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Influences of environmental changes on water storage variations in Central Asia

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Abstract: The spatio-temporal pattern of the global water resource has significantly changed with climate change and intensified human activities. The regional economy and ecological environment are highly affected by terrestrial water storage (TWS), especially in arid areas. To investigate the variation of TWS and its influencing factors under changing environments, the response relationships between TWS and changing environments (climate change and human activities) in Central Asia have been analyzed based on the Gravity Recovery and Climate Experiment (GRACE) data, Climatic Research Unit (CRU) climate data and Moderate Resolution Imaging Spectroradiometer (MODIS) remote sensing data products (MOD16A2, MOD13A3 and MCD12Q1) from 2003 to 2013. The slope and Pearson correlation analysis methods were used. Results indicate that: (1) TWS in about 77 % of the study area has decreased from 2003 to 2013. The total change volume of TWS is about 2915.6×10^8 m^3. The areas of decreased TWS are mainly distributed in the middle of Central Asia, while the areas of increased TWS are concentrated in the middle-altitude regions of the Kazakhstan hills and Tarim Basin. (2) TWS in about 5.91% of areas, mainly distributed in the mountain and piedmont zones, is significantly positively correlated with precipitation, while only 3.78% of areas show significant correlation between TWS and temperature. If the response time was delayed by three months, there would be a very good correlation between temperature and TWS. (3) There is a significantly positive relationship between TWS and Normalized Difference Vegetation Index (NDVI) in 13.35% of the study area. (4) The area of significantly positive correlation between TWS and evapotranspiration is about 31.87%, mainly situated in mountainous areas and northwestern Kazakhstan. The reduction of regional TWS is related to precipitation more than evaporation. Increasing farmland area may explain why some areas show increasing precipitation and decreasing evapotranspiration. (5) The influences of land use on TWS are still not very clear. This study could provide scientific data useful for the estimation of changes in TWS with climate change and human activities.

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1 Introduction

In arid and semiarid regions where the ecological environment is extremely vulnerable, terrestrial water storage (TWS) has important influences on the regional climate change and ecological environment (Liu *et al*., 2013; Zhang *et al*., 2012). TWS changes have become one of the major limiting factors for socio-economic development (Cao *et al*., 2015; Long *et al*., 2014; Ramillien *et al*., 2005). Therefore, studying the spatial and temporal variations of TWS is important in informing sustainable utilization of regional water resources and sustainable socio-economic development.

TWS comprises groundwater, soil moisture, surface water bodies (lakes, rivers and reservoirs), glaciers, snow water equivalent, and canopy water storage (Syed *et al*., 2008). Global water storage is distributed extremely unevenly in time and space, and shows variable trends (Long *et al*., 2015; Schmidt *et al*., 2006; Yang *et al*., 2013). Existing studies have indicated a decreasing trend in TWS in Central and South Asia (Singh *et al*., 2012; Tangdamrongsub *et al*., 2011), of 0.42 ± 0.12 cm·a^{-1} in the Tianshan region, China (Yang and Chen, 2015). Conversely, TWS in the Tarim River Basin shows a generally increasing trend (Yang *et al*., 2015). Glacier and snowmelt are the main important water resources in arid and semiarid regions in Central Asia (Sorg *et al.*, 2012; Chen *et al.*, 2015) where TWS was remarkably affected by climate change (Immerzeel *et al.*, 2010; Sorg *et al.*, 2012). In the study area, glaciers and snow are the main components of TWS as the most beginning of rivers originate from the Tianshan Mountains (Aizen *et al.*, 1997). The results of recent researches indicated that the glacier and snow have different upward or downward tendency, glacier and snowmelt decreased TWS in the mountain and basin regions (Matsuo and Heki, 2010) but increased it in the surrounding basin area (Yang *et al.*, 2015).

Changes in land water reserves are mainly influenced by climate change and human activities. Research shows significant correlation between water storage changes and temperature, precipitation and snow water equivalent in Central and South Asia (Tangdamrongsub *et al*., 2011), and the precipitation in the Amazon Basin has a close relationship with TWS change (Frappart *et al*., 2013). In the Tarim River Basin, rainfall, runoff and evapotranspiration are major factors affecting the water storage (Yang *et al*., 2015), which is consistent with the results of the Amazon Basin (Chen *et al*., 2009). TWS changes in 23 major basins around the world were analyzed by Syed *et al*. (2008), which showed that for water storage changes, evapotranspiration plays a key role in middle altitude regions while snowmelt in high altitude regions and precipitation are dominant factors in the tropical zone. Human activities also play an important role in TWS changes. For example, anthropogenic factors, El Niño-Southern Oscillation (ENSO) and precipitation affected water storage changes in the Nile Basin and Ganges River Basin (Awange *et al*., 2014; Khandu *et al*., 2016). The dominant contributor to the TWS excess was found to be intensive surface water irrigation in the middle and southeastern Yangtze River Basin (Huang *et al*., 2015). On a macro scale, TWS changes are significantly related to vegetation and land use in Northern Eurasia (De *et al*., 2015; Velicogna *et al*., 2015). Thus, current research mainly focuses on single climatic factors or human activities, and mostly on humid and semihumid regions, while comprehensive studies of arid areas are limited.

