# Atmospheric Water Vapor Budget and its Long-term Trend over the Tibetan Plateau

**Hongru Yan[1], Jianping Huang[1*], Yongli He[1], Yuzhi Liu[1], Tianhe Wang[1] and Jiming Li[1]**

[1]Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China

Corresponding author: Jianping Huang (hjp@lzu.edu.cn)

**Key Points:**

- Although air of Tibetan Plateau are moistening, atmospheric water supply could not well alleviate the depletion of surface water storage.
- Characteristics of water vapor balance vary from place to place across the Tibetan Plateau, key areas refer to several basins.
- Regions around Yarlung Zangbo Grand Canyon suffer severe loss of water storage due to overwhelming decrease in water vapor convergence.
- The source region of the Three Rivers also undertakes some risk to the depletion of surface water storage.

## Abstract

As rapid warming and consequent glaciers retreat across the Tibetan Plateau (TP), the problem about whether or not atmospheric water supply could alleviate the depletion of surface water storage need to be examined. Long-term changes of atmospheric water vapor balance across the TP is investigated by the ERA5 reanalysis from 1979 to 2018.Annual accumulated precipitation, water vapor convergence and evaporation generally keep an equilibrium but with different long-term variation trends: 0.68mm/a, 0.68mm/a and -0.18mm/a, respectively. Results suggest that surface water storage will not be well replenished by the water vapor transported from outside of the TP. For different regions of the TP, characteristic of water vapor balance and their long-term trends are completely different. Regions around Yarlung Zangbo Grand Canyon experiences sharp decrease in water vapor convergence and leads to decrease in precipitation. Meanwhile, evaporation keeps increasing due to the warming and melting of glaciers. Loss of surface water storage should be severe. For the source region of the Three Rivers, decrease in water vapor convergence overlaps increase in evaporations leads to no significant changes in total precipitations. Decrease in water transported from outsides brings risk to the depletion of surface water storage. Brahmaputra basin, inner TP and Qilian Mountain show significant wetting trends due to the increases in both convergence of water vapor flux and evaporation. Above regional characteristics of water vapor balances across the TP cause by inhomogeneous variation of atmospheric heat source and changes of atmospheric circulations, which need to be studied in further.



## Plain Language Summary

By analyzing the long-term trends of precipitation, water vapor convergence and evaporation, we try to estimate that whether the increase of atmospheric water vapor could replenish the depletion of surface water storage across the Tibetan Plateau (TP). Results suggest that surface water storage will not be overall replenished by precipitation for the whole year, because water vapor from local evaporation is increase but from outside of the TP is decrease. Meanwhile, long-term trends of water vapor balance and their consequenct impacts on surface water storage vary from place to place across the TP.


## 1 Introduction

The Tibetan Plateau (TP), which has an area of 2.5 million km$^2$ and average elevation of over 4000 m, is the highest and most extensive plateau in the world. It serves as the “world water tower” storing large amounts of water as glaciers, lakes, and rivers (*Lu et al., 2005; Yao et al., 2012*). Seasonal melting of snowpack and mountain glaciers over the TP feeds seven major rivers in Asia, providing abundant fresh water to about 40% of the world's population in this region and its downstream areas. Due to its unique terrain and specific underlying surfaces, the TP is well recognized to exert a dramatic influence on regional and even global climate (*Wu et al., 2012a; Ma et al., 2017*). Therefore, studying the atmospheric water over the TP is critical in climate research and adaptation policy.

Due to Plateau “heat pump effect” (*Wu & Zhang, 1998*), TP can converge water vapor from surrounding oceans or seas (*An et al., 2001; Boo & Kuang, 2010; Molnar et al., 1993; Wu et al., 2007, 2012b*), and becomes an isolated region of humidity in the atmosphere (*Xu et al., 2008a*). The TP plays significant role in adjusting the atmospheric circulation and hydrological cycle. Moreover, the TP is often considered as a “wet pool” and “transfer station” of the east Asian moisture during summer (*Wang et al. 2011*) and to influence the precipitation over downstream regions (*Wan et al. 2017; Xu et al. 2008b*) by transporting the water vapor by the westerly wind and southwest monsoon (*Ding & Chan, 2005*). Meanwhile, the TP snow cover associated with moisture anomaloy have great impacts on East Asian atmospheric circulation (*Li et al., 2018, 2019*). Therefore, it is meaningful to understand the water vapor transport from the TP, one of the most active centers of hydrological cycle in the world, and the further impact on the regional weather and climate.

It was reported that, under climate mean conditions, TP is a moisture sink in summer, having a net moisture convergence of 4 mm/day (*Feng & Zhou, 2012*). On a diurnal scale, *Ueno et al*. (*2008*) found a strong daytime wind speed accompanied by increasing relative humidity prevails along deep valleys in the Himalayas. However, the water vapor stagnates in front of the Himalayas because of the southerly wind with weaker intensity (*Ueno et al., 2008*). Seasonally, it was found that the passing of synoptic trough is expected to contribute strongly to water vapor transport from the Indian Ocean to the TP during the monsoon season (*Sugimoto et al., 2008*). On a long-term scale, it was reported that the precipitable water in the 680–310 hPa layer of the atmosphere has increased significantly since the 1990s, with an upward trend of 6.45 cm per decade and particularly high increases in summer (*Zhang et al., 2013*).

TP experienced a rapid warming over the past 50 years with two times more than the global warming rates (*e.g. Liu & Chen, 2000; Guo & Wang, 2012*). Along with the climate changes, the atmospheric circulation and hydrological cycles must be changed and the local environments would be reshaped. Accompanying the warming, air over the TP moistened (*Xu et al., 2008a*), surface pressure increased significantly (*Moore, 2012*), and surface heating and atmospheric heating became weakened (*Zhu et al., 2008; Duan & Wu, 2008, 2009; Yang et al., 2011a, 2011b*), the wind speed showed a weakening trend (*Lin et al., 2013*). Furthermore, the surface warming depends on elevation (*Liu & Chen, 2000*) and leads to glacier retreat, permafrost degradation (*Cheng & Wu, 2007*), lake expansion (*Zhu et al., 2010*), runoff increase (*Lutz et al., 2014*) and associated disaster risks aggravation (*Yao et al., 2012, 2019*). *Deng et al.* (*2018*) found the terrestrial water storage over the TP increased by 0.20 mm/month during the 2002–2012 period, but decreased by −0.68 mm/month since 2012. In addition, *Immerzeel et al.* (*2010*) projected that the warming may lead to less water resources for the downstream regions in the future.

Combined all these facts, it is urgent to answer following questions: How do every components of atmospheric water vapor budget generally vary on the inter-decadal time scale across the TP? What factors are responsible for such inter-decadal variations? Could the increasing of atmospheric water resources alleviate the depletion of terrestrial water storage caused by the melting of glaciers and the increase of runoff? Answers to these questions could enhance our understanding about inter-decadal variability of water vapor budget over the TP in recent decades and the intrinsic mechanisms, and provide an evidence of the significance of atmospheric water tower in the hydrological cycle on regional and global scales.

In this study, we focus on above questions to present a complete knowledge of atmospheric water resources over the TP. First, we analyze climatology of atmospheric water vapor over the TP based on ERA5 reanalysis data. Second, we examine climatology and long-term variations of every components of water vapor budgets (water vapor transportation, evaporation and precipitation) and give their related dynamical explanation. Finally, atmospheric water balance over the TP has been discussed and summarized. Section 2 describes the data and accuracy of each parameters used in this study. Section 3 presents the results and detailed discussions and Section 4 presents the conclusions.

## 2 Data

ERA5 is the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis for the global climate and weather for the past 4 to 7 decades, which is a replacement of ERA-Interim reanalysis. It has published a detailed record of the evolution of the global atmosphere from 1979 to update and will be from 1950 onwards when complete (*Berrisford et al., 2009; Dee et al., 2011*). Based on the 4D-Var assimilation method, ERA5 provides estimates for each hour of the day, worldwide. The native resolution of the ERA5 atmosphere and land reanalysis is 31km on a reduced Gaussian grid (Tl639) and 63km (TL319) for the ensemble members. The atmospheric component consists of 137 levels in the vertical from the surface up to 1 Pa (about 80km). This spans the troposphere, stratosphere and mesosphere. Data has been regridded to a regular lat-lon grid of 0.25 degrees for the reanalysis. There are two main sub sets: data on pressure levels and data on single levels. The data on pressure levels contain 16 atmospheric quantities on 37 pressure levels from 1000 hPa (surface) to 1 hPa (around the top of the stratosphere). Single-level data are available for a number of atmospheric, ocean-wave and land surface quantities. Information about the current status of ERA5 production, availability of data online, and near-real-time updates of various climate indicators derived from ERA5 data, can be found at http://www.ecmwf.int/research/era. Herein, following parameters: total column water, specific humidity, vertical integral water vapor flux, vertical integral moisture divergence, evaporation, snow evaporation and precipitation from ERA5 monthly dataset have been applied to study the atmospheric water tower over Tibet Plateau.

