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# Investigating basin-scale water budget dynamics in 18 rivers across Tibetan Plateau through multiple datasets

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**Abstract** The dynamics of basin-scale water budgets are not well understood nowadays over the Tibetan Plateau (TP) due to the lack of hydro-climatic observations. In this study, we investigate seasonal cycles and trends of water budget components (e.g., precipitation-P, evapotranspiration-ET and runoff-Q) in eighteen TP river basins during the period 1982-2011 through the use of multi-source datasets (e.g., in situ observations, satellite retrievals, reanalysis outputs and land surface model simulations). A water balance-based two-step procedure, which considers the changes in basin-scale water storage at the annual scale, is also adopted to calculate actual ET. The results indicated that precipitation (mainly snowfall from mid-autumn to next spring), which mainly concentrated during June-October (varied among different monsoons-impacted basins), was the major contributor to the runoff in TP basins. Increased P, ET and Q were found in most TP basins during the past 30 years except for the upper Yellow River basin and some sub-basins of Yalong River, which were mainly affected by the weakening East Asian Monsoon. Moreover, the aridity index (PET/P) and runoff coefficient (Q/P) decreased in most basins, which were in agreement with the warming and moistening climate in the Tibetan Plateau. The results obtained demonstrated the usefulness of integrating multi-source datasets to hydrological applications in the data-sparse regions. More generally, such approach might offer helpful insights towards understanding the water and energy budgets and sustainability of water resource management practices of data-sparse regions in a changing environment.

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# 1 Introduction

As the highest plateau in the globe (the average elevation is higher than 4000 meters above the sea level), the Tibetan Plateau (TP, also called "the roof of the world" or "the third Pole") is regarded as one of the most vulnerable regions under a warming climate and is exposed to strong interactions among atmosphere, hydrosphere, biosphere and cryosphere in the earth system (Duan and Wu, 2006; Yao et al., 2012; Liu et al., 2016b). It also serves as the "Asian water tower" from which some major Asian rivers such as Yellow River, Yangtze River, Brahmaputra River, Mekong River, Indus River, etc., originate, which is a vital water resource to support the livehood of hundreds of millions of people in China and the neighboring Asian countries (Immerzeel et al., 2010; Zhang et al., 2013). Hence sound knowledge of water budget and hydrological regimes in TP river basins and its response to the changing environment would have practical relevance for achieving sustainable water resource management and environmental protection in this part of the world (Yang et al., 2014; Chen et al., 2015).

Despite the importance of TP in this geographic region, advance in hydrological and land surfaces studies in this region has been limited by data scarcity (Zhang et al., 2007; Li F. et al., 2013; Liu X. et al., 2016). For instance, less than 80 observation stations (~10% of a total of ~750 observation station across China) have been established in TP by the Chinese Meteorological Administration (CMA) since the mid-20$^{th}$ century (Wang and Zeng, 2012). These stations are generally sparse and unevenly distributed at relatively low elevation regions, focus only on the meteorological variables and lack of other land surface observations such as evapotranspiration, snow water equivalent and latent heat fluxes. In addition, long-term observations of river discharge, snow depth, lake depth and glacier melts in the TP are also absent (Akhta et al., 2009; Ma et al., 2016). Therefore, the water budget and hydrological regimes for each river basin of TP and their relation with atmospheric circulations are poorly understood (Cuo et al., 2014; Xu et al., 2016). Whilst this shortcoming could be resolved through installation of in-situ monitoring systems (Yang et al., 2013; Zhou et al., 2013; Ma et al., 2015), the overall cost of running the operational sites would be substantial. Another workaround would be through modeling approach, i.e., feeding remote sensing information and meteorological forcing data into physically-based land surface model (LSM) to simulate the basin-wide water budget (Bookhagen and Burbank, 2010; Xue et al., 2013; Zhang et al., 2013; Cuo et al., 2015; Zhou et al., 2015; Wang et al., 2016). However, such approach is not immune from the issue of data scarcity at multiple river basins (with varied sizes and/or terrain complexities) for supporting model calibration and validation purposes (Li F. et al., 2014).

Most recently, several global (or regional) datasets relevant to the calculation of water budget have been released. They include remote sensing-based retrievals (Tapley et al., 2004; Zhang et al., 2010; Long et al., 2014; Zhang Y. et al., 2016), land surface model (LSM) simulations (Rui, 2011), reanalysis outputs (Berrisford et al., 2011; Kobayashi et al., 2015) and gridded forcing data interpolated from the in situ observations (Harris et al., 2014). For example, there are many products related to terrestrial evapotranspiration (ET) such as GLEAM_E (Global Land surface Evaporation: the Amsterdam Methodology, Miralles et al., 2011a), MTE_E (a product integrated the point-wise ET observation at FLUXNET sites with geospatial information extracted from surface meteorological observations and remote sensing in a machine-leaning algorithm, Jung et al., 2010 ), LSM-simulated ETs from Global Land Data Assimilation System version 2 (GLDAS-2) with different land surface schemes (Rodell et al., 2004), ETs from Japanese 55-year reanalysis (JRA55_E), the ERA-Interim global atmospheric reanalysis dataset (ERAI_E) and the National Aeronautic and Space Administration (NASA) Modern Era Retrosphective-analysis for Research and Application (MERRA) reanalysis data (Lucchesi, 2012). Moreover, there are also several global or regional LSM-based runoff simulations from GLDAS and the Variable Infiltration Capacity (VIC) model (Zhang et al., 2014). A few attempts have been made to validate multiple datasets for certain water budget components and to explore their possible hydrological implications. For example, Li X. et al. (2014) and Liu et al. (2016a) evaluated multiple ET estimates against the water balance method at annual and monthly time scales. Bai et al. (2016) assessed streamflow simulations of GLDAS LSMs in five major rivers over the TP based on the discharge observations. Although uncertainties might exist among different datasets with various spatial and temporal resolutions and calculated using different algorithms (Xia et al., 2012), they offer an opportunity to examine the general basin-wide water budgets and their uncertainties in gauge-sparse regions such as the TP considered in this study.

From the multiple datasets perspective, this study aims to investigate the water budget in 18 TP river basins distributed across the Tibetan Plateau; and evaluate seasonal cycles and annual trends of these water budget components. This paper is organized as follows: the datasets and methods applied in this study are described in Sect.2. The results of season cycles and annual trends of water budget components for the river basins are presented and discussed in Sect.3. The uncertainties arise from employing

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multiple datasets are also discussed in the same section. In Sect.4, we generalize our findings which would be helpful for understanding the water balances of the river basins under constant influence of interplay between westerlies and monsoons (e.g., Indian monsoon, East Asian monsoon) in the Tibetan Plateau.

## 2 Data and methods

### 2.1 Multiple datasets used

#### 2.1.1 Runoff, precipitation and terrestrial storage change

We obtained the observed daily runoff (Q) during the period 1982-2011 from the National Hydrology Almanac of China (Table 1). There are < 30% missing data in some gauging stations such as Yajiang, Tongren, Gandatan and Zelingou. Therefore, the VIC Retrospective Land Surface Dataset over China (1952~2012, VIC_IGSNRR simulated) with a spatial resolution of 0.25 degree and a daily temporal resolution from the Geographic Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences, is also used. This dataset is derived from the VIC model forced by the gridded daily observed meteorological forcing (IGSNRR_forcing) (Zhang et al., 2014). A degree-day scheme was used in the model to account for the influences of snow and glacier on hydrological processes.

In terms of precipitation (P), we used the gridded monthly precipitation dataset available at CMA (spatial resolution of 0.5 degree; 1961-2011; interpolated from observations of 2372 national meteorological stations using the Thin Plate Spline method) (Table 1). Since the reliability of this dataset might be restricted by the relatively sparse stations and complex terrain conditions of TP, we make an attempt to incorporate two other precipitation datasets ((IGSNRR_forcing and Tropical Rainfall

Measuring Mission TRMM 3B43 V7). The precipitation from IGSNRR forcing datasets (0.25 degree) was derived by interpolating gauged daily precipitation from 756 CMA stations based on the synergraphic mapping system algorithm (Shepard, 1984; Zhang et al., 2014) and was further bias-corrected using the CMA gridded precipitation.

To get the change in terrestrial storage ($\Delta S$), we used three latest global terrestrial water storage anomaly and water storage change datasets (available on the GRACE Tellus website: http://grace.jpl.nasa.gov/) that were retrieved from the Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004; Landerer and Swenson, 2012; Long et al., 2014). Briefly, they were processed separately at the Jet Propulsion Laboratory (JPL), the GeoForschungsZentrum (GFZ) and the Center for Space Research at the University of Texas (CSR). To minimize the errors and uncertainty of extracted $\Delta S$, we averaged these GRACE retrievals (2002-2013) from different processing centers in this study.

**2.1.2 Temperature, potential evaporation and ET**

We obtained the monthly gridded temperature dataset (0.5 degree) from CMA; and potential evaporation (PET) dataset (0.5 degree, Harris et al., 2013) from Climatic Research Unit (CRU), University of East Anglia. Moreover, we used six global /regional ET products (four diagnostic products and two LSMs simulations, Table 2), namely (1) GLEAM_E (Miralles et al., 2010, 2011), which consists of three sources of ET (transpiration, soil evaporation and interception) for bare soil, short vegetation and vegetation with a tall canopy calculated using a set of algorithm (www.gleam.eu),

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(2) GNoah_E simulated using GLDAS-2 with the Catchment Noah scheme (http://disc.sci.gsfc.nasa.gove/hydrology/data-holdings) (Rodell et al., 2004), (3) Zhang_E (Zhang et al., 2010), which is estimated using the modified Penman-Monteith equation forced with MODIS data, satellite-based vegetation parameters and meteorological observations (http://www.ntsg.umt.edu/project/et), (4) MET_E (Jung et al., 2010) (https://www.bgc-jena.mpg.de/geodb/projects/Home.phs), (5) VIC_E (Zhang et al., 2014) from VIC_IGSNRR simulations (http://hydro.igsnrr.ac.cn/public/vic_outputs.html) and (6) PML_E (Zhang Y. et al., 2016) computed from global observation-driven Penman-Monteith-Leuning (PML) model (https://data.csiro.au/dap/landingpage?pid=csiro:17375&v=2&d=true).

**2.1.3 Vegetation and snow/glacier parameters**

To quantify the dynamics of vegetation of each river basin, we applied the Normalized Difference Vegetation Index (NDVI) and the Leaf Area Index (LAI) (Table 1). Briefly, the NDVI data was obtained from the Global Inventory Modeling and Mapping Studies (GIMMS) (Turker et al., 2005) (https://nex.nasa.gov/nex/projects/1349/wiki/general_data_description_and_access/) while the LAI data was collected from the Global Land Surface Satellite (GLASS) products (http://www.glcf.umd.edu/data/lai/) (Liang and Xiao, 2012). Whist the change in seasonal snow cover and glacier has significant impact on the water and energy budgets in TP river basins; it remains a technical challenge to get reliable observations due to harsh environment (especially at the basin scale). However, recently available satellite-based/LSM-simulated products might provide adequate characterization of the variation of snow cover and glacier. To quantify the change in snow cover at each basin, we applied the daily cloud free snow composite product from MODIS Terra-Aqua and the Interactive Multisensor Snow and Ice Mapping System for the Tibetan Plateau (Zhang et al., 2012; Yu et al., 2015), in conjunction with the snow water equivalent (SWE) retrieved from Global Snow Monitoring for Climate Research product (GlobSnow-2, http://www.globsnow.info/) and the VIC_IGSNRR simulations (Takala et al., 2011; Zhang et al., 2014). We extracted general distribution of glacier of TP from the Second Glacier Inventory Dataset of China (Guo et al., 2014). All gridded datasets used were first uniformly interpolated to a spatial resolution of 0.5 degree based on the bilinear interpolation to make their inter-comparison possible. The datasets were then extracted for each of TP basins.

#### 2.1.4 Monsoon indices

In general, the TP climate is under the influences of the westerlies, Indian summer monsoon and East Asian summer monsoon (Yao et al., 2012). To investigate the changes of monsoon systems and their potential impacts on water budgets in the TP basins, we used three monsoon indices, namely Asian Zonal Circulation Index (AZCI), Indian Ocean Dipole Mode Index (IODMI) and East Asian Summer Monsoon Index (EASMI). Briefly, the IODMI (reflects the dynamics of Indian Summer Monsoon) is an indicator of the east-west temperature gradient across the tropical Indian Ocean (Saji et al., 1999), which can be downloaded from the following website: http://www.jamstec.go.jp/frcgc/research/d1/iod/HTML/Dipole%20Mode%20Index.html. The EASMI and AZCI ($60^o$-$150^o$E) reflect the dynamics of East Asian summer monsoon (Li and Zeng, 2002) and the westerlies (represented by Asian Zonal Circulation index), which can be obtained from Beijing Normal University (http://ljp.gcess.cn/dct/page/65577) and the National Climate Center of China (http://ncc.cma.gov.cn/Website/index.php?ChannelID=43WCHID=5), respectively.

