GRACE, GLDAS and measured groundwater data products show water storage loss in Western Jilin, China

Juana Paul Moiwo, Wenxi Lu and Fulu Tao

ABSTRACT

Water storage depletion is a worsening hydrological problem that limits agricultural production in especially arid/semi-arid regions across the globe. Quantifying water storage dynamics is critical for developing water resources management strategies that are sustainable and protective of the environment. This study uses GRACE (Gravity Recovery and Climate Experiment), GLDAS (Global Land Data Assimilation System) and measured groundwater data products to quantify water storage in Western Jilin (a proxy for semi-arid wetland ecosystems) for the period from January 2002 to December 2009. Uncertainty/bias analysis shows that the data products have an average error <10% ($p < 0.05$). Comparisons of the storage variables show favorable agreements at various temporal cycles, with $R^2 = 0.92$ and RMSE = 7.43 mm at the average seasonal cycle. There is a narrowing soil moisture storage change, a widening groundwater storage loss, and an overall storage depletion of 0.85 mm/month in the region. There is possible soil-pore collapse, and land subsidence due to storage depletion in the study area. Invariably, storage depletion in this semi-arid region could have negative implications for agriculture, valuable/fragile wetland ecosystems and people's livelihoods. For sustainable restoration and preservation of wetland ecosystems in the region, it is critical to develop water resources management strategies that limit groundwater extraction rate to that of recharge rate.

Key words | GLDAS, GRACE, groundwater, soil moisture, storage depletion, Western Jilin

Juana Paul Moiwo
Fulu Tao (corresponding author)
Chinese Academy of Sciences,
Institute of Geographical Sciences and Natural Resources Research,
11 Datun Road, Beijing 100101,
China
E-mail: *taofl@igsnrr.ac.cn*

Wenxi Lu
Key Laboratory of Groundwater Resources and Environment,
Ministry of Education & Jilin University,
Changchun 130021,
China

INTRODUCTION

Water storage depletion is a worsening hydrological phenomenon in especially arid/semi-arid regions across the globe (Scanlon *et al.* 2006; Moiwo *et al.* 2009, 2011a; Strassberg *et al.* 2009). Storage depletion threatens fragile/valuable ecosystems that provide the necessary conditions for biodiversity, global carbon/weather regulation and groundwater recharge/discharge (Pan *et al.* 2006; Ming *et al.* 2007; Dams *et al.* 2008; Moiwo *et al.* 2010). Accurate water resources studies are therefore critical for the development of sustainable wetland management and preservation strategies (Asefa *et al.* 2000; Scanlon *et al.* 2006; Batelaan & De Smedt 2007; Hu *et al.* 2010).

There are various methods for estimating water storage at basin, regional and global scales (Harbaugh *et al.* 2000; Jones *et al.* 2003; Rodell *et al.* 2004; Tapley *et al.* 2005; Batelaan & De Smedt 2007; Gowda *et al.* 2007). With advances in satellite technology, spatially-distributed data are increasingly used in hydrological studies (Batelaan & De Smedt 2007; Rodell *et al.* 2009; Moiwo *et al.* 2011b). The distribution of such data products is further enhanced by the advent of internet technology (Rodell *et al.* 2004; Moiwo *et al.* 2011a).

The Gravity Recovery and Climate Experiment (GRACE) is a gravity satellite mission jointly launched by NASA (National Aeronautics and Space Administration) and DLR (German Aerospace Center) in March 2002 (Swenson *et al.* 2006). It consists of a twin satellite orbiting the Earth in tandem at an initial altitude of ≈450 km and separation distance of ≈200 km (Longuevergne *et al.* 2010). Variations in Earth's gravitational pull cause changes in the inter-satellite separation distance. While the distance changes between the twin satellites are measured by on-board accelerometers (at an accuracy of ≈2 μm), the satellites positions at any point in time are tracked by Global Positioning System (GPS) receivers. This combined distance and position measurement are convoluted for highly accurate gravity fields (Wahr *et al.* 2004; Tapley *et al.* 2005; Rodell *et al.* 2009; Moiwo *et al.* 2011c).

