Seasonal Variations of Total Terrestrial Water Storages in Major River Basins

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ABSTRACT

The total terrestrial water storage (TWS) in six major river basins of the world for the period 1986-1995 were estimated from (1) the Phase-2 of the Global Soil Wetness Project (GSWP2) Multi-Model Analysis (MMA), (2) the combined land-atmospheric water balance method using the ERA-40 and JRA-25 global reanalysis data, and (3) the satellite observation by the Gravity Recovery And Climate Experiment (GRACE). The seasonal variations of the TWS estimated from these three methods were compared, and the results indicate remarkable agreement among each other. It was found that in Amazon River basin, the river channel storage plays a more significant role than soil moisture in the seasonal variations of TWS. This result suggests that it is important to include the contribution from the river channel water in the estimation of global TWS distribution and global water budgets.

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 states and fluxes for various global reservoirs on time scales appropriate to their dynamics are deficient. Terrestrial water storage (TWS), as a fundamental component of global water cycle that include groundwater, soil moisture, snow water equivalent, and water in river, lakes, ponds, reservoirs and wetlands, 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. On the other hand, terrestrial water storage change is a basic quantity in closing the terrestrial water balance [*Ngo-Duc et al.*, 2005*; Hirabayashi et al.* 2005; *Güntner et al.*, 2007; *Yeh and Famiglietti*, 2008]

Despite its importance, there are no extensive networks currently existent for monitoring large-scale variations of TWS and its individual components. Reliable datasets of large-scale TWS are extremely scarce. Historically, global hydrological cycles have been assessed by a synthesis of in-situ observational data, such as precipitation measured by rain gauges and streamflow at gauging stations. On the other hand, global dataset of atmospheric conditions estimated by the four-dimensional data assimilation (4DDA) technique has enabled global water balance estimation by the atmospheric or combined land-atmosphere water balance computations [*Rasmusson*, 1968; *Yeh et al.*, 1998; *Seneviratne et al.*, 2004; *Hirsch et al.*, 2006, 2007; *Yeh and Famiglietti*, 2008]. The column integrated water vapor convergence provides a global distribution of precipitation minus evapotranspiration, if the temporal variation of precipitable water is considered to be zero. Among various components of global water cycle, the TWS is one of the most difficult to estimate. The combined land-atmosphere water balance computation utilizing the atmospheric reanalysis data and river discharge can be used to estimate the temporal change of area-averaged TWS over river basins.

In this study, the seasonal variations of TWS in the six selected major river basins (Table 1) from 1986 to 1995 were estimated by using reanalysis data of ERA-40 and JRA-25, and they were compared with the estimates from both the GRACE (Gravity Recovery And Climate Experiment, see *Tapley et al.* 2004) satellite observation and the Phase-2 of the Global Soil Wetness Project (GSWP2) [*Dirmeyer et al.* 2006]. Under the Global Land Atmosphere Study (GLASS), the GSWP2 produced the first global 1x1 degree Multi-Model Analysis (MMA) of land surface hydrological variables and fluxes for the 10-year period of 1986-1995 at the daily time scale [*Gao and Dirmeyer*, 2006, *Guo and Dirmeyer*, 2006a, b]. Thirteen land surface models were driven by the best available forcing data of the atmospheric conditions (precipitation, downward radiation, air humidity, air temperature, wind speed, and air pressure) with temporal resolution of 3-hourly or higher. In this study, water balance components in major continental river basins were post-processed and the seasonal changes in soil moisture, snow water equivalent, and the water in river channel from the global runoff routing model Total Runoff Integrating Pathways (TRIP) [*Oki et al.*, 1999] were analyzed.

METHODS

The seasonal variations of the TWS in six selected major river basins were estimated by the land-atmospheric water balance method. The water vapor flux convergence was estimated using the ECMWF ERA-40 and JMA JRA-25 global reanalysis data for the period 1986-1995. The 10-year mean value of the atmospheric water vapor convergence was adjusted to match with the climatological mean of the corresponding river discharge from GRDC (Global Runoff Data Center). The seasonal variation of TWS was estimated from the combined land-atmosphere water balance method. The components in the TWS change were investigated using the multi-model products from the GSWP2-MMA. The seasonal changes of the TWS in six selected river basins estimated by both methods were compared to the estimate from the GRACE satellite observation, and basically these three estimates correspond fairly well among each other as shown in the next section.

