# Interannual changes in terrestrial water storage in the Qaidam basin based on multi-mission satellite data and their correlations with climate factors

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**Key Points:**

- Terrestrial water storage(TWS) in the Qaidam basin is estimated using multi-mission satellite data, a hydrological model, and ground data.
- The interannual change in TWS in the QB shows an interesting pattern of increase-decrease-accelerated increase.
- The interannual change in TWS in the QB is highly correlated with the PDO rather than ENSO and AO.

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## Abstract

Regional water storage monitoring is very essential and critical for regional water resource management, hydro-ecological sustainable development and studying interaction between hydrology and climate. We used multi-mission satellite dataset, a global hydrological model, and ground meteorological data to investigate the terrestrial water storage changes (TWSc) in the Qaidam basin (QB). Terrestrial water storage (TWS) exhibited an increasing trend for the past 17 years, and TWSc obtained from different methods or dataset were consistent with precipitation. Through the singular spectrum analysis, we obtained the interannual and seasonal components of TWSc, and significant shifts in the interannual TWSc were observed in the QB. TWS exhibited an increase from 2002 to 2013, a decrease from 2013 to 2016, and an accelerated increase after 2016. Additionally, the study reported that the interannual change in TWS was strongly correlated with the Pacific Decadal Oscillation (PDO), compared to Arctic Oscillation and El Niño-Southern Oscillation.


## Plain Language Summary

Knowledge about terrestrial water storage changes (TWSc) in the Qaidam basin (QB) is important for water management and, environmental protection in the QB. However, it is difficult and expensive to construct ground observation stations to detect TWSc signals. Multimission satellites such as GRACE and GRACE Follow-On can detect TWSc in large areas. In this study, we investigated TWSc in the QB from 2002 to 2019. TWS exhibited an increase from 2002 to 2013, a decrease from 2013 to 2016, and an accelerated increase after 2016. A strong correlation between the interannual change in TWS and Pacific Decadal Oscillation was observed, which indicated considerable influence of climate factors on TWSc in the QB.

## 1 Introduction

Water storage monitoring is a key to water resource management, and hydro-ecological sustainable development and is important to study interactions between hydrology and climate. The Gravity Recovery and Climate Explorer (GRACE), a joint mission of National Aeronautics and Space Administration (NASA) and the German Aerospace Center, has enabled geoscientists to investigate terrestrial water storage changes(TWSc) for more than 15 years at global scales (Rodell et al., 2018), or at regional (basin) scales (Landerer & Swenson, 2012; Yi & Sun, 2016). Launched on May-22, 2018, the GRACE Follow-On (GRACE-FO) mission continues the legacy of GRACE to track mass redistribution and relative movement within the Earth system. The records by GRACE-FO are proven to be consistent with those by GRACE (Landerer et al., 2020); therefore, GRACE-FO gives us the chance to observe the interannual TWSc globally or regionally, particularly under the condition of current extreme climate change.

The Tibetan Plateau (TP) provides water to approximately one-fifth of the world's population. The TWSc in the TP are of great importance to Asia, and TWSc are attributed to ice melting from glaciers (Jacob et al., 2012; Meng et al., 2019). As an important part of the TP, the Qaidam basin (QB) has typical plateau climate with the low precipitation and large evaporation, which has drawn attention to study spatiotemporal changes and causes of its terrestrial water storage (TWS). During the GRACE era, the TWSc in the QB were investigated by combining hydrological model and ground observations. Previous studies reported an increasing trend in TWS in the QB from 2002 to 2012 (Jiao et al., 2015; Bibi et al., 2019), which was mainly caused by an increase in the ground water and not the lake water (Jiao et al., 2015). However,from 2013, TWS in the QB exhibited a decreasing trend at a rate of 37.9 mm/year (Bibi et al., 2019), which was estimated using average results of the GRACE products provided by Center for Space Research (CSR), Helmholtz-Centre Potsdam-German Research Centre for Geosciences

(GFZ) and Jet Propulsion Laboratory (JPL) (Bibi et al., 2019). Recently, after 2017, an increasing trend in TWS was reported by Wei et al. (2021) using GRACE and GRACE-FO data. These results indicated that TWSc in the QB varied considerably during the last two decades.