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After post-processing for north–south trending errors (Swenson & Wahr 2006), glacial isostatic adjustments (Paulson *et al.* 2007) and other non-hydrological effects (Moiwo *et al.* 2011b), the time-variable gravity fields are inverted for terrestrial water storage variations at spatial resolutions of basin scales (Swenson *et al.* 2006). Within the period of 100 years, basin-scale mass redistributions are generally driven by changes in soil moisture and groundwater storage (Rodell *et al.* 2009), which are shown to be commensurate to GRACE-estimated water storage change (Tapley *et al.* 2005; Longuevergne *et al.* 2010). But whereas groundwater measurements exist for most river basins, soil moisture measurements are often lacking, inconsistent and unreliable (Moiwo *et al.* 2011c). However, soil moisture storage can be inferred from satellite data products such as Global Land Data Assimilation System (GLDAS) with a reasonable accuracy (Rodell *et al.* 2004, 2009; Moiwo *et al.* 2011a).

GLDAS is a satellite mission that uses Land Surface Models (LSM) to estimate global distributions of land surface states such as soil moisture (Rodell *et al.* 2004; Hogue *et al.* 2005). A vegetation-tiling approach is used to simulate subgrid variabilities of the land surface states. While the soil/elevation variables are derived from high-resolution global datasets, the baseline meteorological data obtained from NOAA-GDAS (National Oceanic and Atmospheric Administration – Global Data Assimilation System) atmospheric analysis system (Rodell *et al.* 2004) are forced by bias correction products (Berg *et al.* 2005).

Quantifying global water storage change and soil moisture distribution are the main mission goals of GRACE and GLDAS (Longuevergne *et al.* 2010). Augmenting GRACE/GLDAS data products with ground-based data offers a unique opportunity for water balance closures at varying spatio-temporal scales (Moiwo *et al.* 2011a). Therefore, the objective of this study is to integratively use GRACE/GLDAS and piezometric data products to analyze water storage dynamics in the semi-arid wetland ecosystem of Western Jilin. The results of the study will augment existing knowledge on water storage in the region. This research is critical not merely for devising water management strategies and preserving fragile/valuable ecosystems and the environment, but also for providing sustainable livelihoods to the millions of people in the region and beyond.

MATERIALS AND METHOD

Study area

Western Jilin lies between 43°59′–46°18′ N and 121°38′–126°120′ E (Figure 1). It has extensive wetlands, a dense population and a spatial extent that is sufficient for GRACE/GLDAS data application (Moiwo *et al.* 2010, 2011a). The climate is characterized by mild-dry springs, humid-warm summers, windy autumns and frosty-dry winters (Pan *et al.* 2003). Average winter and summer temperatures are −16 and 23 °C, respectively. Precipitation is low and variable in both space and time, with a long-term average annual value of 380 mm. Winds are moderate throughout the year, and with an average speed of 3–6 m/s (Moiwo *et al.* 2010).

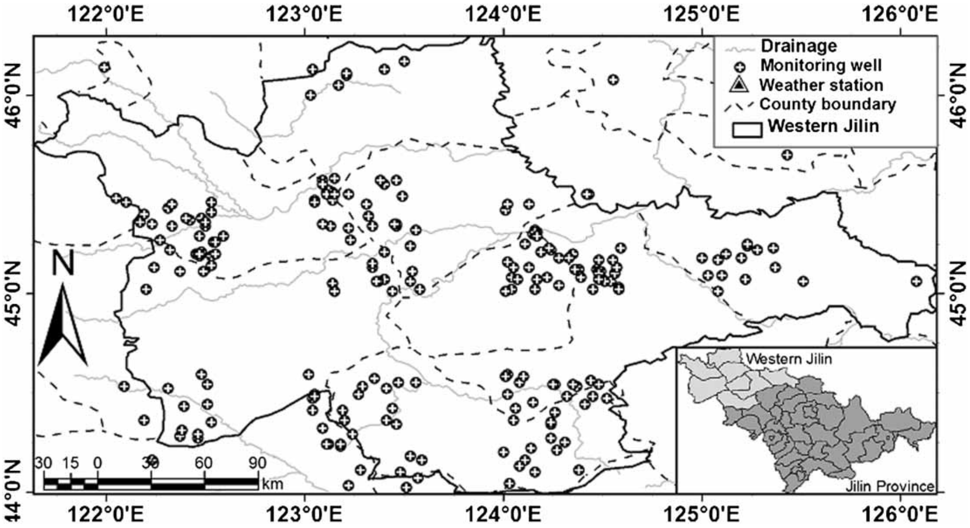

Figure 1 | Map of Western Jilin study area depicting the main drainage system, groundwater monitoring wells and county-level administrative boundaries.

