# Understanding the Spatial Differences in Terrestrial Water Storage Variations in the Tibetan Plateau from 2002 to 2016

Haijun Deng[a,b,c,d,e,*], N.C.Pepin[c], Qun Liu[b], Yaning Chen[b,*]

[a] College of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China

[b] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

[c] Department of Geography, University of Portsmouth, Portsmouth, Uk

[d]Fujian Provincial Engineering Research Center for Monitoring and Assessing Terrestrial Disasters, Fuzhou, 35007, China

[e]State Key Laboratory Breeding Base of Humid Subtropical Mountain Ecology, Fuzhou, 35007, China

*Correspondence to: College of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China; Xinjiang Institute of Ecology and Geography, CAS, 818 South Beijing Road, Urumqi 830011, China. E-mail: denghj@fjnu.edu.cn; chenyn@ms.xjb.ac.cn

Abstract:

Climate change has been driving terrestrial water storage variations in the high mountains of Asia in recent decades. This study is based on Gravity Recovery and Climate Experiment (GRACE) data to analyse spatial and temporal variations in terrestrial water storage (TWS) across the Tibetan Plateau (TP) from April 2002 to December 2016. Regional averaged TWS anomaly has increased by 0.20 mm/month ($p<0.01$) during the 2002-2012 period, but decreased by -0.68 mm/month ($p<0.01$) since 2012. The seasonal variations in TWS anomalies also showed a decreasing trend from May 2012 to December 2016. TWS variations in the TP also shown significant spatial differences, which is decreasing in southern TP but increasing in the Inner TP. And a declining trend was clearly evident in the seasonal variability of TWS anomalies in the south TP (about -30 to -55 mm/a), but increasing in the inner TP (about 10-35 mm/a). Meanwhile, this study links temperature/precipitation changes, glacial retreat, and lake area expansion to explain the spatially differences in TWS. Results indicated that precipitation increases and lake area expansion drove increasing TWS in the Inner TP during the 2002-2016 period, but temperature increases and glacial retreat drove decreasing TWS in southern TP.

Key words: Terrestrial water storage; Climate change; Spatial difference; GRACE; Tibetan Plateau

## 1 Introduction

The Tibetan Plateau (TP) region is rich in water resources and is strongly impacted by climate change (Immerzeel et al., 2010). Regional air temperature has increased by 0.039 ℃/a during the last 50 years (Deng et al., 2017), and the warming drives glacial retreat (Jacob et al., 2012; Yao et al., 2012; Neckel et al., 2014). The rapid glacial retreat is also affected by other factors, such as atmospheric circulations (Yao et al., 2012) and black soot (Xu et al., 2009). Meanwhile, a shorter snow cover duration (-3.5 ± 1.2 days/decades) also with the plateau warming (Xu et al., 2017). As a result, many scholars have focused on the region's distinctive glacial and snow melt-related features, such as terrestrial water storage (TWS) variations (Matsuo and Kosuke, 2010; Song et al., 2015), lake area expansion (Zhang et al., 2013; Song et al., 2015), and runoff changes (Sorg et al., 2012; Lutz et al., 2014; Khadka et al., 2014).

The Gravity Recovery and Climate Experiment (GRACE) satellite mission were launched in March 2002. It monitors monthly variations in Earth's gravitational field to determine the planet's surface mass changes (Wahr et al., 1998). Since GRACE satellites launch, the data have been widely used in hydrological research to i) estimate global and regional TWS variations (Syed et al., 2008; Long et al., 2015); ii) estimate evapotranspiration by evaluating the modelled evapotranspiration on a basin scale through the estimation of results (Rodell et al., 2004; Ramillien et al., 2006); iii) monitor drought by assimilating results to improve drought detection (Houborg et al., 2012; Long et al., 2013); iv) measure groundwater depletion, such as the analysis of groundwater changes in the northwest Indies, which showed groundwater depletion at a rate of 4 cm/a (Rodell, 2009); and v) estimate the mass balance of glaciers, as was done in the Antarctic (Chen et al., 2006), Greenland (Jin and Zou, 2015), and high Asia (Matsuo and Heki, 2010). Therefore, GRACE data now serves as a new data source for hydrological research.

The Tibetan Plateau region serves as Asia's water tower (Immerzeel et al., 2010), and all rivers in the surrounding region originate there. Thus, the TP is very important to the ecological environment as well as to the economic development of the downstream regions. Previous studies indicated a negative glacial mass balance in the TP between 2003 and 2009/2010 (Matsuo and Heki, 2010; Jacob et al., 2012). Yi and Sun (2014) pointed out that there were positive glacial changes of about 30 Gt/a in the Inner TP during 2003-2012. Recent studies also indicate that TWS shows a decreasing trend in the middle Himalayas (-20 mm/a) but an increasing trend in the Inner TP (9.7 mm/a) during the period 2003-2012 (Guo et al., 2016). So why has TWS increased in the Inner TP but decreased in the southern TP? Zhang et al. (2013) suggested that lake area expansion in the Inner TP can explain 61% of the increasing mass. Precipitation changes have also affected TWS variations in the TP (Yi and Sun, 2014). However, current studies lack a systematic and comprehensive analysis of spatial differences in TWS in the TP during recent climate changes.

In this study, we focus on spatially differences in TWS variations in the TP during the 2002-2016 period. First, we describes the temporal and spatial variations in terrestrial water storage in the TP based on GRACE data. Second, we determine impact factors of the spatial differences in TWS in the TP. Section 2 describes the study area, data, and methods. Section 3 presents the results, section 4 provides detailed discussions, and section 5 presents the conclusions.

## 2 Data and Methods

### 2.1 Study area

The Tibetan Plateau is located in the southwest of China. It lies between Central and East Asia, and is largely defined as lying between 25°-39°N, and 70°-106°E (Fig. S1). The average elevation of the TP exceeds 4,000 m, which is why it is sometimes referred to as "the roof of the world" or the "third pole".

Furthermore, it has nearly as many glaciers and glacial areas as Antarctica and Greenland (Yao et al., 2012). The Tibetan Plateau is the headwater area of most rivers in the surrounding regions, including the Yellow River, the Yangtze, the Brahmaputra, the Ganges, and the Indus. The Inner TP is an exorheic drainage basin and the southern TP is an endorheic drainage basin (Fig.S1). The TP has a typical plateau climate (Table S1). The water vapor in this region is largely controlled by the India monsoon and the East Asia monsoon (Yao et al., 2012), with annual precipitation measuring about 472 mm and mainly occurring in summer (Table S1).

## 2.2 Data

### 2.2.1 Temperature and precipitation

We collected observational data from 87 meteorological stations from the Climate Data Center (http://data.cma.cn/). Most stations are located in the southeastern portion of the Tibetan Plateau, while a few are in the northwest (Fig. S1). In this study, we analysed temperature and precipitation trends in the TP using daily observation data.

### 2.2.2 GRACE data

The GRACE data were provided by the Jet Propulsion Laboratory (JPL, available at https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/) of the California Institute of Technology. In this study, the datasets are gridded at 0.5°×0.5°, and the time range is from April 2002 to December 2016. Data were missing for 17 months (i.e., June and July 2002; January and June 2011; May and October 2012; March, August, and September 2013; February and December 2014; June, October, and November 2015; and April, September, and October 2016), and were therefore interpolated based on Long's method (Long et al., 2015).

