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Solid Water Melt Dominates the Increase of Total Groundwater Storage in the Tibetan Plateau

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Key Points:

- Multiple satellite observations, modeling, and reanalysis data were used to reveal groundwater storage changes in the Tibetan Plateau
- Groundwater storage increased (5.59 ± 1.44 Gt/yr) in the entire Tibetan Plateau from 2003 to 2016
- Declining solid water (−17.72 ± 1.53 Gt/yr) including glaciers, snow, and permafrost dominates increasing groundwater storage

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Understanding how groundwater storage (GWS) responds to climate change is essential for water resources management and future water availability in the Tibetan Plateau (TP). However, the dominant factor controlling long-term GWS changes remains unclear and its responses to climate change are not well understood. Here we combined multi-source datasets including in-situ measurements, satellite observations, global models, and reanalysis products to reveal that GWS increased at 5.59 ± 1.44 Gt/yr during 2003–2016 while showing spatial heterogeneities with increasing trends in northern TP and glacial regions and declining trends in central and southern TP. The accelerated transformation from solid water (glaciers, snow, and permafrost; −17.72 ± 1.53 Gt/yr) into liquid water provide more recharge to groundwater, dominating the total GWS increase. This study contributes to a better understanding of the hydrological cycle under climate change and provides key information for projecting water availability under different future scenarios in the TP.

Plain Language Summary

Long-term groundwater storage (GWS; the amount of water stored in the pores, fissures, and caves of soil and rocks within the underground saturated zone) changes in response to climate change in the Tibetan Plateau (TP), and its dominant controlling factor has not been fully understood. There are very limited observation wells in the TP to monitor the groundwater level changes. This study used satellite observations, modeling, and reanalysis data to investigate GWS changes in the TP during 2003–2016. Results show that the GWS increased by 5.59 ± 1.44 Gt/yr during this period. The accelerated climate warming on the TP has led to significant solid water melt, including glacier melt, snow melt, and permafrost thaw. The solid water storage showed a decreasing trend (−17.72 ± 1.53 Gt/yr) and provided more water to infiltrate to recharge groundwater. The solid water melt has been identified to be the dominant source of GWS increase in the TP. The results of this study will help us to better understand the changes in the water cycle on the TP caused by climate change.

1. Introduction

Known as the Asian water tower, the Tibetan Plateau (TP) plays a critical role in providing water resources for over two billion people living downstream (Immerzeel et al., 2010). A better understanding of water storage changes is essential for water resources management to ensure water security and food production (Immerzeel & Bierkens, 2012). Groundwater sustains rivers in winter and buffers droughts to maintain fragile ecosystems, especially in arid or semi-arid regions (de Graaf et al., 2019; Famiglietti, 2014; Fan et al., 2013; Gleeson et al., 2016; Rodell et al., 2009; Taylor et al., 2013; Yao et al., 2021). Over the past decades, TP has experienced dramatic glacier retreat, permafrost degradation, and lake expansions caused by global warming (Brun et al., 2017; Cheng & Wu, 2007; Feng et al., 2019; Ji et al., 2020; Kuang & Jiao, 2016; Yao et al., 2012, 2022; Yi et al., 2021; Zhang et al., 2020). The accelerated transformation from solid water into liquid water may alter groundwater recharge, storage, and discharge to varying degrees, resulting in substantial changes in the groundwater system (Cheng & Jin, 2013; Gao et al., 2018; Huss & Hock, 2018; Lin et al., 2020; Yin et al., 2021). However, how groundwater storage (GWS) responds to climate change is poorly known because of limited observations caused by the harsh environment throughout the TP (Andermann et al., 2012; Feng et al., 2018). The Gravity Recovery and Climate Experiment (GRACE) mission provided an unprecedented opportunity to track water moving around the world (Tapley et al., 2004). By removing other hydrological contributions including soil moisture, ice, and surface water from Terrestrial Water Storage (TWS) changes, GWS changes can be obtained (Rodell & Famiglietti, 2002). GRACE is an effective tool to evaluate large-scale GWS changes in data-scarce or ungauged basins (Chen et al., 2016), especially the TP.

Recently, significant progress has been made in monitoring water storage changes in lakes, glaciers, snow, permafrost, soil moisture, and groundwater over the TP. Lake volume changes in 1,257 lakes (>1 km^2) were monitored by multiple satellites (Li, Long, et al., 2019; Wang, Wang, Li, et al., 2021; Zhang, Bolch, et al., 2021). Hugonnet et al. (2021) estimated global glacier mass changes with high spatio-temporal resolution and precision. Kraaijenbrink et al. (2021) combined the snow model with satellite observations to estimate snowpack variations during the past four decades in High Mountain Asia. Other researchers also simulated active layer thickness (ALT) changes in the TP (Ji et al., 2022; Ran et al., 2021). Soil moisture in-situ observation networks were constructed to validate satellite retrievals and improve the modeling of soil moisture (Dente et al., 2012; Su et al., 2011; Yang et al., 2013). Previous studies found an increasing GWS in the subregions of the TP from the early 2000s (Bibi et al., 2019; Chao et al., 2019; Jiao et al., 2015; Xiang et al., 2016; Zhang et al., 2017) and attributed the GWS changes to various factors including precipitation, evapotranspiration, glacier retreat, permafrost degradation, snow melt, ecological project, etc. However, the dominant factors controlling the long-term changes in GWS remain unclear and its response to climate change is not well understood, thereby calling for improved estimations of the water storage components and a holistic analysis of GWS changes as well as their driving factors.

This study integrates multi-source datasets including in-situ measurements, satellite observations, global models, and reanalysis products to study changes in each water storage component and quantified their contributions to the TWS variations in 2003–2016 over the TP, particularly analyzing GWS changes and their controlling factors. In addition, we compared GRACE-derived GWS (G-GWS) changes with other independent estimations of GWS changes from baseflow recession, wells, Global Hydrological Models (GHMs), and Land Surface Models (LSMs). The value of this work is in providing a better understanding of the hydrological cycle under climate change and fundamental information for projecting water availability under different future scenarios in the TP.

2. Materials and Methods

The TP extends from the northern foothill of the Western Kunlun-Qilian Mountains in the north to the southern foothill of the Himalayas and other southern mountains in the south; from the Hindu Kush Mountains and the western edge of the Pamir Plateau in the west to the eastern edge of the Hengduan Mountains and other eastern mountains in the east with a total area over three million square kilometers and an average elevation of about 4,320 m (Zhang, Li, et al., 2021). It can be divided into the Endorheic Basins (including Amu Dayra, Tarim, Hexi Corridor, Qaidam, and Inner Plateau) and Exorheic Basins (including Indus, Ganges, Brahmaputra, Salween, Mekong, Yangtze, and Yellow (Figure S1 in Supporting Information S1; Zhang et al., 2013). We combined the Amu Dayra, Tarim, and Hexi Corridor (Amu-Tarim-Hexi); the Indus and Ganges (Indus-Ganges); the Mekong and Salween (Mekong-Salween) together, respectively, in analysis to ensure that the area requirement (200,000 km^2) of GRACE's resolution accuracy is met (Rodell et al., 2018).

TWS changes are mainly the summation of water changes in lakes (L), glaciers (G), snow water equivalent (SWE), permafrost (PM), soil moisture (SM), and GWS in the TP (Zhang et al., 2017). Mass change signals caused by tectonic uplift, soil erosion, plant canopy, biomass changes, and river water storage changes were ignored as suggested by Xiang et al. (2016). GWS changes can be calculated by removing contributions of other components from TWS changes using the following water balance equation (Zhang et al., 2017):

$$\Delta \mathrm{GWS} = \Delta \mathrm{TWS} - \Delta \mathrm{L} - \Delta \mathrm{G} - \Delta \mathrm{SWE} - \Delta \mathrm{PM} - \Delta \mathrm{SM} \quad (1)$$

Changes in solid water storage (including G, SWE, and PM) and liquid water storage (including L, SM, and GWS) were also analyzed.

TWS changes were from the Jet Propulsion Laboratory mascon products (JPL-M; Watkins et al., 2015) and the Center for Space Research mascon products (CSR-M; Save et al., 2016; Text S1 and Table S1 in Supporting Information S1). We compiled lake volume changes of 1,257 lakes from Li, Long, et al. (2019), Wang, Wang, Li, et al. (2021), and Zhang, Bolch, et al. (2021) (Text S2, Figure S2, and Table S2 in Supporting Information S1).

Glacier mass changes were from Hugonnet et al. (2021) that used extensive Digital Elevation Models (DEMs) data to estimate global glacier mass changes with high accuracy and fine spatio-temporal resolution and validated against independent measurements (Table S3 in Supporting Information S1). SWE was retrieved from Kraaijenbrink et al. (2021), which combined the regional snow model with satellite observations to model snowpack changes and validated it against in-situ measurements and spaceborne satellite radar data (Text S3, Figure S3, and Table S4 in Supporting Information S1). For the permafrost, we retrieved ALT data from the Community Land Model Version 5 (Lawrence et al., 2019) and converted the ALT changes into mass changes by the method in Xiang et al. (2016) (Text S4, Figure S4–5, and Table S5 in Supporting Information S1). We evaluated 11 SM from LSMs, GHMs, and reanalysis products, and selected the ensemble mean of the Land component of the fifth generation of European ReAnalysis (ERA5-Land; Muñoz-Sabater et al., 2021), Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA2; Gelaro et al., 2017), and Mosaic from Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) because of their superior performances over the TP (Text S5, Figure S6–S8, and Table S4 and S7 in Supporting Information S1). Three other independent estimations including baseflow-derived GWS (B-GWS), well-derived GWS (W-GWS), and GWS from GHMs and LSMs, were compared with G-GWS (Text S7, Figure S9–10, and Table S9–10 in Supporting Information S1). Meteorological data including precipitation and air temperature were used to analyze their effects on GWS changes (Text S8 and Table S8 in Supporting Information S1). Detailed information on processing procedures of data format (Text S8 in Supporting Information S1), trend estimation (Text S9 in Supporting Information S1), uncertainties, and component contribution ratio (Text S10–S11 in Supporting Information S1) are in the Supporting Information.