TWS can be determined through in situ observations, but this is limited to small areas and partial components, such as soil moisture and snow water equivalent (Cayan, 1996; Robock *et al*., 2000; Serreze *et al*., 1999). It is more difficult to monitor water resources at large scales (Alley *et al*., 2002; Lettenmaier and Famiglietti, 2006). Microwave satellite sensors can provide estimates of surface (upper few cm) soil moisture and only in locations where vegetation is sparse (Gao *et al*., 2004; Njoku *et al*., 2003). The accuracy of simulations using land surface models is limited by the difficulty in obtaining the required parameters (Dijk *et al*., 2013; Huang *et al*., 2015). Gravity recovery and climate experiment (GRACE) data have alleviated the shortcomings of the above methods, and could quantify the variations of terrestrial water storage from space. Previous studies have suggested that GRACE accuracy is high enough to resolve mass variations for large river basins or regions of several hundred kilometers extension (Wahr *et al*., 2004; Velicogna and Wahr, 2006) allowing the possibility of quantitative studies of TWS changes at large or medium scale. Until now, GRACE data have been widely used to study water storage changes (Luthcke *et al*., 2006; Rodell *et al*., 2009; Tapley *et al*., 2004). Many studies indicate that TWS changes estimated using GRACE data are consistent with the results simulated by hydrologic models (Han *et al*., 2010; Mohamed *et al*., 2011; Velicogna and Wahr, 2006). Thus, GRACE is an important data source for studying changes in regional water storage.

As a vulnerable ecological region, the gap between supply and demand of water in Central Asia has increased with climate change and intensified human activities in recent years (Bernauer and Siegfried, 2012; Siegfried *et al*., 2012). However, the studies paid little attention to the impact of climate change on regional TWS variations in Central Asia. In order to explore the relationship between water supply and demand we used GRACE data, CRU climate data and remote sensing datasets including evapotranspiration, vegetation index and land use from 2003 to 2013. Using slope and Pearson correlation analysis methods, we have investigated temporally and spatially response relationships between TWS variation and environmental change focusing on climate change and human activities in Central Asia.

2 Study area

The area defined as Central Asia covers five countries of the former Soviet Union (Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan) as well as Xinjiang, an autonomous region in northwestern China (Deng and Chen, 2016). It is largely confined within 34°34′–55°43′N and 46°49′–96°37′E (Figure 1) and covers about 601×10^4 km^2, making up about a third of all arid areas in the world (Chen *et al*., 2008). Located at the center of Eurasia, far from the oceans, with a dry climate, Central Asia belongs to a typical continental climate zone. The annual mean temperature of Central Asia is 4–8℃ (Lioubimtseva and Henebry, 2009), the annual mean precipitation is 100–400 mm (De Pauw, 2008), and the evapotranspiration is up to 900–1500 mm (Qin, 1999). Large quantities of glaciers and permanent snow form “wet islands” in arid inland mountains, and are a main recharge source of rivers and lakes in plains during the dry season. The study area has a total population of 65 million, and cultivated land, natural vegetation and water body cover 70.1×10^4 km^2, 313.2×10^4 km^2, and 13.8×10^4 km^2 of the area, respectively (Chen *et al*., 2013).

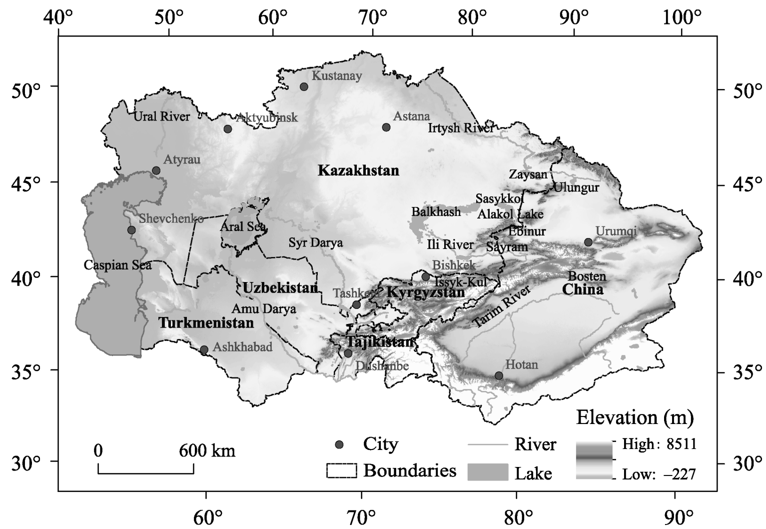


Figure 1 Study area of Central Asia

3 Data and methods

3.1 Data sources

In this study, the spatial and temporal variations of TWS in Central Asia were analyzed using GRACE (Level2 RL05 GSM) products published by the Center for Space Research (University of Texas at Austin) from January 2003 to December 2013 (http://icgem.gfz-potsdam.de/ICGEM/TimeSeries.html).

Meteorological data (2003–2013) used in this paper were produced by the Climate Research Unit (CRU TS v.3.23), University of East Anglia (http://www.cru.uea.ac.uk/cru/data/hrg/). Evapotranspiration data (MOD16A2) were provided by the Numerical Terra dynamic Simulation Group (NTSG), University of Montana (http://www.ntsg.umt.edu/project/mod16). The Shuttle Radar Topography Mission (SRTM) data were used as a digital elevation model. The dataset was provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, CAS (http://datamirror.csdb.cn). Both NDVI data (MOD13A3) and Land-Use and Land-Cover Change (LUCC) data (MCD12Q1) were downloaded from the Goddard Space Flight Center, NASA (https://ladsweb.nascom.nasa.gov/data/search.html). The temporal and spatial resolutions of data used in this study were given in Table 1.

3.2 Data processing

Table 1 Data information

Data name	Temporal resolution	Spatial resolution
GRACE	Monthly	1° × 1°
CRU	Monthly	0.5° × 0.5°
MOD16A2	Monthly	1km × 1km
MOD13A3	Monthly	1km × 1km
MCD12Q1	Yearly	500 m × 500 m
DEM		90 m × 90 m

The monthly spherical harmonics coefficients of GRACE gravity were converted into the equivalent water height by Matlab; then these data and the climate data (precipitation and temperature) from CRU were transformed into raster data to analyze the TWS by ArcGIS. Filling missing data was done using mean value method, a simple and rapid method to interpolate missing data, which does not affect the estimate of the mean value. MODIS data processing (mosaicking, extracting, converting, transforming, resampling, and recoding) was dependent on the MODIS Reprojection Tool (MRT). Data analysis was achieved using ENVI 5.1 and ArcGIS10.2 provided by Environmental Systems Research Institute (ESRI), Inc.