### 2.1.5 Study basins

In this study, we selected 18 river basins of varied sizes (range: 2832-191235 km$^2$; see Table 1 for details) with adequate runoff data over a 30-year period (1982-2011). They are distributed in the northwestern, southeastern and eastern parts of the plateau with multiyear-mean and basin-averaged temperature and precipitation ranging from -5.68 to 0.97 $^{o}$C and 128 to 717 mm, which are solely dominated or under the combined influences of the westerlies, the Indian Summer monsoon and the East Asian monsoon (Yao et al., 2012). There are more glacier and snow covers in the westerlies-dominant basins such as Yerqiang, Yulongkashi and Keliya (10.86~23.27% and 29.16~35.95%, respectively); less for the East Asian monsoon-dominated basins such as Yellow, Yangtze and Bayin (0~0.96% and 9.42~20.05%, respectively) (Table 2).

## 2.2 Methods

### 2.2.1 Water balance-based ET estimation

The basin-wide water balance at the monthly and annual timescales could be written as the principle of mass conservation (also known as the continuity equation, Oliveira et al., 2014) of basin-wide precipitation (P, mm), evapotranspiration ($ET_{wb}$, mm), runoff (Q, mm) as well as terrestrial water storage change (ΔS, mm),

$$ET_{wb} = P - Q - \Delta S \quad (1)$$

The terrestrial water storage (ΔS) in Eq. (1) includes the surface, subsurface and ground water changes. It has been demonstrated cannot be neglected in water balance calculation over monthly and annual timescales due to snow cover change and anthropogenic interferences (e.g., reservoir operation, agricultural water withdrawal) (Liu et al., 2016a). For the period 2002-2011, we calculated basin-wide ET ($ET_{wb}$) directly using the GRACE-derived $\Delta S$ in Eq. (1). Since GRACE data is absent before 2002, we calculated the monthly $ET_{wb}$ using the following two-step bias-correction procedure (Li X. et al., 2014). We defined $P-Q$ in Eq. (1) as biased ET ($ET_{biased}$, available from 1982 to 2011) relative to the "true" ET ($ET_{wb} = P-Q-\Delta S$, available during the period 2002-2011 when the GRACE data is available). Over the period 2002-2011, we first fitted $ET_{biased}$ and $ET_{wb}$ series separately using different gamma distributions, which has been evidenced as an proper method for modeling the probability distribution of ET (Bouraoui et al., 1999). The monthly $ET_{biased}$ series (2002-2011) can then be bias-corrected through the inverse function ($F^{-1}$) of the gamma cumulative distribution function (CDF, F) of $ET_{wb}$ by matching the cumulative probabilities between two CDFs as follow (Liu et al., 2016a),

$$ET_{corrrected}(m) = F^{-1}(F(ET_{biased}(m)|\alpha_{biased}, \beta_{biased})|\alpha_{wb}, \beta_{wb}) \quad (2)$$

Here $\alpha_{biased}, \beta_{biased}$ and $\alpha_{wb}$, $\beta_{wb}$ are shape and scale parameters of gamma distributions for $ET_{biased}$ and $ET_{wb}$. $ET_{corrected}(m)$ and $ET_{biased}(m)$ represent the monthly corrected and biased ET, respectively. The bias correction procedure can be flexibly applied to the period 1983-2011 by matching the CDF of $ET_{biased}$ (1983-2011) to that of $ET_{corrected}$ (2002-2011). The second step of bias correction is to eliminate the annual bias through the ratio of annual $ET_{biased}$ to annual $ET_{corrected}$ calculated in the first step using the following method,

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$$ET_{final}(m) = \frac{ET_{biased}(a)}{ET_{corrected}(a)} \times ET_{corrected}(m) \qquad (3)$$

where $ET_{final}(m)$ is the final monthly ET after bias correction. $ET_{biased}(a)$ and $ET_{corrected}(a)$ represent the annual biased and corrected ET while $ET_{corrected}(m)$ is the monthly corrected ET obtained from the first step. The procedure was then applied to correct the monthly $ET_{biased}$ series and calculated the monthly $ET_{corrected}$ during the period 1982-2001 for all TP basins. We take these results as sufficient representation of the "true" ET ($ET_{wb}$) for evaluating multiple ET products and trend analysis. "

### 2.2.2 Modified Mann-Kendall test method

The Mann-Kendall (MK) test is a rank-based nonparametric approach which is less sensitive to outlier relative to other parametric statistics, but it is sometimes influenced by the serial correlation of time series. Pre-whitening is often used to eliminate the influence of lag-1 autocorrelation before the use of MK test. For example, $X\ (X_1, X_2, \ldots, X_n)$ is a time series data, it will be replaced by $(X_2 - cX_1, X_3 - cX_2, \ldots, X_{n+1} - cX_n)$ in pre-whitening if the lag-1 autocorrelation coefficient (c) is larger than 0.1 (von Storch, 1995). However, significant lag-i autocorrelation may still be detected after pre-whitening because only the lag-1 autocorrelation is considered in pre-whitening (Zhang et al., 2013). Moreover, it sometimes underestimate the trend for a given time series (Yue et al., 2002). Hamed and Rao (1998) proposed a modified version of MK test (MMK) to consider the lag-i autocorrelation and related robustness of the autocorrelation through the use of equivalent sample size, which has been widely used in previous studies during the last five decades (McVicar et al., 2012; Zhang et al., 2013; Liu and Sun, 2016). In the MMK approach, if the lag-i autocorrelation coefficients are significantly distinct from

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zero, the original variance of MK statistics will be replaced by the modified one. In this study, we used the MMK approach to quantify the trends of water budget components in18 TP basins and the significance of trend was tested at the >95% confidence level.

### 2.2.3 Uncertainty analysis

The uncertainty associated multi-source dataset used (no observation or the observations are not adequate at the basin scale) for quantifying the dynamics of certain water budget components (i.e., ET and precipitation) are also analyzed. We investigate the seasonal cycles and trends of these components by using different datasets together in the analysis to show the potential uncertainties in this study.

## 3 Results and Discussion

### 3.1 ET evaluation and General hydrological characteristics of 18 TP basins

We first assessed the VIC_IGSNRR simulated runoff against the observations for each basin (for example, at Tangnaihai and Pangduo stations in Fig.2). If the Nash Efficiency coefficient (NSE) between the observation and simulation is above 0.65, the VIC_IGSNRR simulated runoff is acceptable and could be used to replace the missing runoff values for a given basin. Moreover, the CMA precipitation is consistent with TRMM (Corr = 0.86, RMSE = 8.34 mm/month) and IGSNRR forcing (Corr = 0.94, RMSE = 7.15mm/month) precipitation for multiple basins (i.e., for the smallest basin above Tongren station, Fig.2). Moreover, the magnitudes of GRACE-derived annual mean water storage change ($\Delta S$) in 18 TP basins are relatively less than those for other water balance components such as annual P, Q and ET (Table 3). The uncertainties among GRACE-derived annual mean $\Delta S$ from different data processing centers (CSR, GFZ and JPL) are small for 18 basins except for the basins controlled by Gadatan and Tangnaihai stations.

We then evaluated six ET products in 18 TP basins against our calculated $ET_{wb}$ at a monthly basis during the period 1983-2006 (Fig. 3). The ranges of monthly averaged ET among different basins (approximately 4−39 mm month$^{-1}$) are very close for all products compare to that calculated from the $ET_{wb}$(6−42 mm month$^{-1}$). However, GLEAM_E (correlation coefficient: Corr = 0.85 and root-mean-square-error: RMSE = 5.69 mm month$^{-1}$) and VIC_E (Corr = 0.82 and RMSE = 6.16 mm month$^{-1}$) perform relatively better than others. Although Zhang_E and GNoah_E were found closely correlated to monthly $ET_{wb}$ in the upper Yellow River, the upper Yangtze River, Qiangtang and Qaidam basins (Li X. et al., 2014), they did not exhibit overall good performances (Corr = 0.61, RMSE = 7.97 mm month$^{-1}$ for Zhang_E and Corr = 0.42, RMSE = 10.16 mm month$^{-1}$ for GNoah_E) for 18 TP basin used in this study. We thus use GLEAM_E and VIC_E together with $ET_{wb}$ to anayize the seasonal cycles and trends of ET in 18 TP basins in the following sections.

To investigate the general hydroclimatic characteristics of river basins over the TP, we classify 18 basins into three categories, namely westerlies-dominated basins (Yerqiang, Yulongkashi and Kelia), Indian monsoon-dominated basins (Brahmaputra and Salween), and East Asian monsoon-dominated basins (Yellow, Yalong and Yangtze) referred to Tian et al. (2007), Yao et al. (2012) and Dong et al. (2016). Interestingly, they are clustered into three groups under Budyko framework (Budyko, 1974; Zhang D. et al., 2016) with relatively lower evaporative index in Indian

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monsoon-dominant basins and higher aridity index in westerlies-dominant basins, which reveal various long-term hydroclimatologic conditions (Fig. 4). Overall, the annual mean air temperature increases (-5.68 ~0.97 °C) while multiyear mean glacier area (and thus the glacier melt normalized by precipitation) decreases (23.27 ~ 0%) gradually from the westerlies-dominant, Indian monsoon-dominant to East Asian monsoon-dominant basins. The vegetation status (NDVI range: 0.05~0.43; LAI range: 0.03~0.83) tends to be better and ET increases (and thus runoff coefficient gradually decreases) from cold to warm basins (Fig. 4 and Table 1). The $R^2$ between basin-averaged NDVI and ET is 0.76 which shows a clear vegetation control on ET in 18 TP basins. The results are in line with Shen et al. (2015), which indicated that the spatial pattern of ET trend was significantly and positively correlated with NDVI trend over the TP. The dominant climate systems are overall discrepant for the three TP regions with different water-energy characteristics and sources of water vapor. The westerlies-controlled basins are relatively colder than the Indian monsoon-dominated basins, thus they develop more glaciers (and thus have more snow melt contributions to total river streamflow) and have relatively less vegetation (and thus limit vegetation transpiration). It is a general picture of hydrological regime in high-altitude and cold regions (Zhang et al., 2013; Cuo et al., 2014), which could be interpreted from the perspective of multi-source datasets in the data-sparse TP.

### 3.2 Seasonal cycles of basin-wide water budget components for the TP basins

The multi-year means of water budget components (i.e., P, Q, ET, snow cover and SWE) and vegetation parameters (i.e., NDVI and LAI) are calculated for each calendar month and for 18 TP river basins using multi-source datasets available from 1982 to 2011. Overall, the seasonal variations of P, Q, ET, air temperature and vegetation parameters are similar in all TP basins with peak values occurred in May to September (Fig.5 and Fig.6). The seasonal cycles of snow cover and SWE are generally consistent among the basins (the peak values mainly occur from October to next April, Fig.7). With the ascending air temperature from cold to warm months, the basin-wide precipitation increases and vegetation cover expands gradually (the basin-wide ET also increase). Meanwhile, snow cover and glaciers retreat gradually with the melt water supplying the river discharge together with precipitation. The inter-basin variations of hydrological regime are to a large extent linked to the climate systems that prevail over the TP.

Although the temporal patterns of hydrological components are generally analogous, they vary among the parameters, climate zones and even basins (Zhou et al., 2005). For example, relative to air temperature, the seasonal pattern of runoff is similar to precipitation which reveals that runoff is mainly controlled by precipitation in most TP basins. It is in agreement with that summarized by Cuo et al. (2014). In the westerlies-dominated basins, the peak values of precipitation and runoff mainly concentrate in June-August, which contribute approximately 68-82% and 67-78% of annual totals, respectively. During this period, the runoff always exceeds precipitation which indicates large contributions of glacier/snow-melt water to streamflow. It is consistent with the existing findings in Tarim River (Yerqiang, Yulongkashi and Keliya rivers are the major tributaries of Tarim River), which indicated that the melt water accounted for about half of the annual total streamflow (Fu et al., 2008). The ET (vegetation cover) in three westerlies-dominated basins are relatively less (scarcer) than that in other TP basins while the percentages of glacier and seasonal snow cover are higher in these basins which contribute more melt water to river discharge (Fig.6

and Fig.7). Overall, the SWE in Yerqiang, Yulongkashi and Keliya rivers are higher in winter than other seasons, but they vary with basins and products which reflect considerable uncertainties in SWE estimations.