In most of these studies, the variations after 2017 are rarely discussed. This could be because a gap in data exists from July 2017 to May 2018, in which GRACE ended but GRACE-FO was not yet launched. A long short-term memory (LSTM) neural network was used to fill the data gap in Wei et al. (2021); thus, the data from July 2017 to May 2018 were not observations but LSTM-reconstructed results. In this study, the TWSc in the QB were obtained using GRACE and GRACE-FO satellite products and compared with a global hydrological model and ground observations. The data gap was solved using the datasets of China's land water storage redistribution derived by the National Tibet Plateau Data Center (NTPDC) (Zhong et al., 2020).

The precipitation and evaporation are the controlling factors of TWSc, which are influenced by the climate change. Yang et al. (2017) analyzed the influence of decadal modulation of precipitation patterns over Eastern China using sea surface temperature anomalies. A study on the effect of westerlies and Asian monsoon on precipitation in northern TP reported that the high precipitation in the TP may continue for the next several decades (Cui et al., 2021). Additionally, a 10% increase in global land evapotranspiration was reported from 2003 to 2019, caused by the warming climate of the world. This would have a great influence on the TWSc (Pascolini-Campbell et al., 2021). According to Scanlon et al. (2018), the decreasing trends obtained from GRACE are mostly related to anthropogenic activities and climate variations, whereas increasing trends usually reflect climate variations. Therefore, the connections between TWSc and climate change are critical in investigating global and regional water cycles (Ni et al., 2017). To investigate the influence of climate factors on TWSc in the QB, this study conducted a cross-correlation analysis between TWSc and three climatic factors, including Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), and El Nino-Southern Oscillation (ENSO); this was aimed to investigate interactions between changes in hydrology and climate.

## 2 Study area and data

The QB is located at the northeast edge of the TP and northwest edge of Qinghai Province ($87° - 100°E, 34° - 40°N$; Figure 1). As the highest inland plateau and closed basin in the world,the average altitude of the QB is approximately 3000 m, and it is surrounded with many glaciers located in the Qilian, Altun, Kunlun and Ela mountains. In the alpine mountain area, the altitude ranges from 3500 to 6860 m. These natural conditions lead to low precipitation and high evaporation in this area.

Temporal gravity field models used in this study were the Release 06 version of GRACE and GRACE-FO Level-2 products, which are newest products provided by CSR, with the maximum degree of 96 (GRACE, 2018; GRACE-FO, 2019). In this paper, the monthly gravity models from April 2002 to December 2019 (the missing data of individual months were obtained by interpolation) were used to derive the time series of TWSc in the QB. Additionally, monthly data of CSR RL06 Mass Concentration (mascon) solutions (Save et al., 2016; Save, 2020) were used for comparisons.

The Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) was used as another independent dataset for obtaining TWSc in this study. The data used was the product of GLDAS Noah land surface model with temporal resolution of month and spatial resolution of 0.25° (Beaudoing et al., 2020). The data for snow water equivalent (SWE), and contents of plant canopy surface water (PC) and soil water(SW) from April 2002 to December 2019 were used. The SW data were divided into four layers with depths of 0-10, 10-40, 40-100 and 100-200 cm. The sum of the selected data of GLDAS was obtained, and further, time series of TWSc are obtained. Moreover, ground-based precipitation data was provided by China Meteorological Data Network (CMDN), and the time series of monthly precipitation in QB is given in figure 1(d).

Three dominant climate factors significantly influence the precipitation in the Northern hemisphere from interannual to decadal timescales. They are the AO, PDO, and ENSO (Figure S1). A climate factor is usually represented by an oscillation index, which is a nondimensional function of time derived from relevant meteorological observations. The AO index is provided by the National Centers for Environmental Prediction, United States. Although the time scales of PDO and ENSO are different, PDO and ENSO still have some correlation between their conventional indices because of their geographical juxtaposition in the Pacific Ocean. Therefore, we adopted modified PDO and ENSO indices obtained by Chen and Wallace (2016).

