Water storage variations and their relation to climate factors over Central Asia and surrounding areas over 30 years

Xinwu Li, Xizhang Gao, Yuting Chang, Dapeng Mu, Hailong Liu, Zhongchang Sun and Jinyun Guo

ABSTRACT

Continental or regional water storage variations (WSVs) are crucial to regional economic development and human society and play an important role in coping with global change. Water scarcity is currently an especially key issue in Central Asia (CA), and therefore the study of WSVs can aid in the adoption of measures for mitigating pressures from contemporary environmental changes and economic development in CA. Based on Gravity Recovery and Climate Experiment (GRACE), Global Land Data Assimilation System (GLDAS), and CRU meteorological datasets and a proposed combined filter strategy, WSVs in Central Asia and its surrounding areas over 30 years are investigated in this paper. The results indicate that the WSVs derived from GRACE and GLDAS over CA generally show a decreasing tendency. CRU data demonstrated that CA has been undergoing a warming trend. The water loss in CA may be caused by warming, which will lead to the loss of soil moisture. Moreover, the water mass in the Tibetan Plateau and Tarim basin increases, which may be caused by glacier melting in the Pamirs and Himalaya. The precipitation contributed little to changes in water storage, but at the basin scale, the precipitation anomalies were very similar to the GRACE and GLDAS data, which can be viewed as an indicator of WSVs.

Key words | Central Asia, climate change, GLDAS, GRACE, WSV

INTRODUCTION

Central Asia (CA) is one of most seriously ecologically and environmentally deteriorated regions in the world and now faces vegetation degradation, land desertification, soil salinization, shortages of water resources, discontinuous river flows and disappearing lakes. Water scarcity is currently an especially key issue in this region and has severely restricted economic and societal development. Water storage is a key state variable in the global water cycle and climate change and is an extremely important resource related to economic and societal development.

Water scarcity is currently a key issue, and given that the main rivers are common to state boundaries, conflicts over
water use arise regularly on national and local scales in Central Asia (CA) (Horsman 2001; Bernauer & Siegfried 2012). Millions of people in the geopolitically important region of Central Asia depend on water from international rivers that are driven by snow and glacial meltwater, especially the Syr Darya and Amu Darya Rivers (Aizen et al. 2001). The riparian countries of these rivers have experienced recurring water allocation conflicts since the collapse of the Soviet Union (Siegfried et al. 2010). At the same time, economic development has increased the demand for water resources, and a large amount of terrestrial water resources have been exploited in CA (Stone 2012). This exploitation caused friction between CA countries in arid areas and affected regional stability and national security (Qi & Evered 2008). Climate change is also widely expected to exacerbate water stresses in CA (Siegfried et al. 2010). The warming trends in CA have increased the melting rates of mountain glaciers and snow over the past 50 years and have changed the water resources of major river basins (Qi & Evered 2008). Issues surrounding water resources in CA have become important topics for numerous scholars and various levels of the government (Parry 2007; Siegfried et al. 2010).

Water storage is a key state variable of the global water cycle and climate (Famiglietti 2004), and it is an extremely important resource for economic and societal development (Yang et al. 2013). The study of water storage variations (WSVs) in CA and its surrounding areas (SA) is necessary for analyses of water recycling and climate change and for estimating water resource changes in the future. The Gravity Recovery and Climate Experiment (GRACE) was launched by NASA and the German Aerospace Center in March 2002 to observe the Earth’s gravitational field and energy cycle, and has provided new approaches for WSV measurements of unprecedented accuracy (Tapley et al. 2004a). Over 10 years, GRACE has collected large amounts of spatial data that can aid studies of variations in global and regional water storage, hydrology and water resources (Ramillien et al. 2008). There has recently been considerable progress in the use of GRACE datasets for monitoring WSVs at mid-latitudes in Asia. Xu et al. used GRACE data to estimate the trend in the spatiotemporal variation of water reserves in the Tianshan Mountains during a recent 8-year period (Xu et al. 2013). Yang & Chen studied terrestrial WSVs based on GRACE data and compared the results with those derived from the Tianshan Mountains and the SA using the Global Land Data Assimilation System (GLDAS) model (Yang & Chen 2015). They reached the same conclusion as Xu et al. (2013) for the respective study time frames: the interannual fluctuations in water storage tended to decrease in the Tianshan Mountains. Sun et al. (2014) analyzed the annual variations in water storage over CA using 10 years of GRACE data with support from other data, and the amplitudes of the annual variations in water storage exhibited a general E-W increasing trend.