### 2.2.3 GLDAS data

The Global Land and Data Assimilation System (GLDAS) products are based on satellite- and ground-based observational data products, then using advanced land and surface modeling and data assimilation techniques to generate optimal fields of land and surface states and fluxes (Rodell et al., 2004). The systems included four land and surface models, namely Mosaic, Noah, the Community Land Model (CLM), and the Variable Infiltration Capacity (VIC). In this paper, we selected runoff and evaporation data from the GLDAS-Noah model products. The GLDAS-Noah model is provided on 0.25-degree global grids (available at http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings). Detailed information about the GLDAS land surface model is given in Rodell et al. (2004).

### 2.3 Methods

#### 2.3.1 Terrestrial water storage calculations

In this study, the Mascons approach (for details see Watkins et al., 2015) was used to calculate surface mass change based on the Level-1 GRACE observations, processed at JPL. The characteristic of this method is to helpful eliminate noise from outside the region of interest (ROI). The Earth's oblateness scales (C20) coefficients were replaced in order to reduce uncertainty from the native GRACE-C20 values (Chen et al., 2005; Cheng et al., 2011). Meanwhile, the degree-1 coefficients were estimated using the method from Swenson (2008). Then, a glacial isostatic adjustment (GIA) correction in the model (Geruo and Wahr, 2013) was applied to remove glacial rebound effects, especially in mountains regions and high latitude areas. The data anomalies base period is from January 2004 to December 2009, because there are no missing values in this period. Finally, the scaling factors were applied to the data over the study area, and the scale-corrected time series was calculated as follow:

$$g'(\mathrm{x,y,t}) = g(x,y,t) * s(x,y) \qquad (1)$$

Where x is longitude, y is latitude, t is time (months), g(x,y,t) is the grid surface mass change value, and the scaling grid is s(x,y). The scaling factors are provided by the JPL website (https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/). The uncertainty estimates approach in this study was described in Wahr et al., (2006).

The seasonal cycle of terrestrial water storage has been removed.

### 2.3.3 Trend test

The Mann-Kendall (MK) non-parametric trend test is a powerful trend detection method that is widely used in hydrology and meteorology time series analyses (Hirsch, 1984; Hamed, 1998; Yue, 2002; Hamed, 2008). In this study, the MK trend test was used to detect the trend of TWS, temperature, and precipitation. The slope of the trend is estimated by using Sen's non-parametric trend estimator (Sen, 1968).

## 3 Results

### 3.1 Temporal and spatial variations in TWS

#### 3.1.1 Temporal variations

The temporal variations in TWS anomalies were analysed for the Tibetan Plateau during the period from April 2002 to December 2016. The results (Fig. 1a) showed that a significant increasing trend of about 0.20 mm/month ($p<0.01$) from April 2002 to April 2012, but a decreasing trend from May 2012 to December 2016, with a rate of around -0.68 mm/month ($p<0.01$). The results of seasonal variations in TWS anomalies showed a decreasing trend from May 2012 to December 2016 (Fig. 1b).

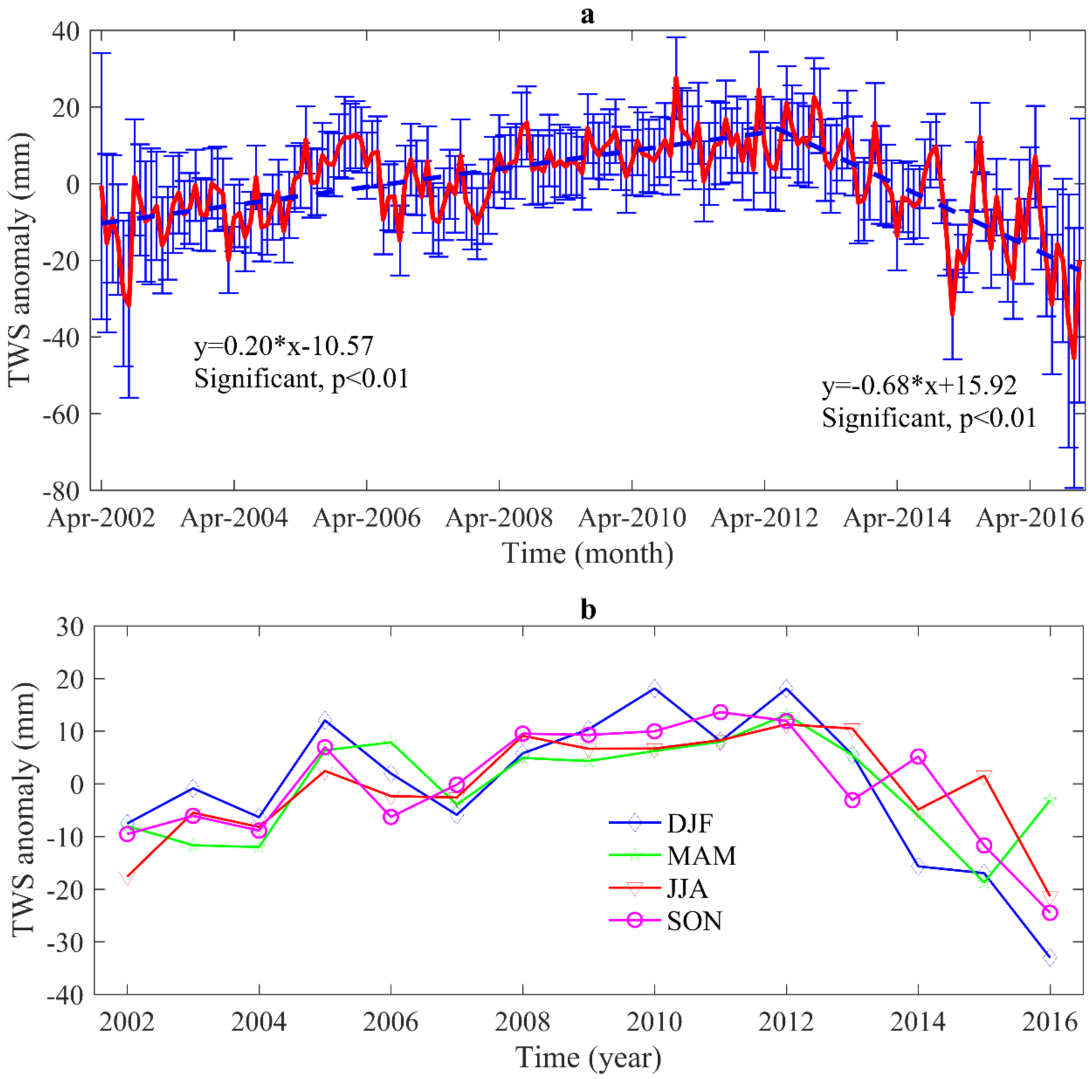


Figure 1a shows the temporal variations in TWS anomalies in the Tibetan Plateau from April 2002 to December 2016 (blue bar represents the uncertainty). Figure 1b illustrates seasonal changes of TWS (DJF, MAM, JJA, and SON).

The results for seasonal variations in TWS anomalies indicate positive anomalies in DJF and MAM (Fig. S2). There were negative anomalies in JJA and SON.

3.1.2 Spatial variations

The spatial variations in TWS anomalies indicate significant spatial differences in all seasons between April 2002 and December 2016 (Fig. 2). A declining trend was clearly evident in the seasonal variability of TWS anomalies in the south TP (about -30 to -55 mm/a), but increasing in the inner TP (about 10-35 mm/a). The results also showed that TWS decreased in the Inner TP since 2012 (Fig.S3), which may be due to rising temperature and increasing evaporation (Fig.S3).

