## Title

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## Permalink

https://escholarship.org/uc/item/472447v8

## Journal

Journal of Geodesy, 81(4)

## ISSN

0949-7714

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## Publication Date

2007-04-01

## DOI

10.1007/s00190-006-0104-2

J Geod (2007) 81:237–245
DOI 10.1007/s00190-006-0104-2

ORIGINAL ARTICLE

# Attenuation effect on seasonal basin-scale water storage changes from GRACE time-variable gravity

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Received: 8 February 2006 / Accepted: 25 September 2006 / Published online: 26 October 2006

**Abstract** In order to effectively recover surface mass or geoid height changes from the gravity recovery and climate experiment (GRACE) time-variable gravity models, spatial smoothing is required to minimize errors from noise. Spatial smoothing, such as Gaussian smoothing, not only reduces the noise but also attenuates the real signals. Here we investigate possible amplitude attenuations and phase changes of seasonal water storage variations in four drainage basins (Amazon, Mississippi, Ganges and Zambezi) using an advanced global land data assimilation system. It appears that Gaussian smoothing significantly affects GRACE-estimated basin-scale seasonal water storage changes, e.g., in the case of 800 km smoothing, annual amplitudes are reduced by about 25–40%, while annual phases are shifted by up to 10°. With these effects restored, GRACE-estimated water storage changes are consistently larger than model estimates, indicating that the land surface model appears to underestimate terrestrial water storage change. Our analysis based on simulation suggests that normalized attenuation effects (from Gaussian smoothing) on seasonal water storage change are relatively insensitive to the magnitude of the true signal. This study provides a numerical approach that can be used to restore seasonal water storage change in the basins from spatially smoothed GRACE data.

**Keywords** GRACE · Spatial smoothing · Water storage estimation · Seasonal variations · Attenuation effect

## 1 Introduction

The primary goal of the gravity recovery and climate experiment (GRACE) twin-satellite gravity mission is to produce measurements of the Earth's time-variable gravity field at approximately 30-day intervals with unprecedented accuracy based on precise measurements of the distance between two satellites orbiting in tandem, as well as data from on-board accelerometers and global positioning system (GPS) receivers (Tapley et al. 2004a).

These time-variable gravity field models can be used to infer global geoid height changes or mass variations in the atmosphere, ocean and land water (e.g., Wahr et al. 1998; Tapley et al. 2004b; Chambers et al. 2004; Rodell et al. 2004a; Chen et al. 2005a). As the high degree and order spherical harmonic coefficients from GRACE are dominated by noise, in order to effectively recover geoid height or surface mass changes using GRACE observed

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time-variable gravity, a certain level of spatial smoothing is required to minimize errors from spatial noise (Wahr et al. 1998).

Gaussian smoothing (e.g., Jekeli 1981), which assumes a Gaussian or normal distribution of spatial errors, is widely used in many recent GRACE related studies (Wahr et al. 2004; Tapley et al. 2004b; Chambers et al. 2004; Chen et al. 2005a,b). When the spatial scale is appropriately chosen, Gaussian smoothing appears to be quite effective in reducing spatial errors in GRACE observed time-variable gravity data. For example, based on comparisons between GRACE-recovered global water storage changes and model-estimated terrestrial water storage changes from the NASA global land data assimilation system (GLDAS) (Rodell et al. 2004b), Chen et al. (2005b) suggest that an 800 km Gaussian smoothing appears (relatively) most effective in reducing spatial errors and yields the minimum mean residuals between GRACE observations (release R001) and model estimates.

Specially designed basin kernels (or functions) can be used to infer basin-scale water storage change from GRACE and to reduce measurement and spectral leakage errors. For example, Swenson and Wahr (2002) proposed a Lagrange multiplier method to optimize water storage extractions for interested basins. Seo and Wilson (2005) developed dynamic basin functions with time-variable weightings based on climate models, which could notably improve the GRACE spatial resolution.

Some optimal smoothing techniques have been developed to more effectively recover GRACE-observed Earth-surface mass changes. Davis et al. (2004) applied an *F*-test (Lunneborg 1994) to determine whether fitting for an annual variation yielded a significant decrease in the scatter of the coefficient time-series, and only chose the Stokes coefficients that passed the 99.95% level of significance, which included only 72 degree/order pairs under spherical harmonic degree 10. This technique can significantly reduce the 'striping' noise in GRACE data. However, the exclusion of the majority Stokes coefficients (including many low-degree terms) will certainly underestimate the variance of the true signal.