3.3 Calculation of TWS changes based on GRACE data

Terrestrial water storage could be estimated according to the GRACE spherical harmonic coefficients at monthly time-scales (Wahr *et al*., 1998). TWS fluctuations would bring changes in gravity field. This change can be expressed by spherical harmonic coefficients. So, water density could be obtained through gravity field, and be transformed into equivalent water height. The equation of equivalent water height with gravity spherical harmonic coefficients is listed as follows (Yang and Chen, 2015):

$$\Delta H(\theta,\phi)=\frac{2a\rho_{ave}\pi}{3\rho_w}\sum_{l=0}^{N}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}W_l P_{lm}(\cos\theta)[\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)] \tag{1}$$

where H is equivalent water height, θ is the latitude, φ is the longitude, a is the equatorial radius, ρ_{ave} is the mean density of the Earth, ρ_w is the density of water, k_l is the Loew coefficient, C_{lm} and S_{lm} are the coefficients of the gravity spherical harmonics coefficients (Stokes' coefficients), and $P_{lm}(\cos\theta)$ is the lth degree and mth order fully-normalized Legendre function, with maximum degree l and order m, expanded to 60, W_l is the weight function, which can be obtained by the following recursion formula:

$$W_0=\frac{1}{2\pi},\quad W_1=\frac{1}{2\pi}\left[\frac{1+e^{-2b}}{1-e^{-2b}}-\frac{1}{b}\right],\quad W_{l+1}=-\frac{2l+1}{b}W_l+W_{l-1},\quad b=\frac{\ln 2}{1-\cos(r/a)}$$

where a is the equatorial radius, and r is the Gaussian smooth radius (r =300 km in this paper).

3.4 Slope analysis method

In order to analyze the fluctuation characteristics of TWS, precipitation, temperature, NDVI and evapotranspiration with time, the slope analysis method was applied to calculate the changing trends. The formula used is as below (Wang *et al*., 2010):

$$Slp=\frac{\mathrm{N}\sum_{i=1}^{\mathrm{N}}iX_i-\left(\sum_{i=1}^{\mathrm{N}}i\right)\left(\sum_{i=1}^{\mathrm{N}}X_i\right)}{\mathrm{N}\sum_{i=1}^{\mathrm{N}}i^2-\left(\sum_{i=1}^{\mathrm{N}}i\right)^2} \tag{2}$$

where Slp is the change slope, i is the corresponding time for X_i (i = 1, in the year of 2003), and N is the quantity of samples (i.e., number of years, N=11, in this paper). If $Slp > 0$, the response relationship between the variables would be a positive trend, otherwise, it would be a negative trend.

3.5 Pearson correlation analysis method

Climate factors, vegetation and land use affect TWS along with time and space. The variables are assumed to be independent and continuous, and in a normal distribution, the Pearson correlation analysis method was used to discuss the close links between these variables in this study. The formula is as follows (Zhou *et al*., 2016):

$$r=\frac{\mathrm{N}\sum_{i=1}^{\mathrm{N}}X_iY_i-\sum_{i=1}^{\mathrm{N}}X_i\sum_{i=1}^{\mathrm{N}}Y_i}{\sqrt{\mathrm{N}\sum_{i=1}^{\mathrm{N}}X_i^2-\left(\sum_{i=1}^{\mathrm{N}}X_i\right)^2}\sqrt{\mathrm{N}\sum_{i=1}^{\mathrm{N}}Y_i^2-\left(\sum_{i=1}^{\mathrm{N}}Y_i\right)^2}} \tag{3}$$

where r is the Pearson correlation coefficient, i is the corresponding time for X_i and Y_i ($i = 1$, in the year of 2003), and N is the number of years (N=11, in this paper). The coefficient r ranges from –1 to 1, and the greater the value of $| r |$, the higher the correlation. There is weak correlation when $| r |$ is less than 0.3, low correlation when greater than 0.3 and less than 0.5, moderate correlation when greater than 0.5 and less than 0.8, and high correlation when greater than 0.8 (Suo *et al*., 2009).

4 Results and discussion

4.1 Temporal and spatial variations of TWSC in Central Asia

In order to analyze the temporal and spatial variations of the terrestrial water storage changes (TWSC) in Central Asia, the monthly and inter-annual TWSC during 2003–2013 were calculated.

4.1.1 Temporal variations of TWSC

Based on equation (1), the earth's surface density was calculated using spherical harmonic coefficients of gravity field. It was converted into equivalent water height, which represents TWSC. The monthly TWSC is shown in Figure 2.