With average surface elevation of 159 m and slope of 23%, the rivers (with shrinking flows) meander across the plain of alluvial deposits (Zhang *et al.* 2003). Inland depressions, lakes, wetlands, steppes, meadows and conifers are the dominant land cover (Pan *et al.* 2006). Substantive water development in the region started after 1949, and this situation has since intensified due to rapid population growth and aggressive food sufficiency drive (Pan *et al.* 2003; Moiwo *et al.* 2010). This change has had the overall effect of a steady water storage loss in the region (Yang *et al.* 2009). It is therefore critical to analyze water storage dynamics in this semi-arid region for preserving the fragile/valuable wetland ecosystems.

Water budget

Studies show that the non-negligible components of total water storage change (TWSC) at basin-scales are soil moisture storage change (SMSC) and groundwater storage change (GWSC) (Tapley *et al.* 2005; Swenson *et al.* 2006; Rodell *et al.* 2009; Longuevergne *et al.* 2010), collectively represented as:

$$\mathrm{TWSC} = \mathrm{SMSC} + \mathrm{GWSC} \tag{1}$$

Note that the storage terms in Equation (1) are spatial averages of over the study area.

GRACE month-to-month gravity fields are inverted for total water storage anomaly (TWSA), from which TWSC is computed (Rodell *et al.* 2009). Storage anomaly is the residual storage content at a given time with respect to the content at a reference epoch. Then storage change is the difference between storage anomalies of any two successive time steps (Moiwo *et al.* 2011b). GLDAS uses LSM to compute global estimates of soil moisture, from which SMSC is computed (Moiwo *et al.* 2011a). Measured depth to groundwater is multiplied by aquifer specific yield (sy) to get groundwater storage anomaly, from which GWSC is computed (Swenson *et al.* 2006). Average sy for the Western Jilin study area is taken as 0.16 (Yang *et al.* 2009).

GRACE/GLDAS data

Because data are missing for June 2002, July 2002 and June 2003, about 91 months of GRACE data (from April 2002 to December 2009) are used in this study. RL-04 (release-04) of the latest version of Center for Space Research (CSR) data products, which constitutes a significant improvement over earlier releases (Rodell *et al.* 2009), is used. Level-2 products of the data are available at http://geoid.colorado.edu/grace/grace.php, and the site also handles a series of hydrological analyses with retrievable end-products as maps, time-series or ascii-files.

The GRACE monthly solutions are filtered for leakage errors such as north–south trending errors (Swenson & Wahr 2006), glacial isostatic adjustments (Paulson *et al.* 2007) and other non-hydrological effects (Longuevergne *et al.* 2010). The 1°-resolution data are smoothed with the Gaussian filter of 200 km half width, fitted with Wahr *et al.* (2004) error bar, and then truncated to within 1° of the study area. This change minimizes the effects of the geographic truncation on the analysis (Moiwo *et al.* 2011c). The fields are afterwards spatially averaged over the study area to create time-series of TWSA, from which TWSC is computed.

The GLDAS Noah data used in this study span for the period from January 2002 to December 2009, and this data product is available at http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=GLDAS10_M. GLDAS combines satellite and ground-based data products to generate optimal fields of land surface states such as soil moisture (Rodell *et al.* 2004). The data fields are also truncated to within 1° of the study area and spatially averaged to create time-series of soil moisture storage, from which SMSC is computed (Moiwo *et al.* 2011a). The computed SMSC and GWSC are then added and compared with the GRACE-derived TWSC at monthly, seasonal, yearly, average and average seasonal cycles. The multi-temporal cycle analyses are not only for the purpose of comparisons, but also for multi-level decision-making and policy/strategy measures. For optimal display, Microsoft Excel and ArcMap environments are use to plot the results.