3. Results

3.1. Water Storage Components Trends and Their Contributions to TWS Variations

In the whole TP, glaciers (−16.61 ± 0.92 Gt/yr) dominated TWS trends, followed by lakes (7.28 ± 0.32 Gt/yr), groundwater (5.59 ± 1.44 Gt/yr), while permafrost (−1.10 ± 0.39 Gt/yr), soil moisture (0.66 ± 1.65 Gt/yr), and snow (−0.27 ± 0.86 Gt/yr) were minor (Figures 1a–1k; Table S11 in Supporting Information S1). Lakes (6.78 ± 0.32 Gt/yr) and glaciers (−14.91 ± 0.72 Gt/yr) played a major role in TWS trends in the Endorheic and Exorheic Basins, respectively. Among the sub-basins, lakes played a predominant role in TWS trends in the Inner Plateau (6.26 ± 0.28 Gt/yr) and Yellow (0.62 ± 0.02 Gt/yr). Glaciers dominated TWS trends in the Indus-Ganges (−7.28 ± 0.41 Gt/yr), Mekong-Salween (−1.43 ± 0.06 Gt/yr), and Brahmaputra (−5.49 ± 0.22 Gt/yr). Soil moisture dominated TWS trends only in the Amu-Tarim-Hexi (−0.74 ± 0.22 Gt/yr). Groundwater dominated TWS trends in the Qaidam (0.66 ± 0.13 Gt/yr) and Yangtze (2.16 ± 0.34 Gt/yr). Snow and permafrost had no prevailing trends in all regions. Besides, solid and liquid water showed distinct divergent changes with declining and increasing trends over the TP, respectively, except for the Mekong-Salween (Figure 1l; Table S13 in Supporting Information S1).

Glaciers (28.70 ± 0.84%) contributed to the largest TWS variations in the whole TP, followed by soil moisture (25.23 ± 1.06%), groundwater (19.28 ± 0.88%), lakes (12.08 ± 0.29%), while both snow (8.53 ± 0.70%) and permafrost (6.19 ± 0.35%) were less than 10% (Figure 1m; Table S12 in Supporting Information S1). Lakes (32.20 ± 0.64%) and glaciers (36.41 ± 1.05%) accounted for most of the TWS variability in the Endorheic and Exorheic Basins, respectively. In the sub-basins, lakes were the major contributor to TWS variations in the Inner Plateau (37.69 ± 0.76%). Glaciers contributed the most TWS variations in the Indus-Ganges (45.24 ± 1.20%) and Brahmaputra (36.55 ± 0.96%). Soil moisture was the major contributor to TWS variability only in the Yangtze (49.33 ± 1.49%). Groundwater has the leading contribution in the Qaidam (45.08 ± 1.60%), Amu-Tarim-Hexi (41.50 ± 1.36%), Mekong-Salween (38.13 ± 1.49%), and Yellow (29.91 ± 1.60%). Snow and permafrost had no predominant contribution in all regions. Contributions of solid and liquid water to TWS variations were 43.87 ± 1.68% and 56.13 ± 1.60% in the whole TP, respectively (Table S13 in Supporting Information S1). Solid water had the dominant contribution only in the Indus-Ganges (58.59% ± 1.74%), while liquid water dominated in other regions.

3.2. Spatio-Temporal Variations of GWS Changes in the TP

GWS showed a statistically significant increasing trend (5.59 ± 1.44 Gt/yr, $p < 0.01$) in the entire TP from 2003 to 2016 (Figure 2c). This means that the total GWS increased by 78.26 ± 20.16 Gt during this period, nearly

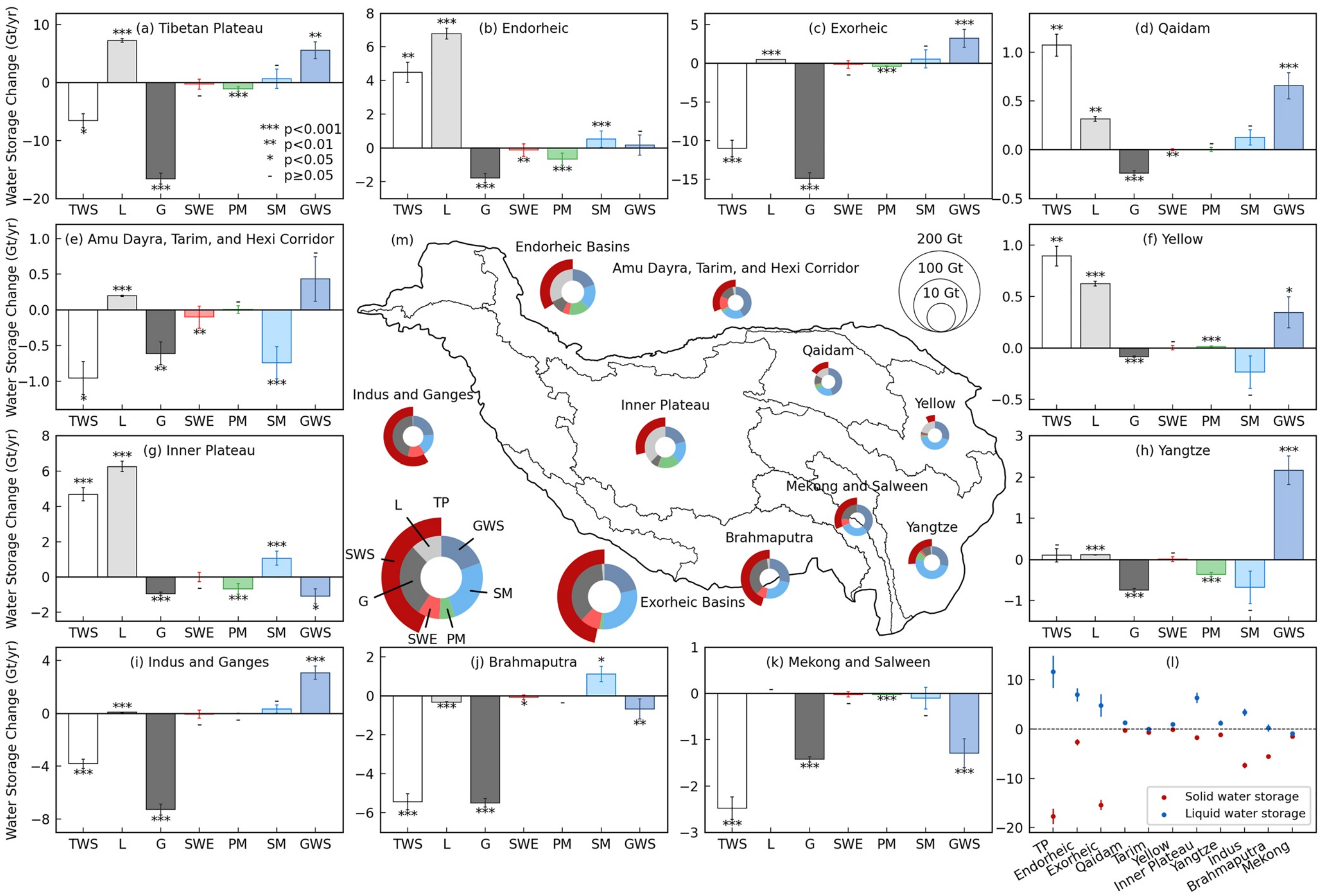

Figure 1. Trend of each water storage component in the (a) Tibetan Plateau (TP), (b) Endorheic Basins, (c) Exorheic Basins, (d) Qaidam, (e) Amu Dayra, Tarim, and Hexi Corridor, (f) Yellow, (g) Inner Plateau, (h) Yangtze, (i) Indus and Ganges (j) Brahmaputra, and (k) Mekong and Salween (k) from 2003 to 2016. (l) Trends of solid and liquid water storage in the TP and its sub-basins in 2003–2016 (Error bars represent the corresponding uncertainty of the GWS trends; *** indicates the significance level $p < 0.001$; ** indicates the significance level $p < 0.01$; * indicates the significance level $p < 0.05$; - indicates the significance level $p \geq 0.05$; Tarim represents Amu Dayra, Tarim, and Hexi Corridor; Indus represents Indus and Ganges; Mekong represents Mekong and Salween). (m) Component contribution ratio of each water storage component to TWS variations in the TP and its sub-basins during 2003–2016 (The inner-circle diagram represents contributions of L, G, SWE, PM, SM, and GWS; the outer-circle diagram represents the contribution of SWS to TWS variations; the size of the circle diagram represents the magnitude of TWS variations). The basin boundaries were from Zhang (2019).

twice as much as the maximum capacity of the Three Georges Reservoir (Jiao et al., 2015). GWS increased both in the Endorheic (0.17 ± 0.60 Gt/yr) and Exorheic (3.23 ± 1.17 Gt/yr) Basins (Figure S11 in Supporting Information S1). However, GWS trends showed substantially spatial heterogeneities with increasing trends in northern TP and glacial areas while declining trends in central and southern TP (Figure 2a). GWS in nearly half of the domain showed declining trends, while the total GWS had an increasing trend. The glacial regions with increasing GWS accounted for small areas but their magnitudes are large than those in areas with declining GWS trends, thus having substantial effects on the whole TP. In sub-basins, GWS showed increasing trends in the Amu-Tarim-Hexi, Yellow, Yangtze, Indus-Ganges, and Qaidam ($0.34 \pm 0.15 \sim 3.06 \pm 0.50$ Gt/yr) while declining trends in other sub-basins ($-1.29 \pm 0.31 \sim -0.67 \pm 0.52$ Gt/yr; Figures 2c and 2d–2k).