In the Indian monsoon and East Asian monsoon dominated basins, the runoff concentrates during June-September (or June- October) with precipitation being the dominant contributor of annual total runoff. For example, the peak values of precipitation and runoff occur during June-September at Zhimenda station (contributing about 80% and 74% of the annual totals) while those occur during June-October at Tangnaihai station (contributing about 78% and 71% of the annual totals, respectively). The results are quite similar to the related studies in eastern and southern TP such as Liu (1999), Dong et al. (2007), Zhu et al. (2011), Zhang et al. (2013), Cuo et al. (2014). The vegetation cover (ET) in most basins is denser (higher) than that in the westerlies-dominant basins. Moreover, the seasonal snow mainly covers from mid-autumn to spring and correspondingly the SWE is relatively higher in these months in all basins except for Yellow River above Xining station, Salwee River above Jiayuqiao station and Brahmaputra River above Nuxia and Yangcun stations.

**3.3 Trends of basin-wide water budget components for the TP basins**

The Q, P and $ET_{wb}$ all ascended under regional warming during the past 30 years in the westerlies-dominated basins (Fig.8), except for P in the Yerqiang River basin (Kulukelangan station). The aridity index (PET/P), which is an indicator for the degree of dryness, slightly declined in all basins in northwestern TP. Although both P and PET were found increase in the Keliya River basin since the 1980s (Shi et al., 2003; Yao et al., 2014), the declined PET/P is, to some extent, attributed to the ascending P exceed the increase in PET. The climate moistening (Shi et al., 2003) in the headwaters of these inland rivers would be beneficial to the water resources and oasis agro-ecosystems in the middle and lower basins. The increase in streamflow was also found in most tributaries of the Tarim River (Sun et al., 2006; Fu et al., 2010; Mamat et al., 2010). Moreover, the westerlies, revealed by the Asian Zonal Circulation Index ($60^o$-$150^o$ E), slightly enhanced (linear trend: 0.21) over the period 1982-2011 (Fig.9). With the strengthening westerlies, more water vapor may be transported and fell as precipitation or snow in northwestern TP (e.g., the eastern Pamir region). Both SWE products (VIC_IGSNRR simulated and GlobaSnow-2 product) showed slightly increase across these basins with rising seasonal snow covers and glaciers (Yao et al., 2012). More precipitation was transformed into snow /glacier and the runoff coefficient (Q/P) exhibited decrease with precipitation obviously increased (Fig.8). In addition, the transpiration in these basins might decrease with vegetation degradation as revealed by the NDVI and LAI (Yin et al., 2016) but the atmospheric evaporative demand indicated by CRU PET increased (significantly increase in the Yulongkashi and Keliya rivers) during the period 1982-2011.

In the East Asian monsoon dominated basins, there are two types of change for basin-wide water budget components. For example, P and Q slightly decreased in the upper Yellow River (Tangnihai, Huangheyan and Jimai stations) and Yalong River (Yajiang station) but increased in other basins (Zelingou, Gandatan, Xining, Tongren and Zhimenda stations) over the period of 1982-2011 (Fig.10). The declind Q and P in

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the upper Yellow and Yalong Rivers (locates at the eastern Tibetan Plateau) were consistent with that found by Cuo et al. (2013, 2014) and Yang et al. (2014), and were in line with the weakening East Asian Summer Monsoon (linear slope: -0.01) (Fig.9). The vegetation turned green while $ET_{wb}$ and PET increased in all East Asian monsoon dominated basins (except for $ET_{wb}$ in the basins above Tongren and Yajing stations) with the significantly ascending air temperature during the period 1982-2011. The aridity index (PET/P) decreased in all basins except for the upper Yellow River basin above Jimai station and the upper Yalong River basin above Yajiang station. Moreover, both the runoff coefficients and SWE decreased except for the Bayin River above Zelingou station and the upper Yellow River above Tongren station in the East Asian monsoon dominated basins.

The P, $ET_{wb}$ and Q also increased in the Indian monsoon-dominated basins (except for $ET_{wb}$ in the basin above Yangcun station) such as Salween River and Brahmaputra River (Fig.11), which are in line with the strengthening (linear trend: 0.01) of the Indian summer monsoon (revealed by the Indian Ocean Dipole Mode Index) during the specific period 1982-2011 (Fig.9). For example, at Jiayuqiao station, the annual streamflow showed a slightly increasing trend which was consistent with that examined by Yao et al. (2012) during the period 1980-2000. The vegetation status, revealed by NDVI and LAI, turned better asscoiated with the ascending air temperature. The aridity index (PET/P) decreased in all basins except for the Brahmaputra River above Tangjia station, which indicated that most basins in the Indian monsoon-dominated regions turned wet over the period of 1982-2011. The runoff coefficient (Q/P) increased at Gongbujiangda and Nuxia while decreased at Jiayuqiao, Pangduo, Tangji and Yangcun stations. Moreover, the basin-wide SWE declined in the upper Salween River and Brahmaputra River above Pangduo, Tangjia and Gongbujiangda stations while increased in Brahmaputra River above Nuxia and Yangcun stations.

### 3.4 Uncertainties

The results may unavoidably associate with some uncertainties inherited from the multi-source datasets used. The primary sources of uncertainty may arise from the precipitation inputs. We compared the seasonal cycles and annual trends in different precipitation products, i.e. CMA_ P, IGSNRR_P and TRMM_P (and their calculated $ET_{wb}$ from the water balance) during the period 2000-2011 (Fig. 12 and Fig. 13). We found there are some uncertainties among different precipitation products and thus among their estimated $ET_{wb}$, especially in the westerlies-dominated basins. However, for each basin, the seasonal cycles of precipitation (and their calculated $ET_{wb}$) calculated from different products are overall similar (especially for the observation-based products, CMA_P and IGSNNR_P). The signs of trend for annual CMA_P and IGSNRR_P (and their calculated $ET_{wb}$) are consistent in most river basins (i.e., 14 out 18 basins for two precipitation products and 17 out 18 basins for their calculated $ET_{wb}$) during the period 1982-2011. The consistency of trends between two precipitation products, to some extent, revealed that the trends in CMA_P were not obviously influenced by the changing density of rain gauges in TP basins. Although some uncertainties exist due to limited and unevenly distributed meteorological stations used in the plateau and the influences of complex terrain, CMA_P is still the best observation-based precipitation product nowadays in China which could be applied to hydrological studies in the TP.

Although the seasonal cycles of $ET_{wb}$ could be captured by GLEAM_E and VIC_E, they still have considerable uncertainties at some stations (e.g., Numaitilangan, Gongbujiangda and Nuxia) (Fig.5). Compared to the annual trend of $ET_{wb}$ (Table 4), most ET products (including the well-performed GLEAM_E and VIC_E) could not detect the decreasing trends in 7 out of 18 basins (Kulukelangan, Tongguziluoke, Xining, Tongren, Jimai, Nuxia and Gongbujiangda) due to their different forcing data, algorithm used as well as varied spatial-temporal resolutions (Xue et al., 2013; Li et al., 2014; Liu et al., 2016a). In particular, it is well known that land surface models have some difficulties (e.g., parameter tuning in boundary layer schemes) when applying to the TP, even though they sometimes have good performances in different regions/basins (Xia et al., 2012; Bai et al., 2016). For example, Xue et al. (2013) indicated that GNoah_E underestimated the $ET_{wb}$ in the upper Yellow River and Yangtze River basins on the Tibetan Plateau mainly due to its negative-biased precipitation forcing. We thus only used $ET_{wb}$ in the trend detection of water budget components in Fig.8, Fig.10 and Fig.11 in this study. The two SWE products also showed large uncertainty with respect to both their seasonal cycles and trends. The VIC_IGSNRR simulated and GlobaSnow-2 SWEs have not been validated in the TP due to the lack of snow water equivalent observations, but in some basins (e.g., Zelingou and Numaitilangan) they showed similar seasonal cycles and annual trends.

The interpolation of missing values of runoff with VIC_IGSNRR simulated runoff and the gridded precipitation data (which interpolated from limited gauged precipitation over the plateau) also introduced uncertainties. There are also considerable uncertainties arising from empirical extending the ET series back prior to the GRACE era. However, the trends in $\mathrm{ET_{wb}}$ have not significantly affected by erroneous trends in the precipitation inputs to the bias-correction based water balance calculation. For example, the trends in CMA_P and IGSNRR_P are opposite in few basins (No. 01, 07, 08, 13 in Fig. 13), but the trends in their calculated $\mathrm{ET_{wb}}$ are both consistent for each basin. It is, to some extent, certified the effectiveness of the bias correction-based ET-estimate approach. With these caveats, we can interpret the general hydrological regimes and their responses to the changing climate in the TP basins from solely the perspective of multi-source datasets, which are comparable to the existing studies based on the in situ observations and complex hydrological modeling.

## 4 Summary

In this study, we investigated the seasonal cycles and trends of water budget components in 18 TP basins during the period 1982-2011, which is not well understood so far due to the lack of adequate observations in the harsh environment, through integrating the multi-source global/regional datasets such as gauge data, satellite remote sensing and land surface model simulations. By using a two-step bias correction procedure, we calculated the annual basin-wide $\mathrm{ET_{wb}}$ through the water balance approach considering the impacts of glacier and water storage change. We found that the GLEAM_E and VIC_E perform better relative to other products against the calculated $\mathrm{ET_{wb}}$.

From the Budyko framework perspective, the general water and energy budgets are different in the westerlies-dominated (with higher aridity index, runoff coefficient and glacier cover), the Indian monsoon-dominated and the East Asian monsoon-dominated (with higher air temperature, vegetation cover and evapotranspiration) basins. In the 18 TP basins, precipitation is the major contributor to the river runoff, which concentrates mainly during June-October (June-August for the westerlies-dominated basins, June-September or June to October for the Indian monsoon-dominated and the East Asian monsoon-dominated basins). The basin-wide SWE is relatively high from mid-autumn to spring for all 18 TP basins except for Keliya River and Brahmaputra River above the Nuxia and Yangcun stations. The vegetation cover is relatively less whereas snow/glacier cover is more in the westerlies-dominant basins compared to other basins. During the period 1982-2011, we found that the P, Q and $ET_{wb}$ increased across most of the basins in Tibetan Plateau; receded at some tributaries located at the upper Yellow River and Yalong River due to the weakening East Asian monsoon. The aridity index (PET/P) exhibited decrease in most TP basins which corresponded to the warming and moistening climate in the TP and western China. Moreover, the runoff coefficient (Q/P) declined in most basins which may be, to some extent, due to ET increase induced by vegetation greening and the influences of snow and glacier changes. Although there are considerable uncertainties inherited from multi-source data used, the general hydrological regimes in the TP basins could be revealed, which are consistent to the existing results obtained from in situ observations and complex land surface modeling. It indicated the usefulness of integrating the multiple datasets (e.g., in situ observations, remote sensing-based products, reanalysis outputs, land surface model simulations and climate model outputs) for hydrological applications. The generalization here could be helpful for understanding the hydrological cycle and supporting sustainable water resources management and eco-environment protection in the Tibetan Plateau under global warming.

***Author contributions***. Wenbin Liu and Fubao Sun developed the idea to see the general water budgets in the TP basins from the perspective of multisource datasets. Wenbin Liu collected and processed the multiple datasets with the help of Yanzhong Li, Guoqing Zhang, Wee Ho Lim, Hong Wang as well as Peng Bai, and prepared the manuscript. The results were extensively commented and discussed by Fubao Sun, Jiahong Liu and Yan-Fang Sang.