Han et al. (2005) developed a non-isotropic Gaussian filter that could yield significantly better spatial resolution in latitude (while remaining the same resolution in longitude as compared to the conventional Gaussian filter). Chen et al. (2006) developed another optimized technique based on proxy signal-to-noise ratios defined as between GRACE-observed terrestrial water storage change and residuals over the oceans. This optimized smoothing technique shows significantly improved spatial resolution in the GRACE-derived surface mass change fields.

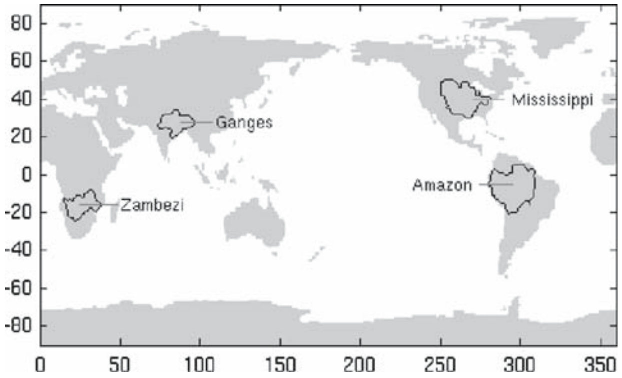

**Fig. 1** Geographical locations of four major river basins examined in this study: Mississippi, Amazon, Ganges and Zambezi

However, no matter what technique is used, any smoothing – either in the spatial or temporal domains – not only reduces noise but also (more or less) attenuates the real signals. The attenuation effect manifests as a change in magnitude of the real signal as a consequence of applying the spatial smoothing, which in most cases will reduce the magnitude of the signal when variations in surrounding regions are relatively less significant (as compared to those in the target area). This is a typical characteristic of major large river basins, where terrestrial water storage changes are mostly more significant than those in other surrounding and minor river basins, or residual variations over the ocean (when the target river basin is close to the ocean, e.g., the Amazon, Ganges and Zambezi basins to be evaluated in this study).

Owing to the lack of other independent knowledge of time-variable gravity, it is practically impossible to fully separate signals from noise in GRACE observations. In this study, we use model-estimated terrestrial water storage changes to assess possible attenuation effects on GRACE-observed time-variable gravity when Gaussian smoothing is applied. We focus on seasonal water storage changes in four major basins: the Amazon, Mississippi, Ganges and Zambezi (see Fig. 1).

We examine annual and semiannual amplitude and phase changes in these four basins as a function of the spatial radius used in the Gaussian smoothing. The estimated amplitude and phase changes can then be applied to GRACE observations to restore the 'real' seasonal water storage changes (after Gaussian smoothing is applied to the GRACE data). The success of this method relies on the assumption that, in these selected river basins, the GLDAS model estimates resemble GRACE-observed seasonal water storage changes, showing similar spatial patterns and seasonal amplitudes.

This approach can be partly justified by the remarkable agreement between GRACE- and GLDAS-estimated water storage changes in major basins (Chen et al. 2005a,b). The spatial distribution of GRACE errors is another factor affecting the success of this 'restoring' method. GRACE errors are strongly correlated with satellite ground-tracks, the often-called 'striping' effect, and hence do not follow a Gaussian distribution. Here we assume that when the spatial radius is appropriately chosen (or large enough), at least for these selected major basins with strong seasonal variability, the errors from spatial noise do not significantly affect the estimated seasonal water storage changes.

Another motivation behind this study is the fact that some 'standard' surface mass change products derived from GRACE time-variable gravity solutions are based on the commonly used Gaussian smoothing, e.g., the online interactive data archive at the GRACE-Tellus Information Website at http://grace.jpl.nasa.gov (Zlotnicki et al. 2005), and GRACE observed terrestrial water storage change products provided by the Global Geophysical Fluids Center's Special Bureau for Hydrology (http://www.csr.utexas.edu/research/ggfc) (Chen and Wilson 2005).

These GRACE-derived products will likely be widely used by researchers, especially hydrologists and oceanographers. A quantitative assessment of potential attenuation effects from Gaussian smoothing at different spatial scales is of great interest to the general geoscience community, and provides a numerical (and also independent) approach to restore GRACE-observed seasonal terrestrial water storage changes in selected river basins (when Gaussian smoothing is applied).

## 2 Data and processing

### 2.1 GRACE observations

GRACE time-variable gravity data are from release 001 (R001), which includes 22 monthly global gravity field models, spanning the period from April 2002 to July 2004, and represent approximately monthly average values, though temporal sampling and averaging intervals are not completely uniform (Tapley et al. 2004a). Tidal effects, including ocean, solid Earth and solid Earth pole tides (rotational deformation) have been removed in the level-2 GRACE data processing. Non-tidal atmospheric and oceanic contributions are also removed in the level-2 de-aliasing process (Bettadpur 2003). This means that the GRACE data represent changes caused by non-atmospheric and non-oceanic mass changes, mainly continental water storage changes, as well as unmodeled atmospheric and oceanic effects.