No.	River	Station	GRDC-ID	Lon (°N)	Lat (°E)	Drainage area- (km^2)	Period
1	Amazon	Obidos	3629000	-55.5	-2.5	4,640,300	1968-1996
2	Mississippi	Vicksburg	4127800	-91.5	32.5	2,964,255	1931-1998
3	Ob	Salekhard	2912600	66.5	66.5	2,949,998	1954-1999
4	Yenisei	Igarka	2909150	86.5	67.5	2,440,000	1955-1999
5	Mackenzie	Arctic red river	4208025	-133.5	67.5	1,660,000	1972-1996
6	Missouri	Hermann	4122900	-91.4	38.7	1,357,678	1927-2000

Table 1. Six world major river basins selected for analysis in this study. The locations of the most downstream streamflow measurement station, their station ID defined by GRDC, the drainage area (given by GRDC and by the TRIP river network), and the localizations (longitude, Lon, and latitude, Lat) and the discharge observation period are shown in this table. All 6 stations have GRDC daily discharge observations during the GSWP2-period (1986-1995).

RESULTS

Figure 1 compares the 10-year (1986-95) monthly streamflow for 6 major basins from two cases of GSWP2-MMA simulations, one with and another without TRIP routing, with the observed GRDC data. For Amazon, Mackenzie, Mississippi and Missouri basins, the simulated TRIP-routed runoff generally agrees well with the GRDC data in terms of the seasonal and interannual variability, whereas for the Yenesei and Ob basins the GWSWP-2 was failed to capture the magnitudes of observed streamflow peaks. On the other hand, the GSWP2 runoff without routing by TRIP exhibits an approximately 2-month earlier arrival of peaks than observations, indicating the significance of global runoff routing scheme for continental river basin streamflow simulations.

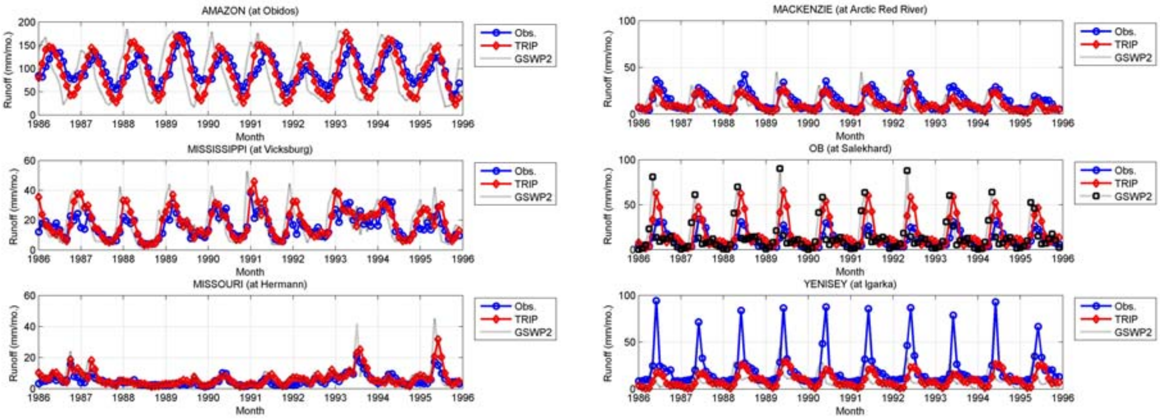

Figure 1 Comparson of 10-year (1986-95) monthly streamflow from the GSWP2-MMA simulations (with and without TRIP routing) with the observations from GRDC.

