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CHANGES AND VARIATIONS OF THE TERRESTRIAL WATER STORAGE ANOMALY OVER THE CORE AREA OF THE SILK ROAD

ABSTRACT

Terrestrial water storage (TWS) plays important role in the food supplies, human and ecosystem health in the world, especially in the arid regions. Therefore, in this study, the changes and variabilities of the TWS anomaly (TWSA) derived from the Gravity Recovery and Climate Experiment (GRACE) satellite dataset are explored over the arid regions of Central Asia during 2003–2014. The total monthly TWSA is decomposed into long-term, seasonal and residual components by the Seasonal Trend decomposition using Loess (STL) method. The linear trends of the long-term components are analyzed in time and space to reveal the spatiotemporal features of the monthly TWSA. To address the dominant spatial mode of the TWSA, the empirical orthogonal function (EOF) method is employed for the monthly TWSA. The major results show that the arid regions of Central Asia have experienced a significant terrestrial water depletion with the rate of -0.44 mm/month based on the long-term component of the monthly TWSA in 2003–2014. Among the four seasons, spring has the largest TWS caused by the increased snowmelt water with the more precipitation and warm climate. The smallest TWS is detected in autumn. For the spatial features of TWSA, the water depletion centers appear in the small part areas of southwestern Kazakhstan (KAZ), part areas of northwestern Uzbekistan (UZB) and Turkmenistan (TKM). While the increasing linear trends mainly appear in southern Tarrim basin and Kunlun Mountain, and part areas of northeastern KAZ. These spatial variations are consistent with the EOF result. This preliminary investigation in the TWS variations is valuable for scientists and decision-makers in formulating scientifically based approaches and policies for water resource management over the arid regions of Central Asia.

KEYWORDS: terrestrial water storage anomaly, assessment and simulation, Silk Road, GRACE satellite dataset

INTRODUCTION

In global water cycle, water precipitates from the atmosphere, travels on the surface and through groundwater to the oceans, and evaporates or transpires back to the atmosphere from land or evaporates from the oceans [Oki, Kanae, 2006]. During this cycling, water molecules pass repeatedly through solid, liquid and gaseous phases between land, the oceans, and the atmosphere. The total terrestrial evapotranspiration is about 65.5 ×103 km^3/year. For the water storage, oceans have the largest water with the volume of 1,338,000 × 10^3 km^3, followed by the glacier and snow (24,064 × 10^3 km^3), and groundwater (23,400 × 10^3 km^3) [ibid].

As the major part of the renewable freshwater resources, terrestrial water storage (TWS) includes the surface water storage (SWS, including canopy interception, reservoirs, wetlands and rivers, lakes and snow water equivalent), soil moisture storage (SMS), and groundwater storage (GWS) [Long et al., 2017]. TWS has been profoundly influenced by climate change and variability and extensive anthropogenic activities which resulted in changes in the hydrological cycle, threatening sustainable water use and agricultural production [Piao et al., 2010; Long et al., 2016].

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The increase in surface temperatures has important consequences for the hydrological cycle, especially in regions where water supply is currently dominated by melting snow or ice [Barnett et al., 2005]. Climate variability and change influences groundwater systems both directly through replenishment by recharge and indirectly through changes in groundwater use which are modified by human activities [Taylor et al., 2013].

Satellite remote sensing products have been proven efficient to monitoring the water storages and fluxes in space and time in a changing world with truly global perspectives. Launched in 2002, the Gravity Recovery and Climate Experiment (GRACE) satellites have been likened to giant weighing scales in the sky which monitor monthly changes in mass as water storage increases or decreases related to climate variability and human activity. With a monthly temporal resolution GRACE can resolve TWS anomaly (TWSA) with sufficient accuracy over scales which range from approximately 200 000 km^2 at low latitudes to about 90 000 km^2 near the poles [Tapely et al., 2004]. GRACE satellite datasets have been widely used in identifying the TWS variations over regional and global scales [Long et al., 2017], analyzing applications of TWS to groundwater, flood and drought, and glaciers mass balance [Yeh et al., 2006], discussing the effects of climate change and human activities on TWS variations.

As the core area of Silk Road, the arid regions of Central Asia have the sensitive and vulnerable ecosystem to the water resource. The main sources of water in this region come from high mountain glaciers, seasonal snowmelt, mid-altitude mountain precipitation, and water emanating from fractured bedrock on the lower mountain slopes. The fragile balance of the water cycle shows unstable spatiotemporal features that reflect climatic change and intensive human activity [Chen, 2012]. However, there are few literatures about the changes and variations of TWSA over Central Asia. Therefore, in this study, the spatiotemporal features of TWSA derived by the GRACE satellite dataset are explored including the linear trend and the dominant spatial pattern.