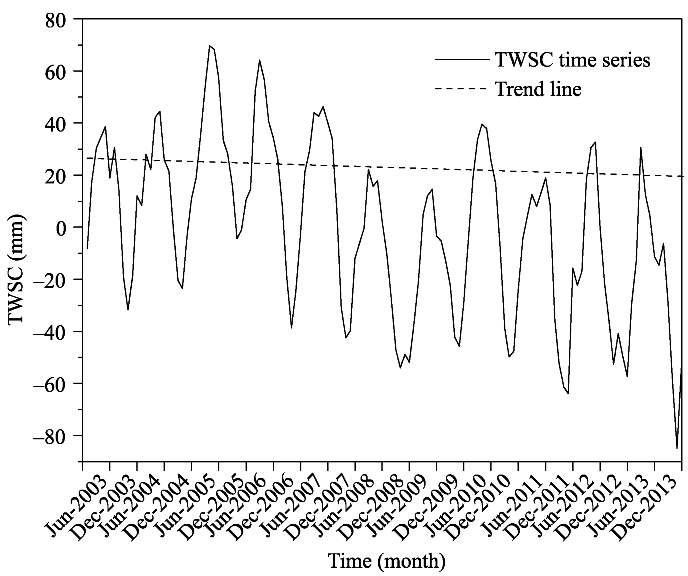


Figure 2 Temporal variations of TWS

TWS anomalies in the GRACE dataset (Figure 2) show a decreasing trend from January 2003 to December 2013, with a slope of -4.85 mm·a^{-1}. The maximum positive anomaly of TWS of 69.61 mm occurred in April 2005, while the minimum negative anomaly of about –84.90 mm occurred in November 2013. Before 2005, TWS increased at a rate of 5.04 mm·a^{-1}, then it began to decrease. The largest decrease of –24.24 mm·a^{-1} occurred from 2006 to 2008. Afterwards, the decreasing trend slowed down to –5.39 mm·a^{-1}. Over the whole period, the reduction of TWS in volume was 2915.6×10^8 m^3.

4.1.2 Spatial variations of TWSC

The first monthly mean values of TWS were calculated every year. Based on the results, the inter-annual variation trend of TWS was obtained. To study the spatial variations in TWSC, the percentage change in the inter-annual variation from 2003 to 2013 compared with TWS in 2003 was computed (Figure 3).

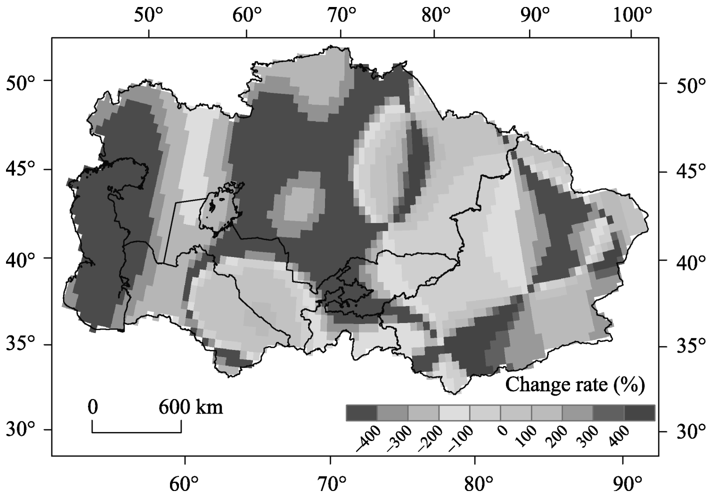


Figure 3 Spatial variations of TWS

Figure 3 shows a decreasing trend in TWS in most parts of Central Asia from 2003 to 2013, and the overall decrease in the west is larger than in the east. The TWS increases are mainly over the northeast of Turkmenistan, the southeast of Uzbekistan, east of Kazakhstan and east of Xinjiang, China. Further analysis revealed a decreasing trend in TWS in 77.04% of Central Asia from 2003 to 2013, and the rate of decrease is more than 400% in the Caspian Sea and its coastal lowlands, the middle of the five Central Asian countries and the north of Xinjiang, China. These areas account for 41.92% of the areas where TWS decreased. While in 22.96% of Central Asia TWS increases, the rate of increase is less than 100% in 46.4% of the above regions and greater than 400% in only 13.44% of the areas in the east of Kazakhstan, the southeast of the Tarim Basin and the west of the Kunlun Mountains. TWS changes may attribute to the melting of glaciers in the upper reach of the Amu Darya River and Ili River as a result of global warming and the changes affecting the terminal lake – Balkhash Lake.

TWS can be described by the water balance equation $\Delta W = P - R - E$, where ΔW is terrestrial water storage, P is precipitation, R is runoff, and E is evapotranspiration. Vegetation has close relationship with precipitation, runoff and evapotranspiration. Temperature also greatly affects evapotranspiration. On the other hand, the human activities altered the water resource redistribution and the land use types. So the factors influencing the water storage variations in Central Asia, including climate change, vegetation change and human activities, are discussed in the following section.

4.2 The influence of climate change on TWSC in Central Asia

To study the influence of climate change on TWSC, the spatial variations of climatic factors were analyzed. The mean correlation coefficients between TWS and both climatic elements of precipitation and temperature were calculated.

4.2.1 Fluctuation characteristics of regional climate

Previous studies have shown that the climate in Central Asia has become warmer and more humid in recent years (Chen *et al.*, 2011; Hu *et al.*, 2014). Accordingly, precipitation and temperature variables were selected to analyze the effects of climate change on TWSC. The change rates of precipitation and temperature (based on the absolute value of 2003) were calculated. The spatial characteristics of climate change are shown in Figure 4.