Following the same method as in Chen et al. (2005b), we computed global water storage changes with 800-km Gaussian smoothing, and truncated the GRACE data at degree and order 60. The degree-2 zonal harmonics $C_{20}$ are excluded because of unquantified large uncertainties in this term (Tapley et al. 2004b). Basin-scale water storage changes are then computed from the inverse global gridded water mass storage change ($\Delta M(\theta,\lambda)$, where $\theta$ and $\lambda$ are latitude and longitude of the grid point) as

$$\Delta S = \frac{\sum_{\theta=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} M(\theta,\lambda)\cdot B(\theta,\lambda)\cdot\cos\theta}{\sum_{\theta=-\frac{\pi}{2}}^{\frac{\pi}{2}} \sum_{\lambda=0}^{2\pi} B(\theta,\lambda)\cdot\cos\theta} \qquad (1)$$

where $B(\theta,\lambda)$ is the basin function of the target area, which equals one within the target basin and zero outside, and $\cos\theta$ represents the cosine latitude weighting of the given grid point.

### 2.2 GLDAS model estimates

Global land data assimilation system parameterizes, forces and constrains sophisticated land surface models with ground and satellite products with the goal of estimating land surface states (e.g., soil moisture and temperature) and fluxes (e.g., evapotranspiration) (Rodell et al. 2004b). In this particular simulation (#173), GLDAS drove the Noah land surface model (Ek et al. 2003) version 2.7.1, with observed precipitation and solar radiation included as inputs. GLDAS terrestrial water storage variations used in our calculations are the sum of soil moisture (to a 2 m column depth) and snow-water equivalent. Greenland and Antarctica are excluded because the Noah model does not include ice sheet physics.

To evaluate spatial smoothing effects on model-estimated seasonal water storage changes in our four selected basins, we first convert GLDAS gridded water storage change into fully normalized spherical harmonics (or Stokes coefficients) up to degree and order 100, equivalent to GRACE observed time-variable gravity, and then follow the same procedures as used in the GRACE data to compute global water storage changes from these GLDAS-estimated spherical harmonics for cases using different spatial radii for Gaussian smoothing. For consistency with GRACE data, GLDAS estimated degree-1 harmonics representing geocenter motion (not provided in GRACE data) and degree-2 zonal harmonics $C_{20}$ are excluded.

Basin-scale water storage changes are then computed from GLDAS-inverted global gridded water storage changes using Eq. 1. The procedures involved can be described as (1) expand GLDAS-gridded data into spherical harmonics, (2) truncate at degree 60 and omit degree-1 terms and $C_{20}$ (same as GRACE), (3) filter the GLDAS spherical harmonics and convert them into gridded water mass changes, and (4) compute mass-change-averaged basin water storage changes in the target areas and then express the results in the frequency domain. The 3-hourly GLDAS time-series are averaged into the same GRACE monthly intervals.

## 3 Results

### 3.1 Attenuation effects based on the GLDAS model

We compute water storage changes in the four selected basins using GLDAS-inverted global gridded water storage changes for cases with no smoothing is applied and the spatial radius changes from 100, 200, 300, …, to 2,000 km. The four panels in Fig. 2 show the recovered basin-scale water storage changes in four particular cases, (a) no smoothing, (b) 400 km, (c) 800 km, and (d) 1,200 km Gaussian smoothing. Attenuation effects are evident for all four river basins, especially in the Ganges and Zambezi. In the case of 1,200 km Gaussian smoothing, the peak values in Ganges and Zambezi are reduced by as much as 70% as compared to the original signals, owing to the relatively smaller basin sizes.

Annual and semiannual amplitudes and phases are estimated using least-squares fit of GLDAS-estimated terrestrial water storage changes for each of the four river basins when different spatial radii are used in the Gaussian smoothing. The two panels of Fig. 3 show the normalized annual and semiannual amplitudes (normalized by the amplitude when no smoothing is applied) of GLDAS-recovered water storage changes as a function of the spatial radius, while the two panels of Fig. 4 show corresponding phase changes.

The normalized amplitudes or amplitude ratios (as the seasonal amplitudes of smoothed signal divided by the amplitudes of the non-smoothed signal) express the attenuation effect numerically and can be used for the GRACE correction. The annual amplitudes steadily decrease as the spatial radius increases. The Amazon and Mississippi basins show relatively less attenuation compared with the Ganges and Zambezi basins.