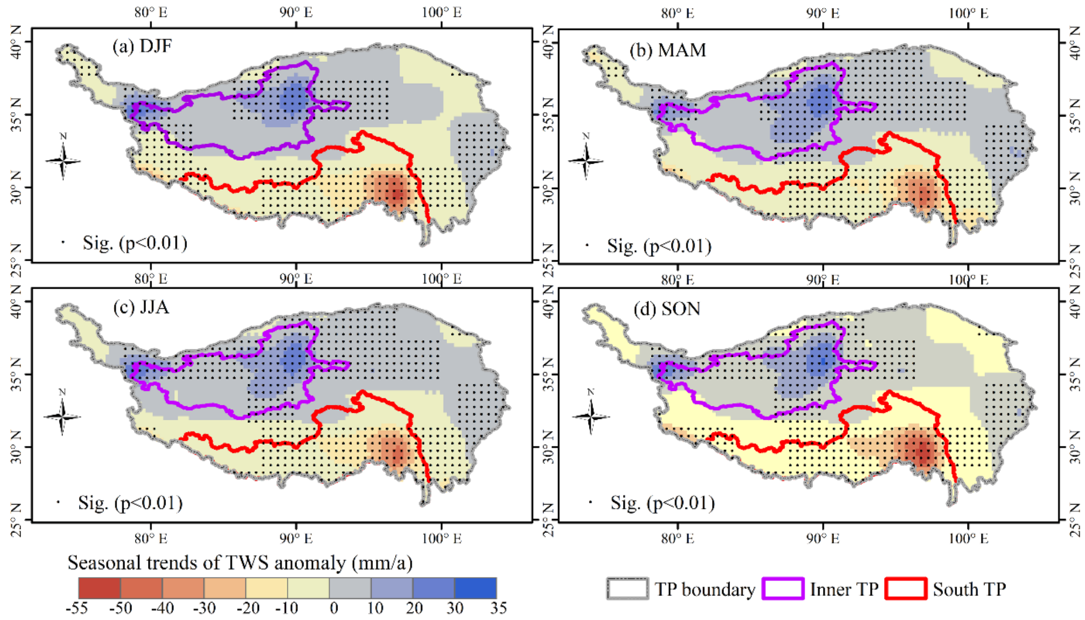


Figure 2 Spatial variations in seasonal TWS anomalies in the Tibetan Plateau between April 2002 and December 2016, with a spatial resolution of 0.5×0.5 degree; a is DJF, b is MAM, c is JJA, and d is SON.

TWS has increased in the full TP and the Inner TP between April 2002 and December 2016 by 0.002 mm/month, and 0.58 mm/month ($p<0.01$), respectively (Table 1). But TWS has decreased in the southern TP by -0.62 mm/month ($p<0.01$) during this period.

Table 1 The TWS variations in the TP and sub regions (Inner TP and south TP) during 2002.04-2016.12. Mean is the average value of TWS anomaly for 2002.04-2016.12.

| | Trend (mm/month) | Significance | Periods |
|---|---|---|---|
| Full TP | 0.002 | | 2002.04-2016.12 |
| Inner TP | 0.58 | ** | 2002.04-2016.12 |
| South river basin | -0.62 | ** | 2002.04-2016.12 |

** Significant at $p<0.01$

3.2 Relationship between TWS variations and recent climate change

Climate change is an important factor driving TWS variations in mountains regions (Deng and Chen, 2017). Temperatures have increased in DJF, MAM, JJA, and SON between April 2002 and December 2016 in the south TP (Fig. 3). In the south TP, precipitation have decreased in DJF, JJA, and SON during this period (Fig. 4), but increased in MAM. In the Inner TP, temperatures decreased in full seasonal (Fig. 3). Precipitation has increased in MAM, JJA, and Son in the Inner TP (Fig.4), but decreased in DJF.

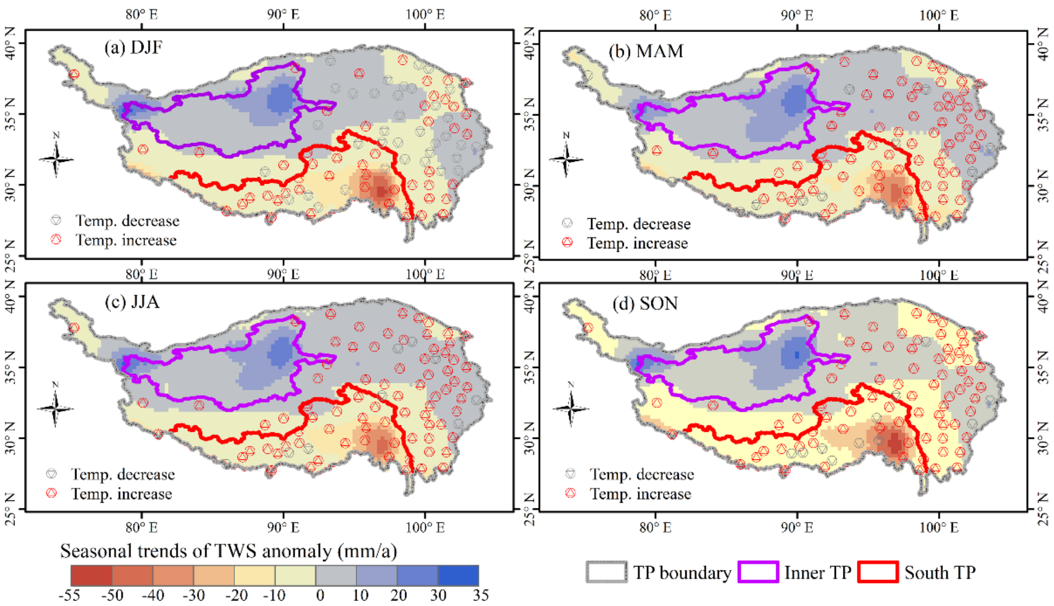


Figure 3 Spatial variations in temperature in the Tibetan Plateau during 2002-2016, a is DJF, b is MAM, c is JJA, and d is SON.

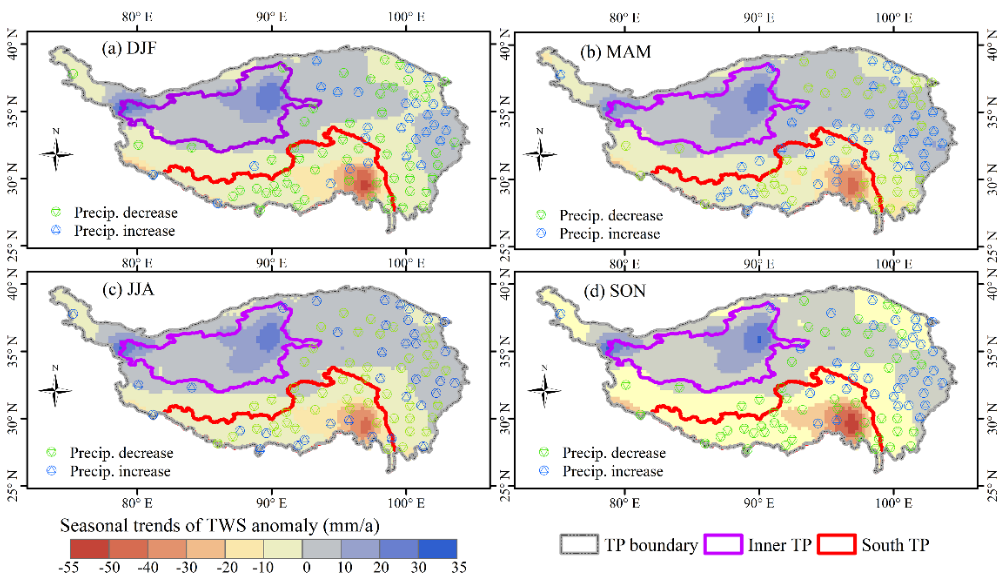


Figure 4 Same as Fig.3 but for precipitation.

