A Simple and Efficient Method for Correction of Basin-Scale Evapotranspiration on the Tibetan Plateau

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Abstract: Evapotranspiration (ET) is one of the important components of the global hydrologic cycle, energy exchange, and carbon cycle. However, basin scale actual ET (hereafter ETₐ) is difficult to estimate accurately. We present an evaluation of four actual ET products (hereafter ETₚ) in seven sub-basins in the Tibetan Plateau. The actual ET calculated by the water balance method (hereafter ETₓ𝑤) was used as the reference for correction of the different ETₚ. The ETₜ and ETₚ show obvious seasonal cycles, but the ETₚ overestimated or underestimated the ET of the sub-basins in the Tibetan Plateau. A simple and effective method was proposed to correct the basin-scale ETₚ. The method was referred to as ratio bias correction, and it can effectively remove nearly all biases of the ETₚ. The proposed method is simpler and more effective in correcting the four ETₚ compared with the gamma distribution bias correction method. The reliability of the ETₚ is significantly increased after the ratio bias correction. The ratio bias correction method was used to correct the ETₚ in the seven sub-basins in the Tibetan Plateau, and regional ET was significantly improved. The results may help improve estimation of the ET of the Tibetan Plateau and thereby contribute to a better understanding of the hydrologic cycle of the plateau.

Keywords: evapotranspiration; ratio bias correction method; water balance method; GRACE; Tibetan Plateau

1. Introduction

Evapotranspiration (ET) represents the total evaporation and transpiration of plants from terrestrial and oceanic surfaces to the atmosphere [1]. ET is a prominent component of the hydrologic cycle, energy exchange, and carbon cycle. In recent years, several global ETₚ have been developed to estimate the distribution of ETₐ, including remote sensing-based methods, land surface models, surface energy balance, and reanalysis products [2–6]. These ETₚ significantly contributed to our knowledge of hydrological components [7]. However, these methods are limited by sparse measurement stations, as well as some uncertainties [8], especially with regard to surface energy balance models. The surface energy balance model, based on satellite images and remote sensing data, is a powerful and accurate method for calculating ET [8–14]. However, accurate measurements depend on the reliability of the input data, especially the remote sensing data at basin scale. The input data to calculate ETₐ of the Tibetan Plateau are limited by sparse measurement stations, as well as some uncertainties [15], especially in high-altitude mountains [6,16]. Long et al. [17] evaluated the uncertainty in evapotranspiration from land surface modeling (5 mm/month). Xue...
et al. [18] compared the annual evapotranspiration of the upper Yellow River and Yangtze River basins with bias $-10.8$–$119.8$ mm/yr and $-120.9$–$77$ mm/yr for four $E_{T_p}$ [2–4]. There is an urgent need to evaluate $E_{T_p}$ in areas with limited observation stations (e.g., the Tibetan Plateau).

Over the past decades, hydrologists and meteorologists have been making efforts to quantitatively evaluate $E_{T_a}$ [16,19–22]. Although many $E_{T_p}$ can be used to estimate actual ET on the Tibetan Plateau, the uncertainty is high [23,24]. The traditional water balance method is a useful tool to calculate $E_{T_a}$ at regional scale [17,20,25,26]. In previous studies, $E_{T_p}$ was estimated as a residual of precipitation ($P$) minus runoff ($R$) at regional scale, and the terrestrial water storage (TWS) changes were often neglected [27,28]. The traditional water balance method cannot be used to estimate $E_{T_a}$ at monthly or finer temporal scales. The Gravity Recovery and Climate Experiment (GRACE) satellite [29,30] provides a relatively accurate TWS estimation at basin scale. The calculated $E_{T_a}$ that uses the water balance of the GRACE TWS was thought to be accurate [17,22,25]. Therefore, many methods have been proposed for correcting $E_{T_p}$ based on the water balance method with GRACE data.

Gamma distribution is an effective method to correct the $E_{T_p}$ [18,20,25]. Li et al. [20] used the gamma distribution method to evaluate the existing $E_{T_p}$ on the Tibetan Plateau at monthly scale. The correction removed the biases and made the root-mean-square errors (RMSEs) decrease in comparison with the original $E_{T_p}$. But this method has some inaccuracies. It can only correct the systematic error caused by the annual change of TWS [20]. Moreover, the correction of $E_{T_p}$ by this method is complicated.

