TERRESTRIAL WATER STORAGE VARIATION INFERRED FROM GRACE SATELLITE AND WATER BALANCE

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ABSTRACT: The GRACE satellite mission of gravity measurement launched in 2002 has been providing new information on terrestrial water storage (TWS) changes across the continents. Recent research has demonstrated that GRACE can be used to estimate TWS changes and other hydrologic quantities in large river basins. However, validation of GRACE water storage data remains difficult owing to the lack of data on TWS and its components, particularly over large areas. In this study, GRACE TWS will be compared with independent TWS estimates from other methods for selected regions and large river basins. Available in situ observations of soil moisture and groundwater depth are used to validate GRACE TWS data in Illinois. Seasonal and inter-annual TWS variations are explored by comparing GRACE TWS estimated from the combined (land-atmosphere) water balance (CWB) analysis for the selected large river basins. The primary goals of this study are to explore the potential for GRACE to observe TWS variations and to develop a framework for its validation.

1. INTRODUCTION

Global water cycle directly affects the global circulation of both atmosphere and ocean and hence is instrumental in shaping weather and climate of the Earth. However, our quantitative knowledge of the global water cycle is quite poor, large-scale measurements of the hydrologic states and fluxes on time scales appropriate to their dynamics are deficient. Terrestrial water storage (TWS), as a fundamental component of the global water cycle, is of great importance for water resources, climate, agriculture and ecosystem. TWS controls the partitioning of precipitation into evaporation and runoff, and the partitioning of net radiation into the sensible and latent heat fluxes. Particularly, TWS change is a basic quantity in closing terrestrial water budgets (Yeh et al., 1998; Yeh and Famiglietti 2008).

Among various components of the global water cycle, TWS is one of the most difficult to estimate. Despite its importance, no extensive networks currently exist for monitoring large-scale TWS variations and its constitutive components. Reliable data sets of large-scale TWS are extremely scarce. Satellite observations of the Earth's time-variable gravity field from the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004), launched in March 2002, have provided another unique opportunity of monitoring TWS variations from space. Monthly, seasonal, and inter-annual variations in gravity on land are largely due to corresponding changes in vertically integrated TWS (Tapley et al., 2004) and atmospheric pressure change. The later has been removed from GRACE time-variable gravity solutions during the de-aliasing process of GRACE data processing. By exploiting the unique relationship between changes in gravity field and changes in mass at the Earth's surface, the month-to-month gravity variations obtained from GRACE can be inverted into global estimates of vertically integrated TWS with a spatial resolution of a few hundred kilometer and larger, with higher accuracy at larger spatial scales.

The objective of this study is to explore the potential for GRACE to observe TWS variations and to develop a framework for its validation. The validation is based on the comparisons between GRACE TWS and other independent estimates, including in situ observations and combined land-atmosphere water balance analysis. The first focus of the present study is on the comparison of GRACE TWS with the corresponding in-situ measurements in Illinois (i.e, soil moisture, groundwater depth and snow water equivalent). It is followed by the evaluation of GRACE TWS estimates over some selected large river basins (with the drainage areas larger than 10^6 sq. km) against the estimates derived from the land-atmosphere water balance analysis based on monthly atmospheric reanalysis data and observational streamflow data.

2. BACKGROUND

2. 1 Combined Land-Atmosphere Water Balance (CWB) Analysis

The terrestrial water balance can be written as follows:

$$\frac{dS}{dt} = nD\frac{ds}{dt} + S_y\frac{dH}{dt} + \frac{dW_S}{dt} = P - E - R \qquad (1)$$

where S [mm] is the total terrestrial water storage (TWS); nD [mm] is the available storage depth of the soil: the product of soil porosity and root zone depth; s [%] is the soil relative saturation (i.e. soil moisture content divided by soil porosity); S_y [%] is the specific yield (i.e., the fraction of water volume that can be drained by gravity in an unconfined aquifer); H [mm] is the groundwater depth; W_S [mm] is the total surface water storage including (accumulated) depth of snowpack (liquid equivalent), water in the lakes, reservoirs; P [mm/mo.] is the precipitation; E [mm/mo.] is the evaporation; and R [mm/mo.] is the total runoff (i.e. measured streamflow). The hydrologic storage terms in Eq. (1) correspond to water storages in soil moisture, groundwater aquifer, and surface water.