Generally, at mid-latitudes in the area of Asia, most analyses of WSVs related to GRACE datasets have focused on the Qinghai-Tibet plateau, Tarim basin and Tianshan Mountain areas. The existing status and trends of future changes in water storage in Central Asia and its SA are still open scientific issues. The aim of this study is to estimate the characteristics of spatial-temporal variations in water storage and their relationship to climate factors that affect CA and the SA by combining GRACE, GLDAS and other datasets from 1979 to 2012, a period of over 30 years, to lay a foundation for more quantitative studies in the future and hopefully provide basic information and theoretical support for the sustainable use and development of water resources in CA and its SA.

STUDY AREA AND DATASETS

Study area

The study area included five countries in Central Asia (Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan and Tajikistan) (Cowan 2007) and the SA (including Xinjiang and the Tibetan Plateau in China, the western part of Mongolia and southern Russia) (Figure 1, left). Central Asia is located in the interior of Eurasia, in which the southeastern edges of mountain ranges cut off warm moist air that flows from the Indian and Pacific Oceans (Mughal 2013). Hence, Central Asia has a typical temperate continental desert and grassland climate. Temperatures and precipitation follow a gradient from north to south and from the lowlands...
to the mountains (Gessner et al. 2013). The annual precipitation in these regions is between 100 and 400 mm (Gessner et al. 2013). The water resources in the study area are preserved in the form of glaciers, lake water, runoff, and soil moisture. The high elevation regions, Tianshan, Pamirs and Tibetan Plateau, contain abundant glaciers, which are very important sources of fresh water. The Pamirs’ glaciers also make a notable contribution to the runoff in the headwater catchments of CA, including those of the Amu Darya and Syr Darya Rivers (Unger-Shayesteh et al. 2013). The Caspian Sea, which is the largest inland body of water in the world, the Aral Sea, Balkhash Lake and Issyk-Kul Lake contain large water resources that are used in CA for agriculture and industry. Agriculture is the largest water consumer in the study area, accounting for more than 90% of water withdrawal (Unger-Shayesteh et al. 2013). Agricultural water consumption has generated many serious environment problems, including the shrinkage of the Aral Sea. The area of the Aral Sea declined by 62% from 2002 to 2009 (Singh et al. 2012). To study the changes in water storage at the basin scale, we selected four typical watershed basins within the study area: the Aral drainage, Issyk-Kul Basin, Balkhash Basin and Tarim River Basin (Figure 1, right).

Datasets

In this study, GRACE Level-2 RL05 variable gravity field spherical harmonic coefficient (SHC) data released by CSR (the University of Texas Center for Space Research) agencies (http://www.csr.utexas.edu/grace/) were used to compute the terrestrial water height (Landerer & Swenson 2012) from January 2003 to December 2012. The GRACE data consist of monthly estimates of SHCs that are developed up to degree and order 60.

Hydrology model datasets from GLDAS terrestrial hydrological assimilation data (Rodell et al. 2004b) were processed to validate, explain and enhance the understanding of the GRACE-derived results. Our study first used the results from GLDAS to validate the results from the GRACE data (Rodell et al. 2004a; Tapley et al. 2004b; Chen et al. 2005), and the GLDAS dataset was then used to extend the variations in water storage beyond the GRACE period to determine the water mass changes (Rodell et al. 2004b) in the study area from 1979 to 2012.