In this study, we propose a simple and efficient method, the ratio bias correction method, to correct four $E_{T_p}$ in seven sub-basins on the Tibetan Plateau. First, we calculated ET by using the water balance method with the GRACE TWS and used it as the reference for correction of the different $E_{T_p}$. Second, we used the proposed ratio bias correction method to correct the $E_{T_p}$ with the help of the $E_{T_ref}$. The gamma distribution bias correction method was also used to correct the $E_{T_p}$. A reasonable and accurate corrected ET on the Tibetan Plateau was obtained after the correction.

2. Materials and Methods

2.1. Study Area

Monthly ET across the Tibetan Plateau was evaluated, including five outflow basins (Yangtze, Yellow, Yarlung Zangbo, Mekong, and Salween) and two endorheic basins (Inner Plateau and Qaidam Basin), as shown in Figure 1. Overview of the seven sub-basins was shown in Table 1 (Data from the National Meteorological Information Centre and GLDAS 2.1 Noah). The total area of the seven sub-basins is approximately $206 \times 10^4$ km$^2$ and covers about 85% of the entire plateau. The Tibetan Plateau is regarded as the “roof of the world” [31]. As it is the source region of the great rivers of Asia, it has also been referred to as the “Asian water tower” [32]. The study areas are dominated by the Indian monsoon and westerlies [33]. The precipitation on the Tibetan Plateau decreases from southeast to northwest [34]. The precipitation of the Yarlung Zangbo basin is largest (73.9 mm/month), and the Qaidam is smallest (13.8 mm/month) (Table 1). The ET on the Tibetan Plateau shows great values (more than 600 mm/yr) in the east and south and small values (less than 50 mm/yr) in the west and north [34–36]. The seasonal variation of the ET on the Tibetan Plateau is generally characterized by small values in the cold season and great values in the warm season [37]. The spatial distribution of vegetation cover was obtained from a digitized Atlas of China’s Vegetation (http://westdc.westgis.ac.cn, accessed date: 1 July 2021), which has a scale of 1:1,000,000 [38,39]. Seven vegetation types were identified on the Tibetan Plateau: Meadow, steppe, forest, shrub, crop, alpine vegetation, and sparse vegetation (Figure 2). The main vegetation types are meadow and shrub in the source regions of Yangtze, Yellow, Mekong, and Salween Rivers. The main vegetation types in the Qaidam Basin and the Inner Plateau are sparse vegetation and steppe. The main vegetation types in the Yarlung Zangbo basin are varied due to its unique geographical location and
complex plateau climate [40]. The vegetation types distributed in this region are meadow, steppe, forest, and alpine vegetation.

![Figure 1. The sub-basin distribution map of the Tibetan Plateau.](image1)

**Table 1. Overview of the seven sub-basins.**

| Sub-Basin          | Area ($10^4$ km$^2$) | P (mm/month) | R (mm/month) | Main Vegetation Types                          |
|--------------------|----------------------|--------------|--------------|------------------------------------------------|
| Yellow             | 21.4                 | 40.6         | 3.3          | Meadow/Shrub                                   |
| Yangtze            | 43.5                 | 54.5         | 9.8          | Meadow/Shrub                                   |
| Yarlung Zangbo     | 25.3                 | 73.9         | 21.3         | Meadow/Steppe/Forest/Alpine vegetation         |
| Salween            | 10.8                 | 59.1         | 13.2         | Meadow/Shrub                                   |
| Menkon             | 8.1                  | 53.6         | 6.7          | Meadow/Shrub                                   |
| Qaidam             | 24.7                 | 13.8         | /            | Sparse vegetation                              |
| Inner Plateau      | 69.3                 | 20.6         | /            | Steppe/Meadow                                  |

![Figure 2. Distribution of vegetation types on the Tibetan Plateau.](image2)

**2.2. Data**

Four global ET$_p$ were assessed, and Table 2 shows the details of the four ET$_p$. ET from a moderate resolution imaging spectroradiometer (MODIS) was calculated by the Penman–Monteith method (hereafter MET) [3]. ET from Zhang et al. [4] was produced based on
the Global Inventory Modelling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) with the modified Penman–Monteith method (hereafter GIE). ET from Chen et al. [41] was produced by an algorithm based on the surface energy balance system (SEBS) (hereafter SET). ET form the Global Land Data Assimilation System (GLDAS) with Noah Land Surface was referred to as GET [2].