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**Table 1**: Overview of multi-source datasets applied in this study

| Data category | Data source | Spatial resolution | Temporal resolution | Available period used | Reference |
|---|---|---|---|---|---|
| Runoff (Q) | Observed, National Hydrology Almanac of China | — | Daily | 1982-2011 | — |
| | VIC_IGSNRR simulated | 0.25° | Daily | 1982-2011 | Zhang et al. (2014) |
| Precipitation (P) | Observed, CMA | 0.5 ° | Monthly | 1982-2011 | — |
| | TRMM 3B43 V7 | 0.25° | Monthly | 2000-2011 | Huffman et al. (2012) |
| | IGSNRR forcing | 0.25° | Daily | 1982-2011 | Zhang et al. (2014) |
| Temperature (Temp.) | Observed, CMA | 0.5 ° | Monthly | 2000-2011 | — |
| Terrestrial storage change ($\Delta S$) | GRACE-CSR | Approx.300-400 km | Monthly | 2002-2011 | Tapley et al. (2004) |
| | GRACE-GFZ | Approx.300-400 km | Monthly | 2002-2011 | Tapley et al. (2004) |
| | GRACE-JPL | Approx.300-400 km | Monthly | 2002-2011 | Tapley et al. (2004) |
| Potential evaporation (PET) | CRU | 0.5 ° | Monthly | 1982-2011 | Harris et al. (2013) |
| Actual evaporation (ET) | MTE_E | 0.5 ° | Monthly | 1982-2011 | Jung et al. (2010) |
| | VIC_E | 0.25° | Daily | 1982-2011 | Zhang et al. (2014) |
| | GLEAM_E | 0.25° | Daily | 1982-2011 | Miralles et al. (2011) |
| | PML_E | 0.5 ° | Monthly | 1982-2011 | Zhang Y et al. (2016) |
| | Zhang_E | 8 km | Monthly | 1983-2006 | Zhang et al. (2010) |
| | GNoah_E | 1.0 ° | 3 hourly | 1982-2011 | Rui (2011) |
| NDVI | GIMMS NDVI dataset | 8 km | 15 daily | 1982-2011 | Tucker et al. (2005) |
| LAI | GLASS LAI Product | 0.05° | 8 daily | 1982-2011 | Liang and Xiao (2012) |
| Snow Cover | TP Snow composite Products | 500 m | Daily | 2005-2013 | Zhang et al. (2012) |
| SWE | VIC_IGSNRR simulated | 0.25° | Daily | 1982-2011 | Zhang et al. (2014) |
| | GlobSnow-2 Product | 25 km | Daily | 1982-2011 | Takala et al. (2011) |
| Glacier Area | the Second Glacier Inventory Dataset of China | _ | _ | 2005 | Guo et al. (2014) |

**Table 2**: Main features of the 18 TP river basins used in this study. The precipitation and temperature statistics for each basin were calculated from the observed CMA datasets while the NDVI and LAI statistics were extracted from the GIMMS NDVI dataset and GLASS LAI product. The GA% and SC% represented the percentages of multiyear-mean glacier cover and snow cover in each basin which were calculated from the Second Glacier Inventory Dataset of China and the daily TP snow cover dataset (2005-2013)

| No. | Station | Altitude (m) | River name | Drainage area ($km^2$) | Multiyear-mean (1982-2011) and basin-averaged parameters | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Q (mm/yr) | Prec. (mm/yr) | Temp.($^{o}$C/yr) | NDVI | LAI | GA% | SC% |
| 01 | Kulukelangan | 2000 | Yerqiang | 32880.00 | 158.60 | 128.34 | -5.68 | 0.05 | 0.03 | 10.97 | 35.03 |
| 02 | Tongguziluoke | 1650 | Yulongkashi | 14575.00 | 151.56 | 134.04 | -4.07 | 0.06 | 0.04 | 23.27 | 35.95 |
| 03 | Numaitilangan | 1880 | Keliya | 7358.00 | 103.18 | 137.14 | -4.78 | 0.06 | 0.03 | 10.86 | 29.16 |
| 04 | Zelingou | 4282 | Bayin | 5544.00 | 41.42 | 340.68 | -4.98 | 0.13 | 0.09 | 0.09 | 21.22 |
| 05 | Gadatan | 3823 | Yellow | 7893.00 | 200.95 | 566.01 | -4.60 | 0.34 | 0.54 | 0.13 | 14.94 |
| 06 | Xining | 3225 | Yellow | 9022.00 | 99.90 | 503.74 | 0.97 | 0.36 | 0.70 | 0.00 | 10.06 |
| 07 | Tongren | 3697 | Yellow | 2832.00 | 149.36 | 533.25 | -1.37 | 0.39 | 0.83 | 0.00 | 9.42 |
| 08 | Tainaihai | 2632 | Yellow | 121972.00 | 159.48 | 540.32 | -2.40 | 0.34 | 0.72 | 0.09 | 15.89 |
| 09 | Huangheyan | 4491 | Yellow | 20930.00 | 31.18 | 386.42 | -4.81 | 0.23 | 0.61 | 0.00 | 17.25 |
| 10 | Jimai | 4450 | Yellow | 45015.00 | 85.50 | 441.48 | -4.16 | 0.26 | 0.52 | 0.00 | 20.05 |
| 11 | Yajiang | 2599 | Yalong | 67514.00 | 237.66 | 717.05 | -0.23 | 0.43 | 0.80 | 0.15 | 18.36 |
| 12 | Zhimenda | 3540 | Yangtze | 137704.00 | 96.23 | 405.66 | -4.83 | 0.20 | 0.26 | 0.96 | 17.87 |
| 13 | Jiaoyuqiao | 3000 | Salween | 72844.00 | 364.26 | 620.88 | -1.89 | 0.29 | 0.44 | 2.02 | 23.73 |
| 14 | Pangduo | 5015 | Brahmaputra | 16459.00 | 348.31 | 544.59 | -1.53 | 0.27 | 0.33 | 1.66 | 23.33 |
| 15 | Tangjia | 4982 | Brahmaputra | 20143.00 | 350.61 | 555.17 | -1.89 | 0.27 | 0.34 | 1.39 | 21.83 |
| 16 | Gongbujiangda | 4927 | Brahmaputra | 6417.00 | 586.96 | 692.06 | -4.24 | 0.27 | 0.36 | 4.12 | 25.99 |
| 17 | Nuxia | 2910 | Brahmaputra | 191235.00 | 307.38 | 401.35 | -0.73 | 0.22 | 0.25 | 1.90 | 13.50 |
| 18 | Yangcun | 3600 | Brahmaputra | 152701.00 | 163.25 | 349.91 | -0.87 | 0.19 | 0.18 | 1.28 | 10.52 |

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**Table 3**: Annual-averaged water storage changes (ΔS) in 18 TP basins derived from GRACE retrievals (2002-2013) from three different processing centers (CSR, GFZ and JPL)

| Basin | Water storage Change (ΔS,mm) | | |
|---|---|---|---|
| | CSR | GFZ | JPL |
| Kulukelangan | -0.16 | -0.16 | -0.00 |
| Tongguziluoke | 0.10 | 0.10 | 0.28 |
| Numaitilangan | 0.24 | 0.22 | 0.41 |
| Zelingou | 0.63 | 0.41 | 0.69 |
| Gadatan | 0.02 | -0.24 | -0.03 |
| Xining | -0.08 | -0.35 | -0.14 |
| Tongren | -0.13 | -0.41 | -0.21 |
| Tainaihai | 0.12 | -0.16 | 0.10 |
| Huangheyan | 0.60 | 0.35 | 0.70 |
| Jimai | 0.41 | 0.15 | 0.48 |
| Yajiang | -0.23 | -0.50 | -0.21 |
| Zhimenda | 0.57 | 0.38 | 0.78 |
| Jiaoyuqiao | -1.00 | -1.13 | -0.79 |
| Nuxia | -1.42 | -1.44 | -1.31 |
| Pangduo | -1.21 | -1.29 | -1.02 |
| Tangjia | -1.40 | -1.46 | -1.24 |
| Gongbujiangda | -1.61 | -1.67 | -1.47 |
| Yangcun | -1.33 | -1.34 | -1.21 |

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**Table 4**: Nonparametric trends for different ET estimates during the period 1982-2006 detected by modified Mann-Kendall test, the bold number showed the detected trend is statistically significant at the 0.05 level

| Basin | $ET_{wb}$ | GLEAM_E | VIC_E | Zhang_E | PML_E | MET_E | GNoah_E |
|---|---|---|---|---|---|---|---|
| Kulukelangan | **-0.09** | 0.09 | **0.18** | _ | 0.03 | -0.01 | 0.07 |
| Tongguziluoke | -0.02 | 0.10 | **0.13** | _ | 0.03 | **-0.08** | 0.19 |
| Numaitilangan | 0.04 | **0.10** | 0.14 | _ | 0.14 | **-0.10** | 0.22 |
| Zelingou | **0.13** | **0.23** | 0.11 | **0.09** | 0.04 | **0.06** | 0.02 |
| Gadatan | -0.09 | 0.25 | 0.070 | -0.10 | -0.01 | **0.06** | -0.07 |
| Xining | -0.06 | **0.54** | 0.01 | -0.08 | 0.01 | 0.02 | -0.06 |
| Tongren | -0.06 | **0.34** | -0.15 | **-0.17** | 0.07 | 0.02 | 0.13 |
| Tainaihai | 0.06 | **0.28** | -0.03 | **-0.11** | 0.04 | **0.05** | 0.04 |
| Huangheyan | 0.08 | **0.19** | -0.01 | **-0.10** | **0.08** | **0.05** | **0.10** |
| Jimai | -0.07 | **0.23** | -0.01 | -0.08 | 0.03 | **0.05** | 0.10 |
| Yajiang | 0.17 | **0.26** | **0.06** | **-0.21** | -0.01 | 0.03 | -0.02 |
| Zhimenda | 0.11 | **0.28** | 0.10 | 0.01 | 0.07 | **0.04** | 0.07 |
| Jiaoyuqiao | **0.18** | **0.28** | 0.10 | **-0.11** | 0.05 | **0.05** | 0.07 |
| Nuxia | **-0.09** | **0.25** | 0.09 | **-0.10** | **0.12** | **0.04** | 0.10 |
| Pangduo | 0.05 | **0.28** | **0.17** | **-0.07** | 0.07 | **0.07** | **0.11** |
| Tangjia | 0.09 | **0.26** | **0.17** | **-0.09** | **0.20** | **0.06** | **0.12** |
| Gongbujiangda | -0.26 | 0.12 | 0.13 | **-0.16** | **0.19** | 0.01 | **0.15** |
| Yangcun | 0.03 | **0.28** | 0.08 | **-0.06** | 0.10 | 0.04 | 0.09 |

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**Figure captions:**

**Figure1.** Map of river basins and hydrological gauging stations (green dots) over the Tibetan Plateau (TP) used in this study. The grey shading shows the topography of TP in meters above the sea level and the blue shading exhibits the glaciers distribution in TP extracted from the Second Glacier Inventory Dataset of China.

**Figure 2.** Comparison of VIC_IGSNRR simulated and observed monthly runoff for Tangnaihai and Panduo stations (a and b) as well as (c) basin-averaged monthly TRMM, CMA gridded and IGSNRR forcing precipitations for the smallest basin (Tongren station) over the period 1982-2011. (d) shows the comparison of TRMM (blue) and IGSNRR forcing (red) precipitations against CMA gridded precipitation for 18 river basins over TP during the period 2000-2011.

**Figure 3.** Comparison of different ET products against the calculated ET through the water balance method ($ET_{wb}$) at the monthly time scale for 18 TP basins during the period 1983-2006. The boxplot of monthly estimates of different ET products for 18 TP basins are shown in (a) while the correlation coefficients and root-mean-square-errors (RMSEs, mm/month) for each ET product relatively to $ET_{wb}$ are exhibited in (b).

**Figure 4**. General water and energy status (a. the perspective of Budyko framework) and their relationships with glacier (b) and vegetation (c and d) for eighteen TP river basins (1983-2006). The ET used in this figure is calculated from the bias-corrected water balance method.

**Figure 5**. Seasonal cycles (1982-2011) of water budget components in westerlies-dominated (column 1), East Asian monsoon-dominated (columns 2-4) and Indian monsoon-dominated (columns 5-6) TP basins.

**Figure 6**. Seasonal cycles (1982-2011) of air temperature and vegetation parameters in westerlies-dominated (column 1), East Asian monsoon-dominated (columns 2-4) and Indian monsoon-dominated (columns 5-6) TP basins.

**Figure 7**. Seasonal cycles (1982-2011) of snow cover and snow water equivalent (SWE) in westerlies-dominated (column 1), East Asian monsoon-dominated (columns

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2-4) and Indian monsoon-dominated (columns 5-6) TP basins. The snow cover was extracted from cloud free snow composite product during the period 2005-2013. It should also be noted that the GlobSnow data are not available for some basins.

**Figure 8**. Sen's slopes of water budget components and vegetation parameters in westerlies-dominated TP basins during the period of 1982-2011. To clearly exhibit the nonparametric trends of all variables in one panel, the Sen's Slopes of Q, P, $ET_{wb}$ and PET have been multiplied by 1/12 (unit: mm/month). The double red stars showed that the trend was statistically significant at the 0.05 level.