Note that the monthly cycles constitute month-to-month data for 2002–2009, averaged only over the study area. Then the average monthly cycles constitute a two-level averaging – both along the 12 months of the year (for 2002–2009) and over the study area. The seasonal and average seasonal cycles are similarly processed. Linear trend lines and regression values are shown in the plots for quick insight into the trends and agreements in the storage terms. The multi-scale plots provide decision-makers and stake-holders the range of choice needed for developing sustainable management policies/strategies.

Uncertainty/bias

Uncertainty/bias analyses in the GRACE/GLDAS datasets are based on the coefficient of variance method discussed by Strassberg *et al.* (2009). Root mean square error

(RMSE) and R^2 (coefficient of determination) are also used as measures of agreements between the GRACE-derived TWSC and that from the combined soil moisture and groundwater storage. Based on the analyses, the average uncertainty/bias in the datasets is $<10\%$ at $p < 0.05$.

RESULTS AND ANALYSES

Storage anomaly

Figure 2 plots time-series of soil moisture, groundwater and TWSA in the study area at monthly/seasonal, average monthly/seasonal and yearly cycles. While the monthly/seasonal trends in both soil moisture and TWSA are negative, that in groundwater depth is positive. This finding implies that all the storage terms indicate storage loss in the study area.

The amplitudes of the average monthly/seasonal plots in Figure 2 suggest that storage is highest in the summer months of June, July and August. Summer is the highest precipitation season in the study area, explaining the high storage amplitudes during this period.

Similar to the monthly/seasonal plots, the yearly trends in soil moisture and TWSA are negative, and that in groundwater storage is positive. This finding further confirms that an overall storage loss exists in the study area for the period 2002–2009.

Storage change

Figure 3 plots time-series of monthly, seasonal, average monthly/seasonal and yearly SMSC, GWSC and TWSC in the study area. While the trends in SMSC and TWSC are negative at the monthly and seasonal cycles, those in GWSC are positive. All the trends are negative at the yearly cycle. At the monthly cycle, over 80% of the amplitudes of the storage change are within ±30 mm. In fact, Figure 3 shows that amplitude ranges generally decrease at higher temporal scales (Rodell *et al.* 2009), suggesting greater noise/error suppressions at higher temporal scales (Swenson *et al.* 2006). The yearly (negative) trends in the storage change are therefore more reliable reflections of storage dynamics in the study area.

The average monthly/seasonal plots in Figure 3 indicate that both SMSC and TWSC are generally highest in summer and lowest in autumn. That of GWSC is highest in spring and lowest in autumn. However, the overall storage change is positive for summer and negative for autumn. These trends largely reflect the prevailing agro-climatic conditions (Pan *et al.* 2003). These conditions are critical for sustainable water management and preservation of fragile/valuable wetland ecosystems in the region (Moiwo *et al.* 2010).

Storage change comparison

The GRACE-derived TWSC is compared with that from soil moisture and groundwater storage (SMSC + GWSC) at monthly, seasonal, average monthly, average seasonal and yearly cycles (Figure 4). The comparisons are generally favorable (significant at $p < 0.05$), and with stronger agreements at higher temporal and averaging levels. The agreements are strongest at the average seasonal ($R = 0.98$; $R^2 = 0.92$; RMSE = 7.43 mm) and weakest at the monthly ($R = 0.75$; $R^2 = 0.68$; RMSE = 21.09 mm) cycles.