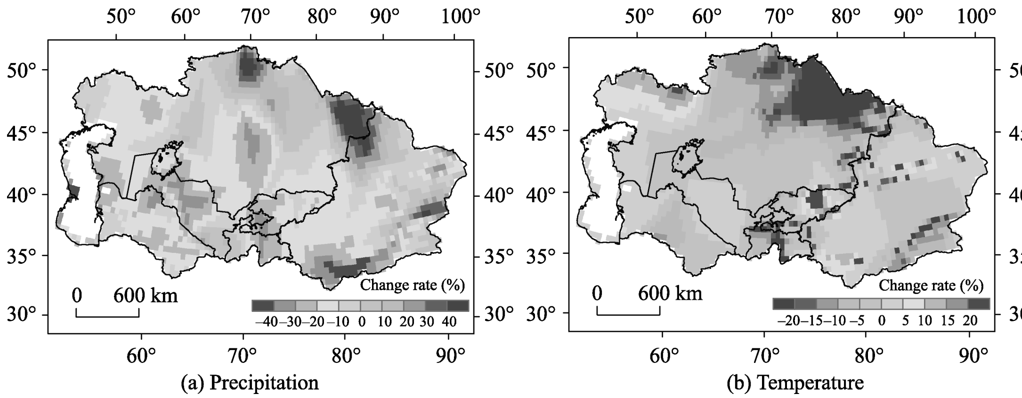
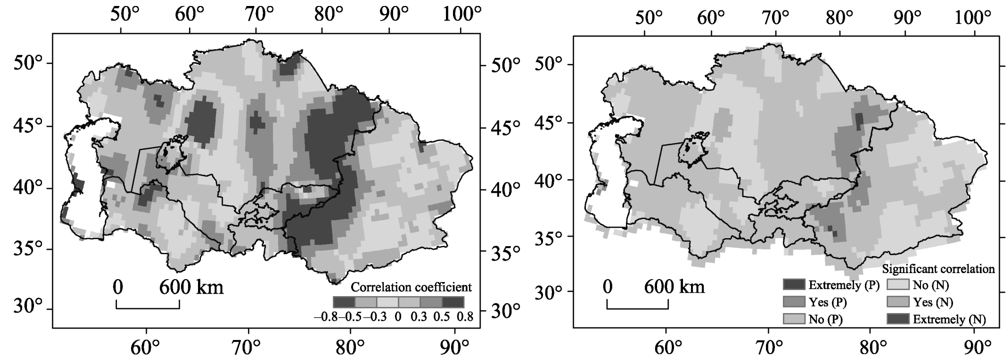


Figure 4 Spatial variations of climatic factors

Figure 4a indicates that precipitation increased in 72.89% and decreased in 27.11% of Central Asia. The areas where precipitation decreased are mainly distributed in the central zone of Uzbekistan, the east of Tajikistan, the west of Kyrgyzstan, south-central Kazakhstan, the south of the Tarim Basin and the west of the Kunlun Mountains. The precipitation data shows an increasing trend in northern and eastern Kazakhstan, northwestern and eastern Xinjiang, China from 2003 to 2013. Figure 4b shows a decreasing trend in temperature in about 64.71% of Central Asia from 2003 to 2013, mainly over northeastern Kazakhstan, central Tajikistan and southeastern Xinjiang. The temperature increase is below 5% in about 73.93% of the region, while the temperature increased more significantly in the northern Turgay Plateau and to the west of it, central Kyrgyzstan and sporadic areas in north-central Xinjiang.

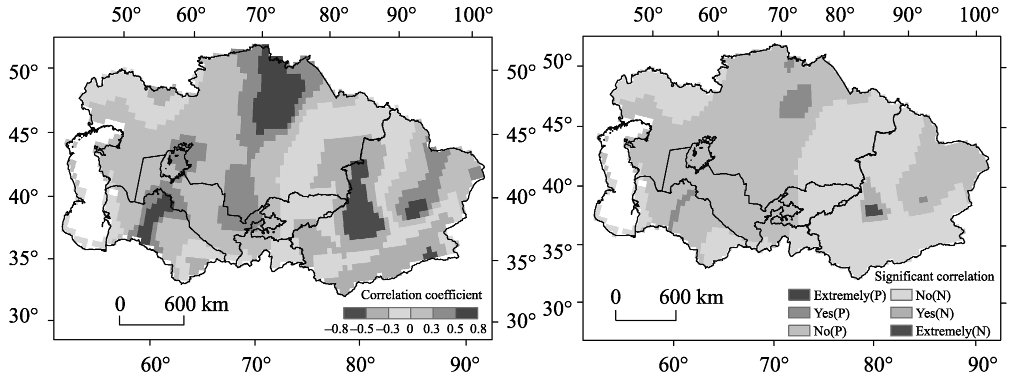
4.2.2 Relationship between climate change and TWSC in Central Asia

To analyze the relationships between TWSC and climate change, the Pearson correlation analysis method was used to calculate the correlation coefficients between TWS and precipitation and temperature. Then, significance tests were carried out (significant when $P<0.05$; extremely significant when $P<0.01$). The results are shown in Figures 5 and 6.



(a) Correlation coefficients (b) Results of significance test

Figure 5 Response relationship between TWS and precipitation



(a) Correlation coefficients (b) Results of significance test

Figure 6 Response relationship between TWS and temperature

In Figure 5a, the mean correlation coefficient is 0.38, indicating low correlation between TWS and precipitation in Central Asia. The variables are positively correlated in 70.82% of the study area. There is weak positive correlation in 55.08% and moderate positive correlation in 18.72% of these areas. The east of Kazakhstan, the west of the Tianshan Mountains in Xinjiang and the northwest of the Tarim Basin are the main regions showing a moderate positive correlation. Mostly, there are weakly negative correlations between TWS and precipitation.

The test results in Figure 5b indicate that TWS is significantly and positively correlated with precipitation mainly in mountainous areas and their piedmont zones in eastern Kazakhstan and western Tianshan of Xinjiang and the basin in front of it. The areas of significant and positive correlation account for about 5.92% of Central Asia. In the eastern part of Kazakhstan, higher elevations result in more rainfall, thus precipitation has become the decisive factor for TWSC. Figures 3 and 4a show that TWS in piedmont areas is recharged by precipitations in mountains. The rainfall in the Altai Mountains significantly increased while TWS in the Balkhash Lake Basin most significantly increased. To the northeast of the Aral Sea, a significantly negative correlation was found between TWS and precipitation in the Turgay Valley, which makes up 1.01% of Central Asia. In this area, TWS decreased even with more precipitation and less evapotranspiration. Human activities may explain the phenomenon observed.