A gridded daily precipitation dataset was adopted in this study. The dataset is interpolated using observation meteorological stations and DEM data. The Assessment Report was conducted by the National Meteorological Information Centre (NMIC). The dataset can explain the spatial-temporal changes of precipitation with only minimal errors [42]. The gridded data sets have a high correlation with observation stations, which are widely used in China, especially for the Tibetan Plateau [43–46].

GLDAS-2.1 Noah monthly river discharge (R) was used in this study. The spatial resolution is 0.25° × 0.25°. The dataset is widely used for the Tibetan Plateau with acceptable errors [46].

The main goal of GRACE is to measure TWS in basin scale [30]. The RL05 gridded data obtained from the Center for Space Research (CSR) of University of Texas, the Jet Propulsion Laboratory (JPL), and the GeoForschungsZentrum (GFZ) were used to estimate TWS. The spatial resolution of the data was 1° from 2003 to 2014. Due to factors such as satellite orbital adjustment, some months of TWS data are missing. A simple linear method was used for data interpolation [20,22]. The arithmetic mean value of TWS from the three agencies after interpolation was adopted.

Monthly time series from the mean values of the precipitation, runoff, and the TWS anomaly during 2003–2014 are shown in Figure 3. The data summary was shown in Table 2. All the data were sampled to 0.05° on average to better capture the data changes at the basin boundary of the seven sub-basins. The advantage of regirding coarser resolution to the high resolution is to eliminate errors caused by the boundaries of sub-basins [47]. In this way, uncertainties caused by sub-basin boundaries would be reduced [48].

| Figure 3. Monthly time series from the mean values of the precipitation(mm/month), runoff (mm/month), and the TWS anomaly (mm/month) during 2003–2014. (a) Yellow River source region; (b) Yangtze River source region; (c) Salween River source region; (d) Mekong River source region; (e) Yarlung Zangbo basin; (f) Qaidam Basin; and (g) Inner Plateau. |
Table 2. Overview of the datasets.

| Datasets | Category                  | Spatial Resolution | Time Range         | Frequency | References |
|----------|---------------------------|--------------------|--------------------|-----------|------------|
| P        | Interpolation with observations | 0.1°  | 1980–2019          | Monthly   | [42]       |
| R        | Land surface model        | 0.25°             | 2000–2016          | Monthly   | [2]        |
| TWS      | Remote sensing            | 1°                | 2003–2017          | Monthly   | [30]       |
| MET      | Penman–Monteith           | 0.05°             | 2000–2015          | Monthly   | [3]        |
| GIE     | Modified Penman-Monteith  | 8 km              | 1982–2015          | Monthly   | [4]        |
| SET      | Surface energy balance system | 0.1°  | 2001–2015          | Monthly   | [41]       |
| GET      | land surface model        | 0.25°             | 1948–2015          | Monthly   | [2]        |

2.3. Methods to Estimate ET

2.3.1. Calculation of ET$_{ref}$

The four actual ET products was represented by ET$_p$. The traditional water balance method with GRACE satellite data was used to estimate ET (hereafter ET$_{ref}$) for the sub-basins [17,25]:

$$\text{Pre} - R - \text{ET} = \Delta \text{TWS} \quad (1)$$

where Pre represents precipitation (mm), R represents river runoff (mm), and ΔTWS is the change in TWS (mm) estimated by reconstructing GRACE satellite data. TWS contains: the soil moisture, snow water equivalent, ice, canopy water, and groundwater. R is zero in the Inner Plateau and Qaidam Basin. The calculated ET$_{ref}$ was used as the reference for correction of the different ET$_p$.