TWS variations have increased in the Inner TP, with a rate of 0.58 mm/month ($p<0.01$) (Fig. 5a), but decreased in the south TP (-0.62 mm/month, $p<0.01$) (Fig. 5b). Temperature and precipitation changes in the Inner TP and south TP were also analysed over during the past decade. Moreover, temperature decreased (-0.38 °C/a) and precipitation increased (1.07 mm/a) in the Inner TP (Fig. 5a), but temperature increased (0.01 °C/a) and precipitation decreased (-2.82 mm/a) in the south TP (Fig. 5b).

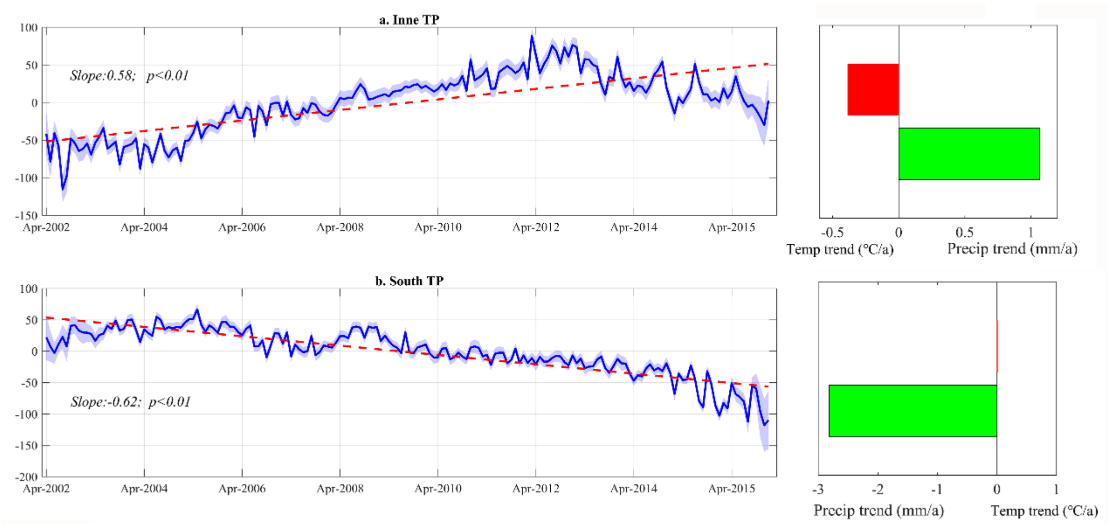


Figure 5. The left plane refers to a, TWS variations in the Inner TP between April 2002 and December 2016, and blue shading is represents uncertainty. Right plane are the trend of temperature and precipitation during this period. “b” is the same to a but for the south TP.

TWS variations have decreased in the Inner TP from May 2012 to December 2016, with a rate of -1- -4mm/month (Fig.6b). We also analysis differences in temperature (Fig.6c), precipitation (Fig.6d), precipitation (Fig.6e), and evaporation (Fig.6f) between April 2002-April 2012 and May 2012-December 2016. The mean and maximum temperature have positive value in the Inner TP, it is means that temperature increased in this region. Precipitation also increased in the Inner TP. Evaporation have increased in the Inner TP. Therefore, the rising temperature resulted in evaporation increased and glaciers retreat are an important factors for TWS variations in the TP.

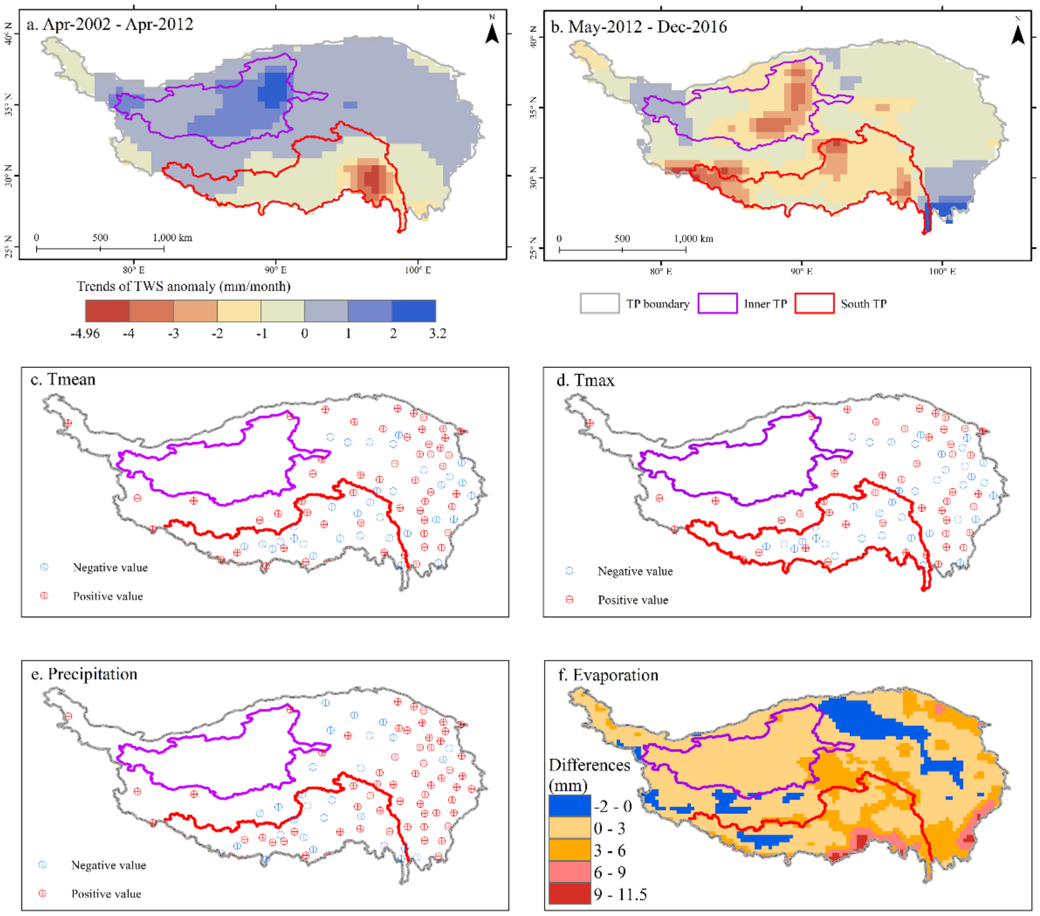


Figure 6 a is the trend of TWS variations in the TP from April 2002 to April 2012. b is the trend of TWS variations in the TP from May 2012 to December 2016. c is the difference in Tmean between April 2002-April 2012 and May 2012-December 2016. d, e, f same as c but for Tmax, precipitation, and evaporation, respectively. The evaporation data was provided by GLDAS Noah model at 0.25×0.25 degree.