MATERIALS AND METHODS OF RESEARCH

The arid regions of Central Asia, including the five states of Central Asia (CAS5) [i.e. Kazakhstan (KAZ), Uzbekistan (UZB), Kyrgyzstan (KGZ), Tajikistan (TJK), and Turkmenistan (TKM)] and the northwest China (NW), the major mountainous (i.e. Altai Mountain, Tianshan Mouontain and Kunlun Mountain), and the major lakes and rivers include the Balkhash Lake, Issyk-Kul Lake, Aral Sea, Syr Darya, Amu Darya and Tarrim River (fig. 1).

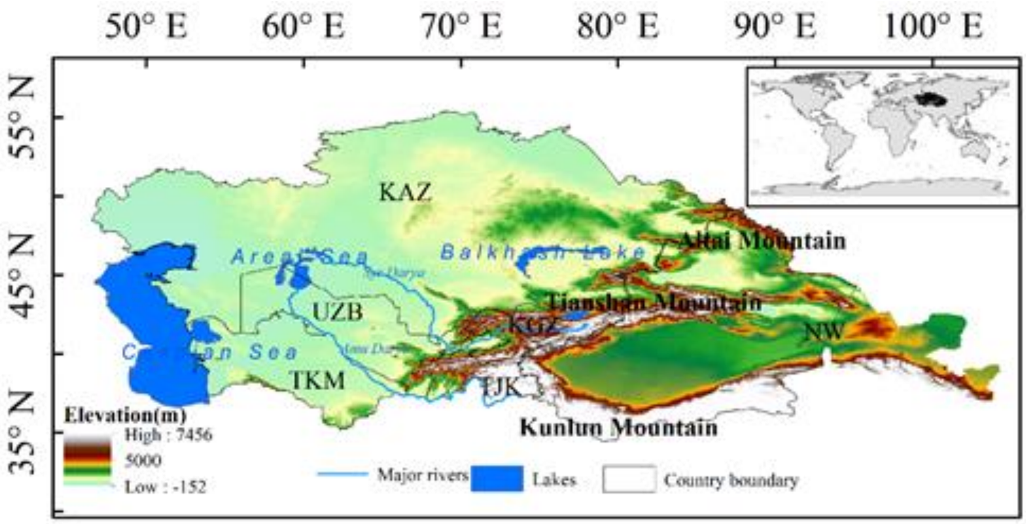

Fig. 1. Study area of the arid regions of Central Asia,
including the major mountainous and the major lakes and rivers

The GRACE twin satellites, launched in March 2002, are used to measure the Earth's gravity field changes and to investigate the water reservoirs over land, ice and oceans [Tapley et al., 2004]. The monthly GRACE Tellus Level-3 products provide the surface mass changes, with most geophysical corrections applied, to analyze changes in the mass of the Earth's hydrologic, cryospheric and oceanographic components (https://grace.jpl.nasa.gov/mission/ grace/). In this study, the Release 5 (RL05) of the Centre for Space Research (CSR) with the spatial resolution of 1°×1° during 2003–2014 is considered (https://grace.jpl.nasa.gov/data/get-data/).

The Seasonal Trend decomposition using Loess (STL) was used to decompose TWSA monthly time series as follows:

$$S_{total} = S_{long\text{-}term} + S_{seasonal} + S_{residual},$$

where the original signal (S_{total}) is decomposed into long-term, seasonal, and residual components, based on procedures outlined in previous study [Scanlon et al., 2018]. The long-term signal is further decomposed into linear and non-linear (inte-rannual) components by fitting a trend using least squares linear regression and attributing the remaining long-term signal to inte-rannual signal. The residuals reflect sub-seasonal signal and noise. Therefore, the TWSA trends in this study refer to the linear trends (K) estimated from the long-term signal after STL analysis. The statistic significant of K is tested by Student's t-test at 95 and 99 % confidence levels ($p<0.05$ and $p<0.01$).

The spatial-temporal structures of the long-term variations of the monthly TWSA of the eight datasets are examined by the empirical orthogonal function (EOF) analyses (Lorenz, 1956). EOF analyses can identify the dominant spatial pattern according to the spatial mode (EOF mode) and obtain the corresponding time coefficients which explain the magnitude of the variation of each EOF model of the monthly TWSA. Following North et al. (1982), a significance test is applied to distinguish the physical signal from the noise in the EOF.