Care was needed when using reanalysis dataset to investigate trends of water vapor, precipitation and evaporation over the TP due to their qualities. *Wang et al.* (*2017*) and *Zhao and Zhou* (*2019*) demonstrated that total column water vapor from ERA5 performance well over TP. We firstly investigate the quality of evaporation and precipitation in ERA5 dataset by comparing with the satellite observation and other reanalysis datasets (Figures not shown). The relatively accurate evaporation data is developed by *Chen et al.* (*2019*), which revised the Surface Energy Balance System (SEBS) parameterization of bare soil to correct the biases of excess resistance to heat transfer and has been demonstrated to perform well. The 2001-2016 monthly mean evaporation from ERA5 is highly correlated with the satellite observations, with correlation coefficient reaching 0.88 and mean absolute deviation of 13.0 mm. Furthermore, the precipitation from ERA5, ERA-interim, Global Precipitation Climatology Project (GPCP, *Adler et al., 2003*) version 2.3 and Climatic Research Unit (CRU, *Harris et al., 2020*) TS version 4.03 have been compared with that from the High Asia Reanalysis (HAR, *Maussion et al., 2014*), which is recognized good performance over the TP (*Li et al., 2020*). Among those datasets, monthly precipitation of ERA5 shows smallest bias of -5.4 mm and highest correlation coefficient of 0.97.

## 3 Results

### 3.1 Climatology/Feature of Atmospheric Water Tower

Based on the ERA5 40-year (1979-2018) monthly reanalysis, considering about the average elevation of the TP over 4000 m, we use specific humidity vertically integrated from 500 hPa to the top of atmosphere to represent the atmospheric water resources over the TP:

$$w = -\frac{1}{g}\int_{500}^{1} q\, dp,$$

where $g$ is gravitational acceleration, $q$ is specific humidity in unit of kg kg $^{-1}$, $p$ is pressure level, and $w$ is vertically integral specific humidity in unit of kg/m$^2$, which is equivalent to millimeter. Figure 1 show the zonal deviation of annual mean vertically integral specific humidity and the black thick line shows the shape of the TP. Compared with the same latitude zone, a maximum of moisture exists right above the southern TP and south of the Himalayan region in the middle and upper stratosphere. Such a long-term existed wet pool in high atmospheric layer presents an image of atmospheric water tower (AWT). Formation of this AWT is due to the elevated terrain of theTP, which acts as a heat source and pumps water vapor from low-levels of Arabian Sea and Indian Ocean to high-levels of TP. And higher altitude helps water vapor transport farer and presents a ''re-channel function'' in planetary-scale (*Xu et al., 2008a*).

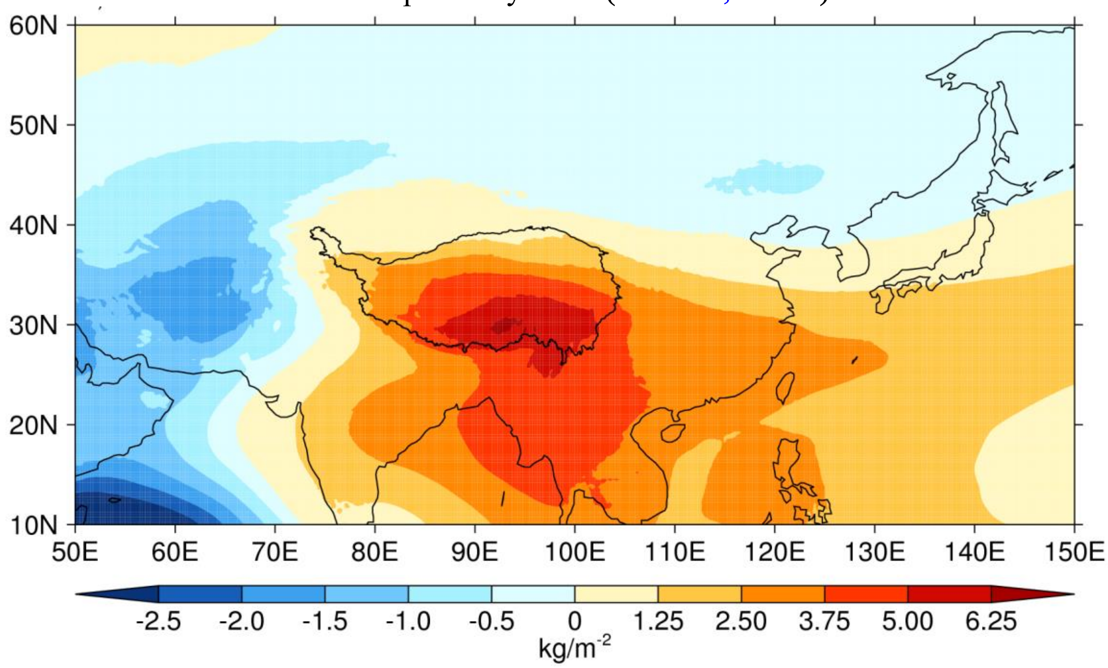


**Figure 1.** The zonal deviation of 40-year (1979-2018) annual mean water vapor content vertically integrated from 500 to the top of the atmosphere.

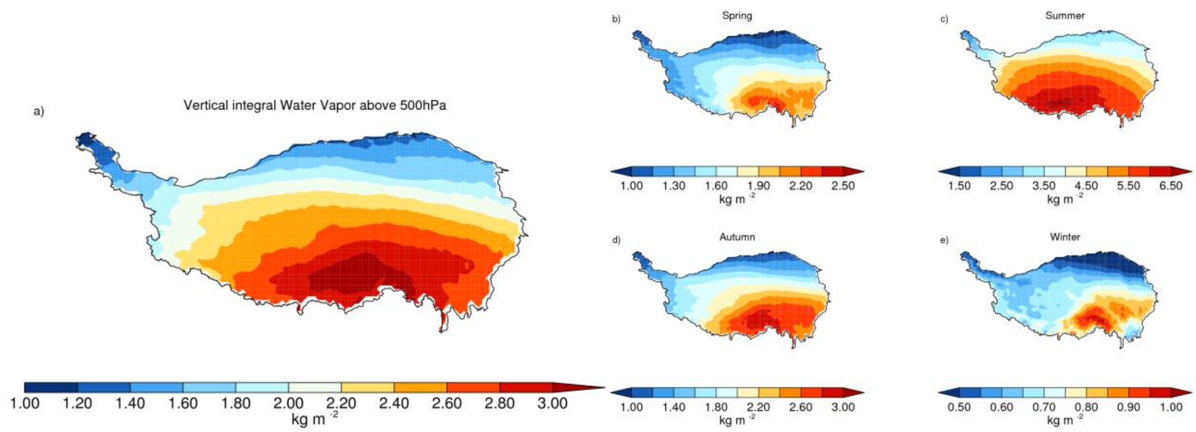


**Figure 2.** The horizontal distribution of 40-year (1979-2018) averaged water vapor content vertically integrated above 500 over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

Take a look at the long-term annual mean and seasonal mean distribution of vertically integral specific humidity above 500 hPa over the TP in (Figure 2), its general characteristics is wet in southern and southeastern TP and dry in northwestern and northeastern TP. Yarlung Zangbo Grand Canyon and relatively lower elevation in southeastern TP provide more chance for the warm and humid airflow from the oceans or seas to climb up the south slope of the TP and come into the inner land. Meanwhile, the polar dry air is blocked on the north side of the TP and water vapor from south is difficult to transport to the north. These processes lead to the extreme dry climate in the north side of the TP. The central location and magnitude of maximal moisture show significant annual variation. In winter, the wettest center is located in the southeast of TP with peak value of vertically integral specific humidity less than 1 $kg/m^2$. As spring coming, the maximum center spreads to north and west with the peak value up to 3 $kg/m^2$. In summer, wet regions occupy the entire southern TP with the maximum value close to 7 $kg/m^2$, then this wet regions shrink back to southeast of the TP along with autumn coming. This annual variation indicates that the atmospheric water resource over the TP is strongly influenced by South Asian monsoon and East Asian monsoon. As the outbreak of the summer Asian monsoon, wet areas expand and moisture in atmosphere increases.