Overall, TWS is weakly correlated with temperature and the mean correlation coefficient is 0.15. Figure 6a shows that the areas where they are positively correlated account for about 57.42% of Central Asia. For these areas, 62.56% showed weakly positive correlation and only 11.31% showed a moderate positive correlation, mostly in west-central Turkmenistan and the north of Kazakhstan. The negatively correlated area covers 42.58% of Central Asia, with weak correlation occupying 62.67%. In western Tianshan of Xinjiang and its southern slope, it makes up 6.9% of the area where TWS is negatively correlated with temperature, the correlation is moderate. Figure 6b indicates that the regions where TWS and temperature are significantly correlated are scattered and only account for 3.78% of Central Asia.

Precipitation and TWS reached a maximum almost at the same time, but peak temperature lagged peak TWS by about three months. When the temperature data time series was moved forward by three months, the mean correlation coefficient between TWS and temperature was 0.78, which represents a high correlation. This is because the precipitation can directly and quickly affect TWS, while the influence of temperature on TWS has to get through evapotranspiration in Central Asia.

4.3 Relationship between vegetation change and TWSC in Central Asia

To investigate the influence of vegetation change on TWSC, the changing trend of vegetation index and the correlation between evapotranspiration and TWSC were analyzed.

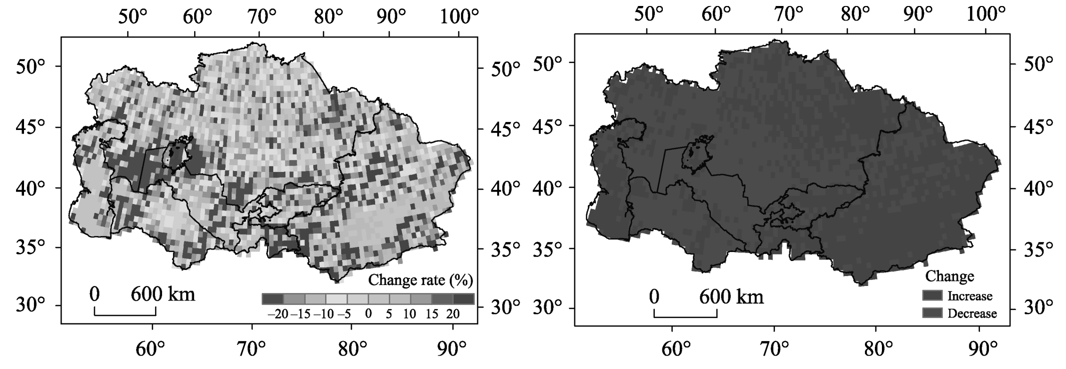
4.3.1 Effects of vegetation change on TWS

Using the aforementioned methods to analyze the changing trend and correlation, the relationship between vegetation index and TWS was analyzed. The results are shown in Figures 7 and 8.

Figure 7 shows that, in the study area, the NDVI is generally higher in the east and lower in the west from 2003 to 2013. The areas where the NDVI is higher are mainly distributed over the east of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Xinjiang, China. These areas make up 50.09% of Central Asia, however NDVI increased by less than 10% in 59.9% of these areas. In the Pamirs, the Tianshan and the Kunlun mountains of Xinjiang, the NDVI showed an obvious increase. On the other hand, the NDVI decreased in 49.91% of Central Asia, mainly on the east coast of the Caspian Sea, the areas surrounding the Aral Sea, and the deserts in five countries of southeast Central Asia.

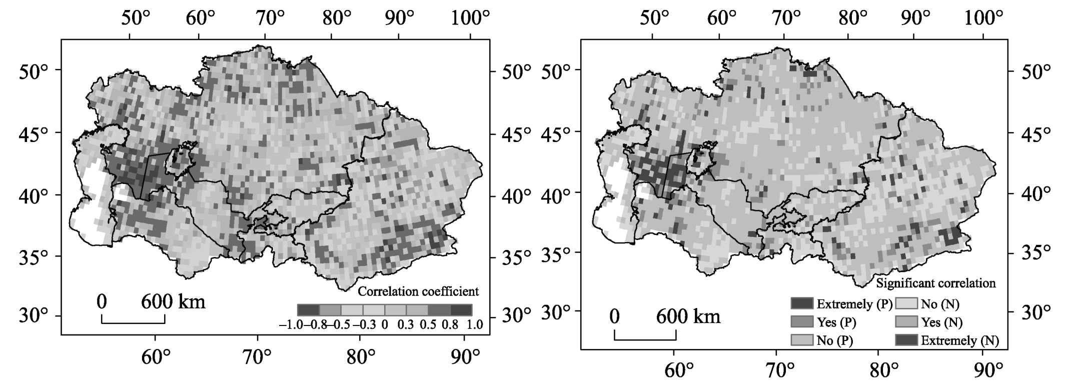
In Figure 8a, TWS and vegetation index are weakly correlated, with a mean correlation coefficient of 0.14. The variables are positively correlated in 74.7% of the study area. The correlation is moderate or high in 30.49% of the aforementioned areas, mostly on the east coast of the Caspian Sea, the areas surrounding the Aral Sea and in southeastern Xinjiang. The regions where there is negative correlation between TWS and vegetation index cover 25.3% of Central Asia, of which 67.51% are weakly correlated. Most of the areas with moderate or high correlation are in the Pamirs, and the middle Tianshan of Xinjiang, which occupy 13.56% of the zones with negative correlation. From Figure 8b, in 13.35% of the research areas, TWS is significantly or extremely significantly correlated with the vegetation index. These areas are mostly located in the desert regions between the Caspian Sea and Aral Sea. The effects of water on vegetation variations are most remarkable in deserts.