RESULTS OF RESEARCH AND DISCUSSION

Decomposition result of STL

For the monthly TWSA variations, the decomposition results of STL are displayed in fig. 2. A statistically significant decreasing linear trend of the long-term composent with the rate of -0.44 mm/month is observed at the 99 % confidence level ($p<0.01$) which indicates the remarkable water depletion over Central Asia during 2002–2014. This water depletion is resulted in by the warmed temperature and the incresed water withdrawal with the rapid ecomonic development [Deng, 2018]. For the seasonal composent, the positive TWSA appears from February to July and the negetive TWSA is detected from August and January with the largest TWSA in April (36.27mm) and the smallest TWSA in October (-40.01mm) (fig. 2). In addition, among the four seasons, the spring has the largest water resource (TWSA=33.03mm) which is caused by the increasing of snowmelt with the warming climate and the increased precipitation during the last three decades [Hu et al., 2014; Chen et al., 2018]. The autumn has the smallest water resource that is caused by the large water use and little precipitation [Chen et al., 2018]. Moreover, the long-term and seasonal composents expalin more than 90 % variance of the monthly TWSA and the residual composent only accout for less than 10 % TWSA variability by a simple computing.

For the spatial distribution of the linear trends of the long-term composents of the monthly TWSA over Central Asia, about 85 % areas have the decreasing linear trends of the long-term composents of the monthly TWSA with the decreasing centers in the small part areas of southwestern KAZ, part areas of northwestern UZB and TKM (fig. 3). The increasing linear trends mainly appear in southern Tarrim basin and Kunlun Mountain, and part areas of northeastern KAZ.

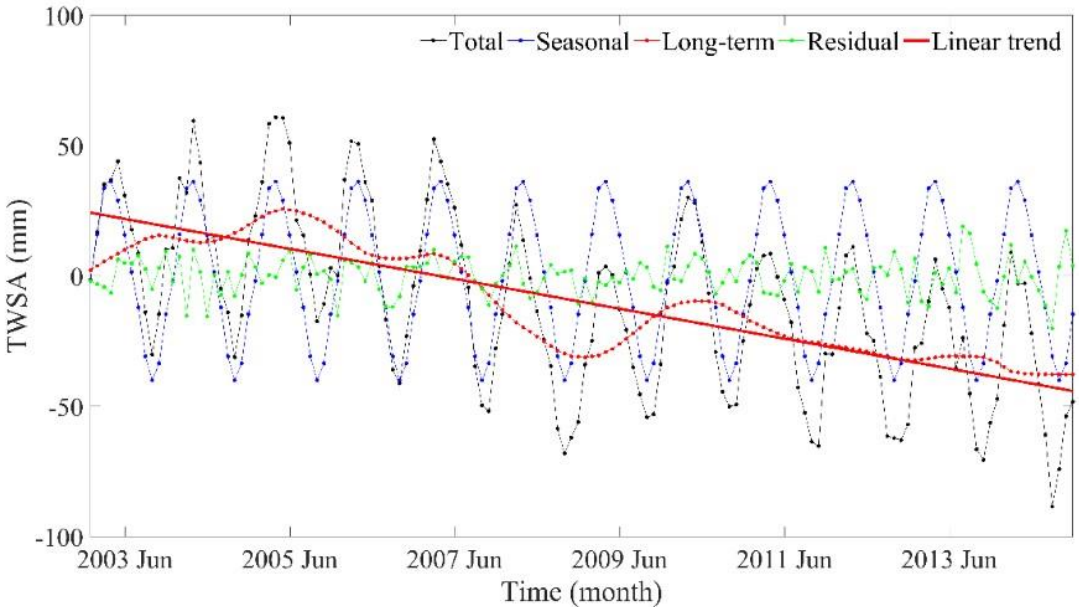

Fig. 2. The seasonal trend decomposition using loess (STL) results of monthly TWSA from CSR in 2003–2014, total, seasonal, long-term, residual components and the linear trend corresponding to the long-term component