On the other hand, the atmospheric water balance equation can be written as:

$$\frac{dW_a}{dt} = E - P + C \qquad (2)$$

where W_a [mm] is the mean precipitable water, $C(= -\nabla \cdot Q)$ [mm/mo.] is the mean convergence of lateral atmospheric vapor flux, and Q [sq. mm/mo.] is the vertically integrated mean total moisture flux. C can be calculated by taking the line integral of the moisture flux around the area under study. W_a and Q can be calculated by integrating the profiles of specific humidity, zonal and meridional wind components from the pressure at the ground surface to that above which moisture content becomes negligible (i.e., 300mb in this study). The approach used here is essentially identical to that used by Yeh et al., (1998) and Yeh and Famiglietti (2008) where more details about the analysis of C can be found. The change of TWS can be derived by combining Eqs. (1) and (2):

$$\frac{dS}{dt} = C - R - \frac{dW_a}{dt} \qquad (3)$$

which provides an independent estimate of total terrestrial water storage change (TWSC). Averaging Eqs. (1) and (2) over long time series, all the derivative terms can be assumed negligible. Thus, $R = C = -\nabla \cdot Q$, which is an expression of that, for any climate equilibrium, the long term convergence of atmospheric moisture towards any hydrologic unit has to be balanced by the long term net discharge of runoff out of the same hydrologic unit. Thus, $\overline{R} = \overline{C}$ (the overbars denote long-term averages) can be conceived as a criterion for evaluating long-term water balance closure. The accuracy of the CWB analysis is highly dependent on the size of the area investigated (>10^6 sq. km; see the discussion of Yeh et al., 1998).

2. 2 GRACE Data

GRACE level-2 gravity fields (monthly Stokes coefficients) are officially released by three data processing centers: CSR (Center for Space Research, USA), GFZ (GeoForschungsZentrum Potsdam, Germany), and JPL (Jet Propulsion Laboratory, USA). Gravity changes observed by GRACE include all mass redistribution processes such as hydrologic redistribution in surface and subsurface, ocean water movements and tides, variations of atmospheric masses, and cryospheric changes. Appropriate corrections are required to separate hydrological signals, and background models are often used to remove other non-hydrological components. The version of "dpc200711" dataset that will be used in this study was de-striped by using a modified algorithm proposed by Chambers (2006). In this study, de-striping and 0-, 300-, 500km-smoothing applied monthly gravity fields from three major data centers are used to compare with other independent TWS estimates.

Previous studies on the evaluation of GRACE accuracy (Swenson et al., 2006; Yeh et al., 2006) have indicated that TWS variations are likely detectable depending on the size of the region and the magnitude of the variations themselves. The accuracy of GRACE estimates of water storage variability depends on the GRACE measurement errors, and the degree to which the gravity signal from the water storage can be separated from other time-variable gravity signals (e.g. atmospheric mass redistribution). In general, uncertainties in the GRACE-derived water storage variations decrease with increasing spatial and temporal scales. GRACE is capable of estimating monthly changes in TWS to accuracies of better than 1 cm of water depth for areas >200,000 sq. km.

3. RESULTS

3. 1 GRACE TWSA vs. in situ Measurements in Illinois

Figure 1 plots 7-year (2003-09) monthly TWSA comparison between GRACE and observations in Illinois. GRACE data taken from CSR, GFZ and JPL, each with three different smoothing radius, 500km, 300km, and non-smoothed, are plotted together in order to quantify the range of uncertainty involved in GRACE data processing by different institutes and methods. Since GRACE data in June 2003 and January 2004 were missing, they were replaced by the linear interpolation from the data of adjacent two months. Also notice that GRACE data from July-October of 2004 provided by GFZ seem to be problematic.

The seasonal amplitude and variation of GRACE TWSA track those of in situ measurements reasonably well, although certain substantial differences exist in month-to-month variations (Figure 1). The correlation coefficients between observed TWSA and CSR/GFZ/JPL GRACE TWSA are 0.67/0.65/0.50 for 500km smoothed data, 0.71/0.62/0.59 for 300km smoothed data, and 0.73/0.52/0.59 for non-smooth data, respectively. The GRACE TWS satisfactorily captures the upward trend of storages during the period from the mid-2007 until 2009 for both positive and negative annual peaks, as well as the magnitude of the trough occurred in the mid-2005 droughts in Illinois. However, although the non-smoothed GRACE data match well with observed timing of negative TWSA peak in 2005, all the smoothed data exhibited a consistent two-month shift from July to September, reflecting the sensitivity of the adopted smoothing filters to estimated GRACE TWS signals. Smoothing (spatial averaging) of GRACE data is necessary to reduce the contribution of noisy short wavelength components of the gravity field solutions. The estimated monthly sets of the spherical harmonic coefficients representing monthly mean global gravity fields is known to contain temporal aliasing errors, which are related to sub-monthly mass variations of atmospheric and oceanic circulations.

Previous analyses of GRACE TWS have focused on the monthly TWS anomalies (TWSA) rather than the monthly TWS change (TWSC), which is a basic term in the water balance equation (i.e. dS/dT in Eq. 1). In most studies of the GRACE hydrologic applications (e.g. Yeh et al., 2006), the interest has been in the total TWSC rather than TWS because of its importance for water balance closure. In the following, the TWSC estimated from the CWB analysis in Eq. (3) will be compared with GRACE TWSC estimates over the selected large river basins.