4. Discussions

4.1. Solid Water Melt Dominates GWS Increase in the TP

From the perspective of sources and sinks of the groundwater budget, the substantial increase in the GWS was empirically linked to more recharge, while we found the declining precipitation from three different sources ($-0.58 \sim -2.00$ mm/yr, $p > 0.05$) during 2003–2016 (Figure S12 in Supporting Information S1). Ma and Zhang (2022) reported the overall increasing evapotranspiration in 1982–2016. Declining precipitation indicated

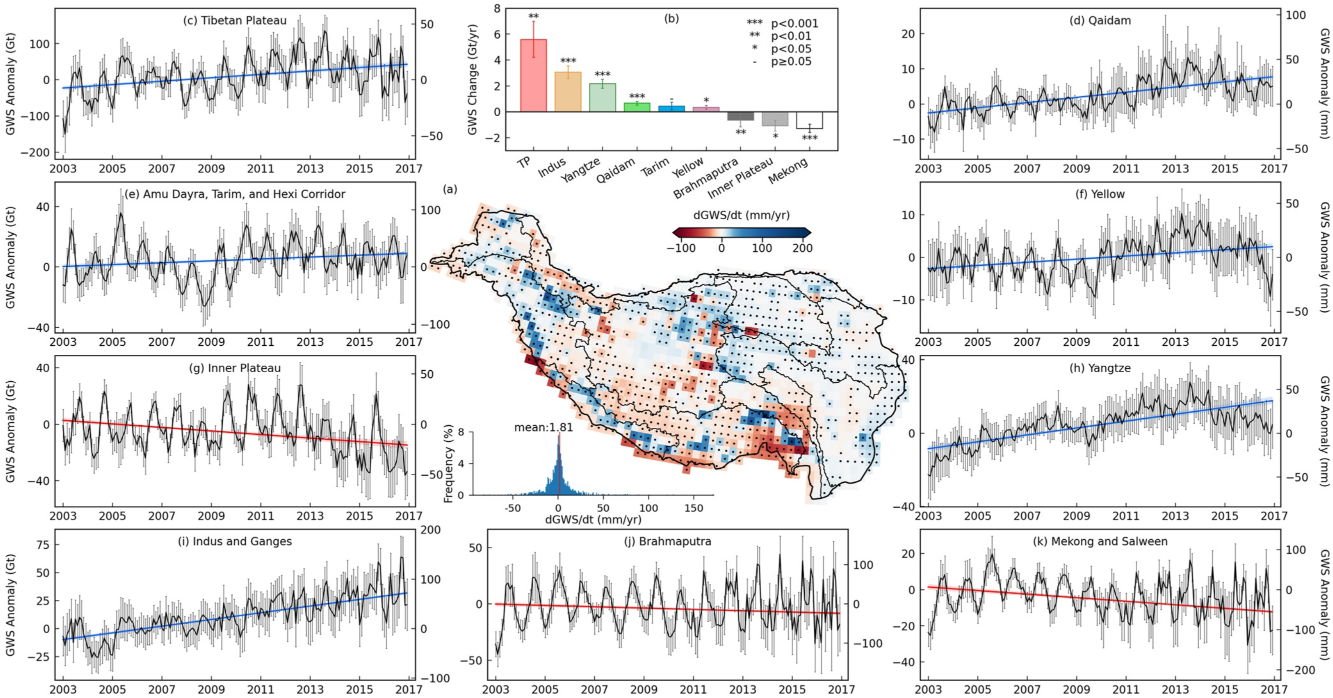

Figure 2. The spatial and temporal variations of groundwater storage (GWS) in the Tibetan Plateau (TP) and its sub-basins. (a) Spatial distribution of GWS trends from 2003 to 2016 in the TP (Grids with the significant trend ($p < 0.05$) are marked with black dots; the frequency histogram is GWS trends at all grids and the red line represents the mean value of all grids). (b) Ranking of GWS trends in the TP and its sub-basins during 2003–2016 (Error bars represent the corresponding uncertainty of GWS trends; *** indicates the significance level $p < 0.001$; ** indicates the significance level $p < 0.01$; * indicates the significance level $p < 0.05$; - indicates the significance level $p \geq 0.05$; Tarim represents Amu Dayra, Tarim, and Hexi Corridor; Indus represents Indus and Ganges; Mekong represents Mekong and Salween). Monthly time series of GWS anomalies in the (c) TP, (d) Qaidam, (e) Amu Dayra, Tarim, and Hexi Corridor, (f) Yellow, (g) Inner Plateau, (h) Yangtze, (i) Indus and Ganges (j) Brahmaputra, and (k) Mekong and Salween during 2003–2016 (Linear trends are shown in red (declining) or blue (increasing) lines and their 95% confidence intervals are illustrated by transparent shades; error bars represent the corresponding uncertainty).

no more groundwater recharge from precipitation, so the increasing GWS should be recharged by other potential sources. Other potential groundwater recharge sources have not significantly changed except for solid water. Hence, the main reason for the increasing GWS was likely that groundwater gained more recharge from solid water melt (glaciers, snow, and permafrost) due to warming (air temperature trends range from −0.01 to 0.07°C/yr over the TP; Figure S13 in Supporting Information S1). We attribute the increasing GWS to declining solid water rather than the specific components because glacier mass changes from Hugonnet et al. (2021) include snow (Wang et al., 2018) that are difficult to separate.

The dominant controlling factors of GWS changes varied among the sub-basins. In the sub-basins including the Amu-Tarim-Hexi, Yellow, and Yangtze with increasing GWS, solid water melt was the dominant factor because of the declining solid water and precipitation (Figures 2e, 2f, and 2h; Figures S13e, S13f, and S13h in Supporting Information S1). Over the Qaidam and Indus-Ganges, solid water melt was still the predominant factor in the upward GWS as the increase in precipitation was not statistically significant enough to explain the increasing GWS (Figures 2d and 2i; Figures S13d and S13i in Supporting Information S1). In other sub-basins with declining GWS including the Inner Plateau, Brahmaputra, and Mekong-Salween, declined precipitation likely dominated the decreasing GWS since solid water was melting (Figures 2g, 2j and 2k; Figures S13g, S13j, and S13k in Supporting Information S1). Although declining GWS seemed to contradict lake expansions in the Inner Plateau, the increasing GWS was consistent with upward lake volume in the northern Inner Plateau (Wang, Wang, Li, et al., 2021). Besides, our results have the same spatial pattern of GWS trends as Qiao et al. (2021) with declining and increasing trends in the northern and southern Inner Plateau (Figure 2a), respectively. The downward GWS in the southern Inner Plateau may leak out by cross-basin groundwater flow through tensional fractures and deep normal faults (Yong et al., 2021). Interestingly, Wang, Wang, Zhou, et al. (2021) found that glacier mass loss in the southeastern TP did not offset the declined runoff in the upper Brahmaputra during 1998–2019. Our results demonstrated that the glacier retreat in the southeastern TP also did not offset the decreasing GWS in the upper

Brahmaputra (Figures 2a and 2j). Although research subjects are different between our study and Wang, Wang, Zhou, et al. (2021), the spatio-temporal changes of runoff and GWS are similar, reflecting the same effects of glacier melt on the long-term changes in surface water and groundwater. The weakened Indian monsoon reduced water vapor transportation (Ouyang et al., 2020; Turner & Annamalai, 2012), resulting in less precipitation after 1998 Wang, Wang, Zhou, et al., (2021) and ultimately declining GWS in the Brahmaputra, while glacier melt did not reverse this downward trend.

Our results can also be supported by previous isotopic studies that demonstrated the dominant role of meltwater in groundwater recharge in glacial regions (Kong et al., 2019; Lone et al., 2021). Kong et al. (2019) found that non-monsoon precipitation (meltwater mainly coming from non-monsoon precipitation) accounts for 87 ± 28% of groundwater recharge at the Mingyong glacier in Hengduan Mountains, southeastern TP, even though this region is affected by the Indian monsoon. The mechanism of the high recharge ratio of groundwater from meltwater in Kong et al. (2019) is that soil water was nearly saturated at the beginning of monsoon seasons and the monsoon precipitation rarely infiltrated because meltwater from glaciers and snow continually infiltrated during non-monsoon seasons and rainfall is too concentrated to infiltrate in monsoon seasons. Besides, Lone et al. (2021) showed that meltwater supplies 83% of groundwater recharge in the upper Indus, highlighting the significance of the cryosphere in maintaining groundwater resources.

Increasing GWS caused by glacier melt was also found in other alpine regions. For example, Castellazzi et al. (2019) found that declining glacier mass was compensated by increased GWS in the Canadian Rocky Mountains and explained that part of the meltwater did not immediately flow into rivers but rather was stored in local aquifers, further supporting our results and indicating that this phenomenon may occur in global alpine regions.

4.2. Comparison of GWS Changes With Previous Studies

Our results showed consistency with previous studies in directions of GWS trends and an improvement in seasonal variations (Table S14 in Supporting Information S1). The directions of GWS trends in our study were in line with Xiang et al. (2016) except for the two regions. The seasonal GWS variations in Xiang et al. (2016) were much larger than our estimates because they only used linear trends of glaciers, lakes, and permafrost in calculations (Figures 1c–1k). In the Yangtze, we estimated an increasing GWS (2.16 ± 0.34 Gt/yr), which was comparable to Chao et al. (2019) (3.80 ± 0.50 Gt/yr). In the Qaidam, our results showed an increasing GWS (0.66 ± 0.13 Gt/yr) in 2003–2016, which was between the estimations in Bibi et al. (2019) (0.45 Gt/yr) and Jiao et al. (2015) (1.62 ± 0.14 Gt/yr). In the Inner Plateau, our results indicated an decreasing GWS (−1.09 ± 0.41 Gt/yr), which were comparable to Qiao et al. (2021) (−0.83 Gt/yr) but quite different from Zhang et al. (2017) (5.01 ± 1.59 Gt/yr). Zhang et al. (2017) concluded that GWS increases were comparable to lake volume increases (7.72 ± 0.63 Gt/yr) during 2003–2009. However, recent studies confirmed that TWS changes in the Inner Plateau were dominated by lake volume changes (Jiang et al., 2020; Xu et al., 2022), which are in agreement with our results. Leaving aside other factors, GWS changes in our study and Qiao et al. (2021) should be more reasonable as current studies use the updated GRACE products.

4.3. Comparison With GWS Estimations From Baseflow Recession and Wells

Figure S14 in Supporting Information S1 shows that the direction of trends in B-GWS and G-GWS are consistent in the eight headwater basins of the TP except for the headwater of Yangtze. Previous studies have confirmed that the magnitude of trends and variations in B-GWS is far lower than that of G-GWS (Cao et al., 2019; Schmidt et al., 2020). However, B-GWS still provides valuable independent information (Liu et al., 2020), and the consistencies between these two independent methods also indicate the robustness of our results. G-GWS has the same direction of GWS trends as W-GWS except in Golmud; G-GWS and W-GWS have the same magnitude of variations and trends In Lhasa, but not in Golmud and Huangzhong (Figure S15 in Supporting Information S1). These differences can be attributed to the unrepresentative single well, mismatched resolutions, or unreasonable specific yield estimations (Shamsudduha et al., 2012).