After shifting the NDVI data time series forward by two months, the correlation coefficient between TWSC and NDVI is up to 0.71, namely, a moderate correlation. This shows



(a) Change rate (b) Change distribution

Figure 7 Spatial variations of vegetation index (NDVI)



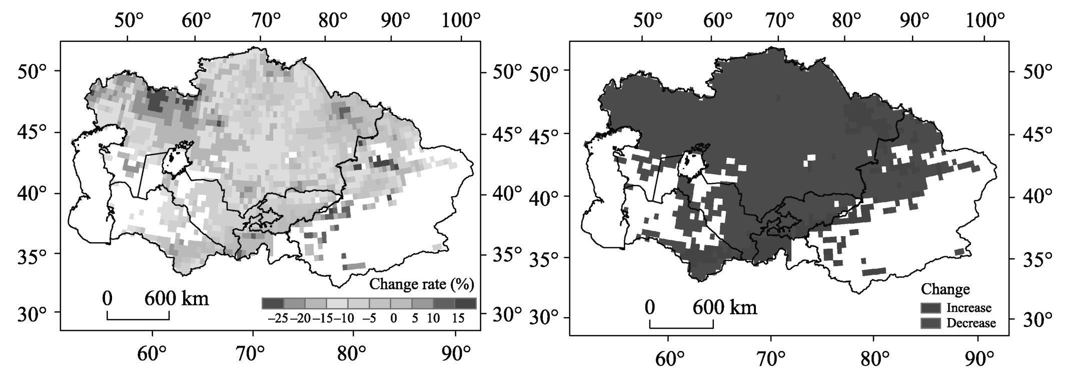
(a) Correlation coefficients (b) Results of significance test

Figure 8 Response relationship between TWS and vegetation

that vegetation growth lags behind TWSC by about two months.

4.3.2 Effects of evapotranspiration on TWS

In this section, the methods used to analyze the impacts of climate change on TWS were used to investigate the spatial variations of evapotranspiration (Figure 9) and the relationship with TWS (Figure 10). Evapotranspiration in areas without any vegetation coverage was not calculated for MOD16A2 products, and its value was set as null in water, desert and the Gobi area.



(a) Change rate (b) Change distribution

Figure 9 Spatial variations of evapotranspiration

Figure 9 shows an increasing trend in the evapotranspiration in only 12.07% of areas (mainly the east and southeast) from 2003 to 2013. 62.33% of areas have trends lower than 5%. The areas with decreasing trends account for 87.93% of Central Asia. The reduction rates are lower than 15% in 66.11% of these areas, and greater than 20% in 8.31% of these areas. The main regions of significantly decreased evapotranspiration are the Turgay Plateau and northwest of the Plateau.

The correlations between TWS and evapotranspiration are positive in 90.69% of Central Asia (Figure 10a). Among those areas, 51.55% show moderate or high correlation, mostly in the northern Turgay Plateau and to the west of it. However, in 9.31% of areas, mainly the Balkhash Lake Basin and desert areas of southern Central Asia, the two variables are negatively correlated. Some 73.26% of negative correlations is weak.

Figure 10b shows significant or extremely significant correlations between TWS and evapotranspiration in 31.87% of the study area, mainly in the grassland of northwestern Kazakhstan and mountainous areas.

Even in conditions of decreased evapotranspiration, TWS shows a declining trend in mountainous regions, the Turgay Plateau and to its west. Reduced precipitation plays a leading role. Decreasing evapotranspiration with increasing temperature in this area is consistent with the "evaporation paradox" (Brutsaert and Parlange, 1998). TWS in plains in northern Kazakhstan decreases with reduced rainfall and evapotranspiration. The increased surface area of arable land may be the main factor explaining this relationship.

4.4 Effects of human activities on TWSC

LUCC was used as an index to reflect human activities. The raw data is acquired from MCD12Q1 data, processed by MRT. According to the Plant Functional Type classification system, determined by a supervised decision tree classification method, 13 types of land use are identified in Central Asia. Figure 11 shows the land use map of the study area in 2003. After summing up the area of each type between 2003 and 2013, the correlation coefficients between TWS and the area of each type were computed. The percentage of land use types in 2003 and the correlation coefficients are shown in Table 2.

As shown in the land use map (Figure 11), grassland makes up 47.37% of Central Asia, mostly distributed in Kazakhstan, Kyrgyzstan and northwestern Xinjiang, China. The area of bare land is only second to the grassland area, with a percentage of 29.44%, mainly covering the desert of southern Central Asia and Xinjiang. The Caspian Sea is the largest water body, accounting for 8.05% of the study area. The shrub land and the cereal crops that are mainly distributed in northern Kazakhstan cover 6.39% and 6.10% of the area. Other land use types cover less than 1%.

Table 2 shows the highest land cover changes from 2003 to 2013 in grassland and shrub land, affecting areas of 8.36×10^4 km^2 and -8.19×10^4 km^2, respectively. But we found low correlations between LUCC and TWS, with correlation coefficients of –0.36 and 0.37, respectively. Areas of water, evergreen needle-leaf forest, cereal and broad-leaf crops changed by more than 2×10^4 km^2, with correlation coefficients with TWS greater than 0.5, namely moderate correlations. The other types of land use changed a little, and the areas of forest are moderately correlated with TWS. In summary, TWS is negatively associated with land use types whose areas increased and positively associated with the area decrease of land use