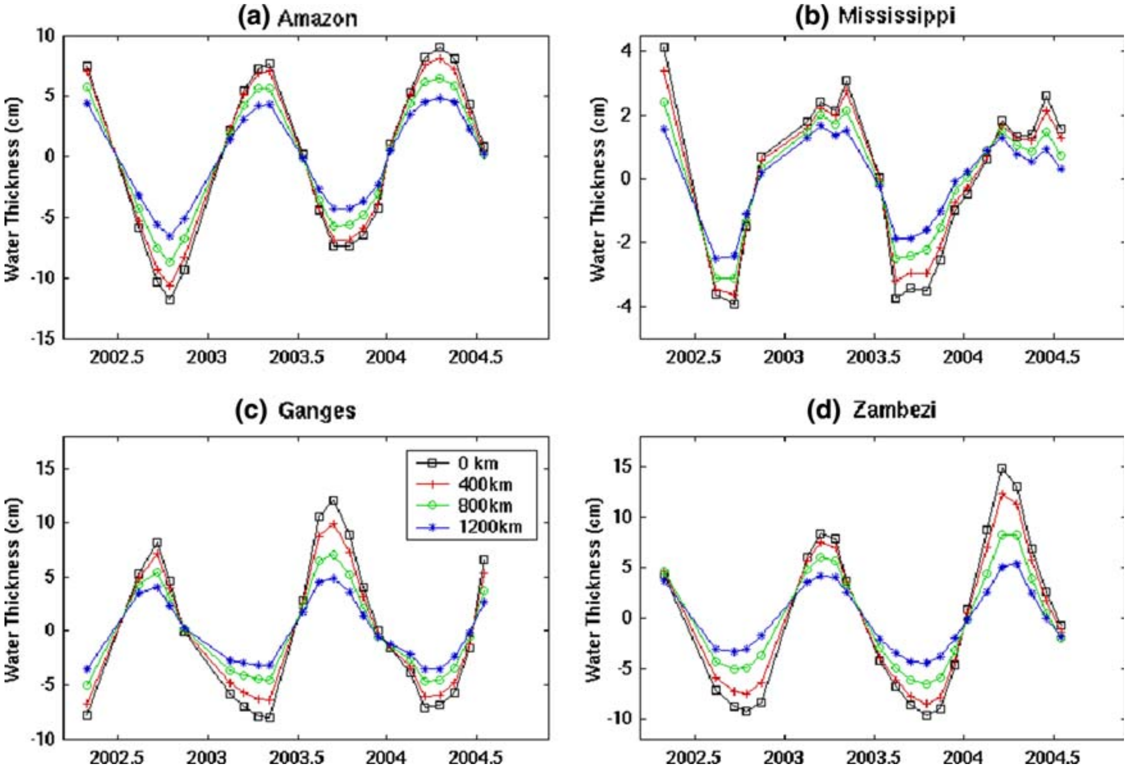

**Fig. 2** Comparisons between GLDAS estimated water storage changes in the **a** Amazon, **b** Mississippi, **c** Ganges and **d** Zambezi basins in four cases: no smoothing (*black*), 400 km Gaussian smoothing (*red*), 800 km Gaussian smoothing (*green*) and 1,200 km Gaussian smoothing (*blue*)

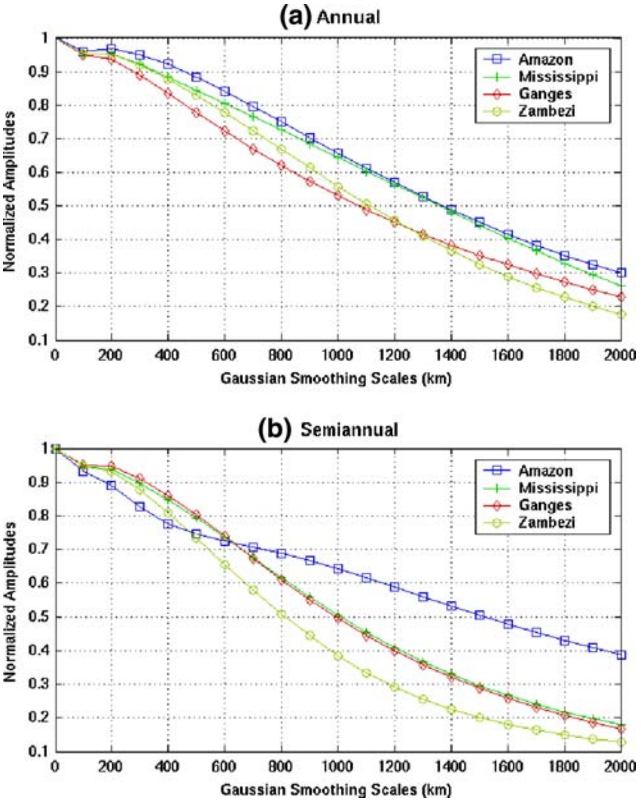

**Fig. 3** Normalized annual (**a**) and semiannual (**b**) amplitudes of GLDAS-estimated seasonal water storage changes in the four selected basins, as a function of the spatial radius used in the Gaussian smoothing; the spatial radius $r = 0$ represents the case when no smoothing is applied