2.3.2. Ratio Correction of ET$_p$

The ratio correction method is mainly based on the traditional water balance method. The ratio of reference ET to the product ET (i.e., $r$ in Equation (2)) was used for correction. In this paper, two timescales were used: monthly scale and annual scale. Schematic diagram of ratio correction is shown in Figure 4.

$$r_i = \frac{\text{ET}_{ref,i}}{\text{ET}_{p,i}} = \frac{\text{Pre}_i - R_i - \Delta \text{TWS}_i}{\text{ET}_{p,i}} \quad (i = 1, 2, 3, \ldots, 12) \quad (2)$$

where $i$ represents the month, $\text{Pre}_i$, $R_i$, and $\Delta \text{TWS}_i$ are monthly average value during the 2003–2014.

![Figure 4. Schematic diagram for monthly ratio correction.](image-url)
A schematic diagram of the ratio bias correction method is shown in Figure 4. This method is used to correct the ETₚ by the ratio of ETₜᵣₑᶠ and ETₚ. The monthly overestimates and underestimates are corrected using the monthly ratio of factors.

2.3.3. Gamma Distribution Correction of ETₚ

Gamma distribution is a continuous probability function, which is a very important distribution [49]. The gamma distribution fits the meteorological factors very well [18,25,50]. The gamma distribution can be expressed as [49]:

\[ F(\text{ET}|\theta, \mu) = x^{\theta - 1} \frac{1}{\mu \Gamma(\theta)} e^{-\frac{x}{\mu}}, \text{ET} \geq 0, \theta, \mu > 0 \]  

(3)

where \( \theta \) is the shape of the function, \( \mu \) is the scale of the function; \( \Gamma \) is the gamma function.

The gamma distribution bias correction method has two steps [18,20,25]. First, the monthly ETₚ and ETₜᵣₑᶠ were fitted by the gamma cumulative distribution, and \( \theta_p, \mu_p \) and \( \theta_{ref}, \mu_{ref} \) were obtained. Then the inverse function \( (F^{-1}) \) was used to calculate the ET with \( \theta_{ref} \) and \( \mu_{ref} \) (Equation (4)). Therefore, the monthly ETₚ was corrected by filling the gap between the two gamma cumulative distribution functions (Figure 5) [20].

\[ \text{ET}_{first} = F^{-1}_\theta \left( F_\theta(\text{ET} | \theta_p, \mu_p) \right) \theta_{ref}, \mu_{ref} \]  

(4)

where ETₜᵣₑᶠ represents the first monthly corrected ET.

![Figure 5. Schematic diagram for the first step of the correction.](image)

Second, the annual bias was removed using the following equation [20]:

\[ \text{ET}_{corrected}(m) = \frac{P(a) - R(a)}{\text{ET}_{first}(a)} \text{ET}_{first}(m) \]  

(5)

where ETₜᵣₑᶠ is the corrected ET, ETₜᵣₑᶠ(\( a \)) and ETₜᵣₑᶠ(\( m \)) is the annual and monthly ET of the first step.

2.3.4. Uncertainty in Water Balance

All the components in the water balance were obtained from independent data sources, the uncertainties of ETₜᵣₑᶠ can be combined by summing uncertainties in each variable in quadrature [51]:

\[ \sigma_{ET_{ref}} = \sqrt{\sigma_{\text{Pre}}^2 + \sigma_{R}^2 + \sigma_{\text{TWS}}^2} \]  

(6)

where \( \sigma \) is the estimated uncertainty of the corresponding variable.

Uncertainty in the precipitation product was estimated in the assessment report, which was evaluated by the NMIC [42]. In the report, the error in precipitation was 5%
for summer and 3% for other seasons. For the monthly GLDAS runoff data, the error was less than 5%, with a correlation coefficient greater than 0.90 on the Tibetan Plateau [46]. In this study, we adopted 5% for the uncertainty assessment. Uncertainties in GRACE TWS were estimated from variability among the three RL05 TWS gridded data. We used the standard error of the three TWS data to represent the uncertainty [52]. The uncertainties were converted to mm/month using the average monthly data of long time series. The uncertainties of different components were summarized in Table 3 in the sub-basins.