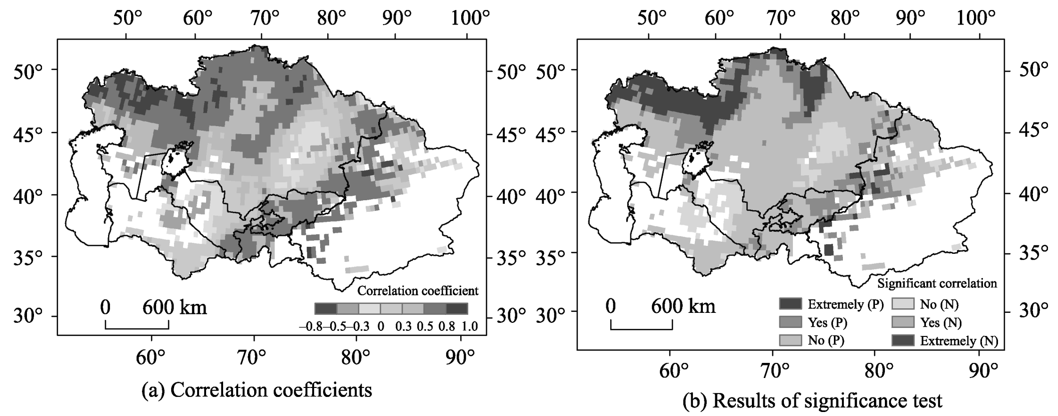


Figure 10 Response relationship between TWS and evapotranspiration

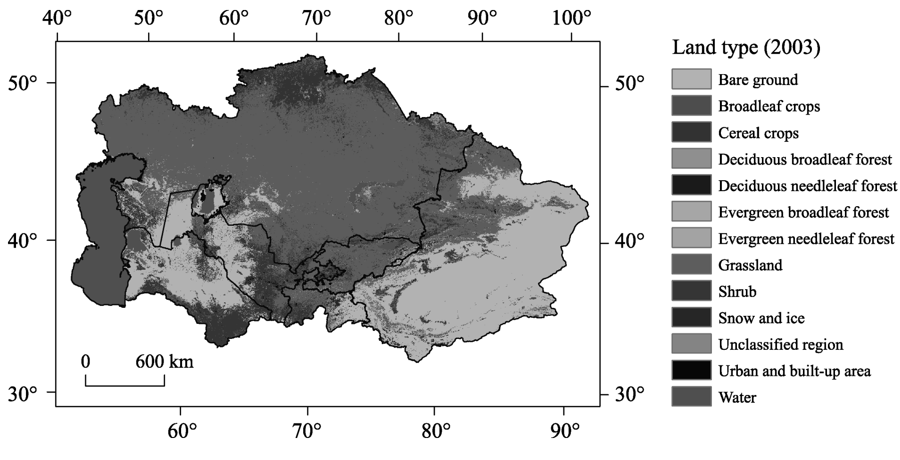


Figure 11 Land use map of Central Asia in 2003

Table 2 LUCC of Central Asia and correlation coefficients with TWS

Land use type	Percentage (%)	Changed area ($\times 10^4$ km^2)	Correlation coefficients
Water	8.05	–2.20	0.81
Evergreen needle-leaf forest	0.21	2.49	–0.76
Evergreen broad-leaf forest	0.02	–0.06	0.56
Deciduous needle-leaf forest	0.05	–0.22	0.75
Deciduous broad-leaf forest	0.17	0.25	–0.62
Shrub land	6.39	–8.19	0.37
Grassland	47.37	8.36	–0.36
Cereal crops	6.10	–5.44	0.55
Broad-leaf crops	1.08	2.32	–0.58
Urban and built-up area	0.34	0.0005	–0.50
Snow and ice	0.70	1.23	–0.27
Bare land	29.44	1.66	–0.15
Unclassified region	0.09	–0.19	0.40

types. Therefore, an analysis of correlations between TWS and land use only considering the area change is not sufficient, and the impacts of human activities on TWSC should be the focus of further research.

5 Conclusions

Based on the slope and Pearson correlation analysis methods, the temporal and spatial variations of TWS were analyzed using GRACE data from 2003 to 2013. The influence of climate change, evapotranspiration and human activities on TWSC in time and space were discussed, using remote sensing data including climate data, evapotranspiration, vegetation index and land use. The conclusions are as follows:

From 2003 to 2013, TWS in Central Asia increased first and then decreased with time, the volume of decreased TWS totaling about 2915.6 × 10^8 m^3. In about 77 % of Central Asia, TWS showed a decreasing trend from 2003 to 2013. The trend is more pronounced in middle-altitude regions of western and middle Central Asia and parts of the Tianshan Mountains in Xinjiang. The change rates are less than 100% over 46.4% of the areas where TWS increased. TWS significantly increased in the middle-altitude regions of the Kazakhstan hills and Tarim Basin.

The mean correlation coefficient between TWS and precipitation is 0.38. These variables, either significantly or extremely significantly, are positively correlated in mountain and piedmont regions, which account for 5.91% of Central Asia. The rainfall in mountainous areas is the main supply source of TWS in piedmont regions, while water storage in the Turgay Valley may be mainly affected by human activities. Air temperature has a weak effect on TWS with a mean correlation coefficient of 0.15, with significant correlation coefficients in only 3.78% of the study area. There is a three-month lag between temperature change and TWSC.

The mean correlation coefficient between TWS and NDVI is 0.14 overall. Correlations are positive and significant or extremely significant in 13.35% of the study area, mainly in the desert between the Caspian Sea and Aral Sea. In this region, the effect of water on vegetation is remarkable, and the response of NDVI to TWS lags by two months.

Significant or highly significant positive correlation was found between TWS and evapotranspiration in 31.87% of Central Asia, mostly the mountainous areas and northwestern Kazakhstan. The decrease of regional TWS is related to the decrease in precipitation rather than evaporation. Even in conditions of precipitation increase and evapotranspiration decrease, TWS still decreases in the north of Kazakhstan. The main reason may be the increase in farmland area.

The effects of land use and land cover change on TWS are analyzed in this paper, but this lacks the consideration of a response mechanism between these variables. Exploring how land use changes affect TWS will be the focus of a future study.

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