an algorithm for predicting the likely errors for any basin. These polynomials summarize the error situation in current GRACE products. Future releases of GRACE products will likely have smaller errors, and the polynomials and other measures of error will certainly change. However, the general method, and other error descriptions such as the SNR map, are likely to be useful tools in the future.