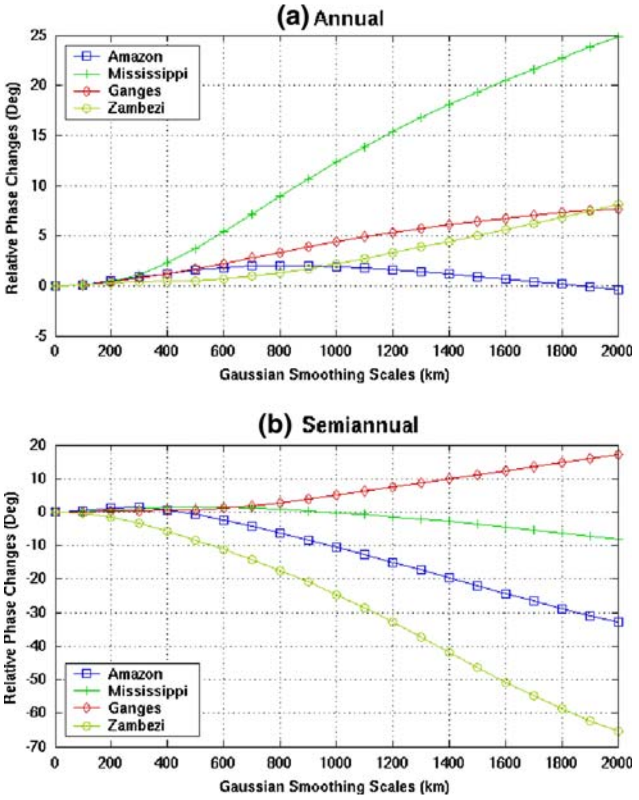

**Fig. 4** Annual (**a**) and semiannual (**b**) phase changes of GLDAS-estimated water storage changes as a function of the spatial radius used in the Gaussian smoothing; the spatial radius $r = 0$ represents the case when no smoothing is applied

The amplitude attenuation effects on semiannual variations appear even more evident than on annual variations (Figs. 3, 4). In addition to the amplitude attenuations, there are also apparent phase changes because of the spatial smoothing. At the annual period, the Mississippi basin shows significantly larger phase changes than the other three basins when the spatial radius becomes larger. The phase changes at the semiannual period appear more evident than at the annual period, which is consistent with amplitude changes.

### 3.2 Sensitivity of attenuation effects to signal amplitudes

Attenuation effects of spatial smoothing on seasonal water storage change may also depend on the true amplitude of the signal. If the GLDAS model has somewhat under- or over-estimated basin-scale water storage changes, will the relative ratios demonstrated in Fig. 3 still be used to evaluate possible attenuation effects on GRACE observations?

Some recent studies (e.g., Tapley et al. 2004b; Chen et al. 2005a,b) suggest that GLDAS-estimated soil and snow water mass changes resemble GRACE estimates remarkably well in main major river basins in the spatial domain. However, in some basins (e.g., the Amazon and Ganges) where GRACE observes very strong and dominant seasonal water storage change, GLDAS appears to have underestimated terrestrial water storage change.

It is easy to prove, mathematically and physically, that if we uniformly scale up (or down) the amplitude of GLDAS-estimated terrestrial water storage change on a global basis, the relative ratios of amplitude change (Fig. 3) and phase change (Fig. 4) from spatial smoothing will be the same. It is also reasonable to assume that if we uniformly scale up (or down) the amplitude of model estimates on large regional basis (e.g., in an area covering the interested river basin and surrounding basins), the amplitude ratios and phase changes will be very much the same. To demonstrate the sensitivity of attenuation effects to signal amplitudes, here we consider a few special or extreme cases when only the amplitude within the interested river basin is increased (or decreased), and anywhere else is kept the same.