Climate data, i.e., temperature and precipitation, released by the University of East Anglia’s Climatic Research Unit (Mitchell & Jones 2005) were used to investigate the relationship between WSVs and climate factors. This dataset is provided in 0.5-degree grids every month and is available at http://www.cru.uea.ac.uk/data.

METHODOLOGY

Figure 2 shows the methodology for analyzing the WSVs in the study area using GRACE and GLDAS. Three aspects are included: (1) preprocessing the GRACE, GLDAS and
CRU datasets, which includes filtering and GIA (glacial isostatic adjustment model) corrections; (2) estimating and analyzing the WSVs based on the least squares spectral analysis method (two parameters, the linear trends and the period components of the WSVs, were derived from the GRACE and GLDAS datasets); and (3) investigating the spatial-temporal characteristics of the WSVs and the relationship between the WSVs and climate factors.

Data pre-processing: combined filter strategy

A key issue of GRACE’s data processing is the selection and establishment of a filter strategy (Werth et al. 2009). In this study, a combined filter strategy with a Fan filter of 300 km was proposed based on the error and time series characteristics of a monthly solution gravity model. This filter strategy included a statistical filter, a Fan filter and a de-correlation filter. A statistical filter was used to reduce unnecessary drops while processing the potential coefficient and saving the original signal. The basic steps were as follows. First, a statistical approach, i.e., the F test (Davis et al. 2008; Huang et al. 2012), was used to examine the linear and periodic components in the time series of GRACE SHCs. If the SHCs passed the test, the datasets remained unchanged; otherwise, a Fan filter (Zhang et al. 2009) was applied. All the SHCs were then filtered using the decorrelation method (Swenson & Wahr 2006) to remove the correlated errors. After filtering, the monthly SHCs were converted into equivalent water heights (EWHs) (Wahr et al. 1998) on one degree grids.

Data pre-processing: post-glacial rebound

GRACE uses satellite perturbations to determine the geoid and its changes. Changes in the geoid are not only caused by mass movements and the redistribution of the Earth but are also a consequence of the Earth as an elastic medium that is globally affected by post-glacial rebound (PGR), with changes at different rates in different regions. GRACE measurements are particularly sensitive to PGR (Velicogna & Wahr 2006a, 2006b). Therefore, this effect should be removed when GRACE is used to invert the mass change of the Earth, especially in North America, North Europe, Greenland and Antarctica, whose change rates due to PGR reach 5–11 mm/yr.
The PGR signal in the study area was investigated using the ICE-5G model, which gives global uplift rates. From Figure 3, the PGR change rate in CA and its SA increased from west to east and was less than 0.5 mm/yr, which amounted to less than a 2 mm EWH correction for GRACE. Considering that the geoid accuracy determined by GRACE is approximately 10 mm, the PGR effect can be ignored in this study area.

WSV estimation based on least squares spectral analysis

The time series of mass anomalies were obtained on a 1° × 1° grid from the GRACE and GLDAS datasets. These mass anomalies mainly indicate a hydrological signal that has significant annual, semi-annual and linear changes. The least squares spectral analysis was applied to perform the deterministic modeling of the mass anomalies (Vaníček 1969; Wu et al. 1995; Craymer 1998). Thus, the fitting of each grid can be conducted as follows:

\[ H(t_i) = A_0 + B_0 t_i + A_1 \cos 2\pi f_1 t_i + B_1 \sin 2\pi f_1 t_i + A_2 \cos 2\pi f_2 + B_2 \sin 2\pi f_2 \]  

(1)

where \( H \) represents the equivalent water height derived from GRACE and GLDAS, \( t \) is time, \( A_0 \) is a constant, \( B_0 \) is the rate, and \( f_1 \) and \( f_2 \) are the annual and semi-annual frequencies. The annual amplitude \( S_1 \), semi-annual amplitude \( S_2 \) and corresponding phase \( \varphi \) can be obtained by

\[ S_j = (A_j^2 + B_j^2)^{1/2} \]  

\[ \varphi_j = \arctan \left( \frac{A_j}{B_j} \right) \quad j = 1, 2. \]  

(2)

The amplitude of the fitting result indicates a strong or weak degree of periodic change, and a linear trend indicates increasing or decreasing water mass during a period (Rodell et al. 2004a).