### 3.3 Effects of lake area changes

Lake water storage is yet another component of TWS in the TP (Xiang et al., 2016), and is mainly distributed in the Inner TP. The number of small lakes (1-10 $km^2$) decreased from 2005 to 2014, but the area also spawned six new lakes ≥10 $km^2$ (Wan et al., 2016). Figure S4 reveals that lakes in the southern TP, between 2005 and 2014, show a decreasing rate by -7%, while those in the Inner and northern TP exhibit a growth rate of 15.5%.

Figure 7 indicates that lake area changes, for areas >100 $km^2$ between 2005 and 2014 in the eastern portion of the Inner TP, exhibit increasing trends. Results show that most of the lake areas increased by at least 20% (Table 2), with Ayakkum Lake and Aqqikkol Lake having increased 30.79% and 31.75%, respectively. Therefore, lake water storage increased in the Inner TP are an important factor for TWS spatial variations in the TP during the past decade. Over the past decade, lakes on the Inner TP have displayed an expand trend. With the increasingly intensive temperature (Fig.3) and precipitation (Fig.4), the large amount of glaciers, snow and permafrost meltwater has caused lakes expanding (Song et al., 2013).

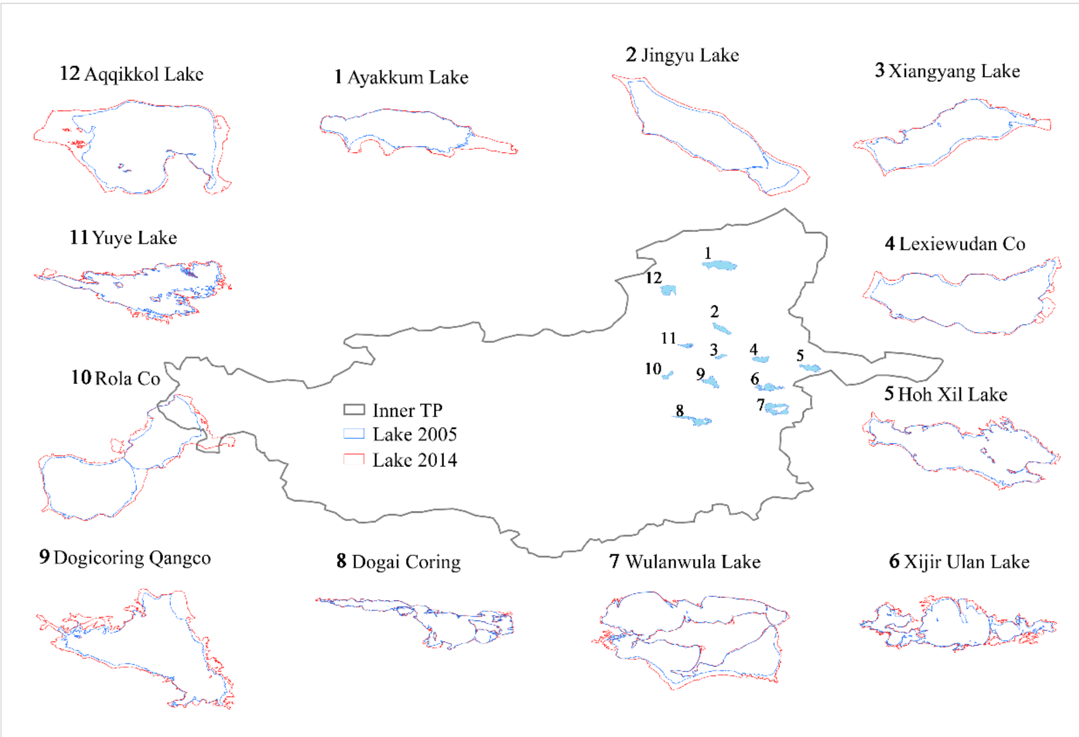


Figure 7. The typical lake area changes in the Inner TP (dataset provided by Wan et al., 2016).

Table 2. Changes in the number and area of lakes in the Tibetan Plateau from 2005 to 2014 (Δ=(Area2014-Area2005)/Area2005*100. The lake data are supported by Wan (2016). (Unite:km$^2$)

| ID | Name | Area 2005 | Area 2014 | Δ（%） | ID | Name | Area 2005 | Area 2014 | Δ（%） |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Aqqikkol Lake | 408.68 | 538.45 | 31.75 | 7 | Wulanwula Lake | 566.74 | 650.99 | 14.87 |
| 2 | Dogaicoring | 313.68 | 403.1 | 28.51 | 8 | Xiangyang | 100.8 | 121.01 | 20.05 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Qangco | | | | | Lake | | | |
| 3 | Dogai Coring | 458.42 | 492.41 | 7.42 | 9 | Xijir Ulan Lake | 371.88 | 462.69 | 24.42 |
| 4 | Jingyu Lake | 280.42 | 339.57 | 21.1 | 10 | Ayakkum Lake | 754.59 | 986.9 | 30.79 |
| 5 | Hoh Xil Lake | 313.14 | 350.38 | 11.89 | 11 | Rola Co | 137.91 | 169.9 | 23.2 |
| 6 | Lexiewudan Co | 342.82 | 273.3 | 12.09 | 12 | Yuye Lake | 122.24 | 145.91 | 19.36 |

### 3.4 Effects of glacial retreat

In the Tibetan Plateau, glaciers have largely retreated over past decades, driven by climate change (Yao et al., 2012), and this has had an impact on water storage changes (Jacob et al., 2012). Table 3 showed that glaciers retreated slightly in the Ayakkum Lake and Dogai Coying areas from 2001 to 2013, with a rate of -1.45% and -1.93%, respectively. Figure 7 also shows that these two basins are located in the eastern Inner TP. The maximum decrease of TWS occurred in the eastern south TP (Fig. 2). Accordingly, glaciers sharply retreated in the Mekong River basin (-8.91%) during 2001-2013 (Table 3). Meanwhile, Table 3 also indicates glacial retreat in the Salween River and Ganges River areas of -2.32% and -3.4%, respectively. The joint results for Figs. S4 and S6 indicate that glacial retreat contributed to TWS decreases in the south TP.

Table 3. Glacier area change in Inner TP and south river basin on the Tibetan Plateau during 2001-2013 (Ye et al., 2017).

| Regions | Basins | Changes (%) | Period |
|---|---|---|---|
| Inner TP | Ayakkum lake | -1.45 | 2001-2013 |
| | Dogai Coying | -1.93 | 2001-2013 |
| South river basin | Mekong River | -8.91 | 2001-2013 |
| | Salween River | -2.32 | 2001-2013 |
| | Ganges River | -3.14 | 2001-2013 |

## 4. Discussion

Terrestrial storage variations are closely related to precipitation and evaporation. Specifically, ΔS=P-E-R, where ΔS is terrestrial water storage， P is precipitation, E is evaporation， and R is runoff. According to the water budget equation, we know that water storage is a transient state that is determined by the relationship between the input and output of the water system. Therefore, the water budget equation can be simplified as $\Delta S = (water)_{in} - (water)_{out}$, where $(water)_{in}$ is the input variable (i.e., precipitation, runoff) and $(water)_{out}$ is the output variable (i.e., evaporation, runoff and human water use). The negative trend of TWS anomalies is caused by input less than output in the water system, i.e., drought. For example, the Amazon Basin experienced a negative trend of TWS anomalies during 2003-2013 due to decreased precipitation (Xavier et al., 2010). The drought events in northwestern India, however, were mainly due to irrigation consumption that led to groundwater overexploitation (Rodell et al., 2009).