### Table 3. Uncertainty Estimates of Different Components for the sub-basins.

| Sub-Basin       | $\sigma_{Pr}$ (mm/month) | $\sigma_R$ (mm/month) | $\sigma_{ATWS}$ (mm/month) | $\sigma_{ETref}$ (mm/month) |
|-----------------|--------------------------|-----------------------|-----------------------------|----------------------------|
| Spring          | ±0.22                    | ±2.70                 | ±2.58                       | ±0.37                      |
| Summer          | ±0.37                    | ±2.12                 | ±0.51                       | ±1.47                      |
| Autumn          | ±0.25                    | ±2.31                 | ±0.68                       | ±1.36                      |
| Winter          | ±0.16                    | ±2.83                 | ±0.86                       | ±0.37                      |
| Mean            | ±0.16                    | ±1.4                  | ±1.7                        | ±0.51                      |
| Yellow          | ±0.52                    | ±4.98                 | ±1.7                        | ±2.8                       |
| Yangtze         | ±4.98                    | ±2.73                 | ±2.8                        | ±4.1                       |
| Yarlung Zangbo  | ±1.08                    | ±3.55                 | ±2.5                        | ±3.5                       |
| Salween         | ±5.40                    | ±0.49                 | ±1.95                       | ±2.7                       |
| Mekong          | ±3.44                    | ±3.42                 | ±0.36                       | ±1.9                       |
| Qaidam          | ±1.36                    | ±0.62                 | ±0.95                       | ±2.7                       |
| Inner Plateau   | ±1.03                    | ±0.72                 | /                           | ±2.1                       |

2.3.5. Evaluation Criteria

The deviation (DE), root-mean-square error (RMSE), and correlation coefficient (CR) were used as test standards

$$DE = \frac{1}{m} \sum_{j=1}^{m} \left( \frac{U_j - V_j}{m} \right)$$  \hspace{2cm} (7)

$$RMSE = \sqrt{\frac{1}{m} \sum_{j=1}^{m} \left( \frac{(U_j - V_j)^2}{m} \right)}$$  \hspace{2cm} (8)

$$CR = \frac{\sum_{j=1}^{m} (U_j - \bar{U})(V_j - \bar{V})}{\sqrt{\sum_{j=1}^{m} (U_j - \bar{U})^2} \sqrt{\sum_{j=1}^{m} (V_j - \bar{V})^2}}$$  \hspace{2cm} (9)

where $m$ is the number of months, $U_j$ represents the monthly $ET_p$ or $ET_{corrected}$, and $V_j$ represents the monthly $ET_{ref}$, $\bar{U}$ represents the monthly mean $ET_p$ or $ET_{corrected}$, and $\bar{V}$ represents the monthly mean $ET_{ref}$.

### 3. Results

#### 3.1. Evaluation of $ET_p$

Figures 6 and 7 show the domain-averaged values of the four $ET_p$ and the $ET_{ref}$ in the seven sub-basins. The $ET_{ref}$ and $ET_p$ is maximum in summer and minimum in winter. The four $ET_p$ are significantly different from each other. The $ET_{ref}$ in the Yarlung Zangbo Basin is the greatest among the seven sub-basins, with an annual mean $ET$ of 659 mm. The annual mean $ET$ of the Qaidam Basin is the smallest, with an annual mean $ET$ of 143 mm. The annual mean $ET_{ref}$ in other sub-basins ranges from 246 to 549 mm. The $ET_p$ overestimated winter $ET$ in almost all the sub-basins and underestimated summer $ET$ in all the sub-basins except the Yellow River Basin.
In general, the four ET\textsubscript{p} are the most accurate with regard to the Yellow River and the worst in terms of the two endorheic basins. GET and GIET are the most accurate in estimating ET, followed by MET. SET is the worst at reproducing monthly ET in the ET\textsubscript{p}. GET is the best at reproducing monthly variations in the source of Yellow, Yangtze, Salween, and the Qaidam Basin. GIET was best for the source of Mekong, Yarlung Zangbo Basin and the Inner Plateau. There is no special advantage of MET and SET in the estimation of ET in the seven sub-basins.