4.4. Inconsistencies in GWS Changes Between Our Study and Global Models

Figure 3a shows that there are varying degrees of differences in trends between G-GWS and other GHMs or LSMs in the TP during 2003–2012. We found that almost all existing GHMs and LSMs could not simulate the

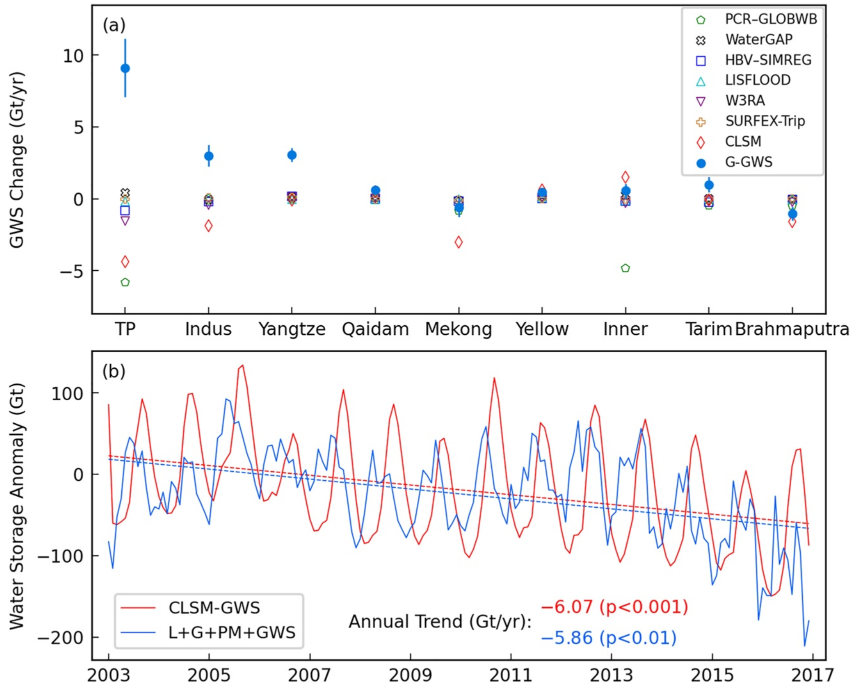

Figure 3. s(a) Comparisons of trends in Groundwater Storage (GWS) with five Global Hydrological Models (GHMs) and two Land Surface Models (LSMs) in the TP and its sub-basins during 2003–2012 (Error bars represent the corresponding uncertainty of GWS trends; information on GHMs and LSM are in Table S10; Inner represents Inner Plateau). (b) Comparisons of GWS anomalies from Catchment Land Surface Model (CLSM-GWS) with the summation of L, G, PM, and G-GWS in the entire TP during 2003–2016 (Red and blue dashed lines are the linear trend of CLSM-GWS and the summation of L, G, PM, and G-GWS, respectively; annual trends and significant levels are also shown).

substantially increasing GWS as G-GWS did (Figure 3a), particularly in the Yangtze and Indus-Ganges with large inconsistencies.

Many factors, including groundwater simulation schemes, incomplete water storage modules, groundwater depth, groundwater recharge formulations, forcing datasets, etc., could account for these inconsistencies. In general, these models used simplified water balance approaches to model GWS changes but did not simulate groundwater fluxes or heads directly, thus may result in inaccurate GWS simulations (Condon et al., 2021; Gleeson et al., 2021). Besides, these inconsistencies may be related to groundwater depths in the TP. Groundwater flow systems are characterized as deep circulation driven by topographic gradients that can reach deeper than 1 ~ 2 km in the TP (Ge et al., 2008), while these models only model shallow groundwater. Groundwater recharge schemes in these models are also important for interpreting these inconsistencies because most models only incorporate diffuse groundwater recharge formulation (Condon et al., 2021). Water-Global Assessment and Prognosis version 2.2 d (WaterGAP v2.2 d) and PCRaster Global Water Balance 2 (PCR-GLOBWB 2) improve it by considering recharge from surface water (Müller Schmied et al., 2021; Sutanudjaja et al., 2018), however, recharge from glaciers, snow, or permafrost is still not represented well in them. Therefore, the absence of lake, glacier, or permafrost modules in these models may largely cause these inconsistencies.

The Catchment Land Surface Model (CLSM) from the GLDAS version 2.2 (GLDAS-2.2) products show quite improvements in groundwater simulation as GLDAS-2.2 particularly assimilates TWS anomalies from the GRACE missions (Li, Rodell, et al., 2019). However, GWS from CLSM (CLSM-GWS) could not capture the increasing GWS affected by climate change in the TP. CLSM computes GWS changes by deducting contributions of other components (SM, SWE, and Canopy Interception) from TWS changes (Li, Rodell, et al., 2019), while the contributions of glaciers, permafrost, and lakes are not separated. Consequently, CLSM-GWS implicitly contains water storage changes in glaciers, permafrost, and lakes over the TP as Figure 3b indicates almost identical trends between CLSM-GWS (−6.07 Gt/yr) and the summation of the lake, glacier, permafrost, and GWS (−5.86 Gt/yr) in 2003–2016.

4.5. Limitations and Uncertainties

One major limitation of this study is the accumulation of intrinsic uncertainties of each water storage component in the water balance approach. Uncertainties from soil moisture exert the largest effects on GWS estimations as using different products may result in opposite GWS trends (Figure S8 in Supporting Information S1). Although we used available in-situ measurements to evaluate soil moisture products, simulations and observations on soil moisture need to be further improved in the TP. Another limitation is the residual closure errors in GWS due to ignoring mass change induced by potential factors including tectonic uplift, soil erosion, plant canopy, biomass changes, water storage changes in the river channel, etc., in the water balance equation. Previous studies concluded that the effects of these factors can be ignored, while Ke et al. (2022) revealed that water storage changes in river channels could account for around 10% of the seasonal GRACE signals in the Upper Brahmaputra River Basin. Although water storage changes in river channels have limited effects on the long-term TWS trends, including them could improve estimations of seasonal GWS variations. In addition, datasets with coarse spatio-temporal resolution as well as simple assumptions and aquifer parameters in the independent GWS estimations from baseflow recession and well can also lead to uncertainties. Moreover, we have to acknowledge that no field observations could validate increasing GWS in the TP although we found this phenomenon in indirect ways. More efforts on observations and simulations will be needed to better understand the impacts of climate change on groundwater in the TP.

5. Conclusions

We combined multi-source data including in-situ measurements, satellite observations, global models, and reanalysis products, finding a substantial increase in GWS (5.59 ± 1.44 Gt/yr) in the whole TP from 2003 to 2016. The GWS changes showed spatial heterogeneities among the sub-basins with declining trends in the Inner Plateau, Brahmaputra, and Mekong-Salween, and increasing trends in other basins. Given the decreasing precipitation and no substantial changes in other potential recharge sources except for declining solid water (-17.72 ± 1.53 Gt/yr), the total GWS increase was likely dominated by groundwater recharge from solid water melt. The GWS contributes $19.28 \pm 0.88\%$ of the TWS variations in the entire TP and its contributions range from 19.64 ± 0.96 to $45.08 \pm 1.60\%$ in its sub-basins. G-GWS shows consistencies in trends with independent estimations of B-GWS, while almost none of the existing LSMs and GHMs could simulate the substantially increasing GWS in the TP due to the lack of cryospheric or lake modules and simplified representations of groundwater. This study identifies the dominant factor controlling long-term GWS changes and provides a better understanding of GWS response to climate change in the data-scarce TP.

Data Availability Statement

Basin boundaries from Zhang (2019) were provided by the National Tibetan Plateau Data Center (https://doi.org/10.11888/BaseGeography.tpe.249465.file). JPL-M products were provided by the Physical Oceanography Distributed Active Archive Center (https://doi.org/10.5067/TEMSC-3JC62). CSR-M products were provided by the Center for Space Research (http://www2.csr.utexas.edu/grace). Lake volume changes from Li, Long, et al. (2019) were provided by PANGAEA (https://doi.org/10.1594/PANGAEA.898411). Lake volume changes from Wang, Wang, Li, et al. (2021) were provided by Zenodo (https://doi.org/10.5281/zenodo.5543615). Lake volume changes from Zhang, Bolch, et al. (2021) were provided by National Tibetan Plateau Data Center (http://doi.org/10.11888/Hydro.tpdc.271169). Glacier mass changes from Hugonnet et al. (2021) were provided by Theia (https://doi.org/10.6096/13). SWE from Kraaijenbrink et al. (2021) were provided by Zenodo (https://doi.org/10.5281/zenodo.4715786). ALT from CLM5 was provided by the Climate Data Gateway at National Center for Atmospheric Research (https://doi.org/10.5065/d6154fwh).