The warming environmental has a significant impact on runoff variations in the TP. Runoff reduction in the southern and eastern TP because of warming and wind stilling led to less precipitation in the monsoon impacted region (Yang et al., 2013). Annual runoff decreased in wet part of TP since 2000 (Liu et al., 2018), but increased in dry part (Wang et al., 2017). According to future climate scenarios and VIC-glacier model, the runoff will remain stable or moderately increase in 2011-2040 relative to 1971-2000 in the six major river basins in the TP, but increase by 2.7-22.4% during 2041-2070 relative to 1971-2000 (Su et al., 2015).

The GLDAS runoff data can fill the gaps from the observation station sparse in TP. Some studies evaluated the runoff product of Noah model against observations station data in five river basin in the TP, and results shown that the best performance in capture the temporal variability of streamflow at monthly and seasonal scales (Bai et al., 2016). The uncertainties in GLDAS runoff simulations has been discussed in detail in Bai et al. (2016), which is indicated that uncertainties sources from three parts: forcing data, model structure, and model parameters. Therefore, the quality of the atmospheric forcing data has significant influences on runoff simulated accuracy (Zaitchik et al., 2010), for example, precipitation and air temperature (Wang et al., 2016).

We used GLDAS-Noah model evaporation and runoff datasets to analysis evaporation and runoff changes in the TP during 2002-2016. With rising air temperature, evaporation increased in most parts of the TP (Fig. S5b). Evaporation increased may be caused lake water storage decreased (Song et al., 2013). With the increasingly intensive climate warming tendency, the runoff of meltwater will be increased from mountainous glaciers/snow. But the runoff analysis results indicated that surface runoff has a decreased trend in most of the TP (Fig. S5c), especially in the south TP.

Recent studies also indicate that TWS shows a decreasing trend in the middle Himalayas (-20 mm/a), but an increasing trend in the Inner TP (9.7 mm/a) during the period 2003-2012 (Guo et al., 2016). The spatio-temporal variations in TWS anomalies in the TP are related to temperature and precipitation. Over the past 40 years, the temperature has increased (You et al., 2015; Deng et al., 2017), such that the increased rate in winter is larger than that in summer (Xu et al., 2008). At the same time, annual mean precipitation also increased, showing obvious seasonal differences (Xu et al., 2008). Since 2000, data at the observation stations in this study show a clear temperature increase. Meanwhile, precipitation has decreased in the southern Tibetan Plateau, but increased in the northern Tibetan Plateau. Figure 4 shows that precipitation changes are consistent with spatial variations in TWS in the TP. The temperature increases likely accelerated the retreat of glaciers in southern regions (Fig. 3), which then led to a declining trend in precipitation (Fig. 4) and TWS anomalies.

Overall, decreases in water storage in the TP were mainly caused by glacier retreat (Singh and Lars, 2004). According to the China Second Glacier Inventory (CSGI, Guo et al., 2014), glaciers cover approximately $4.54\times10^4$ $km^2$ of the TP. Matsuo and Heki (2010) suggested that the glacier mass loss rate of -47 Gt/a in the high mountains of Asia (HMA) from 2003 to 2009 mainly occurred in the Himalayas. Yao et al. (2012) suggested that the glacier retreat in the Himalayas (about -790 mm/a) was due to increased temperatures and decreased precipitation, whereas the glacier advance in the Karakoram and Kunlun Mountains (about +250 mm/a) is caused by increased precipitation (0.01-0.02 mm/day). Meanwhile, glacier retreat is also closely related to freezing level heights (FLH) (Wang et al., 2014). For instance, FLH in the Kunlun Mountains showed a decreasing trend of -2.33 m/a (Chen et al., 2015). Decreased FLH can mainly influence the glaciers mainly either by inhibiting glacier retreat or accumulating snow. Moreover, we also suggest that decreased FLH will probably result in the advance of glaciers in the western TP. Thus, from 2003 to 2013, the increases in precipitation and snowfall, along with decreases in FLH resulting in glacier advance, are the primary impact factors contributing to the positive anomalies of TWS in the northwestern TP.

The total lake area in the TP increased 7.03% during 2005-2014 (Wan et al., 2016). Precipitation increased and glacier retreat are contributed to lake expansion (Song et al., 2013; Zhang et al., 2017). Meanwhile, the increased rates for the total area of lakes were located in the Inner TP (Wan et al., 2016). But lakes in the south river basins are trending towards a decrease. The TWS variations are in good agreement with changes in temperature and precipitation (Fig. 5), and these results are similar to those of Song's (2014), which showed that precipitation increases also supported lake expansion. In endorheic drainage basins, precipitation, glacier and snow melt will promote lake expansion, however, in exorheic drainage basins, the complex correlations between glacier retreat and lake changes depend primarily on differences between the amount of water flowing into and out of the lakes.

Additionally, glacier and snow melt changes also cause groundwater changes. From 2003 to 2009, groundwater in the Inner TP showed an increasing trend (about +1.66 ± 1.52 Gt/a) (Xiang et al., 2016), whereas the groundwater in the Bengal basin of Bangladesh and north-central India (which, in our study, includes the Brahmaputra and Ganges, respectively) exhibited a clear decreasing trend. Figure 4 shows that precipitation has an increasing trend in the Inner TP and a decreasing trend in the south of the TP. Yao et al. (2012) also found that glaciers retreated in the Himalayas region but advanced in the Kunlun region. Therefore, the groundwater changes in these areas may have been caused both by glacial melting and increased precipitation.

Climate changes determine TWS variations by strongly influencing changes in glaciers and snow, lake water, soil moisture, and groundwater. The possible mechanism of TWS variations in endorheic drainage basins (i.e., Inner TP) differs from that in exorheic drainage basins (i.e., south of TP). In the Inner TP, increased precipitation led to increases in both lake water and groundwater storage, so the TWS increased in the inner TP. In endorheic drainage basins, the glaciers' retreat did not lead to a TWS decrease because glacier and snow melt did not flow out of this region. In the southern TP (Fig. 5b), increases in temperature resulted in increases in glacier and snow melt, but decreases in precipitation (especially in snowfall). The end results of these changes were decreases in lake water and groundwater storage, resulting in a TWS decline.

This study mainly focused on the effects of climate changes on TWS variations in high Asia. The work provided a comprehensive analysis of the effects of changes in climate factors on TWS variations in the region. Our future research focus will highlight a typical river basin in the Tibetan Plateau to quantitatively analyse the impact of climate changes on TWS variations.

## 5. Conclusions

In this study, we investigated the temporal and spatial variations in TWS in the Tibetan Plateau from April 2002 to December 2016. The temporal variations in TWS anomalies can be divided into two stages. In the first stage (April 2002 to April 2012), TWS had a significant increasing trend of ~ 0.20 mm/month ($p<0.01$); in the second stage (May 2012 to December 2016), it deceased at a rate of -0.68 mm/month ($p<0.01$). At the same time, spatial variations in TWS anomalies indicate that the Inner TP had an increasing trend (0.58 mm/month, $p<0.01$), whereas the southern TP had a decreasing trend (-0.62 mm/month, $p<0.01$).