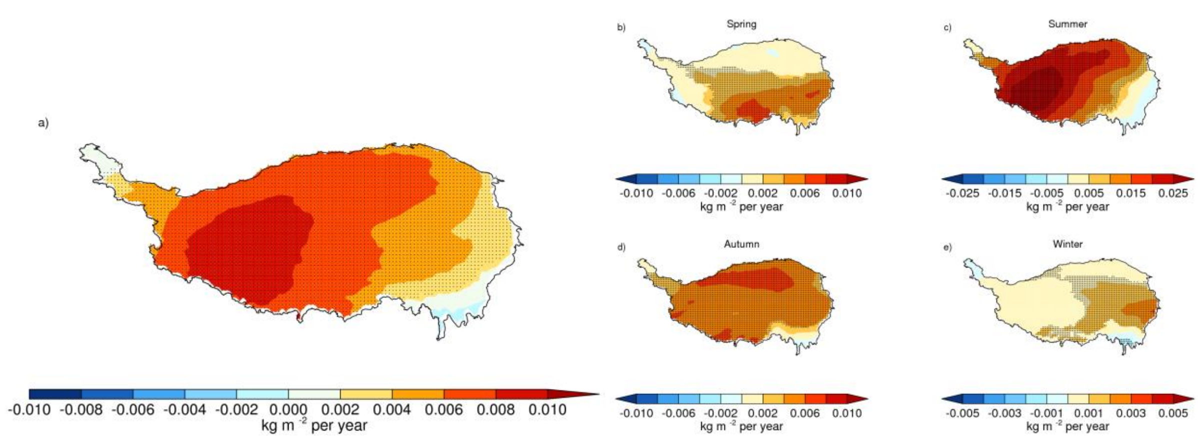


**Figure 3.** The horizontal distribution of long-term (1979-2018) trends of above 500 hPa vertical integral water vapor content over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter

In the past few decades, the increase rate of air temperature in the TP is almost two times higher than that in the global (*Chen et al., 2014*). It would accelerate the melting of glaciers and snow. Since atmospheric water resource is an important supply to surface water resources, long-term trends of atmospheric water resource over the TP should be concerned. Figure 3 shows the horizontal distribution of long-term trends of vertically integral specific humidity above 500 hPa over the TP for annual mean (Figure 3a) and four seasons (Figure 3b-e), respectively. The black dot means that the trend in corresponding grid is confidence in 95% level. From 1979 to 2018, except the wettest region in southeastern TP, the atmospheric water resources across the main body of the TP show significant growth trends. The trends distribution in summer has similar pattern with the overall long-term trends but larger values. For other three seasons, long-term trends are all increase but smaller than that in summer. It suggests that these upward trends are mainly contributed by changes of atmospheric circulation and heat sources in summer. The inner TP, where is relative dry condition, is the most wetting region, while the southeastern TP, the wettest climatology, become slightly dry. As *Xu and Gao* (*2019*) explained that decrease trends in southeastern TP is due to the less water vapor transportation from Indian Ocean.

### 3.2 Atmospheric Water Balance over TP

Previous researches have pointed out that there are many impactors for the changes of water vapor over TP, such as atmospheric circulation, temperature, elevation and land surface process (*eg., Duan et al., 2018; Zhou et al., 2019; Xu & Gao, 2019*). Therefore, analyses referring to water vapor budget are employed to investigate long-term trends of water vapor convergence, evaporation and precipitation across the TP (Fig. 6) as those used in many previous studies (*Chou & Neelin, 2004; Zhou et al., 2019*). The moisture budget equation is expressed as,

$$\frac{\partial w}{\partial t} = -\nabla \cdot Q + E - P + res \tag{1}$$

where *w* is vertically integrated atmospheric water vapor, *P* and *E* are precipitation and evaporation, respectively. $\frac{\partial w}{\partial t}$ is the time derivative of vertically integrated moisture, $-\nabla \cdot Q$ is horizontal divergence of water vapor and *res* is the residual term, which is possible related to the assimilation in the reanalysis dataset. Comparing with other terms in Eq.(1), $\frac{\partial w}{\partial t}$ is much smaller and typically neglected, however, it also determines the trend of atmospheric water vapor over the TP. To investigate the mechanism of long-term variation of atmospheric water tower over the TP under global warming, the horizontal net water vapor flux, evaporation and precipitation were examined individually.

#### 3.2.1 Horizontal Net Water Vapor Flux over the TP

Based on Green's theorem that the sum of fluid outflowing from a volume is equal to the total outflow summed about an enclosing area, there are following two methods (Equation (5) and (6)) to achieve the horizontal net water vapor flux over the TP.

$$IQU = \int_{sfc}^{toa} \frac{qu}{g} dp \tag{2}$$

$$IQV = \int_{sfc}^{toa} \frac{qv}{g} dp \tag{3}$$

$$D = \frac{\partial IQU}{\partial x} + \frac{\partial IQV}{\partial y} \tag{4}$$

$$N = \oint_{tp} IQUdy + IQVdx \quad (5)$$

$$N = \oiint_{tp} D\, d\sigma \quad (6)$$

where $q$ is specific humidity, $u$ and $v$ are wind speeds in eastward and northward, respectively. $IQU$ and $IQV$ are respective eastward and northward water vapor flux. $D$ is the divergence of vertical integrated water vapor flux, this parameter is positive for moisture spreading out, and negative for moisture concentrating or converging. $\sigma$ is the area in unit of $km^2$. $N$ is the net income of atmospheric water resource for the entire area of the TP and the unit is Gt.

Based on Equation (5) and the climatology (1979-2018) from the ERA5 dataset, the vertical integral of water vapor flux in the four boundaries over the TP were shown Figure 4. The western, southern, eastern and northern boundaries are given in red, light blue, yellow and navy blue, respectively. The result shows that the water vapor over the TP was transported from western and southern boundaries with water vapor flux of 1328 Gt /a and 2195 Gt /a, respectively. And water vapor flows out in the eastern and northern boundaries with flux of -2225 Gt /a and -252 Gt /a, which are consistent with previous study based on ERA-interim (*Zhou et al., 2019*). Therefore, the atmospheric water tower is mainly influenced by the water vapor transported from the west and south of the TP, which are associated with the interaction between westerly and monsoon system (*Yao et al., 2019*). *Xu et al*. (*2002, 2019*) provided a conceptual model of the key influence area of water vapor transport "large triangle sector" in the TP and low-latitude ocean monsoon region. This model considers the TP as a transfer station drawing water vapor from Indian Ocean and transferring to downstream. As the water vapor pumping in the TP, 1046 Gt of water vapor in every year are left to form precipitation or increase atmospheric water vapor content.

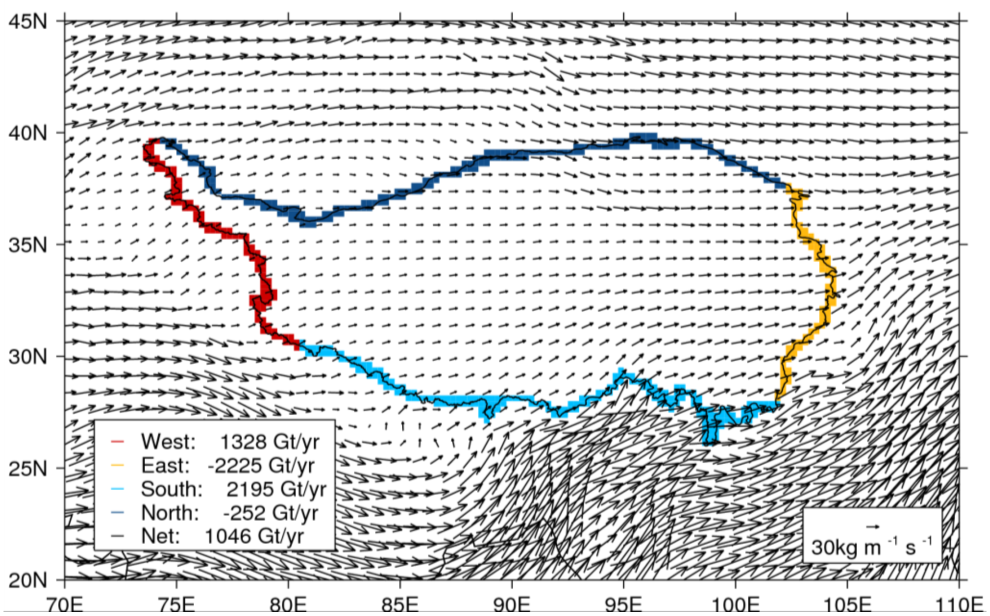


**Figure 4.** Vertical integral of water vapour flux from ERA-Interm (1979-2018) over the Qinghai-Tibet Plateau, whose northern, western, southern and eastern boundary are show in colors.

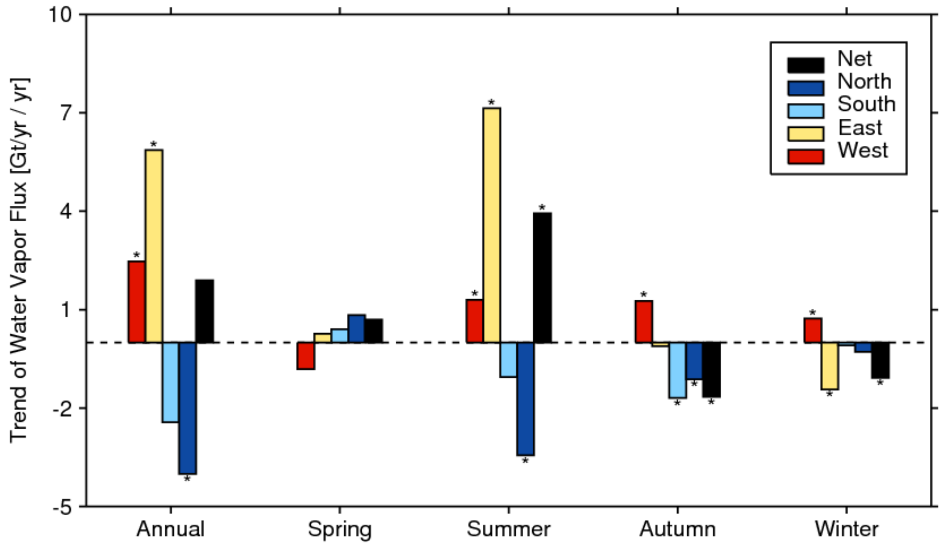


**Figure 5.** The long-term (1979-2018) of the net water vapor flux for north (deep blue), south (light blue), east (yellow), west boundary (red) of Qinghai-Tibet Plateau and net flux (black) respective in spring, summer, autumn, winter and the whole year.