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References

Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P., & Gloaguen, R. (2012). Impact of transient groundwater storage on the discharge of Himalayan Rivers. *Nature Geoscience*, *5*(2), 127–132. https://doi.org/10.1038/ngeo1356

Bibi, S., Wang, L., Li, X., Zhang, X., & Chen, D. (2019). Response of groundwater storage and recharge in the Qaidam Basin (Tibetan Plateau) to climate variations from 2002 to 2016. *Journal of Geophysical Research: Atmospheres*, *124*(17), 9918–9934. https://doi.org/10.1029/2019JD030411

Brun, F., Berthier, E., Wagnon, P., Kääb, A., & Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nature Geoscience*, *10*(9), 668–673. https://doi.org/10.1038/ngeo2999

Cao, Q., Clark, E. A., Mao, Y., & Lettenmaier, D. P. (2019). Trends and interannual variability in terrestrial water storage over the eastern United States, 2003-2016. *Water Resources Research*, *55*(3), 1928–1950. https://doi.org/10.1029/2018WR023278

Castellazzi, P., Burgess, D., Rivera, A., Huang, J., Longuevergne, L., & Demuth, M. N. (2019). Glacial melt and potential impacts on water resources in the Canadian Rocky Mountains. *Water Resources Research*, *55*(12), 10191–10217. https://doi.org/10.1029/2018WR024295

Chao, N., Chen, G., Li, J., Xiang, L., Wang, Z., & Tian, K. (2019). Groundwater storage change in the Jinsha River Basin from GRACE, hydrologic models, and in situ data. *Ground Water*, *58*(5), 735–748. https://doi.org/10.1111/gwat.12966

Chen, J., Famigliett, J. S., Scanlon, B. R., & Rodell, M. (2016). Groundwater storage changes: Present status from GRACE observations. *Surveys in Geophysics*, *37*(2), 397–417. https://doi.org/10.1007/s10712-015-9332-4

Cheng, G., & Jin, H. (2013). Permafrost and groundwater on the Qinghai-Tibet Plateau and in northeast China. *Hydrogeology Journal*, *21*(1), 5–23. https://doi.org/10.1007/s10040-012-0927-2

Cheng, G., & Wu, T. (2007). Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *Journal of Geophysical Research*, *112*(F2), F02S03. https://doi.org/10.1029/2006JF000631

Condon, L. E., Kollet, S., Bierkens, M. F. P., Fogg, G. E., Maxwell, R. M., & Hill, M. C. (2021). Global groundwater modeling and monitoring: Opportunities and challenges. *Water Resources Research*, *57*(12), 1–27. https://doi.org/10.1029/2020WR029500

de Graaf, I. E. M., Gleeson, T., van Rens Beek, L. P. H., Sutanudjaja, E. H., & Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. *Nature*, *574*(7776), 90–94. https://doi.org/10.1038/s41586-019-1594-4

Dente, L., Vekerdy, Z., Wen, J., & Su, Z. (2012). Maqu network for validation of satellite-derived soil moisture products. *International Journal of Applied Earth Observation and Geoinformation*, *17*(1), 55–65. https://doi.org/10.1016/j.jag.2011.11.004

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945–948. https://doi.org/10.1038/nclimate2425

Fan, Y., Li, H., & Miguez-Macho, G. (2013). Global patterns of Groundwater table depth. *Science*, *339*(6122), 940–943. https://doi.org/10.1126/science.1229881

Feng, W., Shum, C., Zhong, M., & Pan, Y. (2018). Groundwater storage changes in China from satellite gravity: An overview. *Remote Sensing*, *10*(5), 674. https://doi.org/10.3390/rs10050674

Feng, Y., Liang, S., Kuang, X., Wang, G., Wang, X.-S., Wu, P., et al. (2019). Effect of climate and thaw depth on alpine vegetation variations at different permafrost degrading stages in the Tibetan Plateau, China. *Arctic Antarctic and Alpine Research*, *51*(1), 155–172. https://doi.org/10.1080/15230430.2019.1605798

Gao, B., Yang, D., Qin, Y., Wang, Y., Li, H., Zhang, Y., & Zhang, T. (2018). Change in frozen soils and its effect on regional hydrology, upper Heihe Basin, northeastern Qinghai-Tibetan Plateau. *The Cryosphere*, *12*(2), 657–673. https://doi.org/10.5194/tc-12-657-2018

Ge, S., Wu, Q. B., Lu, N., Jiang, G. L., & Ball, L. (2008). Groundwater in the Tibet Plateau, Western China. *Geophysical Research Letters*, *35*(18), L18403. https://doi.org/10.1029/2008GL034809

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The Modern-Era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, M. B. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience*, *9*(2), 161–167. https://doi.org/10.1038/ngeo2590

Gleeson, T., Wagener, T., Döll, P., Zipper, S. C., West, C., Wada, Y., et al. (2021). GMD perspective: The quest to improve the evaluation of groundwater representation in continental-to global-scale models. *Geoscientific Model Development*, *14*(12), 7545–7571. https://doi.org/10.5194/gmd-14-7545-2021

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., et al. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), 726–731. https://doi.org/10.1038/s41586-021-03436-z

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. https://doi.org/10.1038/s41558-017-0049-x

Immerzeel, W. W., & Bierkens, M. F. P. (2012). Asia's water balance. *Nature Geoscience*, *5*(12), 841–842. https://doi.org/10.1038/ngeo1643

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. https://doi.org/10.1126/science.1183188

Ji, F., Fan, L., Andrews, C. B., Yao, Y., & Zheng, C. (2020). Dynamics of seasonally frozen ground in the Yarlung Zangbo River basin on the Qinghai-Tibet Plateau: Historical trend and future projection. *Environmental Research Letters*, *15*(10), 104081. https://doi.org/10.1088/1748-9326/abb731

Ji, F., Fan, L., Kuang, X., Li, X., Cao, B., Cheng, G., et al. (2022). How does soil water content influence permafrost evolution on the Qinghai-Tibet Plateau under climate warming? *Environmental Research Letters*, *17*(6), 064012. https://doi.org/10.1088/1748-9326/ac6c9a

Jiang, L., Nielsen, K., Andersen, O. B., & Bauer-Gottwein, P. (2020). A bigger picture of how the Tibetan lakes have changed over the past decade revealed by CryoSat-2 altimetry. *Journal of Geophysical Research: Atmospheres*, *125*, e2020JD033161. https://doi.org/10.1029/2020JD033161

Jiao, J. J., Zhang, X., Liu, Y., & Kuang, X. (2015). Increased water storage in the Qaidam Basin, the north Tibet Plateau from GRACE gravity data. *PLoS One*, *10*(10), e0141442. https://doi.org/10.1371/journal.pone.0141442

Ke, L., Xu, J., Fan, C., Liu, K., Chen, T., Wang, S., et al. (2022). Remote sensing reconstruction of long-term water level and storage variations of a poorly-gauged river in the Tibetan Plateau. *Journal of Hydrology: Regional Studies*, *40*, 101020. https://doi.org/10.1016/j.ejrh.2022.101020

Kong, Y., Wang, K., Pu, T., & Shi, X. (2019). Nonmonsoon precipitation dominates groundwater recharge beneath a monsoon-affected glacier in Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *124*(20), 10913–10930. https://doi.org/10.1029/2019jd030492

Kraaijenbrink, P. D. A., Stigter, E. E., Yao, T., & Immerzeel, W. W. (2021a). Climate change decisive for Asia's snow meltwater supply. *Nature Climate Change*. https://doi.org/10.1038/s41558-021-01074-x

Kuang, X., & Jiao, J. J. (2016). Review on climate change on the Tibetan Plateau during the last half century. *Journal of Geophysical Research: Atmospheres*, *121*(8), 3979–4007. https://doi.org/10.1002/2015JD024728

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., et al. (2019). The Community Land Model Version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4245–4287. https://doi.org/10.1029/2018MS001583

Li, B., Rodell, M., Kumar, S., Beaudoing, H. K., Getirana, A., Zaitchik, B. F., et al. (2019). Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges. *Water Resources Research*, *55*(9), 7564–7586. https://doi.org/10.1029/2018WR024618

Li, X., Long, D., Huang, Q., Han, P., Zhao, F., & Wada, Y. (2019). High-temporal-resolution water level and storage change data sets for lakes on the Tibetan Plateau during 2000-2017 using multiple altimetric missions and Landsat-derived lake shoreline positions. *Earth System Science Data*, *11*(4), 1603–1627. https://doi.org/10.5194/essd-11-1603-2019

Lin, L., Gao, M., Liu, J., Wang, J., Wang, S., Chen, X., & Liu, H. (2020). Understanding the effects of climate warming on streamflow and active groundwater storage in an alpine catchment: The upper Lhasa River. *Hydrology and Earth System Sciences*, *24*(3), 1145–1157. https://doi.org/10.5194/hess-24-1145-2020

Liu, X., Liu, C., & Brutsaert, W. (2020). Mutual consistency of groundwater storage changes derived from GRACE and from baseflow recessions in the central Yangtze River Basin. *Journal of Geophysical Research: Atmospheres*, *125*, e2019JD031467. https://doi.org/10.1029/2019JD031467

Lone, S. A., Jeelani, G., Deshpande, R. D., Mukherjee, A., Jasechko, S., & Lone, A. (2021). Meltwaters dominate groundwater recharge in cold arid desert of Upper Indus River Basin (UIRB), Western Himalayas. *Science of the Total Environment*, *786*, 147514. https://doi.org/10.1016/j.scitotenv.2021.147514

Ma, N., & Zhang, Y. (2022). Increasing Tibetan Plateau terrestrial evapotranspiration primarily driven by precipitation. *Agricultural and Forest Meteorology*, *317*, 108887. https://doi.org/10.1016/j.agrformet.2022.108887

Muñoz-Sabater, J., Dutra, E., Agustí Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

Ouyang, L., Yang, K., Lu, H., Chen, Y., Zhou, X., & Wang, Y. (2020). Ground-based observations reveal unique valley precipitation patterns in the central Himalaya. *Journal of Geophysical Research: Atmospheres*, *125*, e2019JD031502. https://doi.org/10.1029/2019JD031502

Qiao, B., Nie, B., Liang, C., Xiang, L., & Zhu, L. (2021). Spatial difference of terrestrial water storage change and lake water storage change in the Inner Tibetan Plateau. *Remote Sensing*, *13*(10), 1984. https://doi.org/10.3390/rs13101984

Ran, Y., Li, X., Cheng, G., Che, J., Aalto, J., Karjalainen, O., et al. (2021). High-resolution datasets of permafrost thermal state and hydrothermal zonation in the Northern Hemisphere [Dataset]. National Tibetan Plateau Data Center. https://doi.org/10.11888/Geocry.tpdc.271190

Rodell, M., & Famiglietti, J. S. (2002). The potential for satellite-based monitoring of groundwater storage changes using GRACE: The high plains aquifer, central US. *Journal of Hydrology*, *263*(1–4), 245–256. https://doi.org/10.1016/S0022-1694(02)00060-4

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M.-H. (2018). Emerging trends in global freshwater availability. *Nature*, *557*(7707), 651–659. https://doi.org/10.1038/s41586-018-0123-1

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., et al. (2004). The Global land data assimilation system. *Bulletin of the American Meteorological Society*, *85*(3), 381–394. https://doi.org/10.1175/BAMS-85-3-381

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, *460*(7258), 999–1002. https://doi.org/10.1038/nature08238