**Figure 9**. Linear and non-parametric trends of westerly, Indian monsoon and East Asian summer monsoon during the period 1982-2011 revealed prospectively by the Asian Zonal Circulation Index, Indian Ocean Dipole Mode Index and East Asian Summer Monsoon Index.

**Figure 10**. Similar to Figure 8 but for East Asian monsoon-dominated TP basins. It should be noted that the GlobSnow data are not available for some basins. The double red stars showed that the trend was statistically significant at the 0.05 level.

**Figure 11**. Similar to Figure 8 but for Indian monsoon-dominated TP basins. It should be noted that the GlobSnow data are not available for some basins. The double red stars showed that the trend was statistically significant at the 0.05 level.

**Figure 12**. Uncertainties in seasonal cycles of ETwb calculated from three precipitation products (CMA gridded, IGSNRR_Forcing and TRMM precipitation) in 18 TP basins. The comparisons were conducted during the period 2000-2011 when TRMM data was available.

**Figure 13**. Uncertainties in annual trends of $ET_{wb}$ (b) calculated from two precipitation products (CMA gridded and IGSNRR_Forcing) (a) in 18 TP basins. The comparisons were conducted during the period 1982-2011(TRMM data was not available for the whole period).

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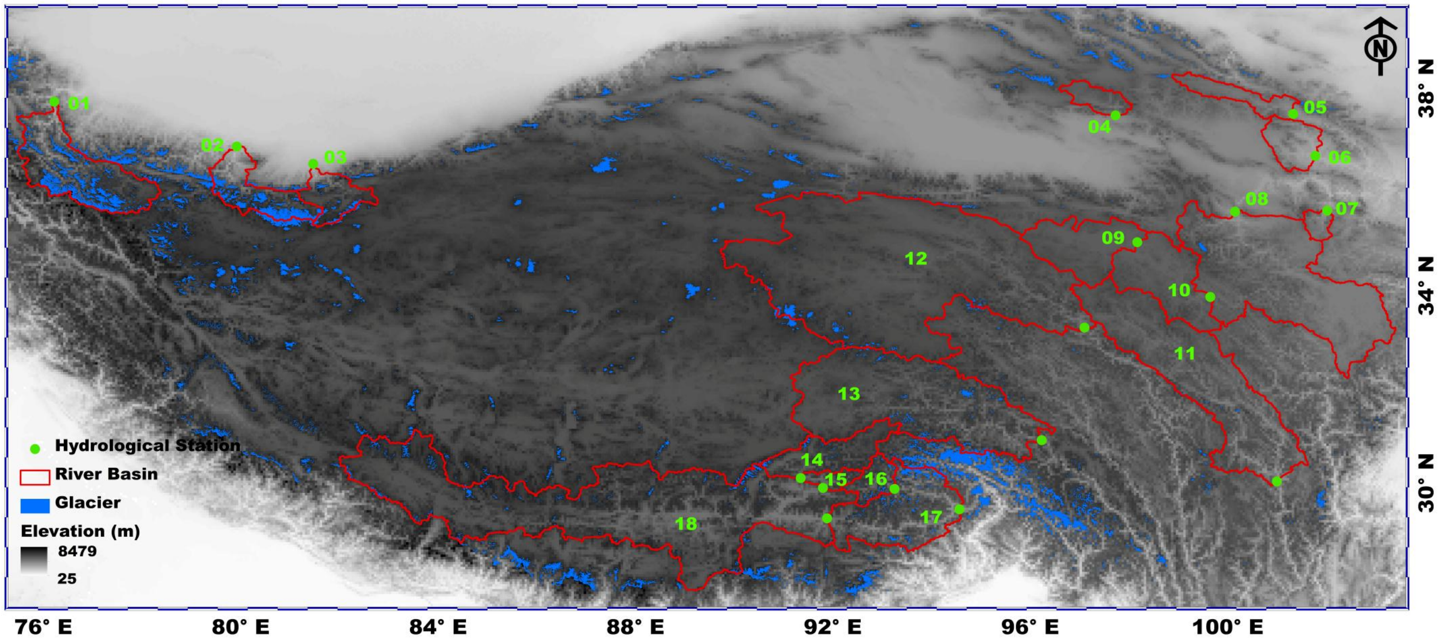
**Figure 1**. Map of river basins and hydrological gauging stations (green dots) over the Tibetan Plateau (TP) used in this study. The grey shading shows the topography of TP in meters above the sea level and the blue shading exhibits the glaciers distribution in TP extracted from the Second Glacier Inventory Dataset of China.



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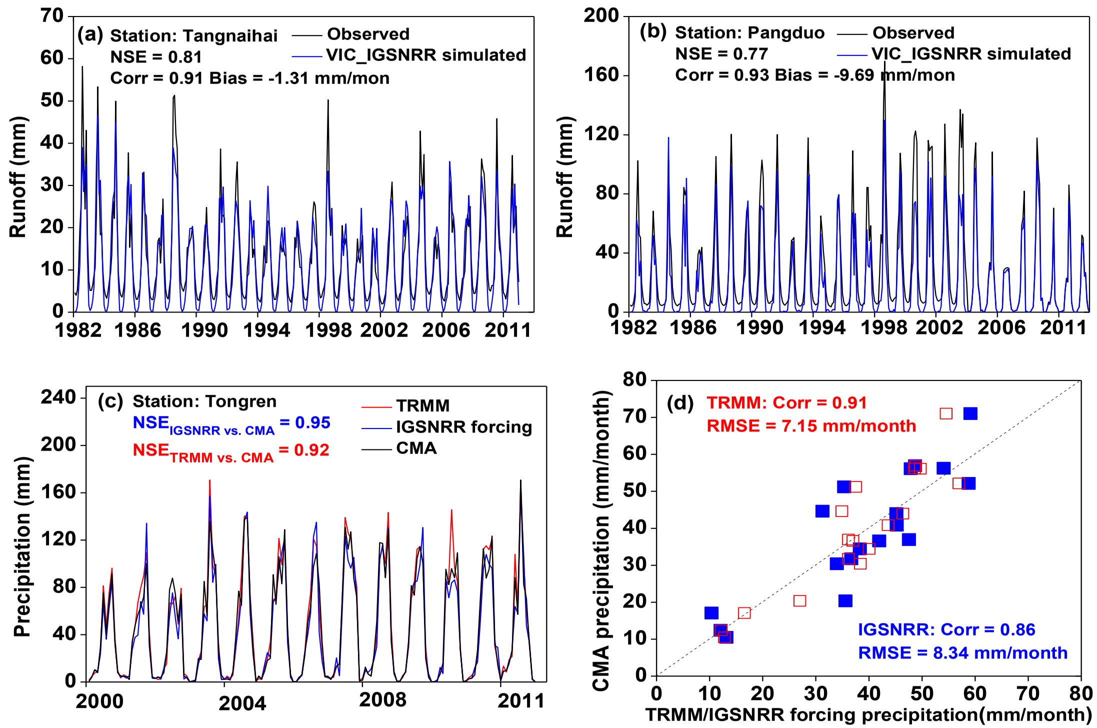

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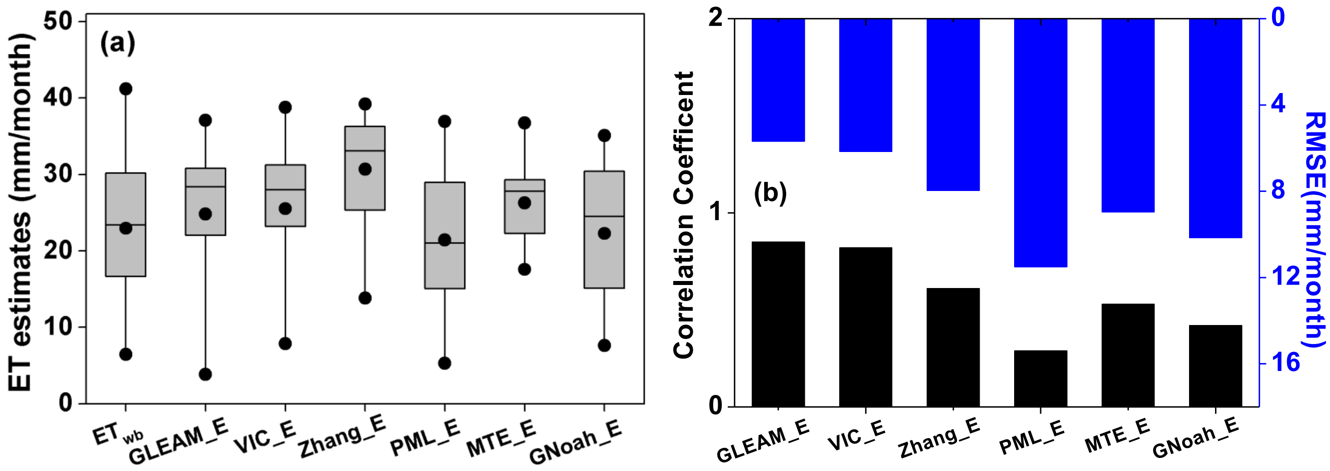
**Figure 3**. Comparison of different ET products against the calculated ET through the water balance ($ET_{wb}$) at the monthly time scale for 18 river basins over the Tibetan Plateau during the period 1983-2006. The boxplot of monthly estimates of different ET products for 18 TP basins are shown in (a) while the correlation coefficients and root-mean-square-errors (RMSEs, mm/month) for each ET product relatively to $ET_{wb}$ are exhibited in (b).



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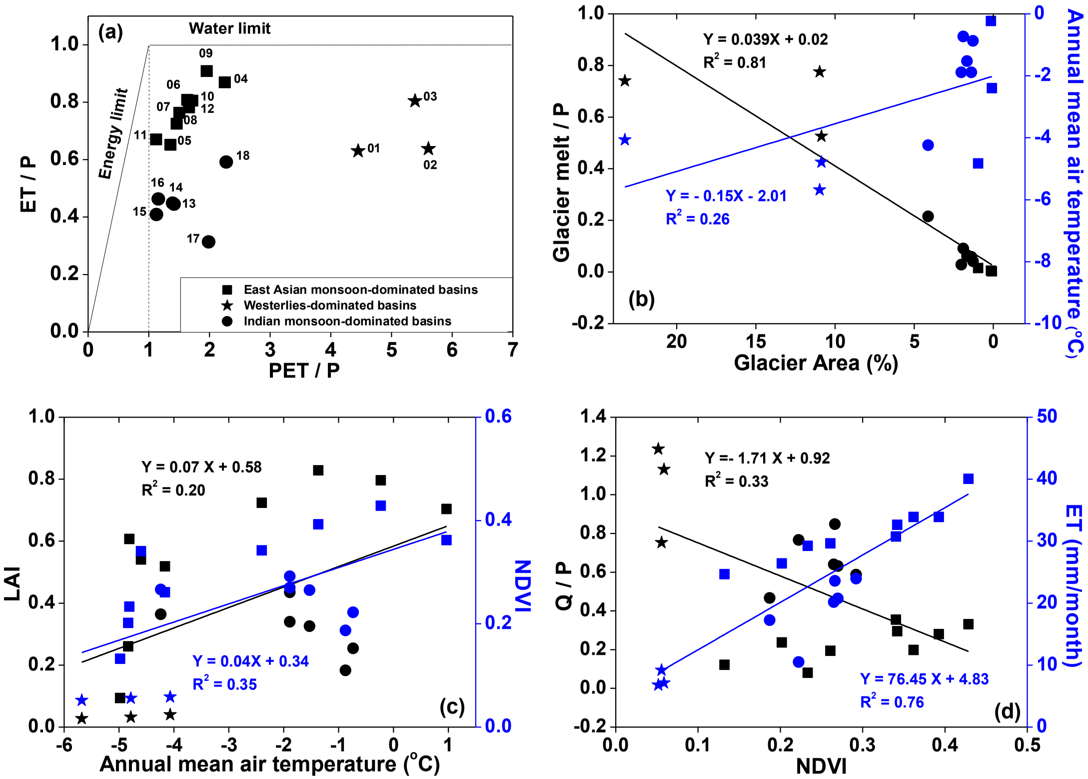