We choose the Amazon basin as an example, and carry out three simulations to examine how Gaussian

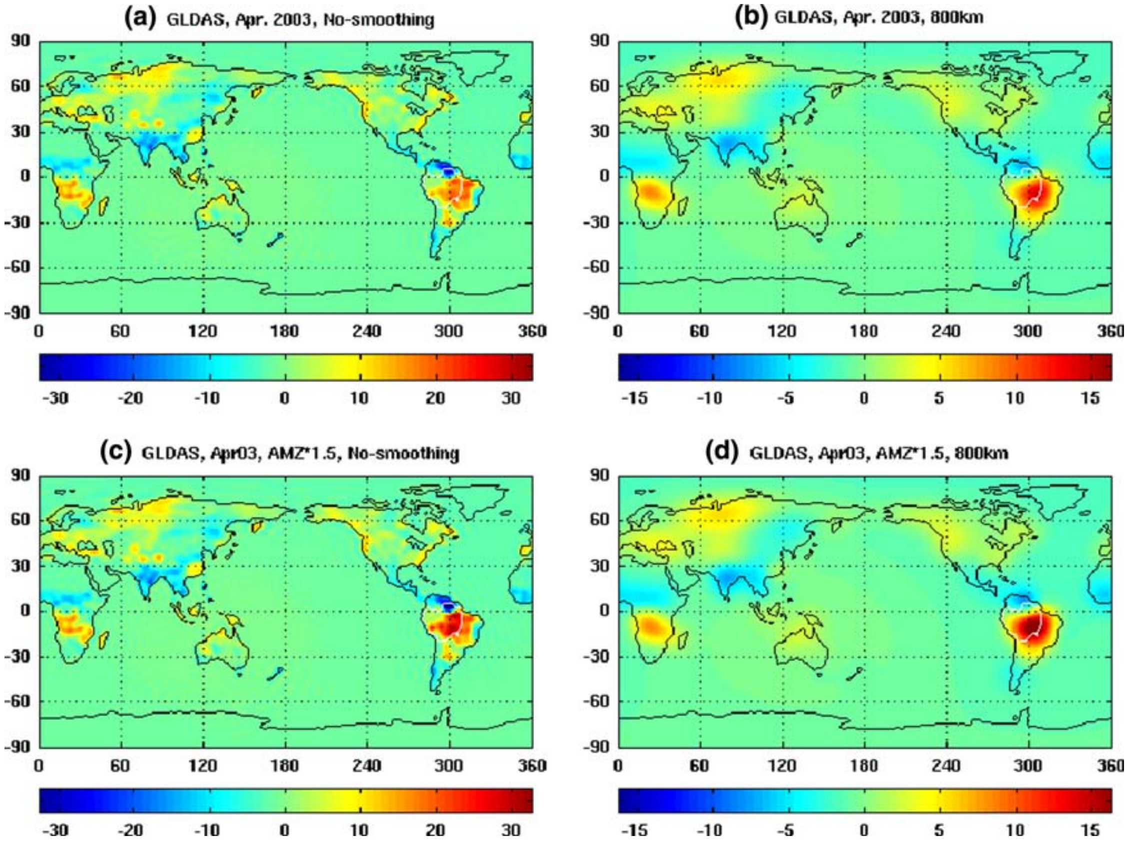

**Fig. 5** GLDAS-estimated global water storage change (in cm of water thickness change) in April 2003 in four cases: **a** GLDAS estimates with no-smoothing, **b** GLDAS estimates with 800 km Gaussian smoothing, **c** GLDAS estimates with Amazon (AMZ) scaled up by 1.5 and no-smoothing, and **d** GLDAS estimates with AMZ scaled up by 1.5 and 800 km Gaussian smoothing

spatial smoothing would affect seasonal amplitude of basin-scale water storage change. The original data are from the same GLDAS model estimates of global terrestrial water storage changes during an entire 3-year period (January 2002 to December 2004). The first simulation is to simply use GLDAS model estimates without any adjustment. This would be basically the same as the results shown in Figs. 3 and 4 for the Amazon basin, except that those results are based on 22 monthly averaged fields during the same period of GRACE solutions and here we use 36 monthly averaged fields.

The second and third simulations use the same GLDAS data, but we artificially multiply the amplitudes of the model estimates within the Amazon basin by 1.25 and 1.50, equivalent to increase the ‘true’ original seasonal signals by 25 and 50%, respectively. At the same time, signals in anywhere outside the Amazon basin remain the same. This adjustment is illustrated in Fig. 5, which show GLDAS-estimated global water storage changes in April 2003 in four cases: (a) original GLDAS estimate with no smoothing, (b) original GLDAS estimate with 800 km Gaussian smoothing, (c) GLDAS estimate with Amazon scaled up by 1.5 and no smoothing and (d) GLDAS estimate with Amazon scaled up by 1.5 and 800 km Gaussian smoothing. We only amplify the magnitudes of signals within the testing basin (the area encircled by white lines in Fig. 5), while keeping signals the same elsewhere.