Save, H., Bettadpur, S., & Tapley, B. D. (2016). High-resolution CSR GRACE RL05 Mascons. *Journal of Geophysical Research: Solid Earth*, *121*(10), 7547–7569. https://doi.org/10.1002/2016JB013007

Schmidt, A. H., Lüdtke, S., & Andermann, C. (2020). Multiple measures of monsoon-controlled water storage in Asia. *Earth and Planetary Science Letters*, *546*, 116415. https://doi.org/10.1016/j.epsl.2020.116415

Shamsudduha, M., Taylor, R. G., & Longuevergne, L. (2012). Monitoring groundwater storage changes in the highly seasonal humid tropics: Validation of GRACE measurements in the Bengal Basin. *Water Resources Research*, *48*(2), 1–12. https://doi.org/10.1029/2011WR010993

Su, Z., Wen, J., Dente, L., van der Velde, R., Wang, L., Ma, Y., et al. (2011). The Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) for quantifying uncertainties in coarse resolution satellite and model products. *Hydrology and Earth System Sciences*, *15*(7), 2303–2316. https://doi.org/10.5194/hess-15-2303-2011

Sutanudjaja, E. H., van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H. C., Drost, N., et al. (2018). PCR-GLOBWB 2: A 5 arcmin global hydrological and water resources model. *Geoscientific Model Development*, *11*(6), 2429–2453. https://doi.org/10.5194/gmd-11-2429-2018

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., & Watkins, M. M. (2004). GRACE measurements of mass variability in the Earth system. *Science*, *305*(5683), 503–505. https://doi.org/10.1126/science.1099192

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., et al. (2019). Contributions of GRACE to understanding climate change. *Nature Climate Change*, *9*(5), 358–369. https://doi.org/10.1038/s41558-019-0456-2

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., et al. (2013). Ground water and climate change. *Nature Climate Change*, *3*(4), 322–329. https://doi.org/10.1038/nclimate1744

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, *2*(8), 587–595. https://doi.org/10.1038/nclimate1495

Wang, J., Song, C., Reager, J. T., Yao, F., Famiglietti, J. S., Sheng, Y., et al. (2018). Recent global decline in endorheic basin water storages. *Nature Geoscience*, *11*(12), 926–932. https://doi.org/10.1038/s41561-018-0265-7

Wang, L., Wang, J., Li, M., Zhu, L., & Li, X. (2021). Lake area and volume variation in the endorheic basin of the Tibetan Plateau from 1989 to 2019. *Earth System Science Data Discussions*, *2021*, 1–36. https://doi.org/10.5194/essd-2021-331

Wang, Y., Wang, L., Zhou, J., Yao, T., Yang, W., Zhong, X., et al. (2021). Vanishing Glaciers at southeast Tibetan plateau have not offset the declining runoff at Yarlung Zangbo. *Geophysical Research Letters*, *48*, e2021GL094651. https://doi.org/10.1029/2021GL094651

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., & Landerer, F. W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *Journal of Geophysical Research: Solid Earth*, *120*(4), 2648–2671. https://doi.org/10.1002/2014JB011547

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. https://doi.org/10.1016/j.epsl.2016.06.002

Xu, F., Zhang, G., Yi, S., & Chen, W. (2022). Seasonal trends and cycles of lake-level variations over the Tibetan Plateau using multi-sensor altimetry data. *Journal of Hydrology*, *604*, 127251. https://doi.org/10.1016/j.jhydrol.2021.127251

Yang, K., Qin, J., Zhao, L., Chen, Y., Tang, W., Han, M., et al. (2013). A Multiscale soil moisture and freeze–thaw monitoring network on the Third Pole. *Bulletin of the American Meteorological Society*, *94*(12), 1907–1916. https://doi.org/10.1175/BAMS-D-12-00203.1

Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., et al. (2022). The imbalance of the Asian water tower. *Nature Reviews Earth & Environment*, 1–15. https://doi.org/10.1038/s43017-022-00299-4

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., et al. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, *2*(9), 663–667. https://doi.org/10.1038/nclimate1580

Yao, Y., Zheng, C., Andrews, C. B., Scanlon, B. R., Kuang, X., Zeng, Z., et al. (2021). Role of groundwater in sustaining northern Himalayan Rivers. *Geophysical Research Letters*, *48*, e2020GL092354. https://doi.org/10.1029/2020GL092354

Yi, W., Feng, Y., Liang, S., Kuang, X., Yan, D., & Wan, L. (2021). Increasing annual streamflow and groundwater storage in response to climate warming in the Yangtze River source region. *Environmental Research Letters*, *16*(8), 084011. https://doi.org/10.1088/1748-9326/ac0f27

Yin, Z., Xu, Y., Zhu, X., Zhao, J., Yang, Y., & Li, J. (2021). Variations of groundwater storage in different basins of China over recent decades. *Journal of Hydrology*, *598*, 126282. https://doi.org/10.1016/j.jhydrol.2021.126282

Yong, B., Wang, C.-Y., Chen, J., Chen, J., Barry, D. A., Wang, T., & Li, L. (2021). Missing water from the Qiangtang Basin on the Tibetan Plateau. *Geology*, *49*(7), 867–872. https://doi.org/10.1130/G48561.1

Zhang, G. (2019). Dataset of river basins map over the TP (2016) [Dataset]. National Tibetan Plateau Data Center. https://doi.org/10.11888/BaseGeography.tpe.249465.file

Zhang, G., Bolch, T., Chen, W., & Crétaux, J.-F. (2021). Comprehensive estimation of lake volume changes on the Tibetan Plateau during 1976–2019 and basin-wide glacier contribution. *Science of the Total Environment*, *772*, 145463. https://doi.org/10.1016/j.scitotenv.2021.145463
Zhang, G., Yao, T., Shum, C. K., Yi, S., Yang, K., Xie, H., et al. (2017). Lake volume and groundwater storage variations in Tibetan Plateau's endorheic basin. *Geophysical Research Letters*, *44*(11), 5550–5560. https://doi.org/10.1002/2017GL073773
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. https://doi.org/10.1002/grl.50462
Zhang, G., Yao, T., Xie, H., Yang, K., Zhu, L., Shum, C. K., et al. (2020). Response of Tibetan Plateau lakes to climate change: Trends, patterns, and mechanisms. *Earth-Science Reviews*, *208*, 103269. https://doi.org/10.1016/j.earscirev.2020.103269
Zhang, Y., Li, B., Liu, L., & Zheng, D. (2021). Redetermine the region and boundaries of Tibetan Plateau [in Chinese]. *Geographical Research*, *40*(6), 1543–1553. https://doi.org/10.11821/dlyj020210138

References From the Supporting Information

Arciniega-Esparza, S., Breña-Naranjo, J. A., Pedrozo-Acuña, A., & Appendini, C. M. (2017). HYDRORECESSION: A Matlab toolbox for streamflow recession analysis. *Computers & Geosciences*, *98*, 87–92. https://doi.org/10.1016/j.cageo.2016.10.005
Beaudoing, H., & Rodell, M., & NASA/GSFC/HSL, (2020a). GLDAS Noah land surface model L4 monthly 0.25 x 0.25 degree V2.1 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/SXAVCZFAQLNO
Beaudoing, H., & Rodell, M., & NASA/GSFC/HSL (2020b). GLDAS VIC land surface model L4 monthly 1.0 x 1.0 degree V2.1 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/VWTH7S6218SG
Beck, H. E., van Dijk, A. I. J. M., Larraondo, P. R., McVicar, T. R., Pan, M., Dutra, E., & Miralles, D. G. (2021). MSWX: Global 3-hourly 0.1° bias-corrected meteorological data including near real-time updates and forecast ensembles. *Bulletin of the American Meteorological Society*, 1–55. https://doi.org/10.1175/BAMS-D-21-0145.1
Bi, H., Ma, J., Zheng, W., & Zeng, J. (2016). Comparison of soil moisture in GLDAS model simulations and in situ observations over the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, *121*(6), 2658–2678. https://doi.org/10.1002/2015JD024131
Brown, J., Hinkel, K. M., & Nelson, F. E. (2000). The circumpolar active layer monitoring (calm) program: Research designs and initial results. *Polar Geography*, *24*(3), 166–258. https://doi.org/10.1080/10889370009377698
Brutsaert, W. (2008). Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. *Water Resources Research*, *44*(2), 1–7. https://doi.org/10.1029/2007WR006518
Cao, B., Zhang, T., Peng, X., Mu, C., Wang, Q., Zheng, L., et al. (2018). Thermal characteristics and recent changes of permafrost in the upper reaches of the Heihe River Basin, Western China. *Journal of Geophysical Research: Atmospheres*, *123*(15), 7935–7949. https://doi.org/10.1029/2018JD028442
Chen, H., Nan, Z., Zhao, L., Ding, Y., Chen, J., & Pang, Q. (2015). Noah Modelling of the permafrost distribution and characteristics in the West Kunlun area, Qinghai-Tibet Plateau, China. *Permafrost and Periglacial Processes*, *26*(2), 160–174. https://doi.org/10.1002/ppp.1841
Chen, J., Zhao, L., Sheng, Y., Li, J., Wu, X., Du, E., et al. (2016). Some Characteristics of Permafrost and Its Distribution in the Gaize Area on the Qinghai—Tibet Plateau, China. *Arctic, Antarctic, and Alpine Research*, *48*(2), 395–409. https://doi.org/10.1657/aaar0014-023
Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Wayne Higgins, R., & Janowiak, J. E. (2008). Assessing objective techniques for gauge-based analyses of global daily precipitation. *Journal of Geophysical Research*, *113*, D04110. https://doi.org/10.1029/2007JD009132
Cleveland, R. B., Cleveland, W. S., McRae, J. E., & Terpenning, I. (1990). STL: A seasonal-trend decomposition procedure based on loess. *Journal of Official Statistics*, *6*(1), 3–73.
Collier, N., Hoffman, F. M., Lawrence, D. M., Keppel-Aleks, G., Koven, C. D., Riley, W. J., et al. (2018). The international land model benchmarking (ILAMB) system: Design, theory, and implementation. *Journal of Advances in Modeling Earth Systems*, *10*(11), 2731–2754. https://doi.org/10.1029/2018MS001354
Dahri, Z. H., Ludwig, F., Moors, E., Ahmad, S., Ahmad, B., Ahmad, S., et al. (2021). Climate change and hydrological regime of the high-altitude Indus Basin under extreme climate scenarios. *Science of the Total Environment*, *768*, 144467. https://doi.org/10.1016/j.scitotenv.2020.144467
Deggim, S., Eicker, A., Schawohl, L., Ellenbeck, L., Dettmering, D., Schwatke, C., et al. (2020). RECOG-LR RL01: Correcting GRACE total water storage estimates for global lakes and reservoirs [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.921851
Deggim, S., Eicker, A., Schawohl, L., Gerdener, H., Schulze, K., Engels, O., et al. (2021). RECOG RL01: Correcting GRACE total water storage estimates for global lakes/reservoirs and earthquakes. *Earth System Science Data*, *13*(5), 2227–2244. https://doi.org/10.5194/essd-13-2227-2021
Dente, L., Su, Z., & Wen, J. (2012). Validation of SMOS soil moisture products over the Maqu and Twente regions. *Sensors*, *12*(8), 9965–9986. https://doi.org/10.3390/s120809965
Dirmeyer, P. A., Gao, X., Zhao, M., Guo, Z., Oki, T., & Hanasaki, N. (2006). GSWP-2: Multimodel analysis and implications for our perception of the land surface. *Bulletin of the American Meteorological Society*, *87*(10), 1381–1398. https://doi.org/10.1175/BAMS-87-10-1381
Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., et al. (2011). The international soil moisture network: A data hosting facility for global in situ soil moisture measurements. *Hydrology and Earth System Sciences*, *15*(5), 1675–1698. https://doi.org/10.5194/hess-15-1675-2011
Dorigo, W. A., Xaver, A., Vreugdenhil, M., Gruber, A., Hegyiová, A., Sanchis-Dufau, A. D., et al. (2013). Global automated quality control of in situ soil moisture data from the international soil moisture network. *Vadose Zone Journal*, *12*(3), vzj2012–0097. https://doi.org/10.2136/vzj2012.0097
Feng, Y., Kuang, X., Liang, S., Liu, S., Yao, Y., Xie, Y., & Zheng, C. (2021). A simple and efficient method for correction of basin-scale evapotranspiration on the Tibetan Plateau. *Remote Sensing*, *13*(19), 3958. https://doi.org/10.3390/rs13193958
Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/joc.5086
Gao, C., Liu, L., Ma, D., He, K., & Xu, Y.-P. (2019). Assessing responses of hydrological processes to climate change over the southeastern Tibetan Plateau based on resampling of future climate scenarios. *Science of the Total Environment*, *664*, 737–752. https://doi.org/10.1016/j.scitotenv.2019.02.013
Global Modeling and Assimilation Office (GMAO). (2015). MERRA-2 tavgU_2d_lnd_Nx: 2d, diurnal, time-averaged, single-level, assimilation, land surface diagnostics V5.12.4 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/W0J15047CF6N
González-Zamora, Á., Sánchez, N., Martínez-Fernández, J., & Wagner, W. (2016). Root-zone plant available water estimation using the SMOS-derived soil water index. *Advances in Water Resources*, *96*, 339–353. https://doi.org/10.1016/j.advwatres.2016.08.001