### 3.2. Correction of ET\textsubscript{p}

The gamma distribution correction method and the ratio bias correction method were used to correct the four ET\textsubscript{p}. In order to compare the correction effects of the two correction methods, the four ET\textsubscript{p} before and after bias correction are compared in the seven sub-basins (Figure 8). The DE, RMSE, and CR values are shown in Table 4. After the gamma distribution and the ratio bias correction, the four ET\textsubscript{p} in the seven sub-basins showed greater CR with the ET\textsubscript{ref}, and smaller RMSE and DE values. Table 4 shows that the ratio bias correction method has the smallest DE and RMSE values and the greatest CR value. These statistical values show that the proposed ratio bias correction method performs better than the gamma distribution correction method. Moreover, the ratio bias correction method is simpler and more efficient to correct the ET\textsubscript{p}.
Figure 7. Seasonal variations of the ET\textsubscript{ref} (mm) and the ET products (mm) in the seven sub-basins averaged during 2003–2014. (a) Yellow River source region; (b) Yangtze River source region; (c) Salween River source region; (d) Mekong source region; (e) Yarlung Zangbo Basin; (f) Qaidam Basin; and (g) Inner Plateau.
Figure 8. Comparison of the monthly ET$_p$ with the ET$_{ref}$ before and after correction for the seven sub-basins on the Tibetan Plateau. The vertical axis represents ET$_p$ before correction, after ratio correction, and after gamma correction, respectively.
Table 4. Bias (mm/month), RMSE (mm/month), and CORR of the correction methods in comparison with the reference ET (mm/month).

| Criteria       | CorrectionMethod | Product ET | Gamma | Monthly Ratio |
|----------------|------------------|------------|-------|---------------|
| DE             | −13.61           | −0.03      | 0.01  |
| RMSE           | 17.6             | 14.2       | 10.1  |
| CR             | 0.95             | 0.91       | 0.97  |

Smaller DE and RMSE and larger CR are in bold.

As shown in Table 4 and Figure 8, the original ET<sub>p</sub> was not in good agreement with the ET<sub>ref</sub>. In terms of DE, the original ET<sub>p</sub> has the largest deviation, up to 13.61 mm, while the deviations of the corrected ET<sub>p</sub> are all less than 0.03 mm. The DE of the monthly ratio correction is the smallest, which is only 0.01 mm. In terms of RMSE, the original ET<sub>p</sub> has the largest deviation (up to 17.6 mm), and the deviation of monthly ratio correction is also the smallest, which is only 10.1 mm. The monthly ET after the ratio correction has the highest correlation with the ET<sub>ref</sub> (up to 0.97), while the gamma distribution bias correction has the lowest correlation (0.91). The proposed method reduced the deviations and the ET<sub>p</sub> became more accurate to represent the regional ET. It is simpler and more effective in correcting the four ET<sub>p</sub> compared with the gamma distribution bias correction method.

3.3. Spatial Distribution and Trend of ET over the Tibetan Plateau

Considering all the criteria, the monthly ratio correction method was adopted to obtain the optimal ET. We use arithmetic averaging to incorporate the four ET<sub>p</sub>. The average corrected ET<sub>p</sub> was combined to draw the distribution of ET on the Tibetan Plateau (Figure 9). Figure 9 shows the corrected ET distribution in the sub-basins on the Tibetan Plateau. The ET decreased from 1600 mm in the south to 26 mm in the north. The spatial distribution of ET is consistent with the distribution of precipitation. The distribution of ET is consistent with the result of Gao et al. [52], which was estimated using gauging stations. The ET of the Yarlung Zangbo Basin is the greatest among the seven sub-basins, ranging from 150 to 1605 mm. The ET is the smallest in the middle reach of the basin and greatest in the downstream. ET in the Qaidam Basin is the smallest, which is 150 mm. The average values of ET in the source regions of Yangtze, Salween, and Mekong River are almost the same at approximately 550 mm. The average ET of the Yellow River source region is 438 mm. The ET in both the Yangtze River source region and the Yellow River source region decreases from southeast to northwest. The distribution of ET of the Inner Plateau and Qaidam Basin also shows a similar pattern. The Inner Plateau is the largest region, located in the central area of the Tibetan Plateau. This region is less affected by monsoons [33], resulting in relatively small ET with an average value of approximately 200 mm. The ET decreases from 400 mm in the south and southeast to 80 mm in the north and northwest.