Long-term trends of the net water vapor flux over the TP region and accumulated water vapor flux passing through four boundaries are further investigated (Figure 5). Stars marked on each histogram mean that the trend is significant in 0.05. The annual mean of net water vapor flux over the TP was slightly increasing by 1.9 Gt/a, which is dominated by the trend of summer. Results showed that the increasing trend of atmospheric water tower was induced by the increasing inflow transportation from western boundaries and the decreasing outflow transportation in the eastern boundary. However, the decreasing inflow transportation from southern boundary and increasing outflow transportation from northern boundary were negatively contributed to the increasing trend of net water vapor flux over the TP. By analyzing the seasonal transportation in four boundaries, we found that the net water flux over the TP were significant increasing in summer but slightly decreasing in autumn and winter. And trends of water vapor flux in four boundaries changed dramatically in summer but lightly in other three seasons. Although the west and south boundaries are main water vapor channels in the climatology, trends of water flux in western and southern boundaries were not larger than that in eastern and northern boundaries, especially in summer. It suggested that increasing of the net water vapor flux over TP may be not induced by the interaction between westerly and monsoon system. The water vapor flux of northern boundary in summer and annual mean were significantly decreasing, which may be related to the northward shift of subtropical westerly jet (*Lin et al., 2013*) and cyclonic anomalous near Lake Baikal (*Zhou et al., 2019*). The decreasing of water flux in east boundary contributes most to the trend of the net water vapor flux and may be associated with the weakening of wind speed over the TP (*Lin et al., 2013*).

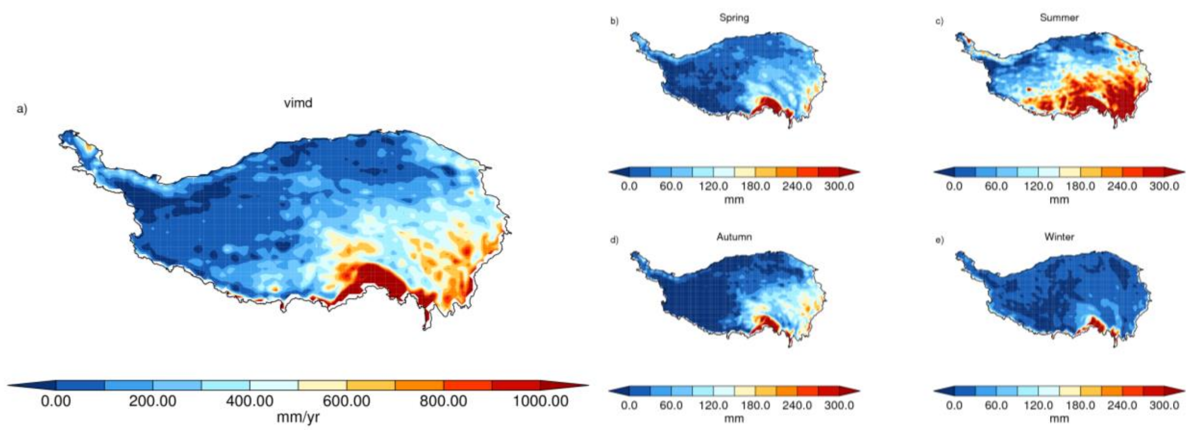


**Figure 6.** The horizontal distribution of 40-year (1979-2018) averaged vertical integrated divergence of water vapor flux over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

Based on Equation (4), the long-term annual and seasonal mean distribution of divergence of vertically integrated water vapor flux (*D*) over the TP are given in Figure 6. It means moisture spreading out (converging) when the value of *D* is positive (negative). Except for a few places in northwest of the TP, water vapor flux is converging for most area of the TP with weak convergences of less than 100 mm every year in western and northern TP as well as strong convergences up to 4000 mm every year in south slope and southeast of the TP. The highest converging center, which is along with Yarlung Zangbo Grand Canyon, has been recognized as the major passageway for water vapor entering the TP (*Xu et al., 2002*). The distribution of divergence of water vapor flux showed significant seasonal variation. In winter, the converging center of water vapor flux is located at the Nyingchi with maximum value about 300 mm but even diverging over the rest area of the TP. In spring and autumn, the converging center expanded to southeast of the TP. As summer coming, water vapor converging region occupies the entire TP and almost half area of the TP with divergence of water vapor flux exceeding 300 mm. Seasonal variation indicates that the atmospheric water vapor transportation over the TP is strongly influenced by South Asian monsoon and East Asian monsoon and the topography of the TP. Based on Equation (6), the net income of atmospheric water vapor for the entire TP is 1103.6 Gt, which is close to that (1046 Gt) calculated by Equation (5).

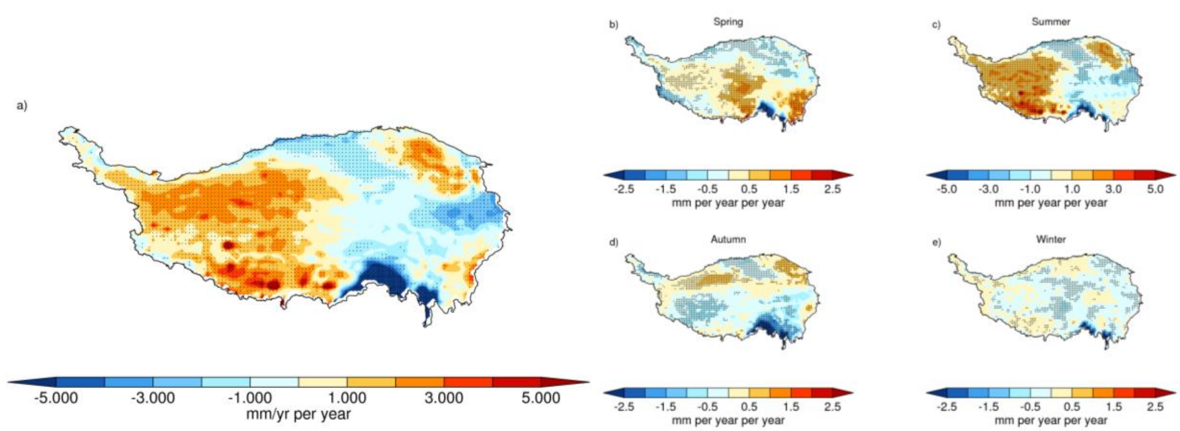


**Figure 7.** The horizontal distribution of long-term (1979-2018) trends of vertical integrated divergence of water vapor flux over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter

Divergence of vertically integrated water vapor flux showed dramatically decrease trends in the highest converging center located at the Yarlung Zangbo Grand Canyon and slightly decrease trends in the Qaidam Basin and the east of the TP. For weak converging area, such as the Qilian Mountain and the inner TP, long-term trends of divergence of water vapor flux showed significant upward trends (Figure 7). For different seasons, long-term trends keep decreasing at the Yarlung Zangbo Grand Canyon. The distribution of long-term trends of water vapor divergence in summer is similar with annual mean and trends are much larger than that in other three seasons. *Duan et al.* (*2018*) found that the heat of the TP showed a weakening trend since the 1980s based on site observations, while *Luo et al.* (*2019*) obtained the opposite trend of plateau heat sources based on reanalysis data. As the observation sites are mainly distributed in the southeast of the plateau but the sites in the middle and northwest of the plateau are seriously missing, changes of heat sources from observations is contrary to those from the reanalysis data. Therefore, the long-term trends of divergence of water vapor flux and heat sources show similar patterns that the southeast side shows a cooling and drying trend, and the central and northwestern parts show a warming and moistening tendency. It reveals that moisture convergence are dominated by atmospheric heat source. *Ma et al.* (*2017*) also speculate that the weakening water vapor transportation in southeast of TP is due to wind stilling. Besides those reasons, less water vapor transportation from Indian Ocean might be another reason to the decrease trend in southeastern TP (*Xu & Gao, 2019*). On the other side, the increasing atmospheric water content would absorb more long-wave radiation and intensify the apparent heating source, which could strengthen the convergence of water vapor and form a positive feedback. While the *Yang et al.* (*2011b*) point out the water vapor increasing might lead to solar diming over the TP. Thus, the feedback of increasing water vapor to heat source need to be resolved in the future.

### 3.2.2 Evaporation over the TP

To estimate the total evaporation over the TP, we use the sum of evaporation and snow evaporation from ERA5 in Figure 8. Annual accumulated total evaporations are up to 800 mm/a in southeast of TP but drop to 100 mm/a in west and northwest of TP. Ranges of evaporations are almost same as that of divergence of water vapor flux in most areas of the TP. As most of the lakes in the TP scattered over the inner TP, evaporation is relative higher in this region. The lowest evaporation (< 100 mm/a) is located at the Qaidam Basin, where is the driest area of the TP. The locations of maximal and minimal evaporation did not change from season to season, while the magnitude of total evaporation show significant seasonal variations due to the changes of air temperature. During summer, areas with evaporation over 200 mm take part of about 80% of the TP. In spring and autumn, the value of evaporation is about two third of that in summer but two times of that in winter.