Gouttevin, I., Krinner, G., Ciais, P., Polcher, J., & Legout, C. (2012). Multi-scale validation of a new soil freezing scheme for a land-surface model with physically-based hydrology. *The Cryosphere*, *6*(2), 407–430. https://doi.org/10.5194/tc-6-407-2012

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 dataset. *International Journal of Climatology*, *34*(3), 623–642. https://doi.org/10.1002/joc.3711

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2019). ERA5 monthly averaged data on single levels from 1979 to present [Dataset]. Chang. https://doi.org/10.24381/cds.f17050d7

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hu, X., & Yuan, W. (2021). Evaluation of ERA5 precipitation over the eastern periphery of the Tibetan plateau from the perspective of regional rainfall events. *International Journal of Climatology*, *41*(4), 2625–2637. https://doi.org/10.1002/joc.6980

Huffman, G. J., Stocker, E. F., Bolvin, D. T., Nelkin, E. J., & Tan, J. (2019). GPM IMERG final precipitation L3 1 month 0.1 degree x 0.1 degree V06 [Dataset]. Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/GPM/IMERG/3B-MONTH/06

Humphrey, V., & Gudmundsson, L. (2019a). GRACE-REC: A reconstruction of climate-driven water storage changes over the last century (version 3) [Dataset]. Figshare. https://doi.org/10.6084/m9.figshare.7670849.v3

Humphrey, V., & Gudmundsson, L. (2019b). GRACE-REC: A reconstruction of climate-driven water storage changes over the last century. *Earth System Science Data*, *11*(3), 1153–1170. https://doi.org/10.5194/essd-11-1153-2019

Humphrey, V., Gudmundsson, L., & Seneviratne, S. I. (2016). Assessing Global Water storage variability from GRACE: Trends, seasonal cycle, subseasonal anomalies and extremes. *Surveys in Geophysics*, *37*(2), 357–395. https://doi.org/10.1007/s10712-016-9367-1

Institute of China Geological Environment Monitoring (ICGEM). (2013). *China geological environment monitoring: Groundwater yearbook [in Chinese]*. Vastplain House.

Jackson, T. J., Bindlish, R., Cosh, M. H., Zhao, T., Starks, P. J., Bosch, D. D., et al. (2012). Validation of soil moisture and ocean salinity (SMOS) soil moisture over watershed networks in the U.S. *IEEE Transactions on Geoscience and Remote Sensing*, *50*(5), 1530–1543. https://doi.org/10.1109/TGRS.2011.2168533

Jackson, T. J., Cosh, M. H., Bindlish, R., Starks, P. J., Bosch, D. D., Seyfried, M., et al. (2010). Validation of advanced Microwave scanning radiometer soil moisture products. *IEEE Transactions on Geoscience and Remote Sensing*, *48*(12), 4256–4272. https://doi.org/10.1109/TGRS.2010.2051035

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077<0437:tnyrp>2.0.co;2

Kim, H., Yeh, P. J. F., Oki, T., & Kanae, S. (2009). Role of rivers in the seasonal variations of terrestrial water storage over global basins. *Geophysical Research Letters*, *36*(17), L17402. https://doi.org/10.1029/2009GL039006

Lehner, B., & Grill, G. (2013). Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, *27*(15), 2171–2186. https://doi.org/10.1002/hyp.9740

Li, B., Beaudoing, H., Rodell, M., & NASA/GSFC/HSL (2020a). GLDAS catchment land surface model L4 daily 0.25 x 0.25 degree GRACE-DA1 V2.2 [dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/TXBMLX370XX8

Li, B., Rodell, M., & Famiglietti, J. S. (2015). Groundwater variability across temporal and spatial scales in the central and northeastern US. *Journal of Hydrology*, *525*, 769–780. https://doi.org/10.1016/j.jhydrol.2015.04.033

Li, F. (2021). Data from: Long-term (1979-present) total water storage anomalies over the global land derived by reconstructing GRACE data [Dataset]. Dryad. https://doi.org/10.5061/dryad.z612jm6bt

Li, F., Kusche, J., Chao, N., Wang, Z., & Löcher, A. (2021). Long-term (1979-Present) total water storage anomalies over the global land derived by reconstructing GRACE data. *Geophysical Research Letters*, *48*(8), 1–26. https://doi.org/10.1029/2021GL093492

Li, F., Kusche, J., Rietbroek, R., Wang, Z., Forootan, E., Schulze, K., & Lück, C. (2020b). Comparison of data-driven techniques to reconstruct (1992-2002) and predict (2017-2018) GRACE-like gridded total water storage changes using climate inputs. *Water Resources Research*, *56*(5). https://doi.org/10.1029/2019WR026551

Li, R., Zhao, L., Ding, Y., Wu, T., Xiao, Y., Du, E., et al. (2012). Temporal and spatial variations of the active layer along the Qinghai-Tibet Highway in a permafrost region. *Chinese Science Bulletin*, *57*(35), 4609–4616. https://doi.org/10.1007/s11434-012-5323-8

Li, X., Long, D., Han, Z., Scanlon, B. R., Sun, Z., Han, P., & Hou, A. (2019). Evapotranspiration estimation for Tibetan Plateau headwaters using conjoint terrestrial and atmospheric Water balances and multisource remote sensing. *Water Resources Research*, *55*(11), 8608–8630. https://doi.org/10.1029/2019WR025196

Luo, D., Jin, H., Lin, L., He, R., Yang, S., & Chang, X. (2012). New progress on permafrost temperature and thickness in the source area of the Huanghe river [in Chinese]. *Scientia Geographica Sinica*, *32*(7), 898–904. https://doi.org/10.13249/j.cnki.sgs.2012.07.898

Messager, M. L., Lehner, B., Grill, G., Nedeva, I., & Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature Communications*, *7*(1), 13603. https://doi.org/10.1038/ncomms13603

Muñoz-Sabater, J. (2019). ERA5-Land monthly averaged data from 1981 to present [Dataset]. Chang. https://doi.org/10.24381/cds.68d2bb30

Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., et al. (2020). The global water resources and use model WaterGAP v2.2d—Standard model output [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.918447

Ni, J., Wu, T., Zhu, X., Hu, G., Zou, D., Wu, X., et al. (2021). Simulation of the present and future projection of permafrost on the Qinghai-Tibet Plateau with statistical and Machine learning models. *Journal of Geophysical Research: Atmospheres*, *126*(2), e2020JD033402. https://doi.org/10.1029/2020JD033402

Obu, J., Westermann, S., Kääb, A., & Bartsch, A. (2018). Ground temperature map, 2000-2016, northern hemisphere permafrost [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.888600

Qin, Y., Wu, T., Zhao, L., Wu, X., Li, R., Xie, C., et al. (2017). Numerical modeling of the active layer thickness and permafrost thermal state across Qinghai-Tibetan plateau. *Journal of Geophysical Research: Atmospheres*, *122*(21), 11604–11620. https://doi.org/10.1002/2017JD026858

Qinghai Provincial Water Resources Department. (2014). Groundwater bulletin of Qinghai Province.