RESULTS VALIDATION AND ANALYSIS

The cross validation of WSVs derived from GRACE and GLDAS datasets

Due to the lack of in situ measurements in Central Asia, cross validations of the WSVs derived from GRACE and GLDAS were conducted to demonstrate the effectiveness of the results.

Figure 4 shows the changes in linear trends from 2003–2012 based on the GRACE (left) and GLDAS data (right). The WSV linear trends for most of the areas showed decreasing tendencies, except for areas such as the Pamir region, Tarim basin, Tibet plateau, Balkhash Basin and parts of Russia. The difference can be mainly attributed to GRACE and GLDAS measurement differences, which will be explained later in this paper.

The correlation coefficients of the WSVs derived from GRACE and GLDAS were used to quantify the effectiveness of the WSVs. Figure 5 shows the spatial variations in the correlation coefficients between the monthly GRACE-based WSVs and the average GLDAS-based WSV.

As shown in Figure 5, the GRACE-born WSV time series indicated a positive correlation with the GLDAS simulations in most locations across the study area. The correlation coefficient was much higher than 0.6 in most of CA and exceeded 0.8 in the Pamirs, Tianshan and northwestern Kazakhstan. In Russia, the correlation coefficient also exceeded 0.8. The correlation coefficients indicate similar changes between the GRACE and GLDAS results. However, there was a distinct negative correlation between Xinjiang and the Tibetan Plateau in China and Mongolia,
which could be attributed to the GLDAS model’s inability to simulate ice sheet flow and mass balance, which was possibly related to groundwater changes. In these areas, the correlation coefficient value was low; it was reduced to 0.2 and even became negative for Kunlun Mountain, which is located on the Tibetan Plateau. The groundwater contribution to WSVs should not be neglected, but it was not included in the GLDAS simulations (Rodell et al. 2004b; Rodell et al. 2009). Thus, the poor correlation between the GRACE data and the GLDAS results was partially due to the inability of the GLDAS simulations to include surface water and groundwater components, especially in arid regions where groundwater can play a more important role than soil moisture in changes in the TWS. Bias and leakage errors due to the GRACE processing procedure may have also contributed to the poor correlation between the GRACE data and the GLDAS simulation results.

In general, the WSV series estimated from the GRACE-based products closely matched the GLDAS simulations in most locations within the study area, and demonstrated that the WSVs derived from GRACE were effective and could be used to investigate changes in WSVs in Central Asia combined with the WSVs derived from GLDAS datasets from 1979 to 2012. In addition, these results will be indirectly validated by the results of lake, soil moisture and vegetation changes over 30 years derived by our research group.

**Interannual variability of water storage from GRACE- and GLDAS-based estimates**

The monthly EWH from the GRACE and GLDAS datasets was obtained using Equations (1) and (2). The trend of
EWH is calculated on 1-degree grids by using the GRACE and GLDAS datasets. In order to investigate the WSV in a wide range, we assigned the mean value of trends in the grids of the study area as the WSVs. Figure 6 shows the results of using the GRACE data (red) and GLDAS data (blue).

The series (Figure 6) estimated from the GRACE and GLDAS data show notable decreasing trends in the EWH across the study area. The amplitude of the changes in the EWH in the study area estimated by the GRACE data was approximately -80 to 90 mm over the duration of the research. The interannual variability amplitude of the GRACE data was approximately 80 mm, which was greater than that of the GLDAS data and similar to the results obtained by Yang & Chen (2015) in the Tianshan Mountains and their adjacent areas. The WSV peaks and troughs generated from the GRACE and GLDAS data generally appeared at the same times, with maxima that were typically identified in March and April and minima identified in September, October and November. However, the loss rates indicated by the GLDAS data were greater than those indicated by the GRACE data, especially during 1999–2012 (Figure 6). As shown in Figure 6, there was a notable shift in the GLDAS WSV. A possible reason may be that the land cover map derived from MODIS, which has a higher resolution, was used to generate the GLDAS datasets, and more accurate GLDAS datasets were therefore obtained (Rodell & Houser 2004).