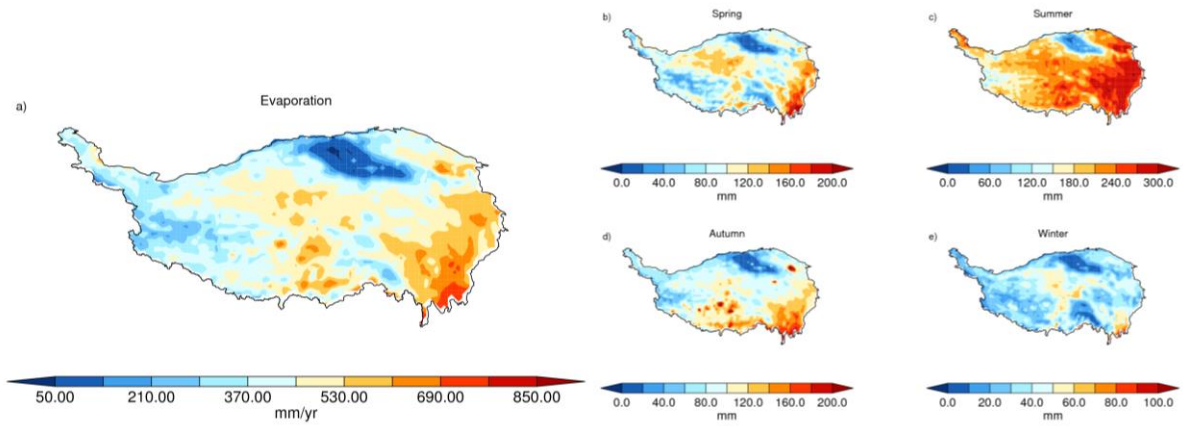


**Figure 8.** The horizontal distribution of 40-year (1979-2018) averaged evaporation over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

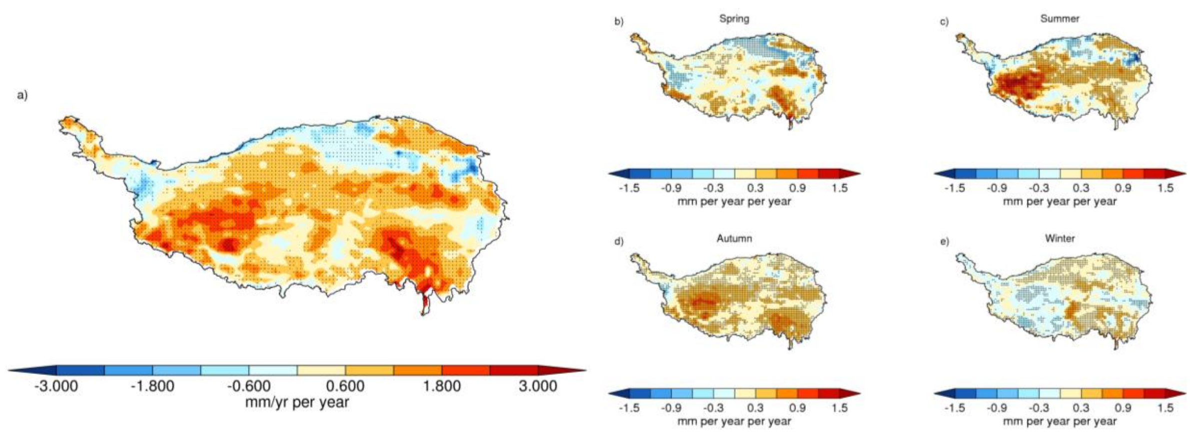


**Figure 9.** The horizontal distribution of long-term (1979-2018) trends of evaporation over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

Total evaporation shows significant increasing trends for the most part of places over the TP, except for a few of places, such as the Qaidam Basin and Karakorum Mountains (Figure 9). In general, it is consistent with the independent modeling study (*Yin et al., 2013*) and site observations (*Zhang et al., 2007; Yang et al., 2014*). As the TP has experienced enhanced temperature increase, glaciers melting and lake expansion in the past few decades (*Yao et al., 2019*), increase in evaporation is consist with expectation. Based on the characteristic of seasonal variation, regions with increasing evaporation can be divided into two categories. One is located in the western and inner TP, which shows significant seasonal variation that notable increase in summer and autumn, slightly increase in spring but decrease in winter. Another one is located in the southeastern TP, where evaporations keep increasing for the whole year with very small seasonal variations. Impacts for actual evaporation includes the water availability at the surface, temperature gradient between air and surface and wind speed. As the latter two impactors dominate the evaporation in wet area, increase in evaporation in the southeast of the TP is mainly due to increase in air temperature. However, increase in evaporation in the western and inner TP is the result of the increases in both temperature and water availability at the surface. Based on Gravity Recovery and Climate Experiment (GRACE) data, *Deng et al.* (*2018*) found that terrestrial water storages were decreasing in the southern TP but increasing in the Inner TP from 2002 to 2016. Meanwhile, based on ground survey and high-spatial-resolution satellite images, *Wan et al.* (*2016*) established a lake data set from 2004 to 2015 for the TP and found the area of lakes mainly increased in the inner TP but decrease in the Brahmaputra basin. This suggests that a consistent trend between the evaporation and water availability at the surface.

### 3.2.3 Precipitation over the TP

Both water vapor flux divergence and total evaporation make up of atmospheric water vapor resources to form precipitation. Figure 10 shows the horizontal distribution of 40-year (1979-2018) annual accumulated total precipitation in annual (Figure 10a) and four seasons (Figure 10b-e). The distribution of precipitation combines characteristics from both divergence of water vapor flux and evaporation. The place of largest precipitation (>1500 mm/a) coincides with the largest converging center located around the Yarlung Zangbo Grand Canyon. And the least precipitation (< 150 mm/a) in the Qaidam Basin is also coexist with the place of the least evaporation. For the inner TP, relative low water vapor convergences (about 300 mm/a) combined with plentiful evaporations (about 500 mm/a) lead to considerable precipitation (about 600 mm/a). Distributions of precipitation in four seasons are similar as that of the annual mean, while the magnitude of precipitation also show significant seasonal variations. The total precipitation is largest in summer, middle in spring and autumn, and smallest in winter.

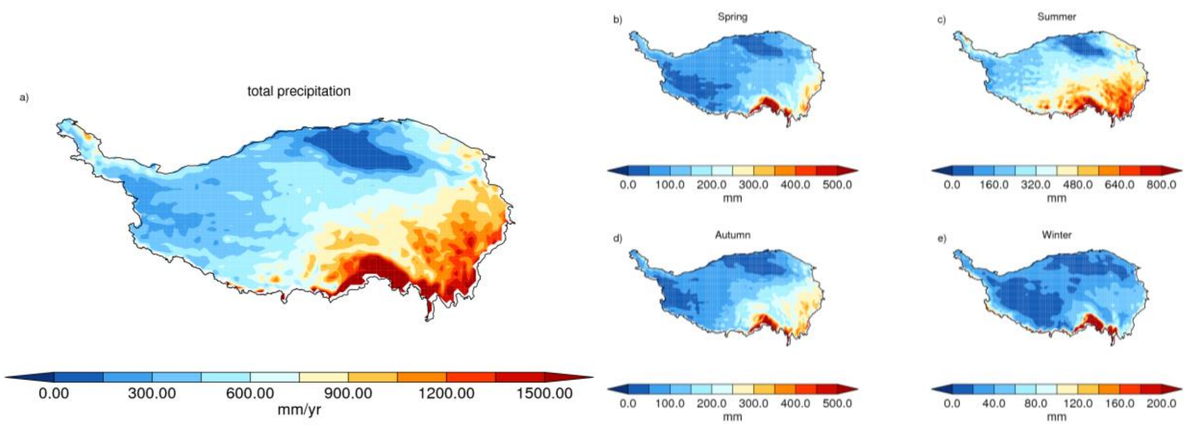


**Figure 10.** The horizontal distribution of 40-year (1979-2018) averaged total precipitation over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter

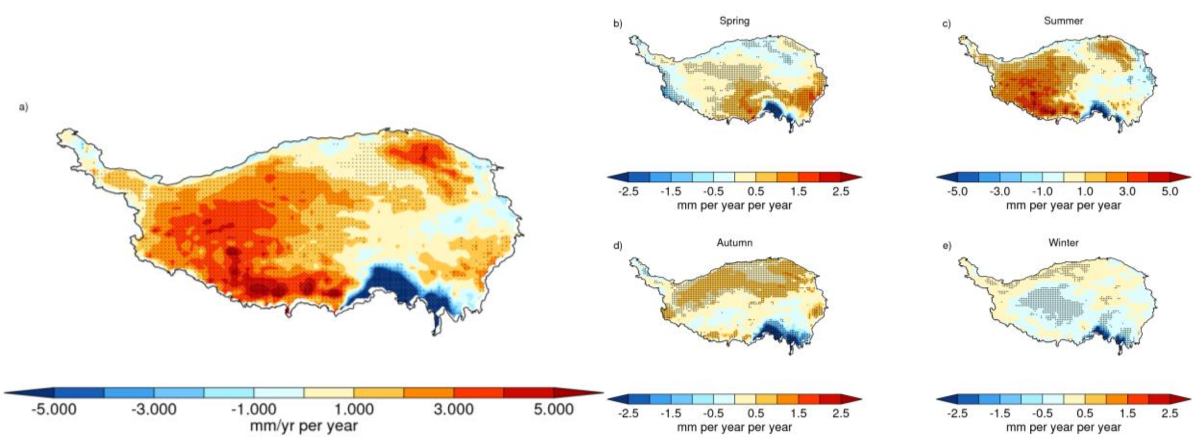


**Figure 11.** The horizontal distribution of long-term (1979-2018) trends of total precipitation over Tibet Plateau for (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter.