# 3 TWSc in the QB

## 3.1 Time series and validation

This study adopted two common methods to compute TWSc using GRACE and GRACE-FO data: global spherical harmonic solutions (GSH) and mascon solutions. GSH method uses the monthly gravity field models from GRACE Level-2 products to compute TWS in terms of equivalent water heights (EWH) (Wahr et al., 1998). The mascon method divides the study area into different subregions;the TWS information in each subregion is derived from mass variation information, which is obtained from K-Band Range Rate, GPS, and accelerometric observations.

Figure 2 shows the time series of the TWSc derived using GSH method, mascon method, GLDAS, and monthly precipitation in the QB. The variation range of water storage was approximately -7 to 17 cm ( Figure 2a-b). The maximum and minimum values of results obtained from GSH method were 9.91 and -6.89 cm, respectively, and the occurrence time was December 2019 and June 2004, respectively. Correspondingly, the maximum and minimum values of results obtained from mascon method were 16.40 and -5.23 cm, respectively, and the occurrence time was July 2019 and June 2004, respectively.The results obtained from GSH and mascon methods were nearly similar. The cross-correlation between them was approximately 0.872, which was consistent with the study by Scanlon et al. (2016). All the results obtained from GSH and mascon methods clearly show an increasing trend of TWSc.

Additionally, the results obtained from GLDAS (Figure 2c) exhibited an increasing trend during the study period (0.25 cm/year), which was consistent with GRACE-derived results. The correlation between the results obtained from GLDAS and GSH or mascon methods was approximately 0.70. The time series of monthly precipitation (Figure 2d) from CMDN did not exhibit an obvious increase during the study period. The precipitation surely has a certain impact on the change in water storage. For example, the peak value of annual water reserves mostly corresponds to the peak value of precipitation; the monthly change in water storage generally lags 1-2 months of precipitation change, which is closely related to the regulation and storage of lakes and, groundwater and soil interception (Xu & Zhang, 2013; Wang et al., 2018). To further analyze the variation in precipitation, the annual time series of precipitation were plotted as given in Figure 3c. The precipitation clearly increased from 2002 to 2013 and decreased from 2013 to 2016. After 2016, there was a rapid increase in precipitation, which could have resulted in the rapid rise of TWS in the QB in the past 3 years as revealed by GSH and mascon methods.

Importantly, this phenomenon of rapid rise in TWS after 2016, which was not obvious in the results obtained from GLDAS, could be because the global models underestimate large decadal declining and rising of TWS relative to GRACE and GRACE-FO satellite datasets (Scanlon et al., 2018). Hence, it is reasonable to believe that groundwater level increased in the QB after 2016.

### 3.2 Interannual and seasonal signals

Using the singular spectrum analysis (SSA) method, the interannual and seasonal signals of the TWSc series obtained from mascon method were separated (Figure 3). Different reconstructed modes of TWSc from GSH and mascon methods are given in Figures S2 and S3. The interannual changes in TWS obtained from GSH and mascon methods exhibited very similar pattern but with slight time shift. Three stages were seen in the interannual change: an increase, decrease, and accelerating increase.

For the mascon method, the interannual signal was obtained by adding the first two modes. The seasonal signal was obtained by subtracting the interannual signal from the original data (Figure 3a). According to Figure 3b, two obvious turning points existed in the TWSc time series, i.e., rise to decline in September 2013 and then to rise in March 2016. The TWS exhibited an increasing trend with a rate of 0.55 cm/year from April 2002 to August 2013 and a decreasing trend with a rate of -0.25 cm/year from September 2013 to February 2016. The decrease has also been reported by Bibi et al. (2019) from 2013 to 2016 (Table 1). From March 2016 to December 2019, the TWS exhibited a sharp increasing trend of 1.70 cm/year. In the interannual signals obtained by GSH method, we can see an obvious turning point of TWSc. Before March 2013, the TWS exhibited an increasing trend with a rate of 0.64 cm/year; whereas after March 2013, it decreased with a rate of -0.45 cm/year. However, after June 2015, the TWSc exhibited an increasing trend with a rate of 1.66 cm/year.