Spatial variabilities of the various estimates determined from GRACE and GLDAS

The least squares spectral analysis was used to capture the linear trends and amplitudes in the WSV. Figure 7 shows the linear trends in the WSV based on the GRACE and GLDAS data for most of the locations in the study area.

From Figure 7, for the five Central Asian countries, generally, the WSVs based on the GRACE and GLDAS data both indicate a decreasing trend, and the water mass loss was 6.13 mm/yr and 7.56 mm/yr from 2003 to 2012, respectively. This means that the soil land surfaces of the five Central Asian countries will have a tendency to become desiccated. Soil moisture change results derived by microwave remote sensing over 30 years in Central Asia support this supposition (Li et al. 2015). In addition, the vegetation greenness showed a significant degradation in Central Asia over 20 years from 1992 to 2012 (Zhou et al. 2015), which also might be related...
to decreases in water storage in Central Asia. For the SA of Central Asia, in the northwestern portion of Kazakhstan, the Caspian Sea area and north Tianshan Mountain area, the WSV showed a significantly decreasing tendency from the GRACE datasets, but increasing trends in the Tibetan Plateau, Tarim River Basin, Balkhash Lake basin, middle border between Uzbekistan and Turkmenistan and part of Russia were observed from the GRACE datasets. For example, a water mass increase of 15.45 mm/yr was detected by GRACE over the Tibetan Plateau from 2003 to 2012. In the Caspian Sea, GRACE revealed a loss rate of 25.86 mm/yr. From the GLDAS datasets, most of the area also showed a decreasing tendency, except for the Qinghai-Tibetan Plateau, Tarim River Basin and northern parts of Pakistan and India. From Figure 7, the WSVs based on the GRACE data were much more spatially heterogeneous than the WSVs based on the GLDAS data, which can be attributed to the fact that GRACE can map total water storage changes (such as soil moisture, lakes, rivers, groundwater and seasonal snow), but GLDAS can only capture soil moisture and seasonal snow changes. In addition, the linear trends of the WSVs based on the GRACE data were greater than those based on the GLDAS data. For example, in the northwestern region of Kazakhstan, the WSV based on the GRACE data decreased from 10 to 15 mm/yr (see Figure 7, left), and the WSV based on the GLDAS data decreased from 8 to 10 mm/yr (see Figure 7, right).

The results of the least squares spectral analysis indicated that the annual amplitudes of the GRACE and GLDAS data varied in space and time in different periods (see Figure 8). The annual amplitude based on the GRACE data indicates a more positive change compared to that based on the GLDAS data. For example, an annual amplitude of greater than 100 mm in the Pamirs was detected by GRACE, and GLDAS's amplitude was less than 40 mm. The GLDAS annual amplitude in the 2000s was much lower than the annual amplitude in the 1990s across the study area, especially in Kazakhstan. In northern Kazakhstan, the annual amplitude decreased by more than 30 mm of EWH (see Figure 8(a) and 8(b)). In the Caspian Sea, the annual amplitude decreased during both periods but to a lesser extent in the 2000s. The GRACE and GLDAS datasets also showed marked differences in the Pamirs from 2005 to 2008 (see Figure 8(c) and 8(d)). The annual fluctuations in the GRACE and GLDAS data were considerable, and the annual fluctuations were much higher for the GRACE data than for the GLDAS data. In a large area such as CA, hydrological signals are dominated by soil moisture. This can explain the similarity between the GRACE and GLDAS datasets. The discrepancies in the linear rates and amplitudes of the GRACE and GLDAS datasets can be attributed to changes in the water masses of lakes, rivers and groundwater.
DISCUSSION

There were notable spatial differences in the WSVs variations in CA from the above analysis. In this section, we thus focus on the discussion of why such spatial differences exist and what the main impact factors are.

