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Climate change and water storage variability over an arid endorheic region

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SUMMARY

Terrestrial Water Storage (TWS) plays an important role in regional climate and water resources management, especially in arid regions under global change context. However, serious lack of in-situ measurements in remote alpine mountains is hindering our current understanding of regional TWS change in the Tarim River Basin (TRB), a large and typical arid endorheic area in Northwest China of Central Asia. To solve the problem, four different hydrology products from the Gravity Recovery and Climate Experiment (GRACE) satellite, model simulations from Global Land Data Assimilation System (GLDAS) in conjunction with in-situ measurements, are utilized to investigate patterns and underlying causes of TWS and its component changes. An excess of precipitation over evapotranspiration (ET) plus runoff contributes to an increase of TWS. The phase of Total Soil Moisture (TSM) lags that of Snow Water Equivalent (SWE), indicating a recharge from snowmelt to TSM. Increasing TWS together with decreasing SWE resulted in an increase of subsurface water. Our results are of great value to amend basin-wide water management and conservation strategies for the similar arid regions considering climate change.

1. Introduction

Terrestrial Water Storage (TWS) plays a fundamental role within the global water, energy, and biogeochemical cycles (Famiglietti, 2004). TWS shapes climate and controls weather through a series of simple to complex processes and feedback mechanisms (Shukla and Mintz, 1982; Eltahir and Bras, 1996). However, TWS has not yet been measured with sufficient accuracy for vast areas due to lack of large scale monitoring means (Rodell and Famiglietti, 1999; Alsdorf et al., 2000; Lettenmaier and Famiglietti, 2006). The Gravity Recovery and Climate Experiment (GRACE) satellite mission was launched in March, 2002 with aims to observe large scale TWS variations (Tapley et al., 2004a). It has been demonstrated that seasonal and inter-annual changes in water storage for continental-scale patterns and for large river basins can be inferred from GRACE observations with an unprecedented accuracy (Tapley et al., 2004b; Ramillien et al., 2005; Schmidt et al., 2008). With the assistance of water storage components simulated by Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004), GRACE can serve as a robust tool to estimate Groundwater Storage (GWS) variations at large basin or continental scales (e.g. Ramillien et al., 2008; Rodell et al., 2009; Shamsudduha et al., 2012).

The extremely arid Tarim River Basin (TRB) in northwest China experienced a steady rise in population since 1960, increasing the need for irrigation. The large scale irrigation in the TRB constitutes a major modification to the natural water balance (Li et al., 2009) and has triggered a range of environmental problems such as soil salinization (Brunner et al., 2007), the unproductive loss of water resources through phreatic evaporation (Brunner et al., 2008) and degradation of riparian ecosystems along the Tarim River (Schilling et al., 2014). Owing to increasing water consumption by modern oasis agricultural development, many rivers in TRB suffer a declining recharge from headstreams and tributaries and gradually lost their hydraulic connections with the main stream of Tarim River (Zhou et al., 2012). Climate and natural environment changes coupling with the regional continental climatic conditions will further deteriorate local water security.

Global warming and intensifying human activities have triggered precipitation and streamflow to change significantly in many regions around the world (e.g. Yang et al., 2008, 2010, 2014; Wang et al., 2014). There are a number of studies addressing the hydrometeorological processes via investigating the changing characteristics of precipitation, runoff and air temperature in the TRB

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(e.g. Yang et al., 2011; Bothe et al., 2012; Zhou et al., 2012; Ling et al., 2013; Shang and Wang, 2013). Remote sensing together with Chloride Method have also been used to quantitatively evaluate the groundwater recharge rate and its distribution in analogous arid and semiarid regions (Brunner et al., 2004). However, so far no investigation concentrated on the vertically integrated TWS based on GRACE data over the TRB can be found. Due to the absence of in-situ equipment for precipitation, glacier, snowpack monitoring, especially in mountainous and desert regions (Fig. 1), little is known about large scale change patterns of hydrology cycle and water resources in TRB, thus seriously restricting to formulate sustainable water management strategies for arid region. Investigating the variability of water storage in the TRB is fundamental for a profound understanding of land-atmospheric and hydrological processes, and thus of great value for regional sustainable water resource management.

The objective of this work is to investigate the changing characteristics of TWS and its components and analyze the underlying causes of TWS variations in the TRB. A suite of GRACE hydrology products and simulations from GLDAS Land Surface Models (LSMs) are used to derive TWS states and fluxes. Results from different GRACE products and GLDAS simulations are quantitatively compared with each other as a cross-validation to evaluate the uncertainty, as compensation for the lack of in-situ measurements. Rainfall, snowfall, evapotranspiration (ET) and runoff (R) from GLDAS simulations as well as in-situ measured precipitation (P) are analyzed to identify the underlying causes of local TWS change. Our study will be of practical merit for a better understanding of the TRB's hydro-climatic variability to formulate sustainable water management strategies in similar arid endorheic regions.