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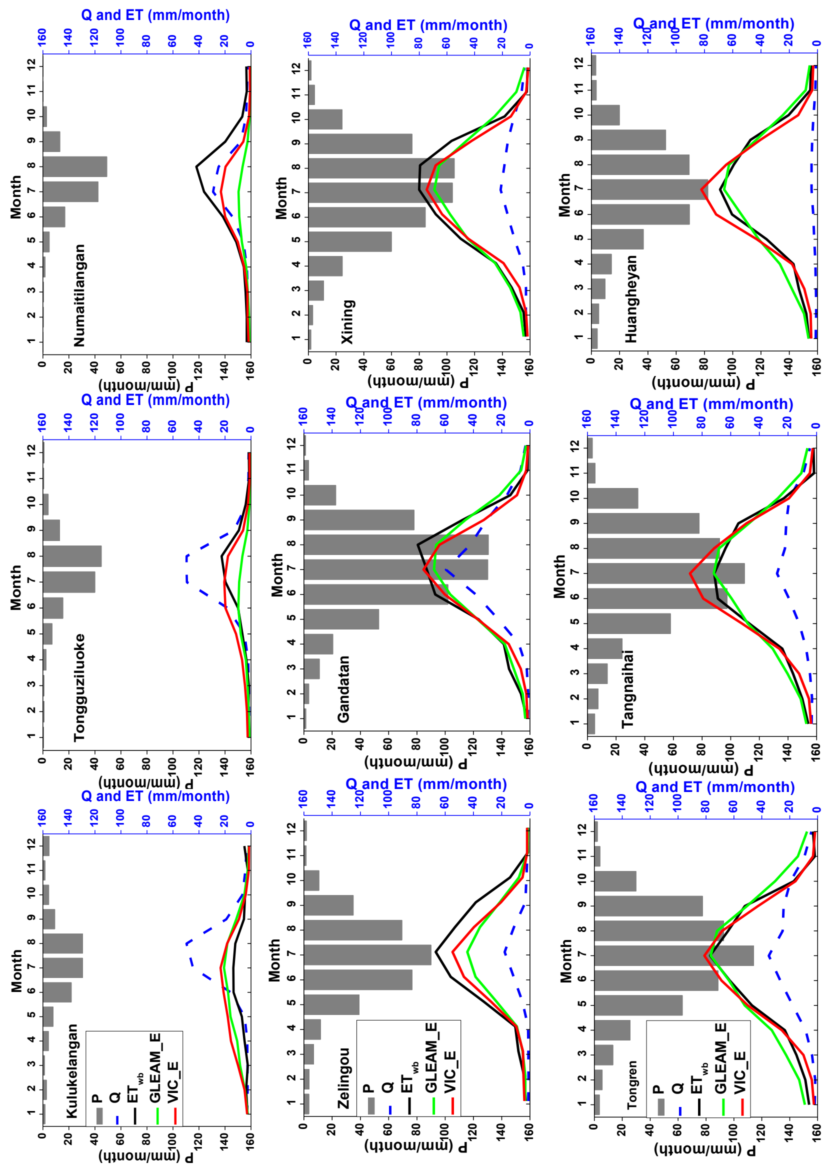

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**Figure 5**: (continued)

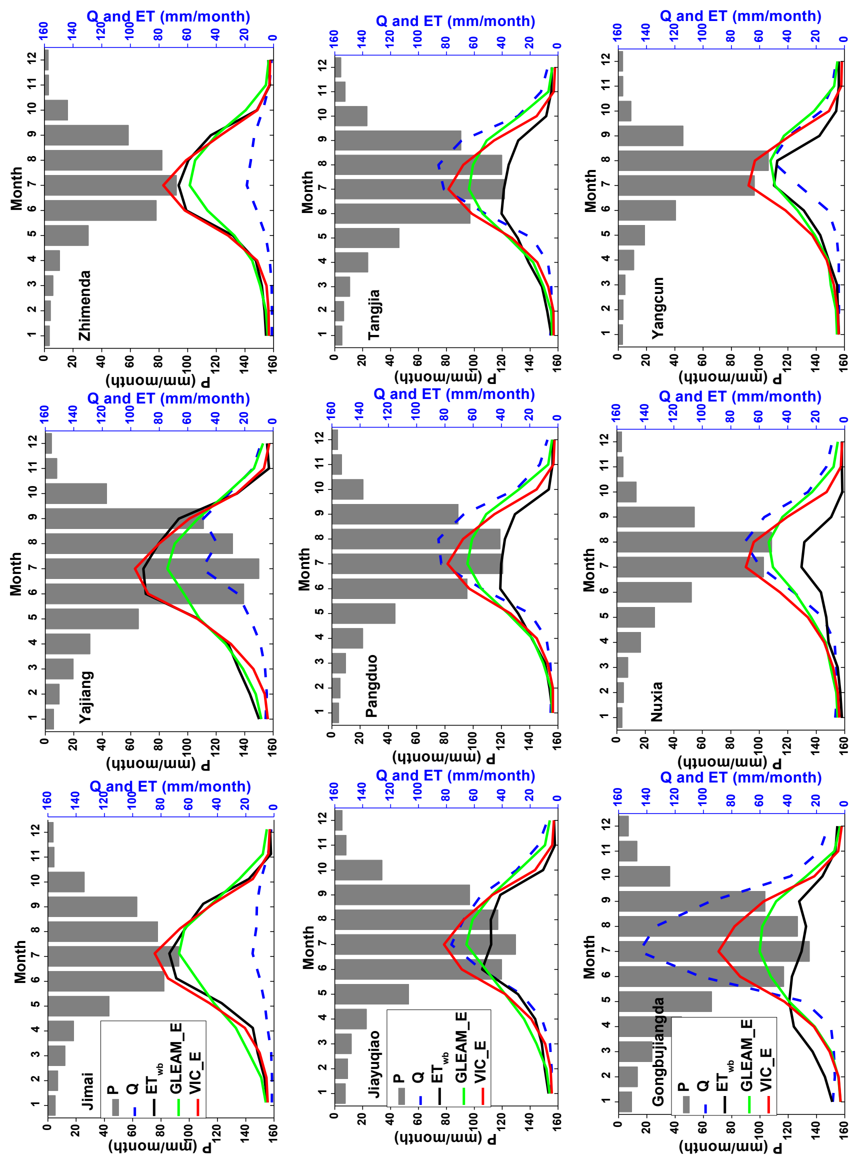

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**Figure 6.** Seasonal cycles (1982-2011) of air temperature and vegetation parameters in westerlies-dominated (column 1), East Asian monsoon-dominated (columns 2-4) and Indian monsoon-dominated (columns 5-6) TP basins.

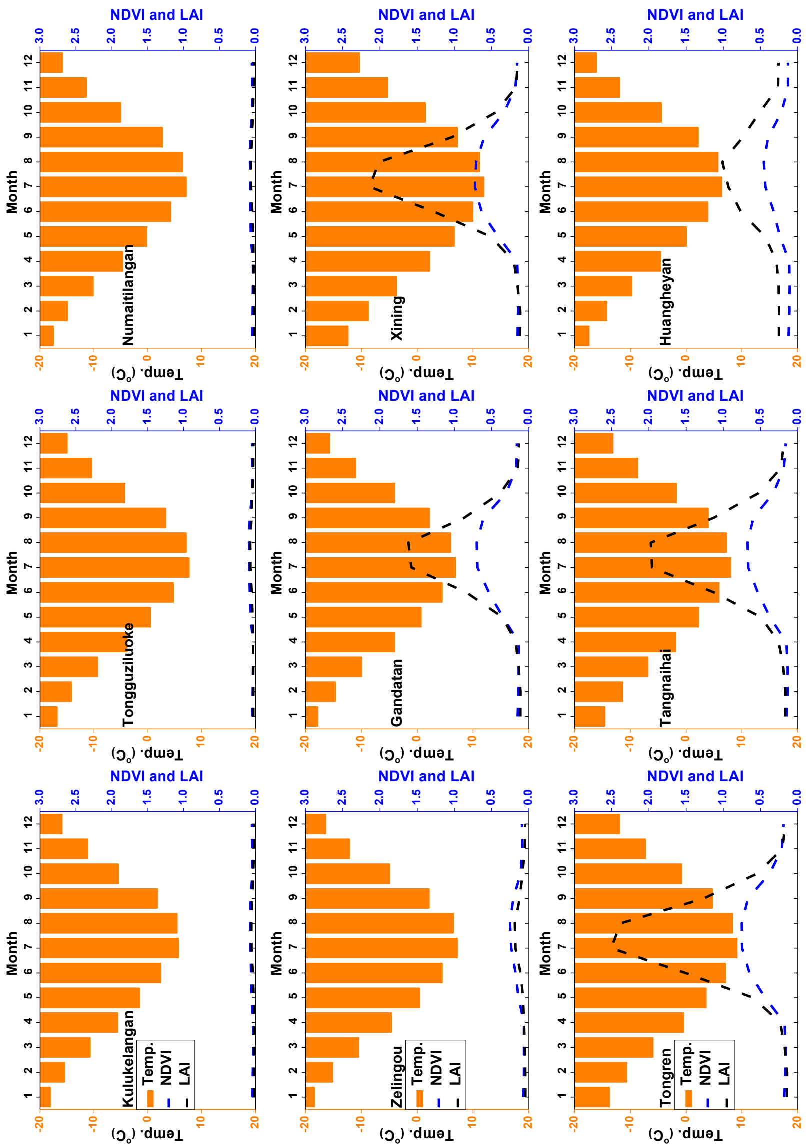

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**Figure 6**: (continued)

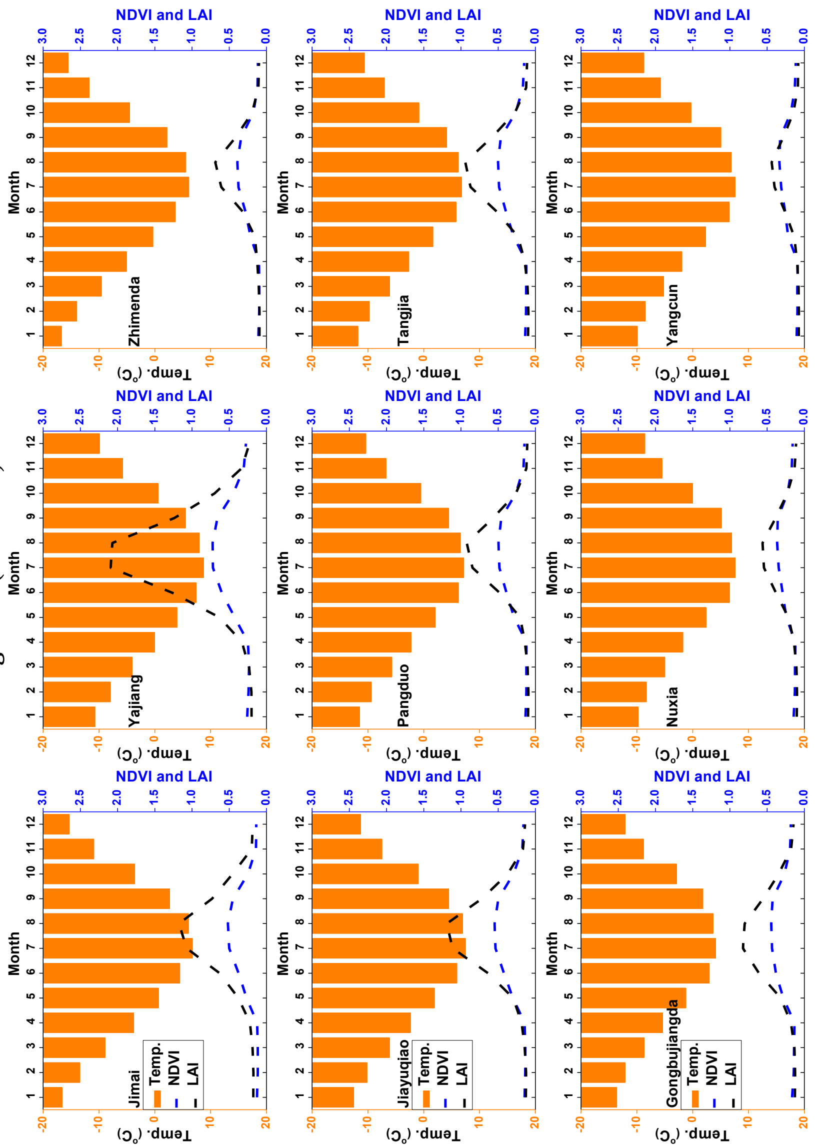

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**Figure 7**. Seasonal cycles (1982-2011) of snow cover and snow water equivalent (SWE) in westerlies-dominated (column 1), East Asian monsoon- dominated (columns 2-4) and Indian monsoon-dominated (columns 5-6) TP basins. The snow cover was extracted from cloud free snow composite product during the period 2005-2013. It should also be noted that the GlobSnow data are not available for some basins.