Effects of glacier on WSVs in typical regions and basins

Substantial changes in the cryosphere of Central Asia and its SA due to global warming have been observed (Hagg et al. 2013; Yang et al. 2014). The glacier mass balance in the study area can be estimated using GRACE data, but the results vary depending on how the GRACE data are processed (Matsuo & Heki 2010; Jacob et al. 2012).

Based on our proposed filter strategy, the glacier mass balance was estimated in the Tianshan, Pamirs and Karakoram following Jacob et al. (2012). GLDAS’s signal from GRACE was removed, as shown in Figure 9, and the melting rates of the glaciers in the Tianshan, Pamirs and Karakoram were $-1.36$, $-3.98$ and $-7.32$ mm/yr (see Figure 9(c) –9(e)). The water mass changes on the Tibetan Plateau (TP) and in the Caspian Sea were greater than those in other regions, as shown in Figures 7 and 9. From 1979 to 2012, the WSV in the Tibetan Plateau and Karakoram increased at a rate of
more than 10 mm/yr (see Figure 7, right). The Tibetan Plateau has experienced overall surface air warming and increases in humidity since the 1980s, which triggered more convective precipitation over the central TP (Yang et al. 2014). The average rate of WSV based on the GRACE data was 15.45 mm/yr in the TP (see Figure 9(a)). The rate was much higher in the northern Tibetan Plateau. The results of some studies have indicated that the water mass increase in the TP can be attributed to the increasing number and levels of glacial lakes (Song et al. 2013; Zhang et al. 2013).

For the Caspian Sea, Swenson and Wahr concluded that the water level of the Caspian Sea increased for the period 2002–2006, as shown in the results from GRACE (RL04 data) and Jason-1. The GRACE RL05 data also indicated that the Caspian Sea gained water at a rate of 25.86 mm/yr from 2003 to 2005 (see Figure 9(b)). We found that the water level substantially retreated after 2006. The results indicate that the changes in the level of the Caspian Sea should be considered to be a multistage process that is affected by geological factors, hydro-climatic factors and...
water balance as well as anthropogenic factors, and the hydro-climatic changes have a dominant influence on the Caspian Sea level (Ramiz 2015).

Hydrological signals are stronger at the basin scale. The time series of the WSV in the four basins (see Figure 1) are shown in Figure 10, and the least squares spectral analysis results are summarized in Table 1. From 2003 to 2012, the linear trends derived in the four basins using the GLDAS data were negative. However, the trends derived using the GRACE data indicated that the WSV increased in the Tarim River Basin from 2003 to 2012. For the longer time series based on the GLDAS data (see Figure 10, right), the first three basins also indicated decreasing trends at rates of −3.3, −1.2 and −3.5 mm/yr. However, the GLDAS data indicated an increasing rate of 3.4 mm/yr in the Tarim River Basin, especially for the period 2000–2006 (see Figure 10, bottom right). Snow and glaciers play an important role in stream flow regimes in the Tarim River Basin, and there is minimal summer precipitation. Analyses based on MODIS data for the period 2000–2007 confirm that the decrease in snow cover duration is continuing and that snowmelt occurs earlier currently (Khalsa & Aizen 2008). Intensified snowmelt in regions surrounding the Tarim River Basin may strongly affect the quantity and seasonal distribution of local runoff, and increasing runoff has been observed in the Tarim River in past decades (Tao