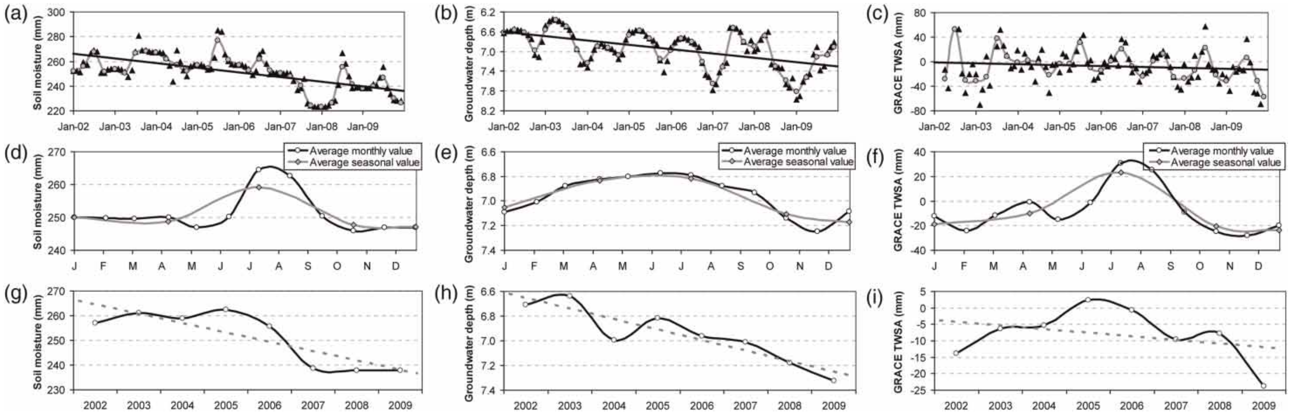

Figure 2 | Plots of monthly/seasonal (top plots), average monthly/seasonal (middle plots) and yearly (bottom plots) trends in soil moisture storage (a, d and g), groundwater storage (b, e and h), and in GRACE total water storage anomaly (TWSA) (c, f and i) for 2002–2009 averaged over the Western Jilin study area.

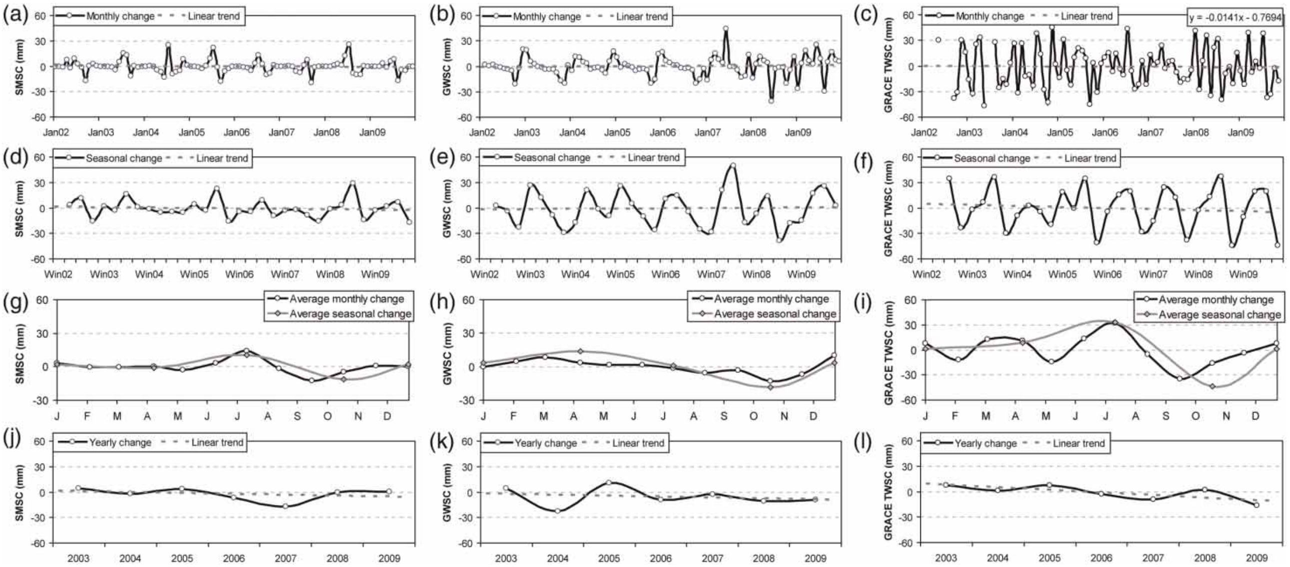

Figure 3 | Plots of trends in soil moisture (a, d, g and j), groundwater (b, e, h and k) and GRACE-derived (c, f, i and l) water storage changes at monthly (top plots), seasonal (upper middle plots), average monthly/seasonal (lower middle plots) and yearly (bottom plots) cycles for 2002–2009 averaged over the Western Jilin study area. SMSC denotes storage change in the 0–200 cm soil depth, GWSC is groundwater storage change and TWSC is GRACE-derived total water storage change.