Figure 6 shows normalized annual amplitudes as a function of spatial radius from the above three simulations. It is evident that at any given spatial radius, the amplitude ratios only decrease slightly when the original signals are scaled up. Even in the case when the original signals are scaled up by 50%, the normalized annual amplitudes only decrease by a few percent, as compared the original simulation.

These simulations demonstrate that relative seasonal amplitude changes (or normalized amplitude ratios), just as for the results of Gaussian spatial smoothing, are quite insensitive to the original signal amplitudes predicted by land surface models (such as GLDAS used in this study). These analyses are equivalent to similar

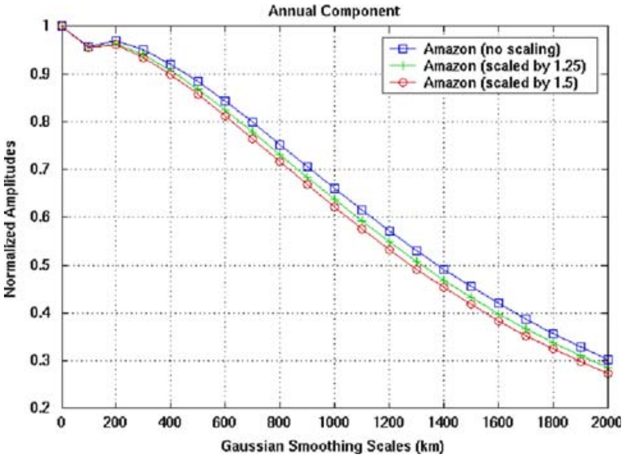

**Fig. 6** Amplitude attenuation effects in the Amazon river basin in three cases: (1) based on original GLDAS model estimates, (2) when water storage change in Amazon basin is scaled up by 25% (multiplied by 1.25), while signals in any other basin remain the same, and (3) when water storage change in Amazon basin is scaled up by 50% (multiplied by 1.5), while signals in any other basin remain the same. These simulations are based on GLDAS monthly water storage change data during a 3-year period from January 2002 through December 2004

cases when the signals within the Amazon basin remain the same, but we uniformly scale down the signals outside the Amazon basin by the same percentage(s).

### 3.3 Restoring seasonal signals in GRACE

Even though GLDAS may have under-estimated the true terrestrial water storage changes in these four selected basins, the above simulations suggest that we can still assume that the statistical relationships shown in Figs. 3 and 4 approximately represent the relative attenuation effects on GRACE-derived basin-scale water storage changes. Therefore, we could apply the amplitude ratios (or normalized amplitudes) or phase changes derived from the GLDAS model to GRACE data to approximately restore the attenuated annual and semiannual basin-scale water storage changes from GRACE.

The four panels in Fig. 7 show comparisons of seasonal (i.e., annual plus semiannual) water storage changes in the four basins from (1) GLDAS with no smoothing applied (blue curves with square markers), (2) GRACE recovered with 800 km Gaussian smoothing (red curves with cross markers), and (3) restored GRACE estimates based on the amplitude and phase changes (when radius $r = 800$ km) shown in Figs. 3 and 4.

After the correction for attenuation effects, GRACE observations are consistently larger than GLDAS model estimates. This further confirms that GLDAS appears to have under-estimated terrestrial water storage changes in these four major river basins (and probably in most other major river basins). These discrepancies could come from a number of sources. GLDAS only estimates soil moisture in the top 2 m of soil, and water storage change in soil below 2 m depth is simply neglected.

How to appropriately determine soil types or yields is a challenging issue in land surface modeling. Uncertainties in the forcing fields (e.g., precipitation data) used in modeling will also greatly affect the estimate of soil and snow water change. Another likely contribution to these discrepancies is that ground-water variations, which are neglected in this and previous studies (e.g., Chen et al. 2005a,b), are also significant and play an important role in driving GRACE-observed time-variable gravity changes.

Preliminary analysis of well measurements of ground-water changes in the Mississippi basin (Rodell et al. 2005) indicates that ground-water in the Mississippi basin shows significant seasonal variability with a slight phase lag to soil water change (as predicted by GLDAS). When considering both GLDAS-estimated soil and snow water with observed ground-water change, the total terrestrial water storage change in the Mississippi basin would agree significantly better with GRACE observations.