The results obtained in previous studies (Jiao et al., 2015; Wang et al., 2018; Bibi et al., 2019; Wei et al., 2021) are summarized in Table 1. Importantly, for the convenience of comparison, all the results are written as annual change rate. As seen in Table 1, TWSc in QB exhibited an overall increasing trend in the past 17 years, with a rate of 0.62 and 0.55 cm/year as derived by GSH and mascon methods, respectively. From 2002 to 2012, almost all the results of TWSc exhibited an increasing trend. After 2013, both GSH and mascon methods revealed a decreasing trend with rate of -2 to 5 mm/year. Bibi et al. (2019) also reported a decreasing trend in TWSc during 2013 $\sim$ 2016. Although some differences exist, it can still be concluded that the results of this study are consistent with the previous studies (Jiao et al., 2015; Wang et al., 2018; Bibi et al., 2019; Wei et al., 2021), because the study periods and data used are different.

### 3.3 Correlation of climate factors and TWSc in the QB

To understand the underlying causes of TWSc in the QB, the correlation analyses were conducted among the TWSc signals (the seasonal and interannual signals of TWSc derived from GSH and mascon methods) and three separate climate factors, i.e., the AO, PDO, and ENSO (Figure 4). The correlations between the seasonal signals of TWSc and the three climate factors and those between the interannual signals of TWSc and the AO and ENSO were very low, which indicated that these climate factors had little influence on the seasonal signal and interannual signals of TWSc in the study area. However, the correlation between the PDO and TWSc was high. The maximum correlations between the PDO and TWSc results obtained from GSH or mascon were -0.52 and -0.59 with phase lags of 87 months and 81 months, respectively. This indicated that the PDO had considerable influence on the interannual signals of TWSc in the QB, though further research is needed.

## 4 Discussion and Conclusion

In this study, TWSc in the QB were reported using multimission satellite data, a global hydrological model, and hydro-ecological records. The usage of CMDN particularly helps to verify the reliability of GRACE/GRACE-FO derived results. The TWS exhibited an increase in the study area, although different methods provided different rates of change. This was consistent with the study by Rodell et al. (2018), in which an increase in TWS was reported in the TP. Furthermore, TWSc data obtained from GSH and mascon methods exhibited significant shifts around 2013 and 2017, which indicated that the interannual changes in TWS in the QB were not linear. It seems that the interannual change in TWS in the QB was driven by precipitation, indicating that the QB will be getting more and more wet. This was consistent with the study by Zhang et al. (2021), who reported that majority of land on Earth is becoming wetter and exhibiting more variable hydroclimate. Years 2018 and 2019 are one of the warmest in the last century (NOAA National Centers for Environmental Information, 2020), which may cause extreme precipitation and evaporation anomalies, and therefore leading to the accelerating increase in TWSc after 2017.

The interannual signal was strongly correlated with the PDO with a phase lag of approximately 7 years. This indicated that the PDO, and not the ENSO and AO, had an influence on the secular change in TWSc. This finding is slightly different from the previous studies by Ni et al. (2017) and Wei et al. (2021), in which they emphasized the strong correlation between the ENSO with TWSc. The reason is that the traditional climate indices were adopted in their studies. As reported by Chen and Wallace (2016), the PDO and ENSO share commonality in their physical behavior because of their geographical juxtrapositon. This should be considered while studying the interaction between hydrologic and climate changes in the future.

Although this study only focused on the QB, the climate factors would also influence the TWSc in other regions in the TP, at least the area near the QB. Hence, the PDO may have similar impacts on the areas near the QB and even the whole TP. To find the deep-rooted reasons of TWSc, we should consider the variations in precipitation and evaporation, and pay much attention to the influences of climate factors, which would be for long-term (Cui et al., 2021). The investigation on climate factors will help us in better understanding the TWSc of the whole TP, which is beneficial for water management of three river resource region. This will be studied in the future. In addition, vegetation changes derived from remote sensing satellites can be used to verify the TWSc (Wu et al., 2020) and evaluate the influence of climate change.

**Acknowledgments**

The authors gratefully appreciate the publicly accessible GRACE and GRACE-FO solutions provided by CSR, the GLDAS data provided by the GSFC and NOAA, grid precipitation data provided by China Meteorological Data Network. The time series of monthly precipitation in QB is stored in Zenodo (https://doi.org/10.5281/zenodo.5205402). We also thank Dr. Chen Xianyao for providing the indices of climate factors. This research was funded by the National Natural Science Foundation of China (No.42074017, 41704080), Fundamental Research Funds for the Central Universities (No. 2652018027), and the Open Research Fund of Qian Xuesen Laboratory of Space Technology, CAST (No.GZZKFJJ2020006).

