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

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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

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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 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.

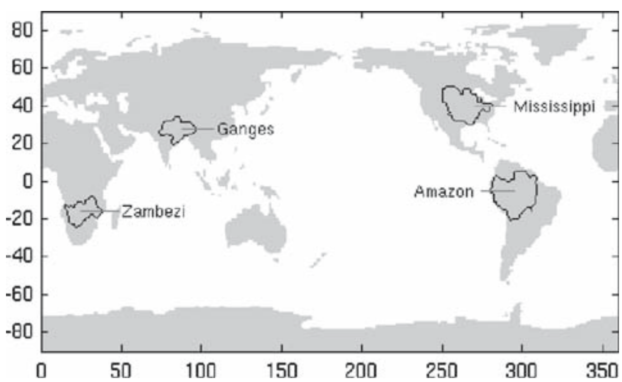

Fig. 1 Geographical locations of four major river basins examined in this study: Mississippi, Amazon, Ganges and Zambezi

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).

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 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.