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Research papers

Influences of recent climate change and human activities on water storage variations in Central Asia

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ABSTRACT

Terrestrial water storage (TWS) change is an indicator of climate change. Therefore, it is helpful to understand how climate change impacts water systems. In this study, the influence of climate change on TWS in Central Asia over the past decade was analyzed using the Gravity Recovery and Climate Experiment satellites and Climatic Research Unit datasets. Results indicate that TWS experienced a decreasing trend in Central Asia from 2003 to 2013 at a rate of -4.44 ± 2.2 mm/a, and that the maximum positive anomaly for TWS (46 mm) occurred in July 2005, while the minimum negative anomaly (-32.5 mm) occurred in March 2008–August 2009. The decreasing trend of TWS in northern Central Asia (-3.86 ± 0.63 mm/a) is mainly attributed to soil moisture storage depletion, which is driven primarily by the increase in evapotranspiration. In the mountainous regions, climate change exerted an influence on TWS by affecting glaciers and snow cover change. However, human activities are now the dominant factor driving the decline of TWS in the Aral Sea region and the northern Tarim River Basin.

1. Introduction

Terrestrial water storage (TWS) comprises groundwater, soil moisture, surface water bodies (lakes, rivers, and reservoirs), glaciers, snow water equivalent, and canopy water storage (Syed et al., 2008; Tangdamrongsub et al., 2015). 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. Changes in temperature and wind speed cause variations in evapotranspiration, which, in turn, cause changes in TWS. TWS is a transient state that is dependent on the relationship between the input (i.e., precipitation and runoff) and output (i.e., evapotranspiration, runoff, and human water use). Global water storage is balanced because input and output are essentially equal on a global scale. However, there are differences between input and output across different regions and seasons, with variations in TWS exhibiting seasonal characteristics (Hirschi et al., 2006; Grippa et al., 2011; Yang and Chen, 2015).

Because TWS is a key variable in the hydrological cycle (Hirschi et al., 2006), it has significant ecological, environmental, societal, and economic impacts (Ramillien et al., 2005; Long et al., 2014; Cao et al., 2015). Glacier and snow melt are important water resources in semi-arid and arid regions, especially in Central Asia (Sorg et al., 2012; Chen et al., 2015), and are affected by various effects of climate change on TWS (Immerzeel et al., 2010; Sorg et al., 2012). Glaciers and snow are important components of TWS in mountainous areas (Aizen et al., 1997), including the study area where most of the rivers originate from the Tian Shan Mountains. Recent research results indicate that increases in glacier and snow melt decreased TWS in the mountain regions (Matsuo and Heki, 2010) but increased it in the surrounding basin area (Yang et al., 2015).

Since being launched in March 2002, the Gravity Recovery and Climate Experiment (GRACE) mission has provided data that can be used for analyzing TWS. Examples of areas that have been studied using GRACE data include the Congo Basin (Crowley et al., 2006), the Mississippi River Basin (Zaitchik et al., 2008), the Amazon Basin (Xavier et al., 2010), and the Yangtze River Basin (Long et al., 2015). Table 1 presents a summary of the relevant literature on estimated TWS variations based on GRACE datasets.

Investigations indicate that climate change has intensified water resources stress in Central Asia over the past few decades. Temperatures have exhibited a rising trend, and precipitation variability has increased (Lioubimtseva et al., 2005; Mannig et al., 2013; Li et al., 2015). Climate change has also led to increasing river runoff variability (Bernauer and Siegfried, 2012) and is

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Table 1
Summary of relevant literature on terrestrial water storage based on GRACE datasets in relation to the aims of this study, which are: (1) to analyze TWS variations; (2) to determine applications of TWS to groundwater, evapotranspiration, flood and drought, and glaciers mass balance; and (3) to analyze the effects of climate change and human activities on TWS variations. We added the current study for completeness. Studies are first listed chronologically, and then in alphabetical order. The symbol 'n.r.' means 'not reported'.