Figure 2 presents the comparison of TWS estimates from three independent methods: GRACE, Land-atmosphere water balance method using ERA-40 and JRA-25 respectively, and GSWP2-MMA. The relative storages plotted in this figure are the TWS estimate subtracting its minimum storage of a year. The lower panel of the figure shows the components of TWS: soil moisture, snow water equivalent, and river channel storage for each basin. The river storage is the channel water storage term output from TRIP. As shown, for most of the six basins the relative storage estimate from land surface models (GWSP2-MMA) agrees reasonably well with GRACE estimates. This agreement is rather surprising for the Amazon and Mississippi basins. Moreover, the relative storages estimate from the combined land-atmosphere water balance using reanalysis data and streamflow observations also correspond fairly well with GRACE and GSWP2-MMA (except for the Amazon basin where the estimates by reanalysis data provide smaller seasonal amplitude). With regard to the storage components, the river storage plays a more significant role in the seasonal variations of TWS than soil moisture for the Amazon basin. For Mississippi basin, however, the river storage is equally important to soil moisture storage, but this importance decreases for the sub-basin Missouri River where soil moisture dominates the TWS. For three northern basins (Ob, Yenesei, and Mackenzie), as expected snow water equivalent dominates seasonal water storage variations from winter to the end of spring, while river storage is the only active storage component in summer months following snow melting.