3. 2 GRACE TWSC vs. CWB Estimates

The application of CWB analysis in deriving the estimate of TWSC (i.e., dS/dT) is largely limited by the availability of observed stream flow data within the GRACE period. Most of river discharge data provided by the Global Runoff Data Center (GRDC) are for the 20th century with only very little available for the 21st century. Therefore, only seven large river basins (Mississippi, Columbia, Colorado, Mackenzie, Zambezi, St Lawrence, and Yukon) are selected for monthly TWSC comparison. The results are presented in Figures 2 and 3. Figure 2 plots the comparison of two TWSC estimates in the Mississippi River basin, where daily discharge data from 2004 to the end of 2009 (with one year missing data around 2005- 2006) were provided by USGS. All the nine GRACE data sets (including respectively three data processing centers and three smoothed radius) are plotted together with their average denoted by black circles. As seen, two independent estimates of monthly TWSC in the Mississippi basin show remarkable agreement in the timing of seasonal march, also both of them have similar amplitude of about 50 mm/month.

Figure 3 presents similar comparisons of two TWSC estimates over the six selected global large river basins: Columbia, Colorado, Mackenzie, Yukon, St Lawrence and Zambezi. The GRACE TWSC data, averaged from the nine data sets (three data centers and three smoothing radius), are plotted in Figure 3, where it clearly shows contrasting magnitudes of TWSC among six selected basins. From this plot, a reasonable match in the seasonal variations between two TWSC estimates can be observed for all the basins examined, but the quality of comparison in terms of both the timing and amplitude vary considerably among basins. The comparisons are relatively good for the Columbia and Yukon basins, while less satisfactorily in the Colorado, St. Lawrence, and Zambezi basins.

Since monthly TWSC is estimated from TWSA by taking the difference between monthly water storage anomalies, small errors in TWSA will be amplified into larger discrepancies in the derived TWSC. Thus the overall agreement in the seasonal cycle as shown in Figs 2 and 3 is encouraging, and indicates that in addition to providing sound estimates of monthly TWSA as shown in Figure 1, GRACE data also have the potential to provide reasonable estimates for monthly total water storage change for the large-scale river basins.

4. CONCLUSIONS

In this study, GRACE terrestrial water storage (TWS) data are compared with other independent estimates of TWS. Long-term in situ measurements of soil moisture and groundwater depth in Illinois are used to validate GRACE TWS estimates. Seasonal and interannual TWS variations at the continental scale are explored by comparing GRACE TWS with estimates inferred from the combined (land-atmosphere) water balance (CWB) method in seven selected large river basins. In general, the comparisons (Figures 1-3) yield overall close agreement on the seasonal pattern of TWS variations between GRACE TWS and other independent estimates. The results obtained here can be expected to provide diagnostic information useful for the GRACE validation over major river basins or large continental regions, as well as to provide a benchmark for the land surface model development and validation. The findings can also be used to support the development of the representation of related TWS processes in land surface hydrological models (e.g. Yeh and Eltahir, 2005).

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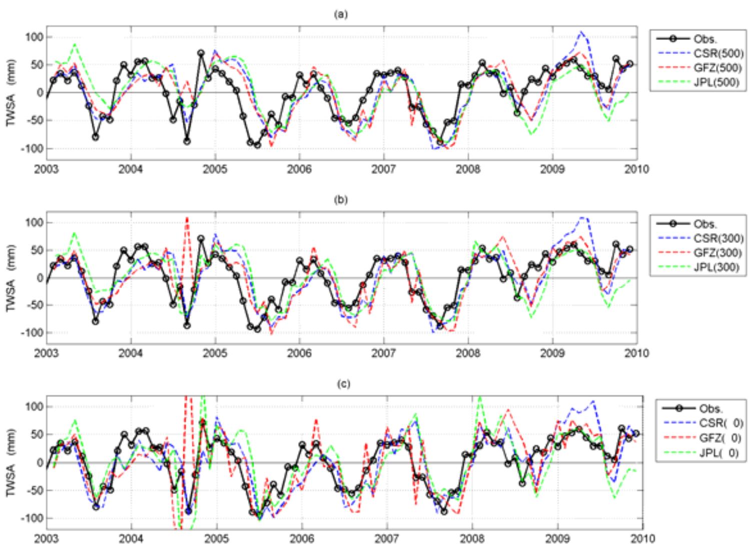

Figure 1 Comparison between observed 7-year (2003-09) TWSA and the GRACE data in Illinois. GRACE data are provided by CSR, GFZ, and JPL, each with different smoothing radius.