Seasonal variations in TWS anomalies indicate positive anomalies in the Inner TP, and shown negative anomalies in the southern TP. Temperatures increased and precipitation decreased has led to TWS declined in the southern TP. But contrast, temperatures decreased and precipitation increased finally resulted in TWS raised in the Inner TP.

Increases in temperature accelerated the retreat of glaciers and evaporation decreased, which, together with precipitation decreases, resulted in TWS anomalies showing a reduced trend in the south TP. However, in the Inner TP, TWS showed an increase from April 2002 to April 2012, which was caused by increased precipitation and temperature decreased. But TWS have a decreased trend from May 2012 to December 2016, which was caused by evaporation increased and glaciers retreat.

**Acknowledgements**

This research was supported by the National Natural Science Foundation of China (41807159). The authors are grateful to the Chinese Meteorology Administration (http://data.cma.cn/) for providing precipitation and air temperature data. In addition, the authors appreciate the comments provided and encouragement made by the reviewers, the editor and the associate editor.

**References:**


Aizen, V.B., Aizen, E.M., Melack, J.M., 1995. Climate, snow cover, glaciers, and runoff in the Tien Shan, central Asia. Water Resources Bulletin, 31(6): 1113-1129.

Bai, P., X. Liu, T. Yang, K. Liang, C. Liu, 2016. Evaluation of streamflow simu-lation results of land surface models in GLDAS on the Tibetan plateau. J. Geophys. Res. Atmos., 121, 12,180-12,197. Doi:10.1002/2016JD025501.

Berghuijs, W.R., Hartmann, A., Woods, R.A., 2016. Streamflow sensitivity to water storage changes across Europe. Geophysical Research Letters, 43(5): 1980-1987. DOI:10.1002/2016GL067927

Berghuijs, W.R., Woods, R.A., Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nature Clim. Change, 4(7): 583-586. DOI:10.1038/nclimate2246

Braun, L.N., Hagg, W., Severskiy, I.V., Young, G., 2009. Assessment of snow, glacier and water resources in Asia. IHP-HWRP, 8: 186.

Chen, J.L., Wilson, C.R., Blankenship, D.D., Tapley, B.D., 2006. Antarctic mass rates from GRACE. Geophysical Research Letters, 33(11): n/a-n/a. DOI:10.1029/2006GL026369

Chen, Z., Chen, Y., Li, W., 2012. Response of runoff to change of atmospheric 0°C level height in summer in arid region of Northwest China. Sci. China Earth Sci., 55(9): 1533-1544. DOI:10.1007/s11430-012-4472-6

Cheng, M., Tapley, B., 2000. Temporal variations in J2 from analysis of SLR data, Proc. 12th International Workshop on Laser Ranging.

Cheng, M., Tapley, B.D., 2004. Variations in the Earth's oblateness during the past 28 years. Journal of Geophysical Research: Solid Earth, 109(B9): B09402. DOI:10.1029/2004JB003028

Deng, H., Y. Chen, 2017. Influences of recent climate change and human activities on water storage variations in Central Asia. Journal of Hydrology, 544: 46-57.

Deng, H., Pepin, N., Chen, Y., 2017. Changes of snowfall under warming in the Tibetan Plateau. Journal of Geophysical Research: Atmospheres, 122(14): 7323-7341. DOI: 10.1002/2017JD026524

Duan, X.J., Guo, J.Y., Shum, C.K., van der Wal, W., 2009. On the postprocessing removal of correlated errors in GRACE temporal gravity field solutions. J Geod, 83(11): 1095-1106. DOI:10.1007/s00190-009-0327-0

Farinotti, D. et al., 2015. Substantial glacier mass loss in the Tien Shan over the past 50 years. Nature Geosci, 8(9): 716-722. DOI:10.1038/ngeo2513

Guo J., Mu D., Liu X., Yan H., Sun Z., Guo B., 2016. Water Storage Changes over the Tibetan Plateau Revealed by GRACE Mission. Acta Geophysica, 64(2): 463-476.

Guo, L., Li, L., 2015. Variation of the proportion of precipitation occurring as snow in the Tian Shan Mountains, China. International Journal of Climatology, 35(7): 1379-1393. DOI:10.1002/joc.4063

Guo, W., Xu, J., Liu, S., Shangguan, D., Wu, L., Yao, X., Zhao, J., Liu, Q., Jiang, Z., Li, P., Wei, J., Bao, W., Yu P., Ding, L., Li, G., Ge, C., Wang, Y., 2014. The Second Glacier Inventory Dataset of China (Version 1.0). Cold and Arid Regions Science Data Center at Lanzhou. DOI:10.3972/glacier.001.2013.db

Hamed, K.H., 2008. Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. Journal of Hydrology, 349(3–4): 350-363. DOI:http://dx.doi.org/10.1016/j.jhydrol.2007.11.009

Hamed, K.H., Ramachandra Rao, A., 1998. A modified Mann-Kendall trend test for autocorrelated data. Journal of Hydrology, 204(1–4): 182-196. DOI:http://dx.doi.org/10.1016/S0022-1694(97)00125-X

Hirsch, R.M., Slack, J.R., 1984. A nonparametric trend test for seasonal data with serial dependence. water Resources Research, 20(60): 727-732. DOI:10.1029/WR020i006p00727

Houborg, R., Rodell, M., Li, B., Reichle, R., Zaitchik, B.F., 2012. Drought indicators based on model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observations. Water Resources Research, 48(7): W07525. DOI:10.1029/2011WR011291

Immerzeel, W.W., Van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate Change Will Affect the Asian Water Towers. Science, 328(5984): 1382-1385. DOI:10.1126/science.1183188

Irannezhad, M., Ronkanen, A.K., Kløve, B., 2016. Wintertime climate factors controlling snow resource decline in Finland. International Journal of Climatology, 36(1): 110-131. DOI:10.1002/joc.4332

Jacob, T., Wahr, J., Pfeffer, W.T., Swenson, S., 2012. Recent contributions of glaciers and ice caps to sea level rise. Nature, 482(7386): 514-518. DOI:10.1038/nature10847

Kanamitsu M, Ebisuzaki W, Woollen J, et al. 2002. NCEP-DEO AMIP-II Reanalysis (R-2). Bulletin of the American Meteorological Society, 83(11): 1631-1643.