The trends on the Tibetan Plateau were estimated using the least square method [18,53]. The arithmetic average of the four corrected ET<sub>p</sub> was used to draw the distribution trend of ET on the Tibetan Plateau (Figure 10). The ET on the Tibetan Plateau increased from 2003 to 2014 with an average value of 1.2 mm/yr. The trend of ET decreased from 17 mm/yr in the southeast to −8 mm/yr in the northwest. The trend of ET in the Inner Plateau was decreasing among the seven sub-basins, while the others were increasing from 2003 to 2014. But the Inner Plateau has only a slight decreasing trend (−0.15 mm/yr). The trend in the Salween is the greatest among the seven sub-basins at 2.88 mm/yr. The trend in the Yangtze, Mekong, and Yarlung Zangbo Basins are similar, at about 2.5 mm/yr. The trends in the Yellow and Qaidam are 1.32 mm/yr and 0.50 mm/yr, respectively. The significance analysis shows that ET trends in the Inner Plateau, Qaidam, west of Yarlung Zangbo Basin, and Yellow River source region have not been identified (p > 0.1). The trends in the Salween, Yangtze, Mekong, and east of Yarlung Zangbo Basin are significant (p < 0.05).
Figure 9. Distribution of average corrected ET in the sub-basins on the Tibetan Plateau. (a) The spatial distribution of average corrected ET, (b) The statistics of average corrected ET in each sub-basin.

Figure 10. Distribution of corrected ET trends in the sub-basins on the Tibetan Plateau. (a) The spatial distribution of corrected ET trends, stippling denotes regions where the trend is significant at the 90% level ($p < 0.1$, t-test). (b) The statistics of corrected ET trends in each sub-basin. The * represents $p < 0.1$, and ** represents $p < 0.05$.

4. Discussion

4.1. Uncertainty of $ET_{rf}$

The $ET_{rf}$ (derived from the water balance) is to be taken as a reference. The uncertainty of $ET_{rf}$ is important, as this is a basis to correct $ET_p$ and is related to the reliability of the
corrected results. Table 3 shows the uncertainties of P, R, and TWS. The uncertainties of ET\textsubscript{ref} vary in the seven sub-basins (Tables 3 and 5). The annual uncertainties of ET\textsubscript{ref} in the five outflow basins (Yangtze, Yellow, Yarlung Zangbo, Mekong, and Salween) are less than 6%. But the annual uncertainties of ET\textsubscript{ref} in the two endorheic basins (Inner Plateau and Qaidam Basin) are 19% and 30%. The reason for this is that the vegetation cover in these areas is very minimal and the quality of remote sensing data is poor [38,44,52].

Table 5. The comparison of the average annual ET\textsubscript{p}, ET\textsubscript{ref}, and corrected ET of the sub-basins.

| Sub-Basin      | ET\textsubscript{p} (mm/yr) | ET\textsubscript{ref} (mm/yr) | Corrected ET (mm/yr) |
|----------------|-----------------------------|--------------------------------|----------------------|
| Yellow         | 440                         | 604                            | 445 ± 24             |
| Yangtze        | 506                         | 638                            | 535 ± 20.4           |
| Yarlung Zangbo | 389                         | 563                            | 664 ± 33.6           |
| Salween        | 369                         | 556                            | 571 ± 30             |
| Mekong         | 465                         | 623                            | 574 ± 22.8           |
| Qaidam         | 137                         | 161                            | 124 ± 24             |
| Inner Plateau  | 310                         | 331                            | 83 ± 25.2            |

We must also admit that the estimates of uncertainties are weak according to Li et al. [51] and the national technical report [42]. The uncertainty may not be very precise because there are few observations on the Tibetan Plateau. But the uncertainty can represent the relative differences among the seven sub-basins. We can use more precise data or integration of several reliable products to eliminate data uncertainty [17,22].