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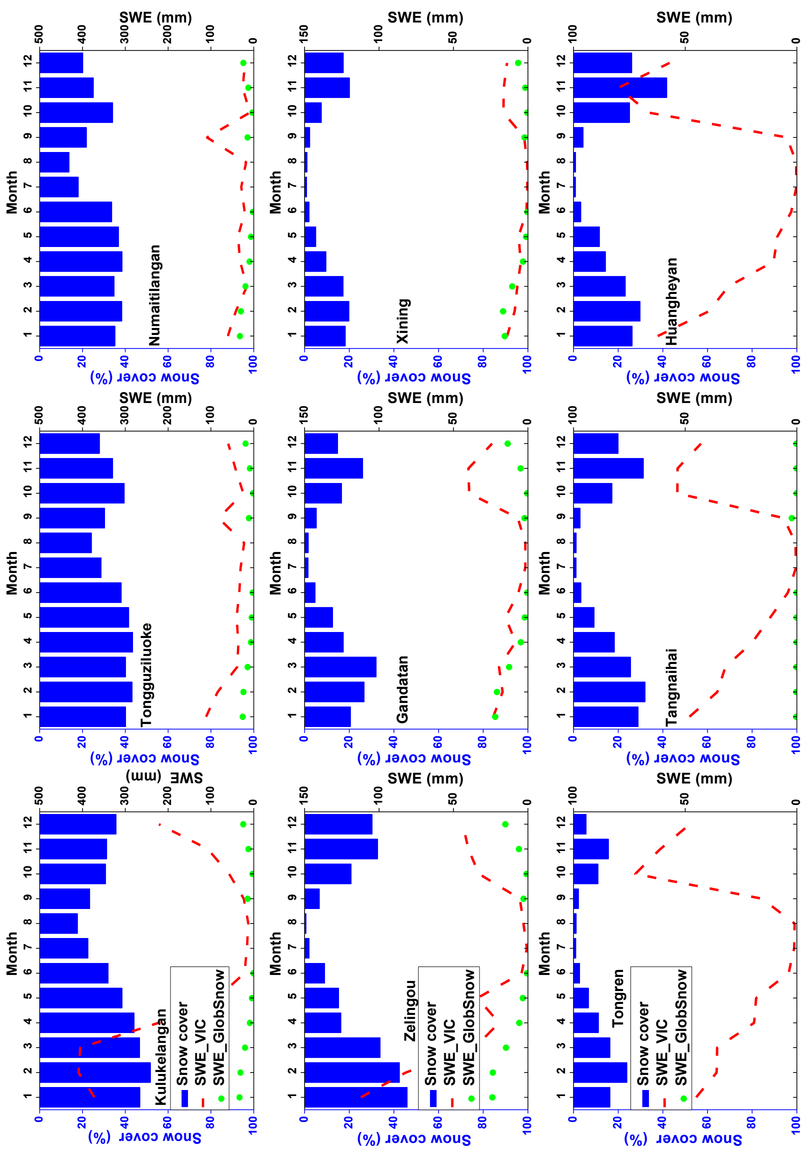

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**Figure 7**: (continued)

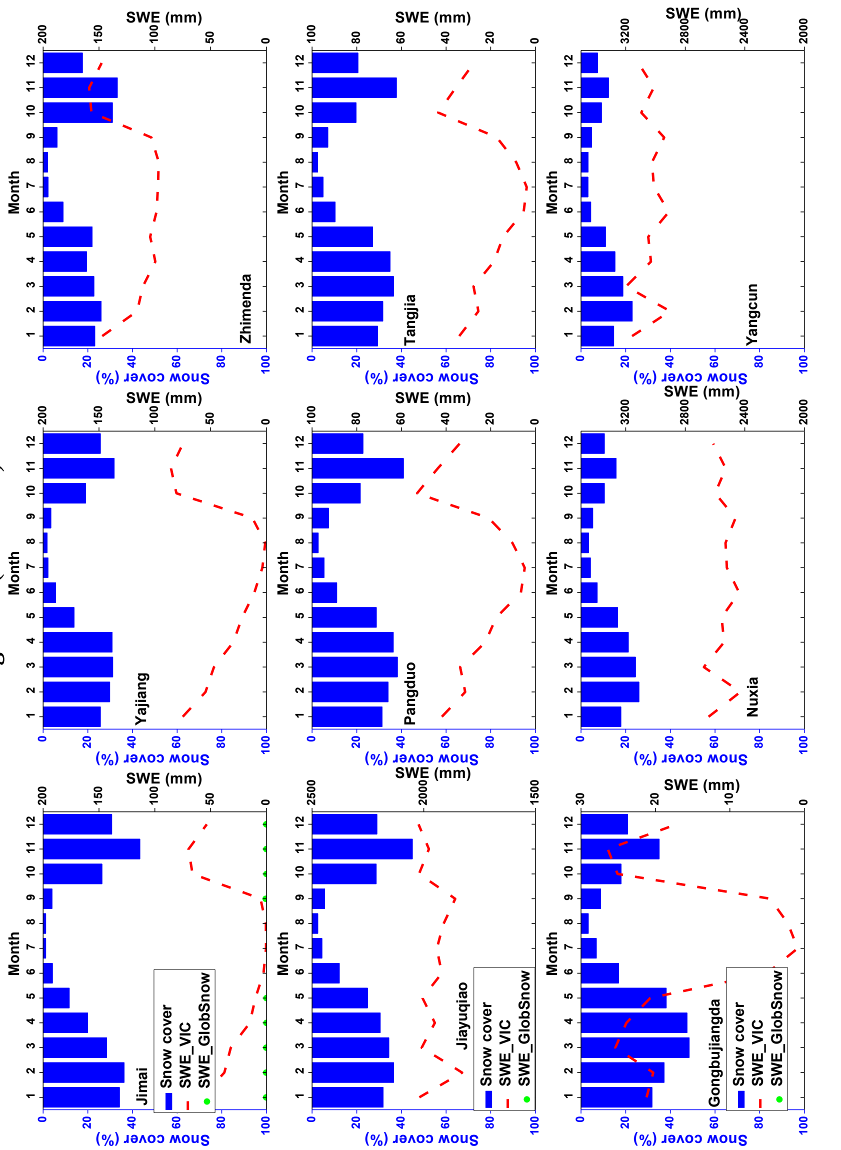

**Figure 8**. Sen's slopes of water budget components and vegetation parameters in westerlies-dominated TP basins during the period of 1982-2011. To clearly exhibit the nonparametric trends of all variables in one panel, the Sen's Slopes of Q, P, $ET_{wb}$ and PET have been multiplied by 1/12 (unit: mm/month). The double red stars showed that the trend was statistically significant at the 0.05 level.

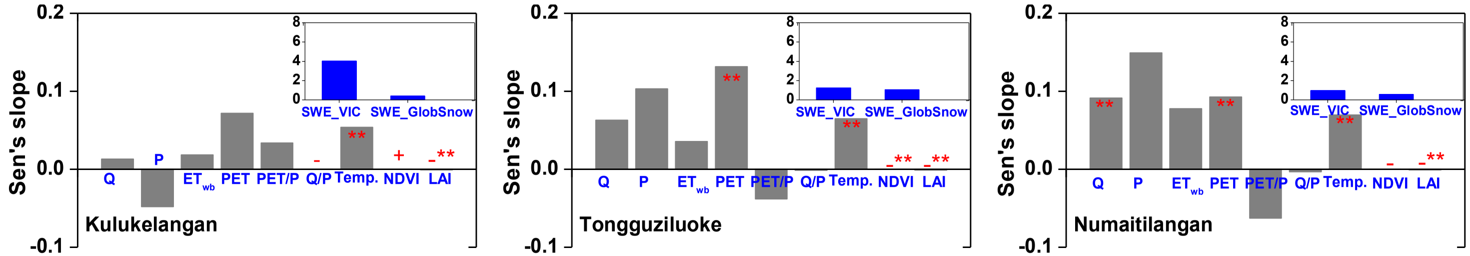

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**Figure 9**. Linear and non-parametric trends of westerly, Indian monsoon and East Asian summer monsoon during the period 1982-2011 revealed prospectively by the Asian Zonal Circulation Index, Indian Ocean Dipole Mode Index and East Asian Summer Monsoon Index.

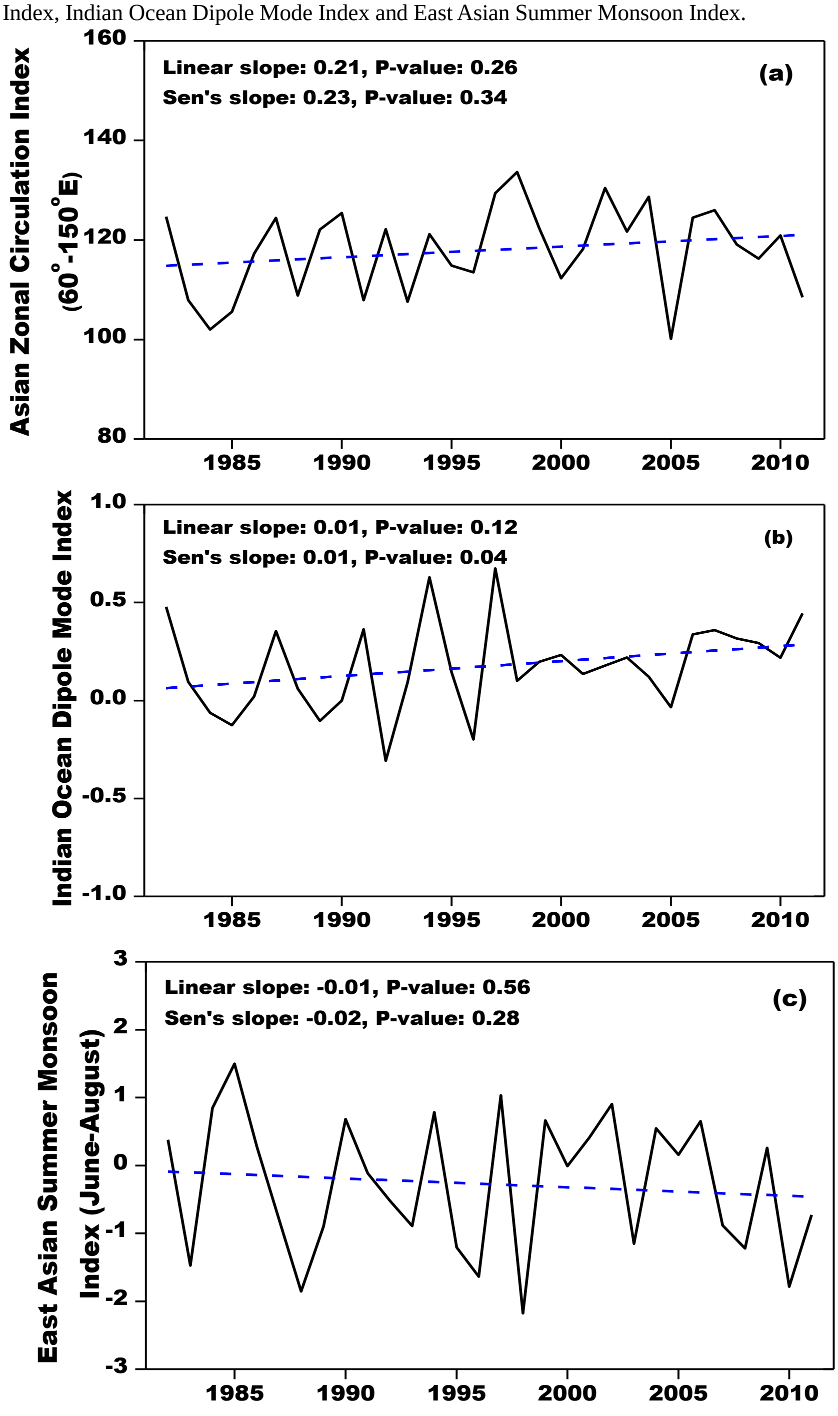

**Figure 10**. Similar to Figure 8 but for East Asian monsoon-dominated TP basins. It should be noted that the GlobSnow data are not available for some basins.