Rateb, A., Scanlon, B. R., Pool, D. R., Sun, A., Zhang, Z., Chen, J., et al. (2020). Comparison of Groundwater storage changes from GRACE satellites with monitoring and modeling of major U.S. Aquifers. *Water Resources Research*, *56*(12), 1–19. https://doi.org/10.1029/2020WR027556

RGI Consortium. (2017). Randolph Glacier inventory—A dataset of global glacier outlines: Version 6.0 [Dataset]. National Snow and Ice Data Center. https://doi.org/10.7265/4m1f-gd79

Rodell, M., Beaudoing, H., & NASA/GSFC/HSL (2007a). GLDAS CLM land surface model L4 3 hourly 1.0 x 1.0 degree subsetted V001 [Dataset]. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/83NO2QDLG6M0

Rodell, M., Chen, J., Kato, H., Famiglietti, J. S., Nigro, J., & Wilson, C. R. (2007). Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal*, *15*(1), 159–166. https://doi.org/10.1007/s10040-006-0103-7

Sakumura, C., Bettadpur, S., & Bruinsma, S. (2014). Ensemble prediction and intercomparison analysis of GRACE time-variable gravity field models. *Geophysical Research Letters*, *41*(5), 1389–1397. https://doi.org/10.1002/2013GL058632

Save, H. (2020). CSR GRACE and GRACE-FO RL06 mascon solutions v02 [Dataset]. https://doi.org/10.15781/cgq9-nh24

Scanlon, B. R., Zhang, Z., Save, H., Sun, A. Y., Müller Schmied, H., van Beek, L. P. H., et al. (2018). Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data. *Proceedings of the National Academy of Sciences*, *115*(6), E1080–E1089. https://doi.org/10.1073/pnas.1704665115

Scanlon, B. R., Zhang, Z., Save, H., Wiese, D. N., Landerer, F. W., Long, D., et al. (2016). Global evaluation of new GRACE mascon products for hydrologic applications. *Water Resources Research*, *52*(12), 9412–9429. https://doi.org/10.1002/2016WR019494

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., & Rudolf, B. (2014). GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. *Theoretical and Applied Climatology*, *115*(1–2), 15–40. https://doi.org/10.1007/s00704-013-0860-x

Schneider, U., Becker, A., Finger, P., Rustemeier, E., & Ziese, M. (2020). GPCC full data monthly product version 2020 at 0.25°: Monthly land-surface precipitation from rain-Gauges built on GTS-based and historical data [Dataset]. https://doi.org/10.5676/DWD_GPCC/FD_M_V2020_025

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Strassberg, G., Scanlon, B. R., & Chambers, D. (2009). Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States. *Water Resources Research*, *45*(5), 1–10. https://doi.org/10.1029/2008WR006892

Sutanudjaja, E. H., van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H. C., Drost, N., et al. (2017). PCR-GLOBWB 2 input files version 2017_11_beta_1 (v_2017_11_beta_1) [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.1045339

Wang, B., Ma, Y., Su, Z., Wang, Y., & Ma, W. (2020a). Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau. *Science Advances*, *6*(26). https://doi.org/10.1126/sciadv.aay8558

Wang, T., Yang, D., Yang, Y., Piao, S., Li, X., Cheng, G., & Fu, B. (2020b). Permafrost thawing puts the frozen carbon at risk over the Tibetan Plateau. *Science Advances*, *6*(19). eaaz3513. https://doi.org/10.1126/sciadv.aaz3513

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., & Viterbo, P. (2014). The WFDEI meteorological forcing data set: WATCH forcing data methodology applied to ERA-interim reanalysis data. *Water Resources Research*, *50*(9), 7505–7514. https://doi.org/10.1002/2014WR015638

Wiese, D. N., Yuan, D.-N., Boening, C., Landerer, F. W., & Watkins, M. M. (2019). JPL GRACE mascon Ocean, Ice, and hydrology equivalent water height RL06 CRI Filtered version 02 [Dataset]. PO.DAAC. https://doi.org/10.5067/TEMSC-3JC62

Wu, Q., Zhang, T., & Liu, Y. (2012). Thermal state of the active layer and permafrost along the Qinghai-Xizang (Tibet) Railway from 2006 to 2010. *The Cryosphere*, *6*(3), 607–612. https://doi.org/10.5194/tc-6-607-2012

Xie, P., & Arkin, P. A. (1997). Global precipitation: A 17-year monthly analysis based on Gauge observations, satellite estimates, and Numerical model outputs. *Bulletin of the American Meteorological Society*, *78*(11), 2539–2558. https://doi.org/10.1175/1520-0477(1997)078<2539:gpayma>2.0.co;2

Xing, Z., Fan, L., Zhao, L., De Lannoy, G., Frappart, F., Peng, J., et al. (2021). A first assessment of satellite and reanalysis estimates of surface and root-zone soil moisture over the permafrost region of Qinghai-Tibet Plateau. *Remote Sensing of Environment*, *265*, 112666. https://doi.org/10.1016/j.rse.2021.112666

Xu, L., Chen, N., Zhang, X., & Chen, Z. (2019). Spatiotemporal changes in China's terrestrial Water storage from GRACE satellites and its possible drivers. *Journal of Geophysical Research: Atmospheres*, *124*(22), 11976–11993. https://doi.org/10.1029/2019JD031147

Xu, Z., Cheng, L., Liu, P., Makarieva, O., & Chen, M. (2021). Detecting and quantifying the impact of long-term terrestrial water storage changes on the runoff ratio in the head regions of the two largest rivers in China. *Journal of Hydrology*, *601*, 126668. https://doi.org/10.1016/j.jhydrol.2021.126668

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J. C., et al. (2017). A high-accuracy map of global terrain elevations. *Geophysical Research Letters*, *44*(11), 5844–5853. https://doi.org/10.1002/2017GL072874

Yang, M., Nelson, F. E., Shiklomanov, N. I., Guo, D., & Wan, G. (2010). Permafrost degradation and its environmental effects on the Tibetan plateau: A review of recent research. *Earth-Science Reviews*, *103*(1–2), 31–44. https://doi.org/10.1016/j.earscirev.2010.07.002

You, Q., Cai, Z., Pepin, N., Chen, D., Ahrens, B., Jiang, Z., et al. (2021). Warming amplification over the Arctic Pole and Third Pole: Trends, mechanisms and consequences. *Earth-Science Reviews*, *217*, 103625. https://doi.org/10.1016/j.earscirev.2021.103625

Yuan, X., Yang, K., Lu, H., He, J., Sun, J., & Wang, Y. (2021). Characterizing the features of precipitation for the Tibetan Plateau among four gridded datasets: Detection accuracy and spatio-temporal variabilities. *Atmospheric Research*, *264*, 105875. https://doi.org/10.1016/j.atmosres.2021.105875

Zanaga, D., Van De Kerchove, R., De Keersmaecker, W., Souverijns, N., Brockmann, C., Quast, R., et al. (2021). ESA WorldCover 10 m 2020 v100 [Dataset]. https://doi.org/10.5281/zenodo.5571936

Zeng, J., Li, Z., Chen, Q., Bi, H., Qiu, J., & Zou, P. (2015). Evaluation of remotely sensed and reanalysis soil moisture products over the Tibetan Plateau using in-situ observations. *Remote Sensing of Environment*, *163*, 91–110. https://doi.org/10.1016/j.rse.2015.03.008

Zhang, G. (2021a). Lake volume changes on the Tibetan Plateau during 1976–2019 (>1 km^2) [Dataset]. National Tibetan Plateau Data Center. https://doi.org/10.11888/Hydro.tpdc.271169

Zhang, G., Yao, T., Xie, H., Zhang, K., & Zhu, F. (2014). Lakes' state and abundance across the Tibetan Plateau. *Chinese Science Bulletin*, *59*(24), 3010–3021. https://doi.org/10.1007/s11434-014-0258-x

Zhang, P., Zheng, D., van der Velde, R., Wen, J., Zeng, Y., Wang, X., et al. (2020). A 10-year (2009-2019) surface soil moisture dataset produced based on in situ measurements collected from the Tibet-Obs (Version 7) [Dataset]. 4TU.ResearchData. https://doi.org/10.4121/12763700.v7

Zhang, P., Zheng, D., van der Velde, R., Wen, J., Zeng, Y., Wang, X., et al. (2021). Status of the Tibetan Plateau observatory (Tibet-Obs) and a 10-year (2009–2019) surface soil moisture dataset. *Earth System Science Data*, *13*(6), 3075–3102. https://doi.org/10.5194/essd-13-3075-2021

Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A., & Brown, J. (2008). Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geography*, *31*(1–2), 47–68. https://doi.org/10.1080/10889370802175895

Zhao, L., Hu, G., Zou, D., Wu, T., Du, E., Liu, G., et al. (2021b). A synthesis dataset of permafrost for the Qinghai-Xizang (Tibet) Plateau, China (2002-2018) [Dataset]. National Tibetan Plateau Data Center. https://doi.org/10.11888/Geocry.tpdc.271107

Zhao, L., Hu, G., Zou, D., Wu, X., Ma, L., Sun, Z., et al. (2019). Permafrost changes and its effects on hydrological processes on Qinghai-Tibet plateau. *Bulletin of Chinese Academy of Sciences*, *34*(11), 1233–1246. https://doi.org/10.16418/j.issn.1000-3045.2019.11.006

Zhao, L., & Sheng, Y. (2019). *Permafrost and its changes in the Qinghai-Tibet plateau [in Chinese]*. Science Press.

Zhao, L., Zou, D., Hu, G., Du, E., Pang, Q., Xiao, Y., et al. (2020). Changing climate and the permafrost environment on the Qinghai–Tibet (Xizang) Plateau. *Permafrost and Periglacial Processes*, *31*(3), 396–405. https://doi.org/10.1002/ppp.2056

Zhao, L., Zou, D., Hu, G., Wu, T., Du, E., Liu, G., et al. (2021c). A synthesis dataset of permafrost thermal state for the Qinghai–Tibet (Xizang) Plateau, China. *Earth System Science Data*, *13*(8), 4207–4218. https://doi.org/10.5194/essd-13-4207-2021

Zhao, M., Zhang, J., Velicogna, I., Liang, C., & Li, Z. (2021a). Ecological restoration impact on total terrestrial water storage. *Nature Sustainability*, *4*(1), 56–62. https://doi.org/10.1038/s41893-020-00600-7