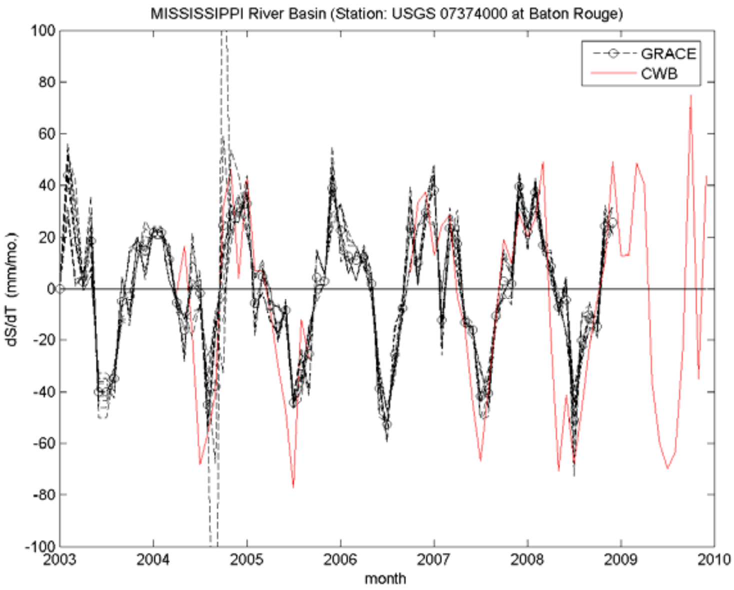

Figure 2 Comparison of monthly TWS change (TWSC) derived from GRACE and from the CWB in the Mississippi River basins (Gauging station USGS 07374000).

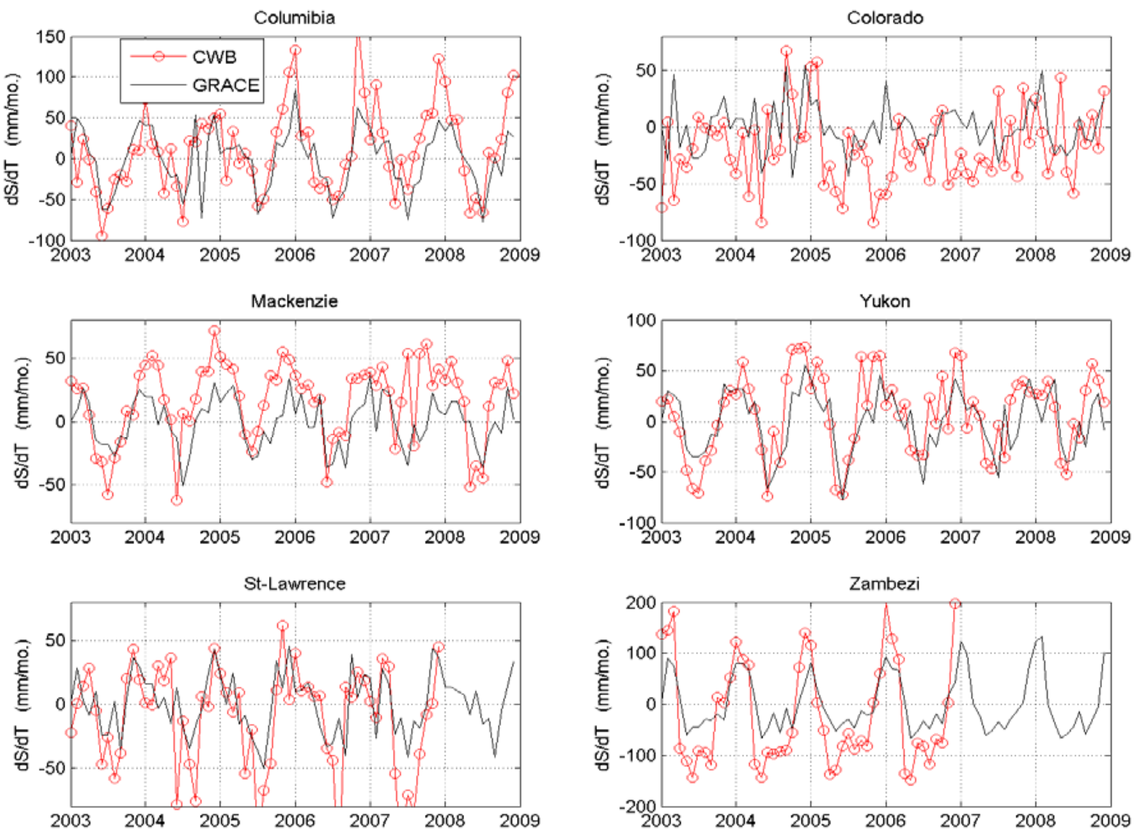

Figure 3 Comparison of monthly TWS change (TWSC) estimates derived from GRACE and from the CWB analysis in six global large river basins.