![Figure 10](image_url) | WSVs (expressed in EWH, unit: mm) in four basins (see Figure 1, right).
Table 1 | The results of the least squares spectral analysis for four basins (see Figure 1, right)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Result</th>
<th>Annual A (mm)</th>
<th>P (month)</th>
<th>Semiannual A (mm)</th>
<th>P (month)</th>
<th>Rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aral</td>
<td>GRACE</td>
<td>61</td>
<td>–1.20</td>
<td>4</td>
<td>–0.04</td>
<td>79-12 05-12</td>
</tr>
<tr>
<td></td>
<td>GLDAS</td>
<td>25</td>
<td>–0.62</td>
<td>5</td>
<td>–1.40</td>
<td>03-12 03-04</td>
</tr>
<tr>
<td>Issyk-Kul</td>
<td>GRACE</td>
<td>52</td>
<td>–1.08</td>
<td>3</td>
<td>–0.61</td>
<td>05-08 09-12</td>
</tr>
<tr>
<td></td>
<td>GLDAS</td>
<td>33</td>
<td>–0.35</td>
<td>1</td>
<td>2.41</td>
<td>03-04 05-08</td>
</tr>
<tr>
<td>Balkhash</td>
<td>GRACE</td>
<td>42</td>
<td>–1.04</td>
<td>5</td>
<td>–0.05</td>
<td>09-12 05-08</td>
</tr>
<tr>
<td></td>
<td>GLDAS</td>
<td>29</td>
<td>–0.10</td>
<td>3</td>
<td>2.30</td>
<td>03-04 05-08</td>
</tr>
<tr>
<td>Tarim</td>
<td>GRACE</td>
<td>22</td>
<td>–2.84</td>
<td>6</td>
<td>0.52</td>
<td>09-12 05-08</td>
</tr>
<tr>
<td></td>
<td>GLDAS</td>
<td>24</td>
<td>–1.72</td>
<td>2</td>
<td>–2.21</td>
<td>03-12 05-08</td>
</tr>
</tbody>
</table>

Note: A is the amplitude, and P is the phase. The rates in different periods were estimated using data in the corresponding periods. The linear trends of the four basins varied in different periods (see Table 1). It can be inferred from Figure 10 and Table 1 that the GRACE and GLDAS datasets showed stronger decreasing trends from 2005 to 2008.

et al. 2011). Yang et al. (2015) concluded that increasing snow/ice melt water draining into the Tarim River Basin may be the underlying cause of the increasing WSV (Yang et al. 2015).

As shown in Table 1, the GRACE and GLDAS datasets varied in their annual amplitudes, with the exception of the linear trends. In general, the GRACE data’s annual amplitudes were much greater than those of the GLDAS data, except for the annual amplitude for the Tarim River Basin. This is easily understood, because the total water mass signal based on the GRACE data was stronger than the soil moisture data from the GLDAS dataset. For example, the annual amplitude for the Aral drainage based on the GRACE data was almost 2.5 times higher than that based on the GLDAS data (see Table 1). This can be explained by runoff and lake water, which were not included in the GLDAS simulations.

Effects of climate change on WSVs

According to high resolution regional climate models implemented for CA, temperatures are projected to increase up to 7 °C until the end of the 21st century (Mannig et al. 2015). The effects of human activities are excluded in the consideration of these data. The warming trend will aggravate the retreat of glaciers and the loss of surface waters over CA. Precipitation is another important contributing factor for WSVs. Many drought events in the basins have been triggered by extreme reductions in precipitation (Chen et al. 2009). We have analyzed the interannual variabilities in the precipitation and temperature for our research period to evaluate the causes of the interannual variability in water storage based on the GLDAS data.

Effects of temperature on WSVs

Similar to the meteorological station and reanalysis data, the CRU temperature data for 1979–2012 also demonstrated that the five countries in CA experienced warming trends (see the red line in Figure 11). In Figure 11, the temperature represents the average of grids in the five countries in CA, and the temperature data for 2004 meet the Mann-Kendall test for trends, which indicates that the warming trend was significant. The time series based on the GLDAS data for the five countries in CA in 2002 meets the Mann-Kendall test for trends (see Figure 11). The significance statistic for temperature in 2002 was 1.94, which approximated the significance level (see Figure 11). Moreover, except some years (1984–1987), the statistical values of the temperature have been greater than zero since 1980 (see Figure 11), which indicate that the temperature has an obvious rising trend. By contrast, the statistical values of water reserve change have been less than zero except in 1988, which indicates the water reserve has been reducing all the time. This relationship between temperature and the GLDAS data implied that warming trends had a potential influence on WSVs.