## 4 Conclusion

On the basis of the GLDAS-model-estimated water storage changes, we investigate possible amplitude attenuations and phase changes in GRACE data as a result of Gaussian spatial smoothing. Our analysis indicates that Gaussian smoothing significantly affects seasonal amplitudes of basin-scale water storage changes, and also introduces non-negligible phase changes possibly because of asymmetric spectral leakage errors from surrounding basins. For example, in the case when 800-km Gaussian smoothing is applied, the annual amplitudes are reduced by about 25% in the Amazon and Mississippi basins, and 35% in the Ganges and Zambezi basins. The GLDAS-model based analysis can be used as a proxy estimate of possible attenuation effects on seasonal basin-scale water storage changes from GRACE time-variable gravity when the same Gaussian smoothing is applied.

This analysis provides quantitative assessments of attenuation effects on GRACE-observed seasonal water storage changes in selected basins when different Gaussian smoothing (i.e., with different spatial radii) are applied. These quantitative assessments will be helpful to people (e.g., hydrologists) who use the general

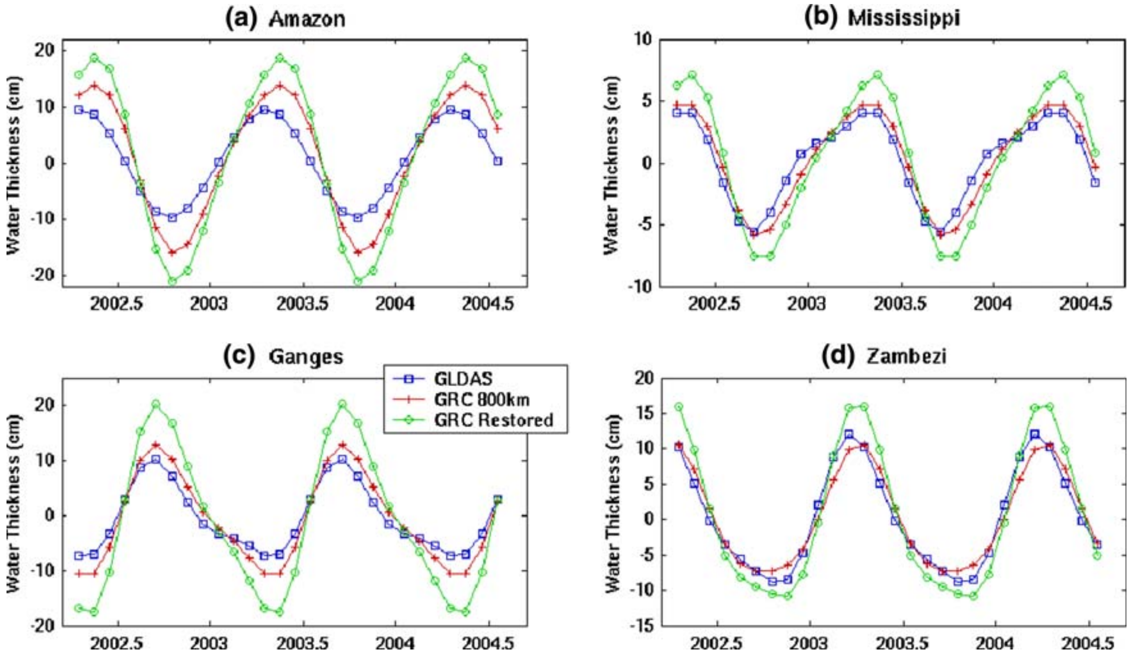

**Fig. 7 a–d** Comparisons between non-smoothed GLDAS-estimated and GRACE-derived seasonal (annual and semiannual) water storage changes in the four selected basins. Two GRACE-based estimates are provided, one with 800 km Gaussian smoothing (GRC 800 km), and the other with 800 km Gaussian smoothing and restoration of the attenuation effects from the Gaussian smoothing (GRC rRestored)

GRACE products, which are derived based on Gaussian smoothing, to correctly interpret and apply GRACE-observed basin-scale terrestrial water storage changes.

The methodology used in this study can also be applied to other types of spatial smoothing schemes, under the same assumption that model-estimated basin-scale water storage changes approximately resemble the real signals (with similar magnitude and spatial patterns). As long as people are not able to fully separate noise from signals in GRACE measurements, any spatial smoothing techniques will more or less attenuate the true signal while also suppressing the noise. Therefore, this type of numerical simulation, based on advanced land surface models, would provide a proxy quantitative assessment of potential attenuation effects on 'true' signals from a given spatial smoothing technique. The contribution of the spectral leakage error into the discrepancies in phases needs more investigation in the future.

**Acknowledgments** The authors are very grateful to an anonymous reviewer (Reviewer 1) for the comprehensive, in-depth and thoughtful review, which led to improved presentation of the results. This research was supported by NASA's Solid Earth and Natural Hazards and GRACE Science Programs (NNG04GF10G, NNG04GF22G, NNG04GE99G, JPL-1259524).

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