The seasonal trends in storage change have di-peaks in 2003 and 2005 (Figure 4(b)), probably driven by the precipitation/irrigation processes in those years. In the region, storage change is generally highest in summer and lowest in autumn (Figure 4(d)). Also, whereas storage is low in 2004 and 2007, it is high in 2005 and 2008 (Figure 4(e)). The dynamics is influenced by agro-hydrologic processes in the region (Yang *et al.* 2009; Moiwo *et al.* 2010).

Storage spatial distribution

Spatial distributions of linear trend maps of water storage derived from the monthly soil moisture, groundwater and GRACE TWSA maps for 2003–2009 are plotted in Figure 5. Also in Figure 5 is the average annual precipitation distribution, which generally increases from west to east. Soil moisture follows a similar trend, except that it is skewed (in arc-shape) from the north through the south, and then to the west. High moisture zones are apparent along the drainage courses (Figures 1 and 5).

Groundwater storage is mainly driven by pumping events in the region (Yang *et al.* 2009). The corresponding GRACE-derived storage in Figure 5 represents the overall trend in the storage distribution as influenced by agro-hydrologic factors. The GRACE storage trend not only suggests an overall storage loss, but also higher storage losses in low precipitation regions of the study area.

DISCUSSION

In the study area, the main hydrologic input and output are precipitation and groundwater pumping. As over 70% of the precipitation falls in summer, groundwater use during this period is minimal (Pan *et al.* 2003; Moiwo *et al.* 2010). Also, the potential for water storage is therefore highest in summer. Hence the groundwater apparently recovers during the summer season (Figure 2(e)).

In fact, steady storage loss exists in all main crop production regions across China (Yang *et al.* 2009; Hu *et al.* 2010). The trends in the monthly/seasonal and yearly curves in Figure 2 also confirm storage loss in the study area. The trends in the monthly and seasonal curves in Figure 3 suggest not only narrowing soil moisture storage, but also increasing total water storage loss. Interestingly, however, the monthly and seasonal trends in Figure 3 suggest increasing groundwater storage. Irrespectively, all the seasonal plots depict a clear seasonality of storage in the region.

As intensive groundwater irrigation is the main mode of agriculture in the region (Pan *et al.* 2003; Zhang *et al.* 2003; Moiwo *et al.* 2010), the depicted gain in groundwater storage change could be indicative of agricultural water saving, soil-pore/aquifer compaction or merely noise in the dataset. Soil-pore collapse during land subsidence forces the water table to rise from the bottom to sometime within the root zone. The proximity of the water table in the root zone