The changes in the glaciers in CA were influenced more by climatic factors, especially temperature (Hagg
et al. 2013; Yang et al. 2014). To demonstrate the effect of temperature here, two regions, Kunlun Mountain (R01, 37–39N, 88–89E) and the eastern Pamirs (R02, 36–38N, 74–76E), which are adjacent to the TP and the Tarim River Basin, respectively, were selected for this study. These two selected regions are covered by ice and snow, which supply water resources to the SA. The CRU data confirmed that the temperatures of R01 and R02 increased at rates of 0.46 °C and 0.39 °C/decade, respectively (see Figure 12). Although the warming trend was notable, the highest annual mean temperature during 1979–2012 was below the freezing point. This warming trend may not accelerate glacial melting. Actually, the shrinkage of glaciers is highly related to the trend of increasing temperatures in the summer (Kriegel et al. 2013). The CRU also revealed that R01 and R02 have experienced increasing trends in June, July and August at rates of 0.49 °C and 0.29 °C/decade, respectively (see Figure 12).
Effects of precipitation on WSVs

Precipitation has an important effect on WSVs (Chen et al. 2009). As indicated by the CRU data, the precipitation over the five countries in CA was stable during the period of the study (see Figure 11). No abnormal change was detected by the Mann-Kendall test. However, we cannot conclude that precipitation did not contribute to the WSVs over the study area.

The precipitation anomalies were obtained by subtracting the mean precipitation value from 2003 to 2012. The precipitation anomalies in the four basins (see Figure 1, right) were averaged and were determined to be consistent with the GRACE and GLDAS data in the Aral drainage, Issyk-Kul and Balkhash basins (see Figure 13). In these three basins, the CRU precipitation decreased during 2005–2008, similar to the GRACE and GLDAS data. The precipitation anomaly, GRACE data and GLDAS data all indicated minimum precipitation in 2008. A possible reason was that a drought event might have occurred during that year. The change pattern in the Tarim River Basin was different from that in other basins; the precipitation anomaly reached a minimum in 2009. The fluctuations in the GRACE data, GLDAS data and precipitation anomaly were also different. A possible reason is that the geographical environment in the Tarim River Basin is more complicated than the environments in other basins because the large Taklimakan Desert is located in this basin. It is noteworthy that the magnitude of the precipitation anomaly was lower than the magnitudes indicated by the GRACE data and the GLDAS data. In addition, other contributions from runoff, lake water and groundwater cannot be neglected. Generally, at the basin scale, the precipitation anomalies were very similar to the GRACE and GLDAS data, which can be viewed as an indicator of WSVs.

CONCLUSIONS

Based on GRACE, GLDAS and CRU meteorological data-sets, variations in water storage in Central Asia and its SA over 30 years were investigated in this paper.

![Figure 13](http://dx.doi.org/10.2166/ws.2017.206)
The result indicates the following. (1) The water storage values obtained from GRACE and GLDAS over CA generally exhibited a decreasing tendency, and the results from GRACE over CA were spatially more heterogeneous than those from GLDAS. (2) For CA’s SA, the water storage presented a different change tendency due to the effects of natural factors such as snow or glacier melting. (3) The water losses in the five CA countries may be caused by warming, which will lead to the loss of soil moisture, and furthermore, the water increases in the TP and Tarim basin may be caused by glacier melting around the Pamirs and Himalaya. At the basin scale, the precipitation anomalies were very similar to the GRACE and GLDAS data, which can be viewed as an indicator of WSVs.

Due to a lack of in situ measurements related to water resource changes, a full quantitative analysis and assessment of the change tendency of WSVs was not conducted in this paper. In addition, because human and social economic data were not included in this study, the mechanisms of changes in water storage were not fully explained and understood. In the future, to further investigate water storage changes under a background of global change, an observational network needs to be constructed, and more datasets need to be collected to fully understand tendencies in water storage changes and their mechanisms and how these changes affect the ecological environment of Central Asia and its surroundings.

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