Features of long-term trends of total precipitation also combines the characteristics of trends of water vapor convergence and evaporation (Figure 11). Total precipitations present overall long-term increasing trends for the most areas of the TP except for the Yarlung Zangbo Grand Canyon, where is the region with the maximum of water vapor convergence and also the most rapid decreasing of water vapor convergence. Same as the long-term trends of vertical integrated divergence of water vapor flux, total precipitation keeps going down around Yarlung Zangbo Grand Canyon during the whole year. It suggests that water vapor convergence related to atmospheric circulation dominate the changes of precipitation in this area. Generally, the locations of increasing centers of precipitation changes from season to season. The pattern of long-term trends in summer is very close to that of the annual mean. In spring, precipitation increase in south of the TP and decrease in north of the TP, while this pattern reverse in autumn. In winter, long-term trends of precipitation are very tiny. For Brahmaputra basin, inner TP and south of Qilian Mountain, increases in both water vapor flux convergence and total evaporation bring about obvious increase in total precipitation. According to the values of long-term trends, evaporation plays a relative important role in the increasing of precipitation in the inner TP, while water vapor convergence dominates in Brahmaputra basin and south of Qilian Mountain. For the source region of the Yangtze River, Yellow River and Lancang River located at the center of eastern TP, overlaps of the decrease in water vapor convergence and increase in evaporations give rise to no significant changes of total precipitations. As the source region of three rivers supply adequate freshwater to downstream areas to feed about 40% of the world's population, changeless in precipitation amount and increase in evaporation will lead to decrease in surface water storage, which might be a warning alarm to us.

#### 3.2.4 Discussion of Atmospheric Water Balance over the TP

Long-term means and trends of the terms in Eq. (1) are summarized in Table 1. The annual vertically integrated moisture over the TP is only 15.02 Gt, which is much less than precipitation, evaporation and vertical integrated water vapor convergence. This result suggests that moisture converged from surround regions and/or evaporated from surface mostly leave atmosphere through precipitation, only very small percent of water could be left in the atmosphere. Annual accumulated precipitation is 2220.0 Gt, which is slightly less than the sum of convergence of moisture (1103.6 Gt) and evaporation (1245.5 Gt). It means that atmospheric water budget almost keeps equilibrium. Coincidently, total column water (TCW) rises steadily at the rate of 0.011 mm/a. Precipitation over the TP is also increasing at the rate of 0.68 mm/a, which is slightly less than the trend of evaporation (0.69 mm/a). However, the trend of convergence of moisture decreases at the rate of -0.18 mm/a, which is not significant at 0.05 probability level. Generally, changes in convergence of water vapor are caused by the changes in atmospheric circulation, and more evaporation are due to expansion of the lake area and melting of glaciers over the TP. Therefore, evaporation provide atmospheric water vapor locally, while the divergence of water vapor flux are mainly the water transported from outside of the TP. If the decrease trend of water vapor convergence turns to significant and continues, the water storage of TP will be slowly depleted in the further. However, when we just check trends in summer, all of the terms in Eq. (1) show increasing tendency. It suggests that increasing in both water vapor convergence and evaporation brings about increasing in precipitation, and convergence of water vapor (0.3 mm/a) contributes more than evaporation (0.18 mm/a). We can speculate that the long-term trends of water storage in the TP is increasing in summer, which is the largest atmospheric water obtain season.

**Table 1.** *Atmospheric Water Budgets over the TP*

| | Properties | Regional [Gt] | Annual Mean [mm/m$^2$] | Trend (1979-2018) [mm/a] | Trend in JJA (1979-2018) [mm/a] |
|---|---|---|---|---|---|
| **TCW** | Status | 16.10 | 5.16 | 0.011 | 0.030 |
| $\partial \mathbf{W}$ | Accumulated | 0.009 | 0.003 | 0.000 | 0.003 |
| $-\nabla(\mathbf{q}\vec{V})$ | Accumulated | 1103.6 | 375.0 | -0.18 | 0.30* |
| **E** | Accumulated | 1245.5 | 432.7 | 0.69* | 0.18* |
| **P** | Accumulated | 2220.0 | 761.9 | 0.68* | 0.76* |

*Note.* * means the trend is significant in 95% confident level.

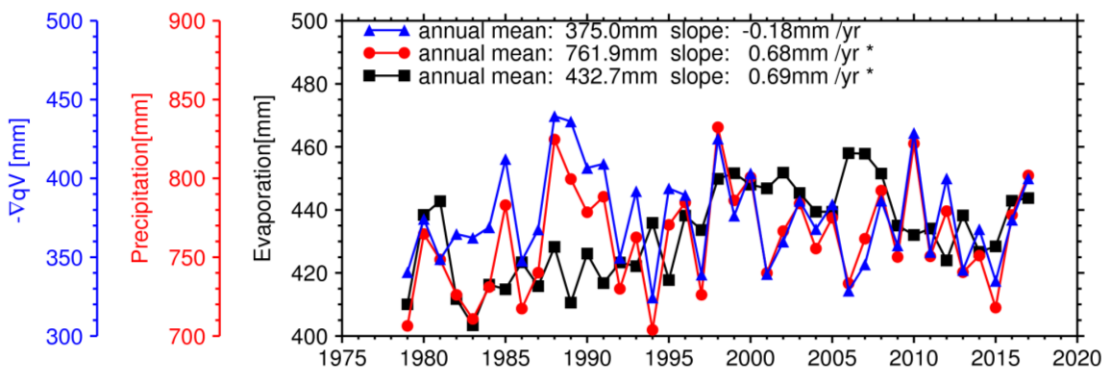


**Figure 12.** The time series (1979-2018) of annual vertical integrated divergence of water vapor flux (blue), total precipitation (red) and total evaporation (black) over the Tibet Plateau.

To further investigate the long-term variation of moisture balance over the TP, time series of annual total evaporation, precipitation and convergence of water vapor were shown in Figure 12. Results suggest that the variation of annual total precipitation is closely matched with that of convergence of water vapor over the TP, while their long-term trends are different. It means the water vapor convergence generally dominate the precipitation across the TP and evaporation just play an assistant role. Evaporation has an obvious decadal transition from an increasing period (1985-2005) to a decreasing period (2005-2015). Different with warming hiatus phenomenon in globe and China, the temperature over the TP keeps same warming rate during warming hiatus period (1998-2014) (*Duan et al., 2015*). The trend analysis based on the observation found that decreasing net radiation and wind speed contribute to the decreasing of evaporation in recent decades (*Zhang, et al., 2018*). Convergence of water vapor do not show such a decadal transition, and influence by more complex changes of atmospheric circulations, such as transportation from Indian Ocean (*Xu & Gao，2019*) and cyclonic anomaly near Lake Baikal (*Zhou et al., 2019*).

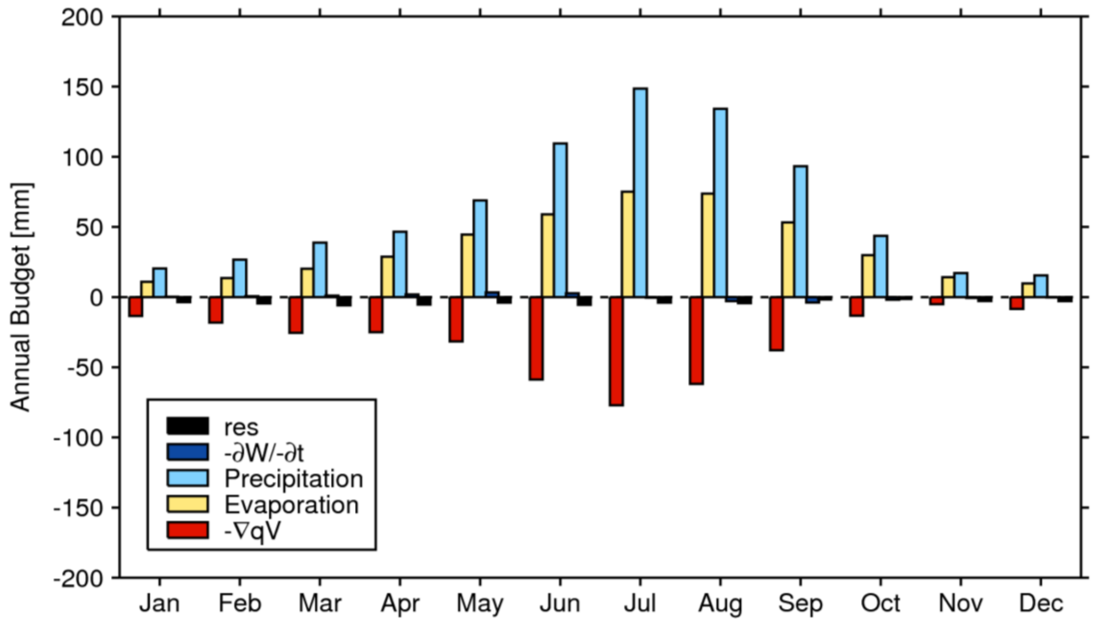


**Figure 13.** Climatology (1979-2018) of annual variation of $\frac{\partial w}{\partial t}$ (deep blue), precipitation (light blue), evaporation (yellow) and vertical integrated divergence of water vapor flux (red) and residual (black).