4.2. The Monthly Coefficients of Ratio Bias Correction

The ratio bias correction coefficients for the most optimal corrected ET\textsubscript{p} in each sub-basin are shown in Figure 11. The result shows different performances in each sub-basin and each month. In addition to the Inner Plateau and the Yellow River, the correction coefficients in spring and summer (March–August) are greater than 1, indicating that the original ET\textsubscript{p} would overestimate ET\textsubscript{a} in hot weather. All the correction coefficients are less than 1 in autumn and winter, indicating that the original ET\textsubscript{p} underestimated ET in cold weather for each sub-basin (Figure 9). The most significant overestimations occurred in the Qaidam Basin, the Yarlung Zangbo Basin, and the Salween River from April to June. The correction coefficients are much greater than 1. This may be related to the climate features of these basins. The climate in the Qaidam Basin is very dry, and the ET is relatively small.

![Figure 11](image_url) Figure 11. The coefficients of the monthly ratio bias correction in the seven sub-basins.
Uncertainties in the $ET_p$ come from the input of meteorological and surface cover data [18]. It is difficult to calculate ET in the Qaidam Basin due to the dry climate, which leads to a large error in $ET_p$. In the southwest Tibetan Plateau, clouds are formed due to the water vapor. The overestimations of ET in the Yarlung Zangbo Basin and the source of the Salween River Basin are affected by clouds. The $ET_p$ for the source regions of the Yellow River and the Mekong River most seriously underestimated the ET, with the correction coefficients less than 1 in all seasons. The correction coefficient of December was only about 0.2 in these two sub-basins. The freezing phenomenon in cold weather may be the main reason for the underestimation, because most remote sensing data have difficulty capturing phenomenon of freezing [54]. Other sub-basins were characterized by slight overestimation before monsoon and underestimation after monsoon (Figure 11).

4.3. Limitations

The monthly ratio correction method was adopted as an effective method to correct the ET. The corrected $ET_p$ are more reasonable and accurate than the original $ET_p$. But we should also be fully aware of the following limitations in the proposed monthly ratio correction method.

The water balance method with a corrected TWS was used to calculate the monthly ET as the $ET_{ref}$. Although the corrected results are reliable, the uncertainty in TWS is relatively large [17,18]. $ET_{ref}$ was calculated using the water balance method with the GRACE TWS, whereas the spatial resolution of the TWS data is $1^\circ$ and the temporal scale is monthly [30]. The $ET_{ref}$ is relatively accurate on the basin scale, and has been widely used to evaluate the change of global ET [22]. However, the resolution of this data is too coarse to capture the spatial variation of evaporation in small catchments [51]. The proposed correction should be carried out in large basins [20]. The uncertainty caused by the boundary effect should be considered when applying this method in small basins [17].

The input data (P and R) should also be considered carefully to calculate the $ET_{ref}$. The reliability of $ET_{ref}$ depends on the accuracy of P and R. In this study, the estimates of uncertainty is weak according to Li et al. [51] and the national technical report [42]. The integration of several reliable products will improve the accuracy of input data (P and R) [17,22,51].

5. Summary and Conclusions

This study presents an evaluation of four $ET_p$ in seven sub-basins in the Tibetan Plateau with the $ET_{ref}$ calculated by the water balance method. Obvious seasonal cycles were found in the $ET_{ref}$ and $ET_p$. The ET was at maximum in summer and minimum in winter over the period of 2003–2014. The four $ET_p$ are significantly different from the $ET_{ref}$, regardless of time series or monthly average.

Two correction methods were compared to correct the four $ET_p$. The proposed ratio bias correction method is simpler and more effective in correcting the four $ET_p$ compared with the gamma distribution bias correction method. The corrected ET improved the correlation coefficients, and reduced the biases and RMSEs.

The average corrected $ET_p$, which was obtained from the arithmetic mean of the four corrected $ET_p$, was combined to draw the distribution and trend of ET in the Tibetan Plateau. The ET on the Tibetan Plateau decreases from southeast to northwest. The average value of ET is 380 mm/yr ranging from 26 mm/yr to 1600 mm/yr. There is a general increasing trend of ET in the Tibetan Plateau, with an average value of 1.2 mm/yr over the period of 2003–2014.

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