2. Study region

TRB is China's largest endorheic basin with a drainage area of $1.04 \times 106\ \text{km}^2$ in Northwest China (Fig. 1). At an altitude of 800–8600 m, the basin slopes down from west to east, forming a typical sector-like pattern from its margin to its center, where is located the world famous Taklamakan Desert bordered by mountains and Gobi. The basin has four typical ring structures from the margin to the inside, with oasis and Gravel Gobi at the basin margin, desert at middle of the basin and Lop Nor at east of the basin.

The TRB has an extreme continental arid climate characterized by hot summers and cold winters, rare precipitation and strong evaporation. The mean annual temperature varies from 10.6 to 11.5 °C with 43.6 °C being the maximum and −27.5 °C being the minimum. The mean annual precipitation is 116.8 mm. Extremely uneven temporal and spatial distribution of water resources further results in a negative influence on highly efficient utilization of water resources. The variability and availability of water resources is a critical factor affecting the sustainability of regional socio-economy in the TRB, where agriculture development is heavily dependent on irrigation (Zhang et al., 2012).

Precipitation in TRB surrounding mountains plays an important role in recharging surface water and groundwater in downstream oasis and desert areas. Besides, seasonal melting water from mountain snowpack and glaciers also has a decisive effect on runoff processes (Yang, 1981). Located in the north part of TRB (Fig. 1), Tien Shan Mountain has shown significant regional climate change considering its temperature, precipitation, snowpack and glacier in global change context (Sorg et al., 2012). Almost all meteorological stations have recorded rising temperatures since the 1970s. Mean annual precipitation has increased in the outer (Aizen et al., 1997) and in the eastern ranges (Tao et al., 2011), but has decreased at higher altitudes in the inner ranges (Sorg et al., 2012). Increasing air temperatures have resulted in a decrease in the proportion of solid precipitation and enhanced snowmelt (Aizen et al., 1997; Qin et al., 2006). Glacier shrinkage in Tien Shan Mountain, especially in peripheral, lower-elevation ranges near the densely populated forelands, has led to significant seasonal alterations in runoff (Sorg et al., 2012). Precipitation, glaciers and snowpack change in

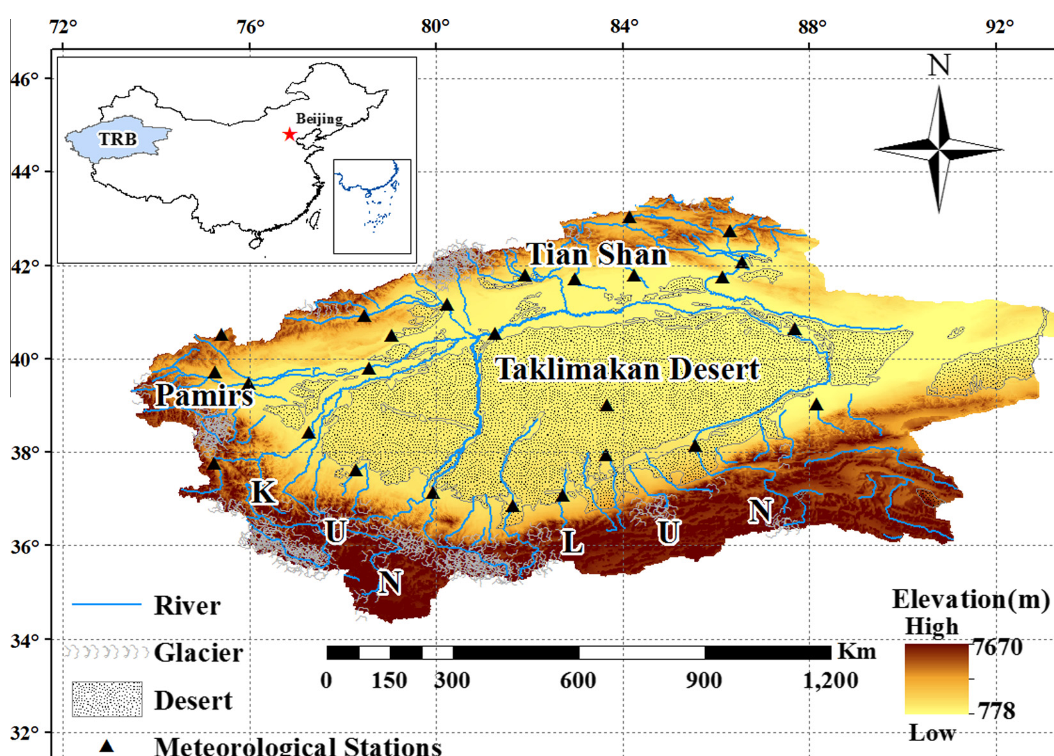

Fig. 1. Location of Tarim River Basin, a typical endorheic area in the Arid Region of Central Asia.