Figure 13 presents the monthly climatology of the precipitation, evaporation and convergence of water vapor. Divergence of water vapor flux, evaporation and precipitation show one-peak seasonal variation with strong in summer and weak in winter. Precipitation overwhelms evaporation in the warm half year and just slightly exceeds evaporation in the cold half year. It suggests that gross surface water budget in the TP is gaining. The residuals of the water vapor balance should include phase transformation of water vapor and cross-tropopause mass exchange, both of which are tiny (*Tian et al., 2014*) in theory. Negative value of residual means that more resources of water vapor are left in atmosphere and positive value means opposite, that more moisture are removed from atmosphere by precipitation. Herein, the monthly-accumulated residual term with small negative number can be neglected.

## 4 Conclusions

The Tibetan Plateau (TP) is known as the "Asian Water Tower" (*Yao et al., 2012*), acts as a “heat pump” to converge water vapor from the surrounding oceans to plateau region. Combined with the contribution of the local evaporation, TP forms an isolated region of humidity in the atmosphere (*Wu et al., 2007; Xu et al., 2008*). It can be called as “Atmospheric Water Tower (AWT)” of the plateau. Based on ERA5 reanalysis data from 1979 to 2018, general characteristics of AWT shows slightly drying trends in southern and southeastern TP, where is the most wetting region of the TP, but huge wetting trends in northwest, northeast and hinterland of the TP, where are relative dry region of the TP.

To reply the question that whether water vapor supply could alleviate the depletion of surface water storage caused by the melting of glaciers and the increase of runoff under rapid warming, we analyses long-term trends of water vapor budgets including items of water vapor transportation, evaporation and precipitation over the TP. Annual accumulated precipitation

(2220.0 Gt) across the TP is almost equivalent to the sum of convergence of moisture (1103.6 Gt) and evaporation (1245.5 Gt). Although the long-term trend of total precipitation seems increase at the rate of 0.68 mm/a, the surface water storage would not be well replenished because that the evaporation increase at the rate of 0.69 mm/a and the net gain of water vapor transportation do not show significant long-term changes based on two independent methods: one is the integration of water vapor flux along the boundary of the TP and another is integration of divergence of water vapor flux over the enclosing area of the TP. However, in summer, the largest water obtain season, the trend of convergence of water vapor flux significantly increases at the rate of 0.3 mm/a, which was induced by the increasing inflow transportation from western boundaries and the decreasing outflow transportation in the eastern boundary. *Zhou et al.* (*2019*) found that when a cyclonic (an anticyclonic) anomaly occurs near Lake Baikal, there is less (more) water vapor over the TP, then attributed the decreasing outflow in the eastern boundary to a summer atmospheric circulation anomaly near Lake Baikal.

For different regions of the TP, characteristic of water vapor balance and their long-term trends are completely different. Regions around Yarlung Zangbo Grand Canyon, where is the major passageway of water vapor transported from south oceans to TP, experiences the sharp decrease in water vapor convergence and then leads to decrease in precipitation. Meanwhile, the evaporation still increases due to the increasing of temperatures and melting of glaciers. Surface water storage would be tremendously lost in this area. For the center of eastern TP, where is source region of the Yangtze River, Yellow River and Lancang River, decrease in water vapor convergence overlaps increase in evaporations leads to no significant changes in total precipitations. As the evaporations provide the water vapor from local regions while water vapor convergence transport water resources from the outside of the TP, it should be on the alert that the water storage of this area would be slowly depleted in the further. For Brahmaputra basin, inner TP and south of Qilian Mountain, there are significant wetting tendencies because that the increases in both convergence of water vapor flux and evaporation bring about obvious increase in total precipitation.

All above regional feature of water vapor balance across the TP are the result of complex interaction between atmospheric heat source (*Yang et al., 2014*), atmospheric circulation from high latitude regions, such as cyclone near the Lake Baikal (*Zhou et al., 2019*), and/or low latitude regions, such as monsoon from the Indian Ocean (*Xu & Gao, 2019*). Meanwhile, *Liu et al.* (*2019*) found that the slow increasing of precipitation may be affected by the increasing dust aerosol transported from central Asian or Taklamakan desert. This study presents a general view of AWT and details about impacts of the long-term changes of atmospheric water vapor balance on surface water storage across the TP. It is sure to improve our understanding about “Asia Water Tower” in climate research and adaptation policy.

**Acknowledgments**

This study is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA2006010301). The ERA5 data are available from https://cds.climate.copernicus.eu/

## References

An, Z., Kutzbach, J. E., Prell, W. L., & Porter, S. C. (2001). Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. *Nature*, 411, 62-66, https://doi.org/10.1038/35075035.

Adler, R.F., Huffman, G.J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., et al. (2003). The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *J. Hydrometeor.*, 4,1147-1167.

Berrisford, P., Dee, D.P., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., & Uppala, S.M. (2009). The ERA-Interim Archive. *ERA Report Series*, No.1. ECMWF: Reading, UK.

Boos, W. R., & Kuang, Z. (2010). Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. *Nature*, 463, 218-223, doi:10.1038/nature08707.

Chen, D.L., Xu, B.Q., Yao, T.D., Guo, Z.T., Cui, P., Chen, F.H., et al., 2015: Assessment of past, present and future environmental changes on the Tibetan Plateau. *Chin. Sci. Bull.*, 60, 3025–3035, https://doi.org/10.1360/N972014-01370. (in Chinese)

Chen, X., Massman, W. J., & Su, Z. ( 2019). A column canopy-air turbulent diffusion method for different canopy structures. *Journal of Geophysical Research: Atmospheres*, 124, 488– 506. https://doi.org/10.1029/2018JD028883.

Cheng, G., & Wu, T. ( 2007), Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau, *J. Geophys. Res.*, 112, F02S03, doi:10.1029/2006JF000631. Chou, C. , & Neelin, J. D. (2004). Mechanisms of global warming impacts on regional tropical precipitation. *Journal of Climate*, 17(13), 2688-2701.

Dee, D. P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. R. Meteorol. Soc.*, 137, 553–597.

Deng, H., Pepin, N. C., Liu, Q., & Chen, Y. (2018). Understanding the spatial differences in terrestrial water storage variations in the Tibetan Plateau from 2002 to 2016, *Clim. Change*, 151(3–4), 379–393, doi:10.1007/s10584-018-2325-9.

Ding, Y., & Chan, J. (2005). The east Asian summer monsoon: an overview. *Meteorol. Atmos. Phys.*, 89(1):117–142.

Duan, A., & Wu, G. (2008). Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part I: observations. *J. Clim.*, 21, 3149–3164.

Duan, A., & Wu, G. (2009). Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part II: connection with climate warming. *J. Clim.*, 22, 4197–4212.

Duan, A., & Xiao, Z. (2015). Does the climate warming hiatus exist over the Tibetan Plateau?. *Sci. Rep.*, 5, 13711. https://doi.org/10.1038/srep13711.

Duan, A., Liu, S., Zhao, Y., Gao, K., & Hu, W. (2018). Atmospheric heat source / sink dataset over the Tibetan Plateau based on satellite and routine meteorological observations. *Big Earth Data*, 00(00), 1–11. https://doi.org/10.1080/20964471.2018.1514143

Feng, L., & Zhou, T. (2012). Water vapor transport for summer precipitation over the Tibetan Plateau: Multidata set analysis, *J. Geophys. Res.*, 117, D20114, doi:10.1029/2011JD017012.

Gao, L., Gou, X., Deng, Y., Wang, Z., Gu, F., Wang, F. (2018). Increased growth of Qinghai spruce in northwestern China during the recent warming hiatus. *Agricultural and Forest Meteorology*, 260–261, 9-16.

Guo, D., & Wang, H. (2012). The significant climate warming in the northern Tibetan Plateau and its possible causes. *Int. J. Climatol*. 32, 1775–1781, http://dx.doi.org/10.1002/ joc.2388.

Harris, I., Osborn, T.J., Jones, P., Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, 7, 109, https://doi.org/10.1038/s41597-020-0453-3

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P. (2010). Climate change will affect the Asian water towers. *Science*, 328, 1382–1385

Li, D., Yang, K., Tang, W., Li, X., Zhou, X., & Guo, D. (2020). Characterizing precipitation in high altitudes of the western Tibetan plateau with a focus on major glacier areas, Int. J. Climatol., (February), doi:10.1002/joc.6509.

Li, W., Guo, W., Qiu, B., Xue, Y., Hsu, P. C., & Wei, J. (2018). Influence of Tibetan Plateau snow cover on East Asian atmospheric circulation at medium-range time scales. *Nat. Commun.*, 9(1), doi:10.1038/s41467-018-06762-5.