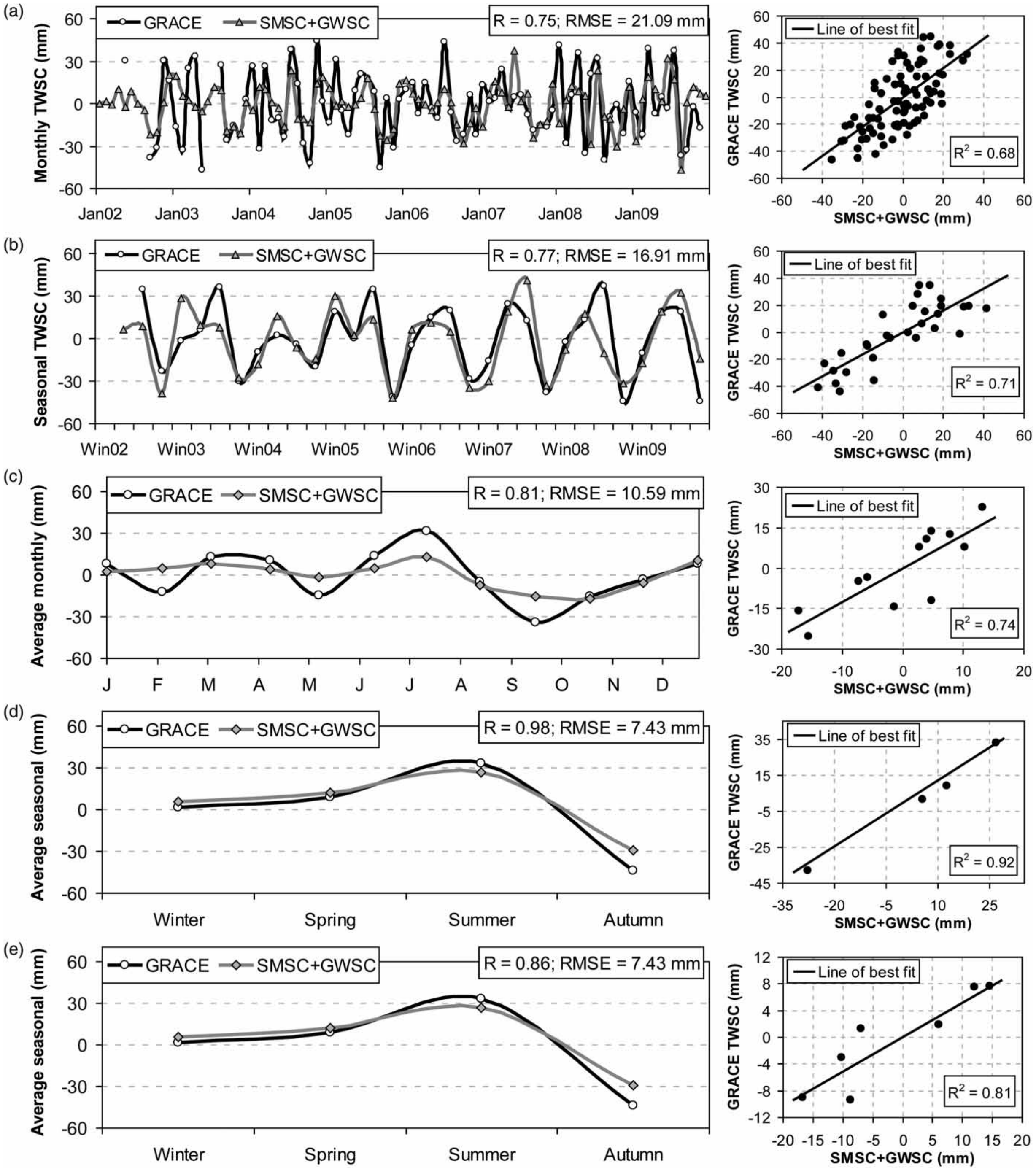

Figure 4 | Time-series (left plots) and corresponding scatter-plot (right plots) comparisons of total water storage change (TWSC) derived from GRACE with that from combined soil moisture and groundwater storage (SMSC + GWSC) at monthly (a), seasonal (b), average monthly (c), average seasonal (d) and yearly (e) cycles in the Western Jilin study area.

stabilizes soil moisture which, in turn, minimizes root-zone soil moisture storage change. Seasonal storage dynamics is equally critical for sustainable water resources management strategies in the study area.

As outlier effects on data behavior decrease at higher temporal and averaging levels (Swenson *et al.* 2006; Moiwo *et al.* 2011a), the yearly trends in Figures 2 and 3 could be more reflective of the storage dynamics, which indicate a general storage loss in the study area (Yang *et al.* 2009; Moiwo *et al.* 2010). Storage loss in the region could have negative implications for the fragile wetland ecosystem, agriculture and people's livelihood.