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**Table 1.** The trends of changes in terrestrial water storage (TWSc) in the Qaidam basin (QB) in different time interval obtained by different investigations

| Source | Time Interval | Data Source | Rate (mm/year) |
|---|---|---|---|
| CSR-mascon | 2002.04 - 2019.12<br>2002.04 - 2013.08<br>2013.09 - 2016.02<br>2016.03 - 2019.12 | CSR (RL06) | 5.5<br>5.5<br>-2.5<br>17.0 |
| CSR-GSH | 2002.04 - 2019.12<br>2002.04 - 2013.02<br>2013.03 - 2015.05<br>2015.06 - 2019.12 | CSR (RL06) | 6.2<br>6.4<br>-4.5<br>16.6 |
| Jiao et al. (2015) | 2003.01 - 2012.12 | JPL (RL05) | 8.75 |
| Wang et al. (2018) | 2003.01 - 2015.12 | GFZ (RL 05) | 3.1 |
| Bibi et al. (2019) | 2002 - 2012<br>2013 - 2016 | CSR, GFZ, JPL (RL05) | 25.5<br>-37.9 |
| Wei et al. (2021) | 2002.03 - 2020.03 | CSR(RL06) | 5.16 |

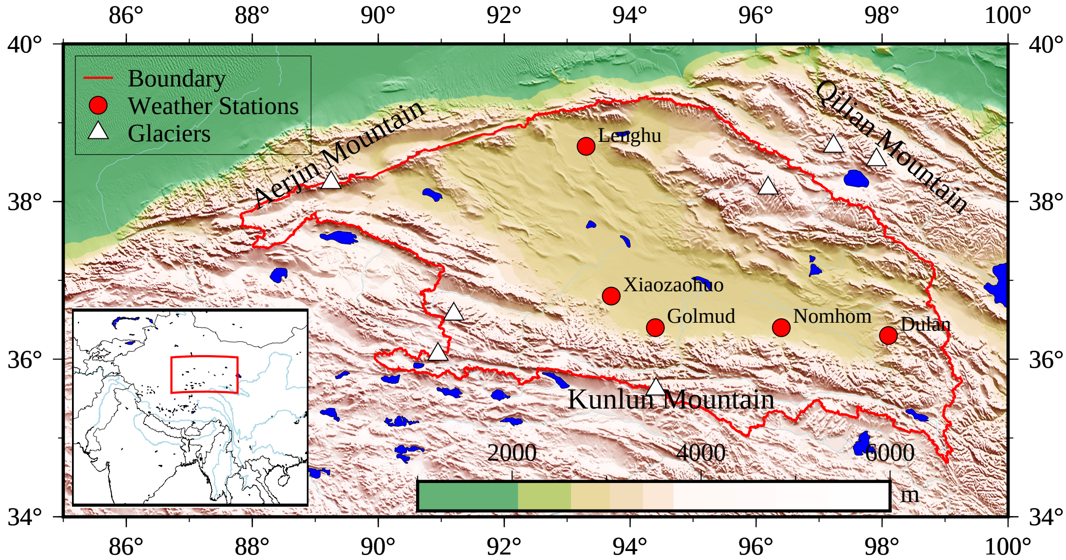


**Figure 1.** The Study area with topography and ground meteorological stations. The red curve represents the boundary of the Qaidam basin (QB), and the white triangles represent mountain glaciers surrounding the QB.