Study	Scales	Degree/spatial resolution/time span	Key results
1-Ramillien et al. (2005)	Global	30/660 km/2 years	1. Estimate water volume changes over eight large river basins in the tropics 2. Estimate an average value of the evapotranspiration over each river basin, using the water balance equation 3. n.r.
2-Crowley et al. (2006)	Congon Basin	70/600 km/4 years	1. Estimates exhibit significant seasonal (30 ± 6 mm of equivalent water thickness) and long-term trends 2. n.r. 3. Precipitation contributed roughly three times the peak water storage after anomalously rainy seasons, in early 2003 and 2005
3-Strassberg et al. (2014)	USA	n.r./400 km/ 30 months	1. Correlation between GRACE-based TWS and measured GWS is significant (R = 0.58) 2. The results show the potential for GRACE to monitor groundwater storage changes in semiarid regions 3. n.r.
4-Yirdaw et al. (2008)	Canadian Prairie	n.r./800 km/ 46 months	1.The TWS decreased over the whole of Western Canada 2.Drought assessment 3.n.r.
5-Rodell et al. (2009)	Northwest India	60/300 km/ 73 months	1. n.r. 2. During the period of August 2002 to October 2008, groundwater depletion was equivalent to a net loss of 109 km^3 of water 3.Caused by irrigation and other anthropogenic uses
6-Xavier et al. (2010)	Amazon Basin	n.r./300 km/ 73 months	1. Focused on interannual variability of TWS over 2003–2008 2. n.r. 3. TWS shown to be highly correlated with the ENSO
7-Grippa et al. (2011)	West Africa	60/400 km/2003–2007 years	1. Water storage spatial distribution, including zonal transects, its seasonal cycle, and its and interannual variability 2. n.r. 3. n.r.
8-Houborg et al. (2012)	America	60/300 km/August 2002 to July 2009	1.n.r. 2. GRACE-based drought indicators 3. n.r.
9-Feng et al. (2013)	North China	60/200/2003–2010	1. n.r.; 2. The rate of groundwater depletion in North China was 2.2 ± 0.3 cm/a from 2003 to 2010 3. Caused by Irrigation
10-Long et al. (2013)	Texas	n.r./n.r./one year	1. GRACE shows depletion in TWS of 62.3 ± 17.7 km^3 during the 2011 drought 2. Drought detect 3. n.r.
11-Thomas et al. (2014)	Amazon, Zambezi, Texas, southeastern United states	n.r./n.r./127 months	1. n.r. 2. Combine storage deficits with event duration to calculate drought severity 3. n.r.
12-Long et al. (2015)	Global	60/300 km/January 2003–July 2013	1. Large differences in TWS anomalies from three processing approaches (scaling factor, additive, and multiplicative corrections) were found in arid and semiarid region, areas with intensive irrigation, and relatively small basins 2. n.r. 3. n.r.
13-Yi and Wen (2016)	United States	60/500 km/2003–2012	1. The equivalent water thickness increasing from −4 to 9.4 cm in the north and decreasing from 4.1 to −6.7 cm in the south 2. Drought assessment 3. n.r.
14-This study	Central Asia	60/300 km/2003–2013	1. (a) During the past decade, TWS variations in Central Asia presented a decreasing trend at a rate of −4.44 ± 2.2 mm/a; (b) The declining rate of TWS in western and northern Central Asia, Tian Shan Mountains, and northern Tarim River Basin are −10.68 mm/a, −3.86 mm/a, −3.6 mm/a, and −0.82 mm/a, respectively 2. n.r. 3. TWS decreased in northern Central Asia and Tian Shan Mountains was driven by climate factors, but in western Central Asia and northern Tarim River Basin was driven by human activities

driving more drought events (Lioubimtseva and Henebry, 2009). These effects will result in increased water resources stress (Siegfried et al., 2012) and consequently increase international conflicts over water resources in Central Asia (Bernauer and Siegfried, 2012).

As a semi-arid and arid region, Central Asia is highly vulnerable to changes in climate (Lioubimtseva and Henebry, 2009; Chen et al., 2016). Therefore, variations in TWS have significant impacts on the social and ecological environments of the region. However, previous studies paid little attention to the impact of climate