Li, W., Qiu, B., Guo, W., Zhu, Z., & Hsu, P. C. (2019). Intraseasonal variability of Tibetan Plateau snow cover, Int. J. Climatol., (November), doi:10.1002/joc.6407.

Lin, C., Yang, K., Qin, J., & Fu, R. (2013). Observed Coherent Trends of Surface and Upper-Air Wind Speed over China since 1960. *J. Climate*, 26, 2891–2903, https://doi.org/10.1175/JCLI-D-12-00093.1.

Liu, Y., Zhu, Q., Huang, J., Hua, S., & Jia, R. (2019). Impact of dust-polluted convective clouds over the Tibetan Plateau on downstream precipitation. *Atmos. Environ.*, 209, 67-77. doi: 10.1016/j.atmosenv.2019.04.001.

Liu, X., & Chen, B. (2000). Climatic warming in the Tibetan Plateau during recent decades. *Int. J. Climatol.*, 20, 1729–1742.

Lu, C., Yu, G., & Xie, G. (2005). Tibetan Plateau serves as a water tower. *IEEE Trans. Geosci. Remote Sens.*, 5, 3120– 3123.

Luo,X., & Xu, J. (2019). Estimate of atmospheric heat source over Tibetan Plateau and its uncertainties. *Climate Change Research*, 15(1): 33-40.(in Chinese)

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., & Bierkens, M. F. P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation, *Nat. Clim. Chang.*, 4(7), 587–592, doi:10.1038/nclimate2237.

Ma, Y., Ma, W., Zhong, L., Hu, Z., Li, M., Zhu, Z., Han, C., Wang, B., & Liu, X. (2017). Monitoring and Modeling the Tibetan Plateau's climate system and its impact on East Asia, Sci. Rep., 7, 1–6, doi:10.1038/srep44574.

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J., & Finkelnburg, R. (2014). Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis. *J. Climate*, 27, 1910–1927, doi:10.1175/JCLI-D-13-00282.1.

Molnar, P., England, P., & Martinod, J. (1993). Mantle dynamics, uplift of the Tibetan Plateau, and the Indian Monsoon, *Rev. Geophys.*, 31(4), 357-396, doi:10.1029/93RG02030.

Moore, G.W.K. (2012). Surface pressure record of Tibetan Plateau warming since the 1870s. *Q. J. R. Meteorol. Soc.*, 138, 1999–2008.

Sugimoto, S., Ueno, K., Sha, W. (2008). Transportation of Water Vapor into the Tibetan Plateau in the Case of a Passing Synoptic-Scale Trough. *Journal of the Meteorological Society of Japan*, 86(6):935-949.

Tian, H., Tian, W., Luo, J., Zhang, J., & Zhang, M. (2017). Climatology of cross-tropopause mass exchange over the Tibetan Plateau and its surroundings. *Int. J. Climatol.*, 37: 3999-4014, doi:10.1002/joc.4970

Ueno, K., Toyotsu, K., Bertolani, L., & Tartari, G. (2008). Stepwise onset of monsoon weather observed in the Nepal Himalayas. *Mon. Weather Rev.*, 136, 2507– 2522.

Wan, W., Long, D., Hong, Y., Ma, Y., Yuan, Y., Xiao, P., et al. (2016). A lake data set for the Tibetan Plateau from the 1960s, 2005, and 2014. *Sci. Data*, 3:160039 doi: 10.1038/sdata.2016.39

Wan, B., Gao, Z., Chen, F., & Lu, C. (2017). Impact of Tibetan Plateau Surface Heating on Persistent Extreme Precipitation Events in Southeastern China. *Monthly Weather Review*, 145, 3485–3505.

Wang, Y., Xu, X., Lupo, A. R., Li, P., & Yin, Z. (2011). The remote effect of the Tibetan Plateau on downstream flow in early summer. *J. Geophys. Res.*,116, D19108, doi:10.1029/2011JD015979.

Wang, Y., Yang, K., Pan, Z., Qin, J., Chen, D., Lin, C., et al. (2017). Evaluation of precipitable water vapor from four satellite products and four reanalysis datasets against GPS measurements on the Southern Tibetan Plateau. *J. Clim.*, 30(15), 5699–5713, doi:10.1175/JCLI-D-16-0630.1.

Wu, G., Liu, Y., He, B., Bao, Q., Duan, A., Jin, F. F. (2012a). Thermal controls on the Asian summer monsoon. *Sci. Rep.*, 2, 4, https://doi.org/10.1038/ srep00404.

Wu, G. X., Liu, Y. M., Dong, B. W., Liang, X. Y., Duan, A. M., Bao, Q., & Yu, J. J. (2012b). Revisiting Asian Monsoon Formation and Change Associated with Tibetan Plateau Forcing: I. Formation. *Clim. Dyn.*, 39(5), 1169-1181, doi:10.1007/s00382-012-1334-z.

Wu, G. X., Liu, Y. M., Wang, T. M., Wan, R. J., Liu, X., Li, W. P., et al. (2007). The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate, *J. Hydro. Meteor. Spec. Sect.*, 8, 770-789, doi:10.1175/JHM609.1.

Wu, G. X., & Zhang, Y. S. (1998). Tibetan Plateau Forcing and the Timing of the Monsoon Onset over South Asia and the South China Sea. *Monthly Weather Review*, 126(4):913-927.

Xu, X., Zhou, M., Chen, J., Bian, L., Zhang, G., Liu, H., et al. (2002). A comprehensive physical pattern of land-air dynamic and thermal structure on the Qinghai-Xizang Plateau, *Science in China Series D: Earth Sciences*, 45(7), 18–24.

Xu, X., Lu, C., Shi, X., & Gao, S. (2008a). World water tower: An atmospheric perspective. *Geophys. Res. Lett.*, 35(20), 525-530, doi:10.1029/2008GL035867.

Xu, X. D., Shi, X. Y., Wang, Y. Q., Peng, S. Q., & Shi, X. H. (2008b). Data analysis and numerical simulation of moisture source and transport associated with summer precipitation in the Yangtze River Valley over China. *Meteorol. Atmos. Phys.*, 100, 217-231, doi:10.1007/s00703-008-0305-8.

Xu, Y., & Gao, Y. (2019). Quantification of evaporative sources of precipitation and its changes in the Southeastern Tibetan Plateau and Middle Yangtze River Basin. *Atmosphere*, 10(8). https://doi.org/10.3390/atmos10080428.

Yang, K., Guo, X., & Wu, B. (2011a). Recent trends in surface sensible heat flux on the Tibetan Plateau. *Science in China Series D: Earth Sciences*, 54, 19–28.

Yang, K., Guo, X., He, J., Qin, J., & Koike, T. (2011b). On the climatology and trend of the atmo- spheric heat source over the Tibetan Plateau: an experiments-supported revisit. *J. Clim.*, 24, 1525–1541.

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Glob. Planet. Change*, 112, 79–91, doi:10.1016/j.gloplacha.2013.12.001.

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. *Nat. Clim. Change*, 2: 663–667.

Yao, T. (2019). Tackling on environmental changes in Tibetan Plateau with focus on water, ecosystem and adaptation. *Science Bulletin*, 64: 417

Yin, Y., Wu, S., Zhao, D., Zheng, D., & Pan, T. (2013). Modeled effects of climate change on actual evapotranspiration in different eco-geographical regions in the Tibetan Plateau. *J. Geogr. Sci.*, 23, 195–207.

Zhang, D., Huang, J., Guan, X., Chen, B., & Zhang, L. (2013). Long-term trends of precipitable water and precipitation over the Tibetan Plateau derived from satellite and surface measurements. *Journal of Quantitative Spectroscopy & Radiative Transfer*, 122:64-71.

Zhang, Y., Liu, C., Tang, Y., & Yang, Y. (2007). Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan Plateau, *J. Geophys. Res. Atmos.*, 112(12), 1–12, doi:10.1029/2006JD008161.

Zhang, C., Liu, F., & Shen, Y. (2018), Attribution analysis of changing pan evaporation in the Qinghai–Tibetan Plateau, China. *Int. J. Climatol*, 38, e1032-e1043, doi:10.1002/joc.5431

Zhao, Y., & Zhou, T. (2019). Asian water tower evinced in total column water vapor: a comparison among multiple satellite and reanalysis data sets. *Clim. Dyn.*, 54, 231-245, doi:10.1007/s00382-019-04999-4.

Zhou, C., Zhao, P., & Chen, J. (2019). The interdecadal change of summer water vapor over the Tibetan Plateau and associated mechanisms. *J. Clim.*, 32, 4103–4119, doi:10.1175/JCLI-D-18-0364.1.

Zhu, Y.X., Ding, Y.H., & Xu, H.G. (2008). Decadal relationship between atmospheric heat source of winter and spring snow over Tibetan Plateau and rainfall in East China. *Journal of Meteorological Research*, 65, 946–958.

Zhu, L., Xie, M., & Wu, Y. (2010). Quantitative analysis of lake area variations and the influence factors from 1971 to 2004 in the Nam Co basin of the Tibetan Plateau. *Chinese Science Bulletin*, 55, 1294–1303.