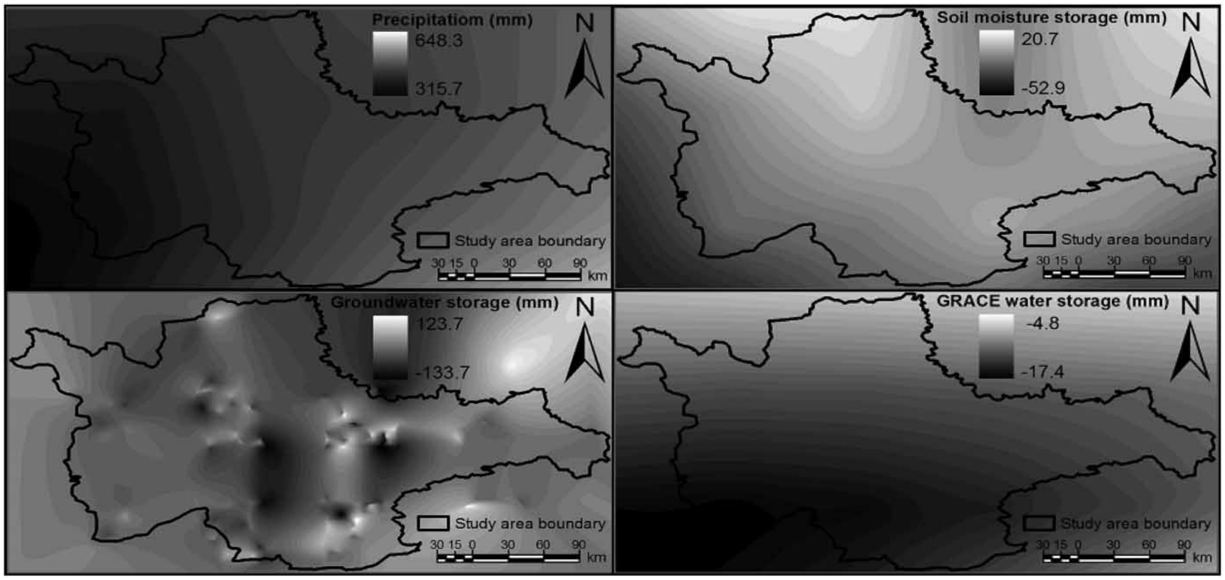

Figure 5 | Plots of spatial distribution of average annual precipitation along with linear trend maps of water storage derived from soil moisture, groundwater and GRACE monthly water storage anomaly maps for 2003–2009 in the Western Jilin study area.

The favorable comparisons in Figure 4 at the different temporal scales suggest that GRACE sufficiently detects storage signal in the study area. It also suggests that water storage in the region occurs mainly in soil moisture and groundwater. In other words, the assumptions in Equation (1) hold true for the study area. It then implies that in the region, sustainable water resources management strategies should largely focus on optimizing soil moisture and groundwater storage.

The spatial distributions in Figure 5 (especially that of GRACE water storage) suggest overall storage depletion in the region. Further analysis shows that average storage depletion in the study area is 0.85 mm/month (10.18 mm/year). This finding could negatively impact the valuable/fragile semi-arid wetlands that not only depend on groundwater discharge, but also recharge the groundwater system (Pan *et al*. 2006; Ming *et al*. 2007; Moiwo *et al*. 2010). For the restoration, preservation and sustainability of wetland ecosystems in the region, it is critical to develop water resources management strategies that limit groundwater extraction rate to recharge rate.

CONCLUSIONS

In this study, water storage in Western Jilin (a proxy for semi-arid regions) is analyzed for 2002–2009 using GRACE/GLDAS and measured groundwater data products. The results are compared at monthly, seasonal, average monthly/seasonal and yearly cycles, all of which show favorable agreements. The presented results at the spatial and various temporal scales allow not only comparisons, but also the development of parallel water resources management policies/strategies in the region.

Over 80% of the amplitudes of the monthly storage change are within ±30 mm, showing the average magnitude of storage fluctuation in the study area. While the seasonal time-series show a clear seasonality of storage change in the region, the yearly trends clearly depict storage loss. The average monthly/seasonal trends show that storage is highest in summer and lowest in autumn. This implies that decision-makers/stake-holders of water resources in the region should focus water-saving measures on the months/seasons with storage loss and use the yearly trends to gauge the success of adopted policies/strategies. This comprehensive approach ensures the preservation and sustainability of water resources which will, in turn, ensure a sustained livelihood for the millions of people in the region and beyond.

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