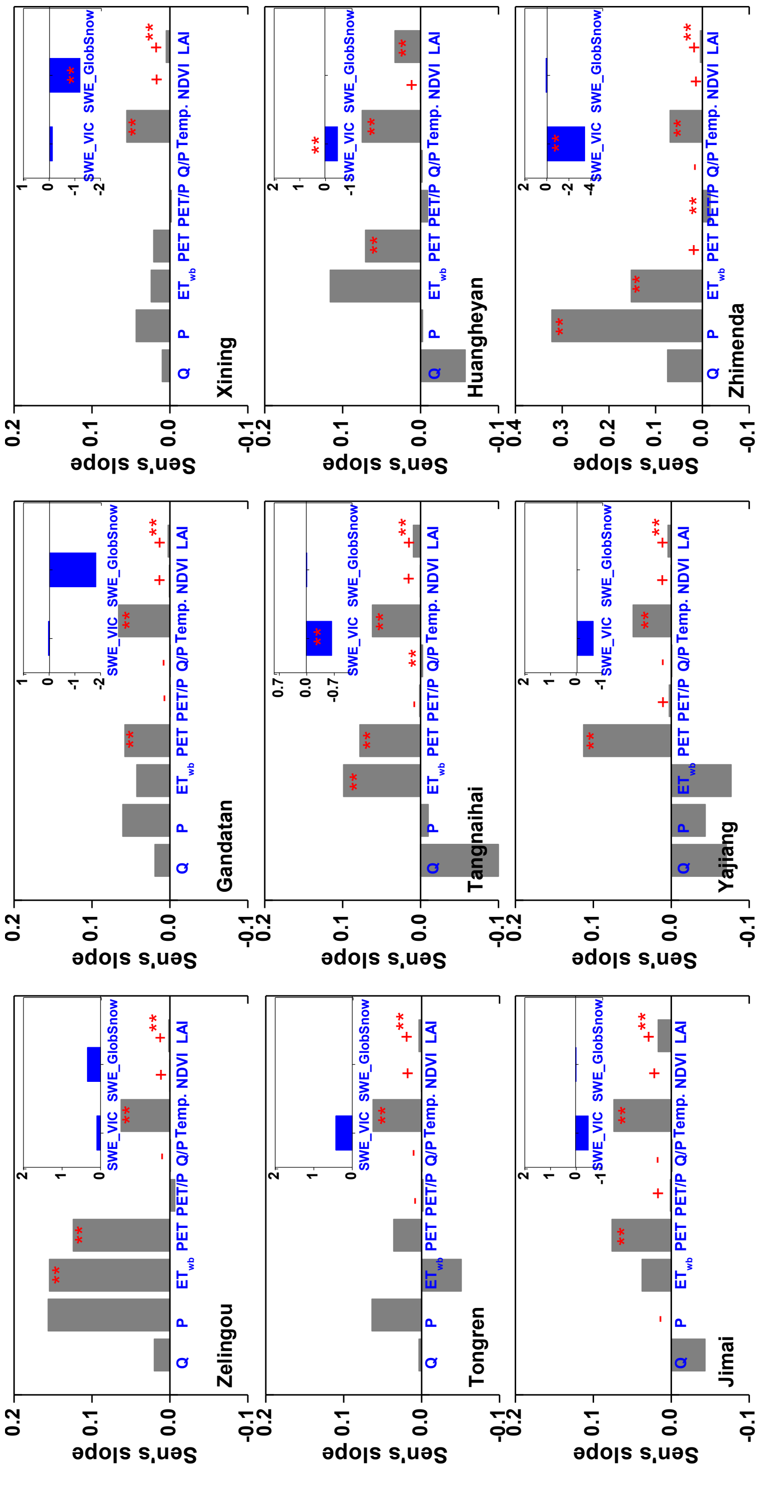

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**Figure 11**. Similar to Figure 8 but for Indian monsoon-dominated TP basins. It should be noted that the GlobSnow data are not available for some basins.

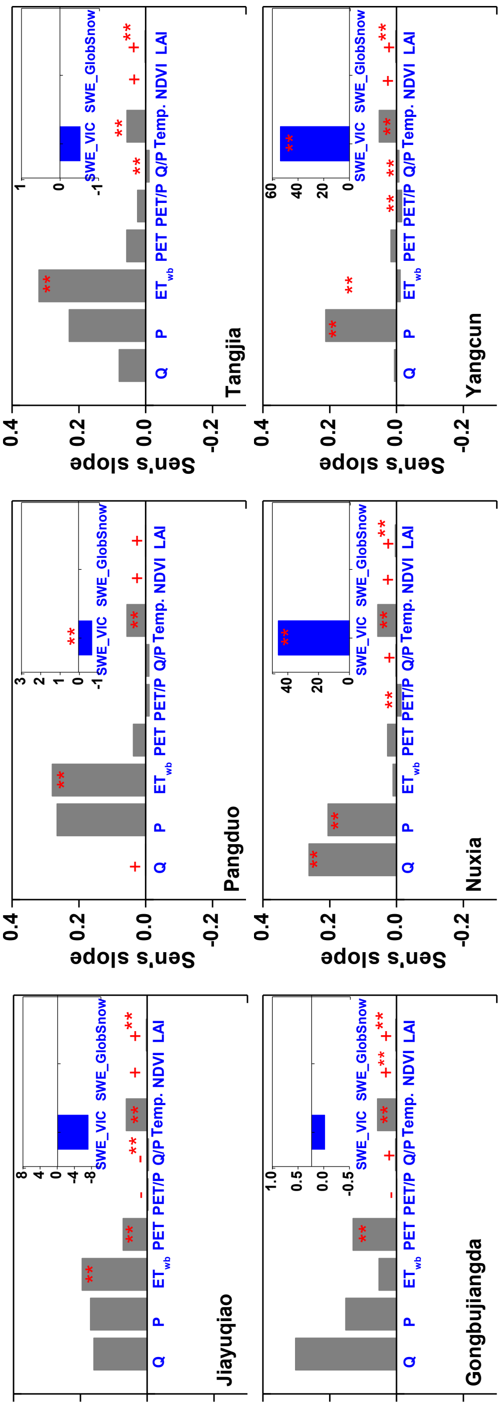

**Figure 12**. Uncertainties in seasonal cycles of $ET_{wb}$ calculated from three precipitation products (CMA gridded, IGSNRR_Forcing and TRMM precipitation) in 18 TP basins. The comparisons were conducted during the period 2000-2011 when TRMM data was available.

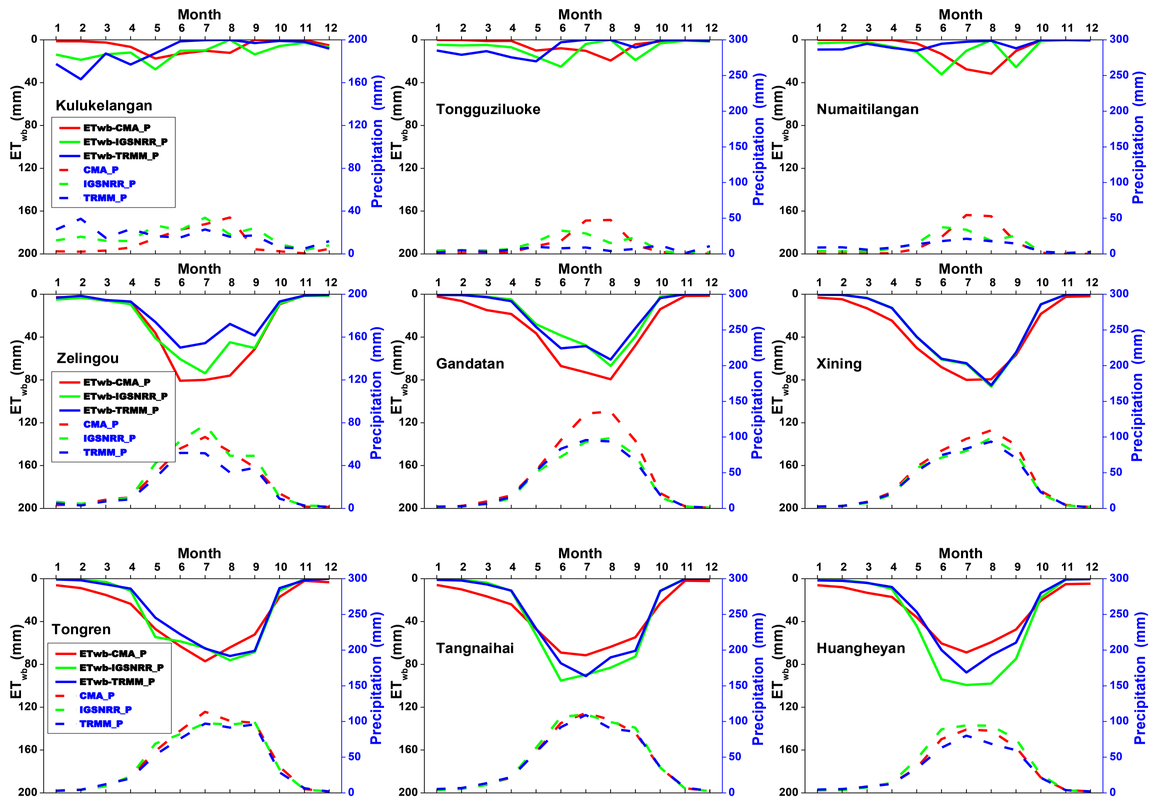

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**Figure 12:** (continued)

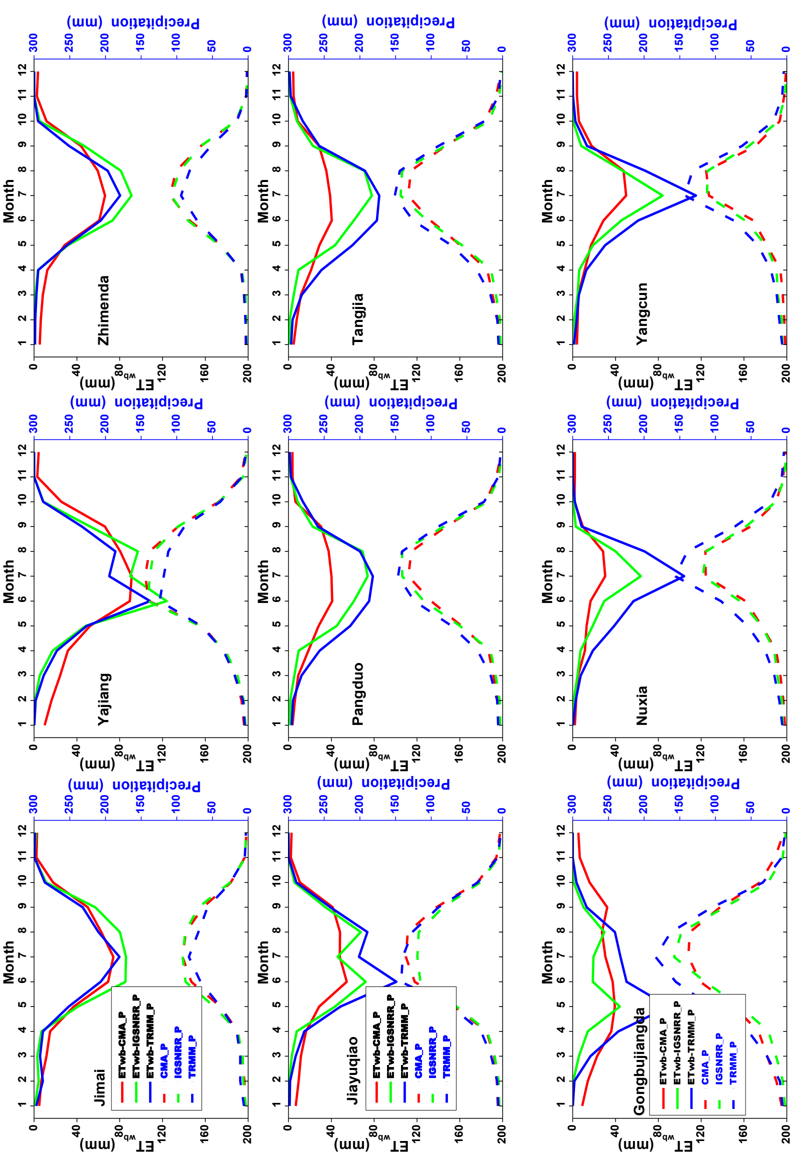

**Figure 13**. Uncertainties in annual trends of $ET_{wb}$ (b) calculated from two precipitation products (CMA gridded and IGSNRR_Forcing) (a) in 18 TP basins. The comparisons were conducted during the period 1982-2011(TRMM data was not available for the whole period).