Khadka, D., Babel, M.S., Shrestha, S., Tripathi, N.K., 2014. Climate change impact on glacier and snow melt and runoff in Tamakoshi basin in the Hindu Kush Himalayan (HKH) region. Journal of Hydrology, 511: 49-60. DOI:http://dx.doi.org/10.1016/j.jhydrol.2014.01.005

Liu, J., Zhang, W., Liu, T., Li, Q., 2018. Runoff Dynamics and Associated Multi-Scale Responses to Climate Changes in the Middle Reach of the Yarlung Zangbo River Basin, China. Water, 10, 295. Doi: 10.3390/w10030295

Long, D., Scanlon, B R., Longuevergne, L., Sun, A Y., Fernando, D N., Save, H., 2013. GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas. Geophysical Research Letters, 40(13): 3395-3401. DOI:10.1002/grl.50655

Long, D., Yang, Y., Wada, Y., Hong, Y., Liang, W., Chen, Y., Yong, B., Hou, A., Wei, J., Chen, L., 2015. Deriving scaling factors using a global hydrological model to restore GRACE total water storage changes for China's Yangtze River Basin. Remote Sensing of Environment, 168: 177-193. DOI:http://dx.doi.org/10.1016/j.rse.2015.07.003

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B., Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Clim. Change, 4(7): 587-592. DOI:10.1038/nclimate2237

Ma, N., Szilagyi, J., Niu, G Y., Zhang, Y., Zhang, T., Wang, B., Wu, Y., 2016. Evaporation variability of Nam Co Lake in the Tibetan Plateau and its role in recent rapid lake expansion. Journal of Hydrology, 537: 27-35. DOI:http://dx.doi.org/10.1016/j.jhydrol.2016.03.030

Matsuo, K., Heki, K., 2010. Time-variable ice loss in Asian high mountains from satellite gravimetry. Earth and Planetary Science Letters, 290(1–2): 30-36. DOI:10.1016/j.epsl.2009.11.053

Ramillien, G., Frappart, F., Güntner, A., Ngo‐Duc, T., Cazenave, A., Laval, K., 2006. Time variations of the regional evapotranspiration rate from Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry. Water Resources Research, 42(10): n/a-n/a. DOI:10.1029/2005WR004331

Rodell, M., Famiglietti, J S., Chen, J., Seneviratne, S I., Viterbo, P., Holl, S., Wilson, C R., 2004. Basin scale estimates of evapotranspiration using GRACE and other observations. Geophysical Research Letters, 31(20): L20504. DOI:10.1029/2004GL020873

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature, 460(7258): 999-1002.

Sen, P.K., 1968. Estimates of the Regression Coefficient Based on Kendall's Tau. Journal of the American Statistical Association, 63(324): 1379-1389. DOI:10.1080/01621459.1968.10480934

Singh, P., Bengtsson, L., 2004. Hydrological sensitivity of a large Himalayan basin to climate change. Hydrological Processes, 18(13): 2363-2385. DOI:10.1002/hyp.1468

Song, C., Huang, B., Ke, L., 2013. Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data. Remote Sensing of Environment, 135: 25-35. DOI:http://dx.doi.org/10.1016/j.rse.2013.03.013

Song, C., Ke, L., Huang, B., Richards, K.S., 2015. Can mountain glacier melting explains the GRACE-observed mass loss in the southeast Tibetan Plateau: From a climate perspective? Global and Planetary Change, 124: 1-9. DOI:http://dx.doi.org/10.1016/j.gloplacha.2014.11.001

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M., 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Clim. Change, 2(10): 725-731. DOI:10.1038/NCLIMATE1592

Su, F., Zhang, L., Ou, T., Chen, D., Yao, T., Tong, K., Qi, Y., 2015. Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau. Global and Planetary Change, 136: 82-95. DOI: 10.1016/j.gloplacha.2015.10.012

Syed, T.H., Famiglietti, J.S., Rodell, M., Chen, J., Wilson, C.R., 2008. Analysis of terrestrial water storage changes from GRACE and GLDAS. Water Resources Research, 44(2): W02433. DOI:10.1029/2006WR005779

Vehviläinen, B.,1992. Snow cover models in operational watershed forecasting [M].

Helsinki, Finland: National Board of Waters and the Environment, 16 pp.
Wahr, J., Molenaar, M., Bryan, F., 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. Journal of Geophysical Research: Solid Earth, 103(B12): 30205-30229. DOI:10.1029/98JB02844
Wan, W., Long, D., Hong, Y., Ma, Y., Yuan, Y., Xiao, P., Duan, H., Han, Z., Gu, X., 2016. A lake data set for the Tibetan Plateau from the 1960s, 2005, and 2014. Scientific Data, 3: 160039. DOI:10.1038/sdata.2016.39
Wang, S., Zhang, M., Pepin, N C., Li, Z., Sun, M., Huang, X., Wang, Q., 2014. Recent changes in freezing level heights in High Asia and their impact on glacier changes. Journal of Geophysical Research: Atmospheres, 119(4): 1753-1765. DOI:10.1002/2013JD020490
Wang, W., Cui, W., Wang, X J., Chen, X., 2016. Evaluation of GLDAS-1 and GLDAS-2 Forcing Data and Noah Model Simulations over China at the Monthly Scale. Journal of Hydrometeorology, 17: 2815-2833. Doi:10.1175/JHM-D-15-0191.1
Wang, Y., Zhang, Y., Chiew, F., Lu, Z., Li, H., Qin G., 2017. Contrasting runoff trends between dry and wet parts of eastern Tibetan Plateau. Scientific Reports, 7(1): 15458.
Xavier, L., Becker, M., Cazenave, A., Longuevergne, L., Llovel, W., Rotunno, Filho OC., 2010. Interannual variability in water storage over 2003–2008 in the Amazon Basin from GRACE space gravimetry, in situ river level and precipitation data. Remote Sensing of Environment, 114(8): 1629-1637. DOI:10.1016/j.rse.2010.02.005
Xiang, L., Wang, H., Steffen, H., Wu, P., Jia, L., Jiang, L., Shen, Q., 2016. Groundwater storage changes in the Tibetan Plateau and adjacent areas revealed from GRACE satellite gravity data. Earth and Planetary Science Letters, 449: 228-239. DOI:http://dx.doi.org/10.1016/j.epsl.2016.06.002
Xu, Z.X., Gong, T.L., Li, J.Y., 2008. Decadal trend of climate in the Tibetan Plateau—regional temperature and precipitation. Hydrological Processes, 22(16): 3056-3065. DOI:10.1002/hyp.6892
Yang, K., Wu, H., Qin,J., Lin, C., Tang, W J., Chen, Y Y., 2014. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. Global and Planetary Change, 112: 79-91.
Yao, T., Thompson L., Yang W., Yu W., Gao Y., Guo X., Yang X., Duan K., Zhao H., Xu B., Pu J., Lu A., Xiang Y., Kattel D., Pu J., 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nature Clim. Change, 2(9): 663-667. DOI:10.1038/NCLIMATE1580
Yi, S., Sun, W., 2014. Evaluation of glacier changes in high - mountain Asia based on 10 year GRACE RL05 models. Journal of Geophysical Research: Solid Earth, 119(3): 2504-2517.
You, Q., Min, J., Zhang, W., Pepin, N., Kang, S., 2014. Comparison of multiple datasets with gridded precipitation observations over the Tibetan Plateau. Clim Dyn, 45(3): 791-806. DOI:10.1007/s00382-014-2310-6

Yuan, W., Xu, W., Ma, M., Chen, S., Liu, W., Cui, L., 2016. Improved snow cover model in terrestrial ecosystem models over the Qinghai–Tibetan Plateau. Agricultural and Forest Meteorology, 218–219: 161-170. DOI:http://dx.doi.org/10.1016/j.agrformet.2015.12.004

Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. Journal of Hydrology, 259(1–4): 254-271. DOI:http://dx.doi.org/10.1016/S0022-1694(01)00594-7

Zaitchik, B. F., M. Rodell, F. Olivera, 2010. Evaluation of the Global Land Data Assimilation System using global river discharge data and a source- to -sink routing scheme. Water Resour. Res., 46, W06507. Doi:10.1029/2009WR007811.

Zhang, G., Yao, T., Xie, H., Kang, S., Lei, Y., 2013. Increased mass over the Tibetan Plateau: from lakes or glaciers? Geophysical Research Letters, 40(10): 2125-2130.