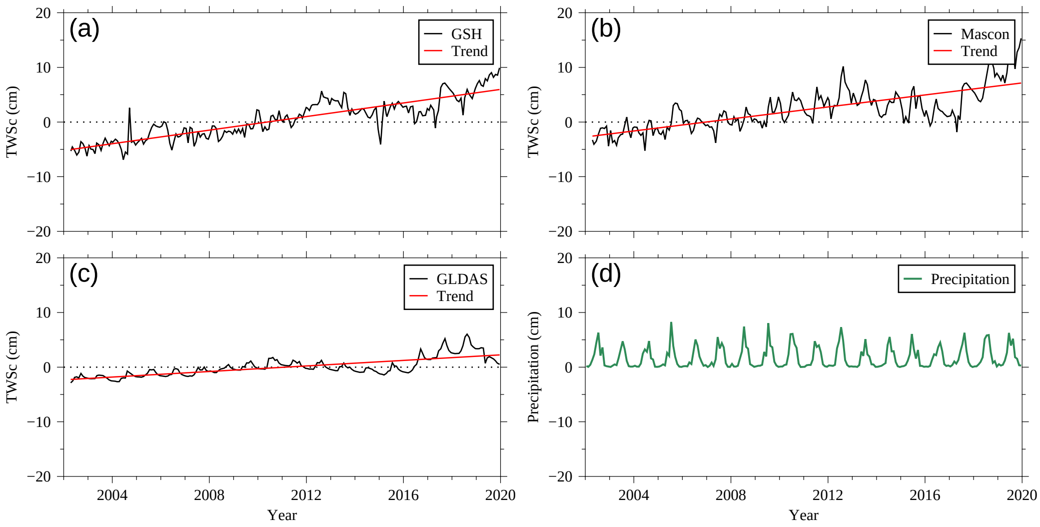


**Figure 2.** The changes in terrestrial water storage (TWSc) in the QB based on (a) the GSH method, (b) the mascon method, (c) the GLDAS model,and (d) the monthly precipitation derived from ground weather stations. Red curves represent trends obtained by least square fitting.