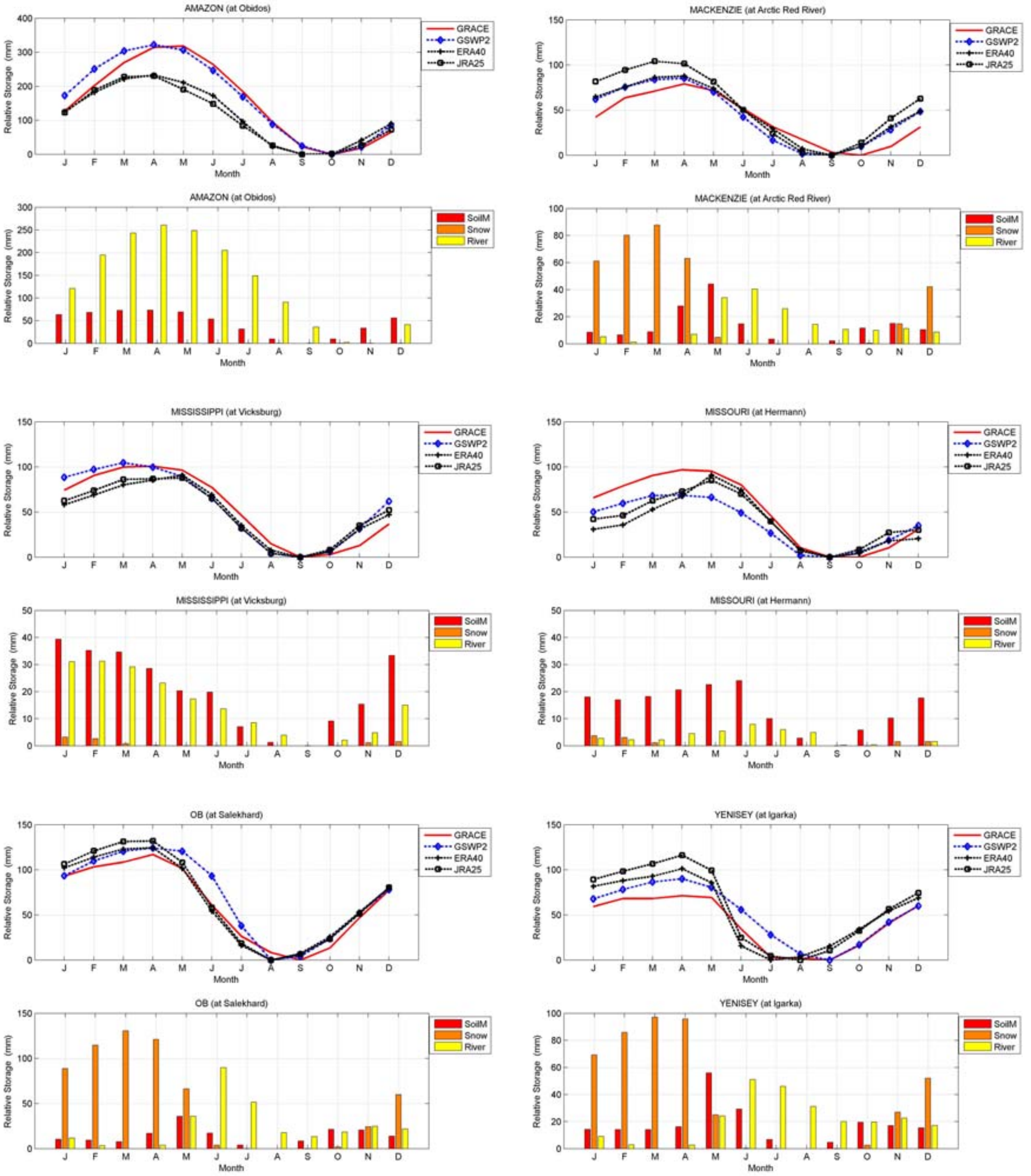

Figure 2 Seasonal change of total water storage estimated by satellite data (GRACE), land surface models (GSWP2), and the land-atmosphere combined water balance method (ERA40 and JRA25).

SUMMARY

In this study, the combined land-atmosphere water balance method, the output from the GSWP2 Multi-Model Analysis, and the remote sensing data by GRACE satellite were used to estimate the seasonal terrestrial water storage (TWS) variations over selected six major river basins of the world. The main objectives of this study are to inter-compare these approaches and to explore what are the dominant components of TWS variation over these river basins.

First the atmospheric water vapor convergence was estimated using the ECMWF ERA-40 and JMA JRA-25 reanalysis data for the period from 1986 to 1995. The seasonal change of TWS was then estimated from the combined land-atmosphere water balance method, and compared with the land surface model-simulated TWS from the multi-model product from the GSWP2. Both estimated were also compared with the TWS estimates from the GRACE satellite. Even through the bias correction of atmospheric vapor convergence was required to meet the water balance with the observed discharges, the estimates by the combined land-atmosphere water balance correspond fairly well with that by the GSWP2-MMA. Moreover, both of them in general agree well with the GRACE estimates. For the Amazon basin, the river channel storage plays the most significant role in the seasonal variations of TWS. For Mississippi basin, the significance of river channel storage is equivalent to soil moisture storage, while this significance decreases for the Missouri sub-basin where the soil moisture storage dominates TWS. In northern basins (Mackenzie, Ob, and Yenesei), the contribution of snow water equivalent is large in winter, whereas water stored in river channel contributes significantly to the seasonal change of TWS during summer. From these results, it can be concluded that the reanalysis data can provide useful information to validate continental hydrological model simulations for global hydrological cycle studies.

The advantage of using the combined water balance computation is that it is based on the relatively abundant atmospheric data that have been routinely measured for decades. The accuracy of this estimates lie to a large extent on the accuracy of computed convergence. Most large-scale studies of atmospheric water cycle rely on the reanalysis data from 4DDA (four-dimensional data assimilation) system. However, these data contain systematic errors and need corrections, but currently there is no any convincing way for this purpose [*Yeh and Famiglietti*, 2008].

Given the constraints of the sptio-temporal resolution of the GRACE and the reanalysis data, and the lack of global availability of the long-term river discharge data, continental hydrological models remain the only suitable tool to estimate TWS variability before extensive network (either from ground or from space) of monitoring terrestrial water storage is established. However, most continental hydrological models do not account for all water storage components. Therefore, research effort should be directed towards the enhancement of parameterizations in global hydrological model [e.g. *Oki et al.* 1999; *Yeh and Eltahir*, 2005] such that the importances of river channel storage, as shown for major river basins in this study, as well as of groundwater storage can be faithfully represented in global simulations. Finally, since GRACE data can be an important additional constraint on the output of hydrological models as they represent the total vertically integrated effect of water mass changes, the assimilation of GRACE data into land surface model simulation is essential.

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