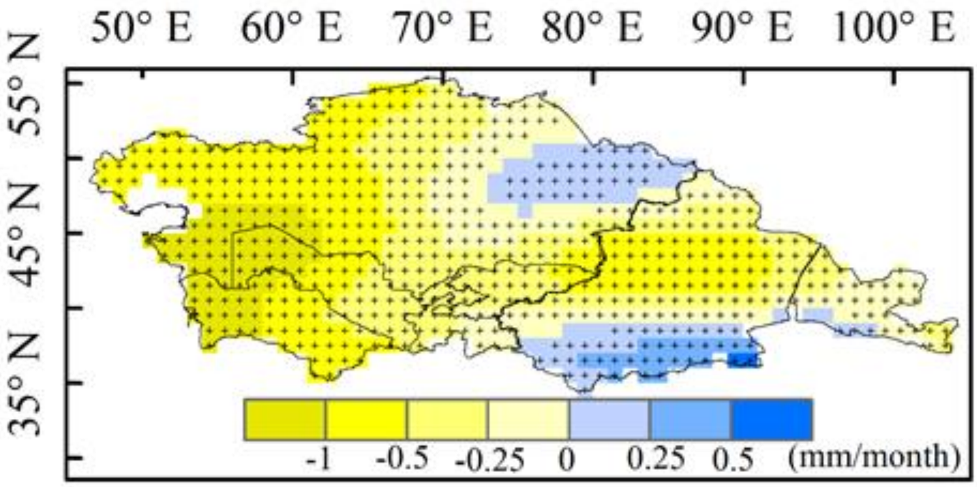

Fig. 3. Spatial distributions of the linear trends from the longterm components of the monthly CSR TWSA

EOF result of the monthly TWSA

To have a furthure research on the spatial features of the water resource over Central Asia during 2003–2014, the EOF method is applied to the monthly TWSA in fig. 4. Almost all the areas of Central Asia show the positive values from the EOF-1 result which indicates the consistent water depletion variations. The negative EOF-1 values exist in the small part areas of southeastern Xinjiang and southern Hexi Corrion (fig. 4). Furthermore, EOF-1 mode explains 72 % variance of the spatial variability of the monthly TWSA that is statistically significant at the 95 % confidence level.

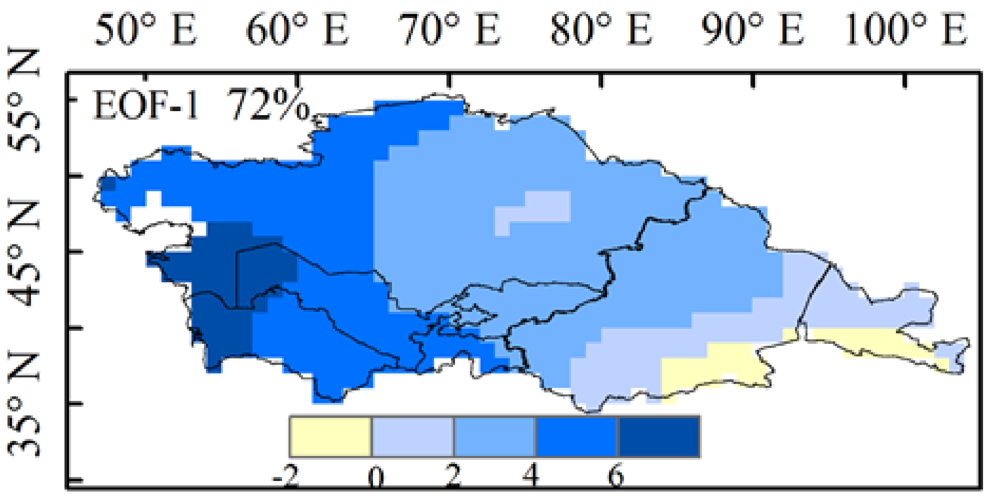

Fig. 4. EOF-1 of the monthly TWSA from CSR dataset

CONCLUSIONS

In this study, the changes and variabilites of the TWSA derived from the GRACE satellite dataset are explored over the arid regions of Central Asia during 2003– 2014. The total monthly TWSA is decomposed into long-term, seasonal and residual components by the STL method. The linear trends of the long-term components are analyzed in time and space to reveal the spatiotemporal features of the monthly TWSA. To address the dominant spatial mode of the TWSA, EOF method is employed for the monthly TWSA. The major results are concluded as follows.

In 2003–2014, the arid regions of Central Asia have experinced a significant terrestrial water depletion with the rate of -0.44 mm/month based on the long-term component of the monthly TWSA. Among the four seasons, spring has the largest TWS cased by the increased snowmelt water with the more precipitation and warm climate. The smallest TWS is detected in autumn. This depletion may be caused by the climate variations and human activities. For the spatial features of TWSA, the water depletion centers appear in the small part areas of southwestern KAZ, part areas of northwestern UZB and TKM. While the increasing linear trends mainly appear in southern Tarrim basin and Kunlun Mountain, and part areas of northeastern KAZ. These spatial variations are consistent with the EOF result.

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