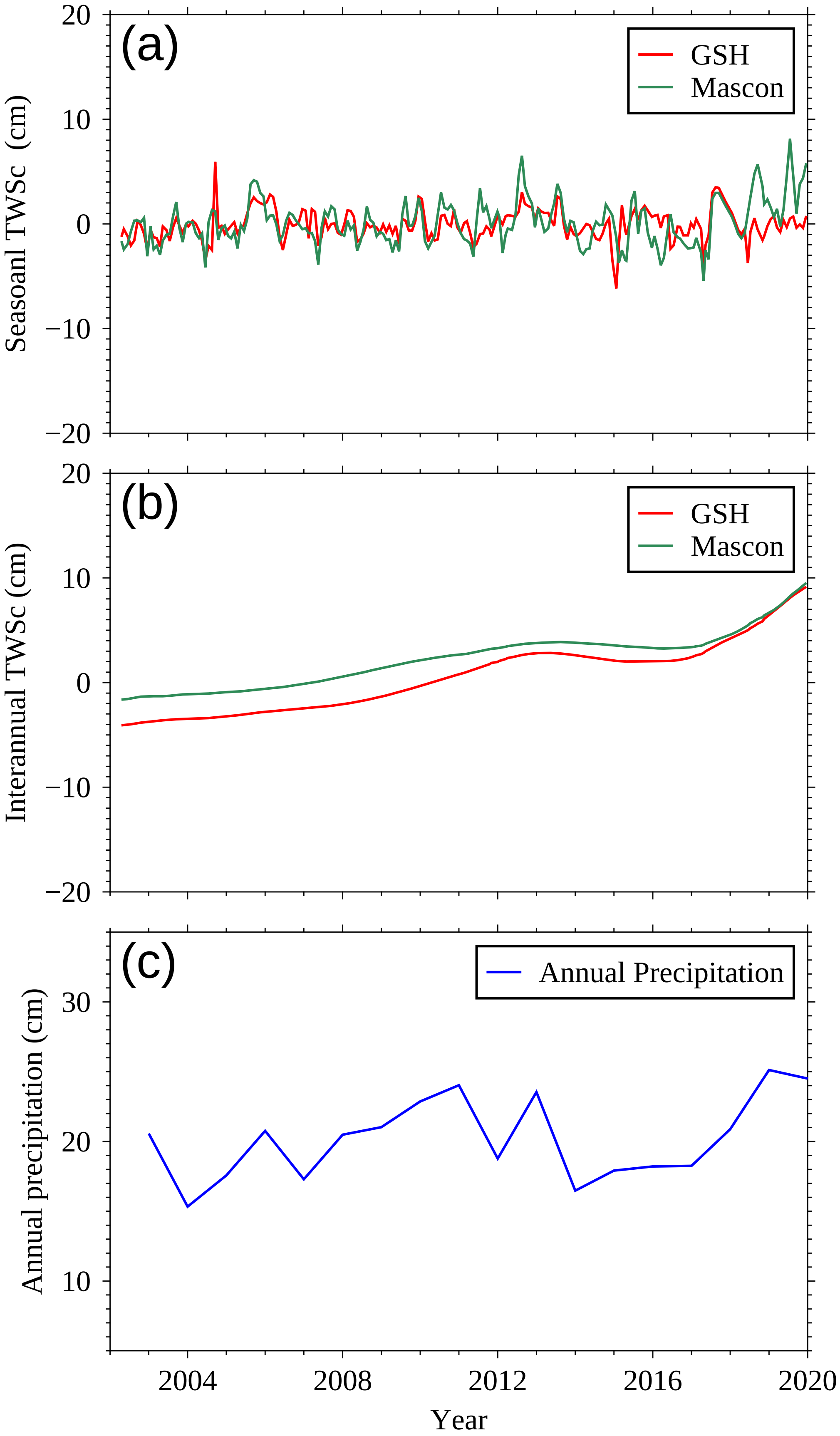


**Figure 3.** Singular spectrum analysis derived (a) seasonal and (b) interannual components of TWSc in the QB. (c), The annual precipitation in the QB.

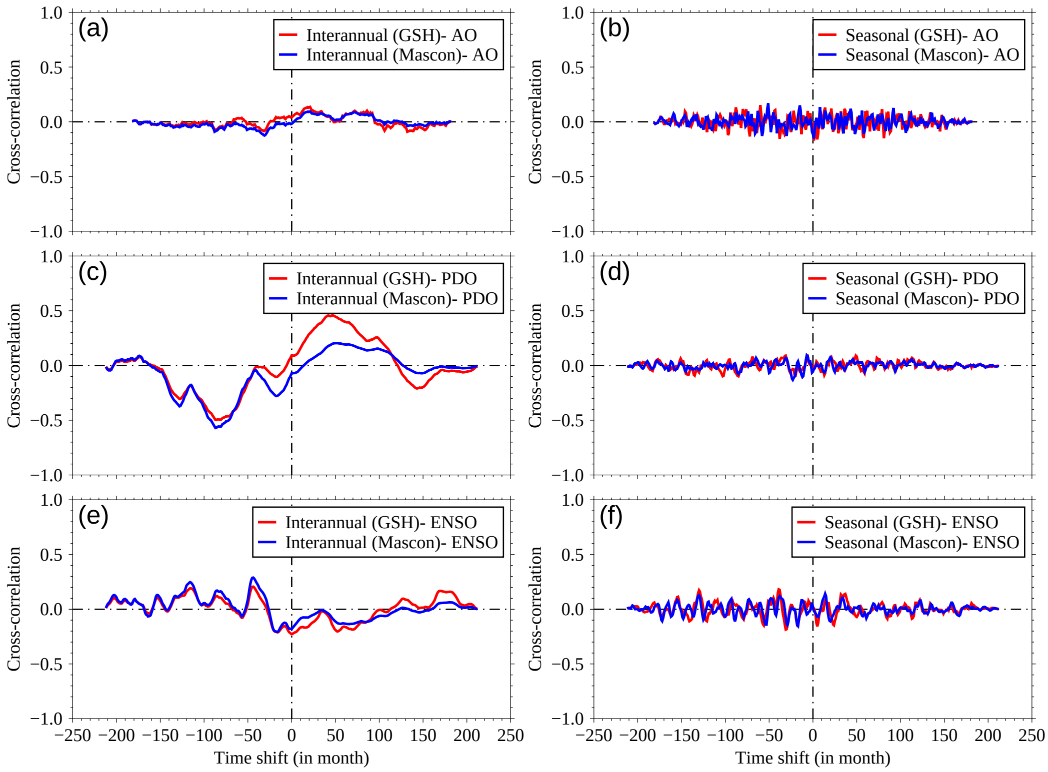


**Figure 4.** The correlation functions of interannual TWSc signals with respect to three climate factors (a,c and e) and of seasonal TWSc signals with respect to three climate factors (b,d and f) in the QB during 2002-2019.