Satellite evidence for no change in terrestrial latent heat flux in the Three-River Headwaters region of China over the past three decades

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Terrestrial latent heat flux (LE) in the Three-River Headwaters region (TRHR) of China plays an essential role in quantifying the amount of water evaporation and carbon sink over the high altitude Tibetan Plateau (TP). Global warming is expected to accelerate terrestrial hydrological cycle and to increase evaporation. However, direct field observations are lacking in this region and the long-term variability in LE remains uncertain. In this study, we have revised a semi-empirical Penman LE algorithm based on ground eddy covariance (EC) observations from an alpine grass site and provided new satellite-based evidence to assess LE change in the TRHR during 1982–2010. Our results show that the average annual terrestrial LE in the TRHR is about 38.8 W/m^2 and there is no statistically significant change in annual LE from 1982 to 2010. We also found that during the same time period, terrestrial LE over the east region of the TRHR significantly decreased, on average, by 0.7 W/m^2 per decade, which was driven primarily by the surface incident solar radiation (R_s) limitation, offsetting the increased LE over the west region of the TRHR caused by the increased precipitation (P) and soil moisture (SM).

1. Introduction

The terrestrial latent heat flux (LE) refers to the flux of heat from soil evaporation and vegetation transpiration and regulates climate change by altering the exchange of terrestrial energy, water and carbon with the atmosphere (Fisher *et al.* 2008; Trenberth *et al.* 2009; Liang *et al.* 2010; Yao *et al.* 2015). Especially in the Three-River Headwaters region (TRHR), which is a typical zone of the Tibetan Plateau (TP) of China and is most sensitive to climate change with the warming trend over past decades, LE is considered as a robust climatic predictor of water evaporation and carbon sink (Liu *et al.* 2008, 2014; Li *et al.* 2012; Zhang *et al.* 2013; Yao *et al.* 2016). Therefore, accurately estimating spatio-temporal variation in terrestrial LE over the TRHR is critical for understanding the hydrological cycle of the high altitude TP.

Global warming is expected to accelerate terrestrial hydrological cycle and to increase LE and evaporation in the TRHR (Liu *et al.* 2008; Trenberth *et al.* 2009). However, direct eddy covariance (EC) observations are lacking in the TRHR and hamper

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to verify the expected changes in LE and evaporation. Although many satellite evapotranspiration (ET) products, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) product (MOD16), are widely used to monitor the change in regional LE (Fisher *et al.* 2008; Jung *et al.* 2010; Mu *et al.* 2011; Yao *et al.* 2013), data are missing in the TRHR due to the existing gaps of MOD16 product. Many satellite-based LE algorithms (e.g., Budyko equation, energy residual method) are also used to assess the variation in LE in the high altitude TRHR (Liu *et al.* 2008). These studies show that an increasing trend in annual terrestrial LE occurs in the TRHR over the past two to three decades (Liu *et al.* 2008; Zhao *et al.* 2009). However, large uncertainties exist among these algorithms because recalibration of the algorithm parameters is generally neglected in previous studies for lack of needed data in the TRHR. As a result, little is accurately known about the spatio-temporal characterization of the response of the LE in the TRHR to hydro-climate on large spatial scales over the past three decades.

Recently, Wang *et al.* (2010) proposed an operational semi-empirical Penman (SEMI-Penman) algorithm to monitor global terrestrial LE on decadal scales based on a Penman equation and up-scaling local EC observations. One limitation of the SEMI-Penman algorithm is that the land cover types of the training EC observation sites do not include alpine grass, which makes LE estimates uncertain in the TRHR. Because the main land cover type is grassland and alpine meadow accounting for more than 65% of the total area of the TRHR, EC observed data for alpine meadow sites in Qinghai Province, China, can be considered as references to revise the SEMI-Penman algorithm for LE estimation in the TRHR. In this study, we assessed the variation in terrestrial LE in the TRHR and its attributions over the past three decades with an alternative revised SEMI-Penman algorithm.

2. Materials and methods

2.1 *Study area*

The TRHR, the source area of the Yellow, Yangtze and Lantsang rivers, is located in the southern region of Qinghai Province, China, with the latitude ranging from 31.65° to 36.20°N and longitude being 89.75° to 102.38°E (figure 1). The TRHR is known as 'Chinese water tower' because the topography of the most parts of the study area is a plateau region with average 4000 m above sea level. The annual mean temperature is below 10°C and annual mean rainfall of this region is about 513 mm. More than 80% of the annual rainfall occurs during the summer season from June to August. Alpine meadow, widely distributed at 3500–4000 m, is the main ecosystem type in the TRHR and is dominated by *Kobresia* spp (Xu *et al.* 2008a; Fan *et al.* 2010). Figure 1 shows the International Geosphere–Biosphere Programme (IGBP) land cover types from MOD12 products that characterise the study region.

2.2 *Data*

Ground-measured flux data of eddy covariance (EC) from 1 January, 2002, to 30 December, 2004, at Haibei flux tower site adjacent to the THTR were collected from Asiaflux website (http://www.asiaflux.net/). The corresponding flux data including LE, sensible heat flux (H), surface incident solar radiation (R_s), surface net radiation flux (R_n), soil heat flux (G), precipitation (P), relative humidity (RH), wind speed (WS), vapour pressure (e) and air temperature (T_a), averaged over 30 min, were used in this study. Post-processing of the EC data steps includes de-spiking, sonic temperature, and coordinate corrections (Xu *et al.* 2008b). We also used the method developed by Twine *et al.* (2000) to correct the LE values at the Haibei site due to the energy imbalance problem of the EC method. Because the ecosystem type of the Haibei site is also alpine meadow and both the TRHR and Haibei site belong to the same plateau continental climate, the EC data can be used to revise the SEMI-Penman algorithm for estimating LE in the TRHR.

To drive the SEMI-Penman algorithm, we used the bimonthly NOAA/AVHRR normalised difference vegetation index (NDVI) product provided by the Global Inventory Modeling and Mapping Studies (GIMMS) group at NASA GSFC at a spatial resolution of 8 km during 1982–2010 (Tucker *et al.* 2005). The daily NDVI values were temporally interpolated from the bimonthly averages using linear interpolation. To estimate regional LE, we used the gridded meteorological datasets for daily T_a, P, R_s, RH, WS and e for the period 1982–2010, on a 0.1°× 0.1° grid. These datasets were developed by Data Assimilation and Modeling Center for Tibetan Multi-spheres, Institute of Tibetan Plateau Research and Chinese Academy of Sciences (CAS) and provided by Environmental & Ecological Science Data Center for West China (Yang *et al.* 2010; Chen *et al.* 2011; He and Yang 2011). Land surface soil moisture (SM) was derived from the Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR–E) sensor on the Aqua satellite for the period 2003–2010 on a 0.25 degree spatial resolution provided by the National Snow and Ice Data Center (NSIDC) (Lobl 2001). To better correspond with the gridded meteorological datasets, the GIMMS-NDVI and

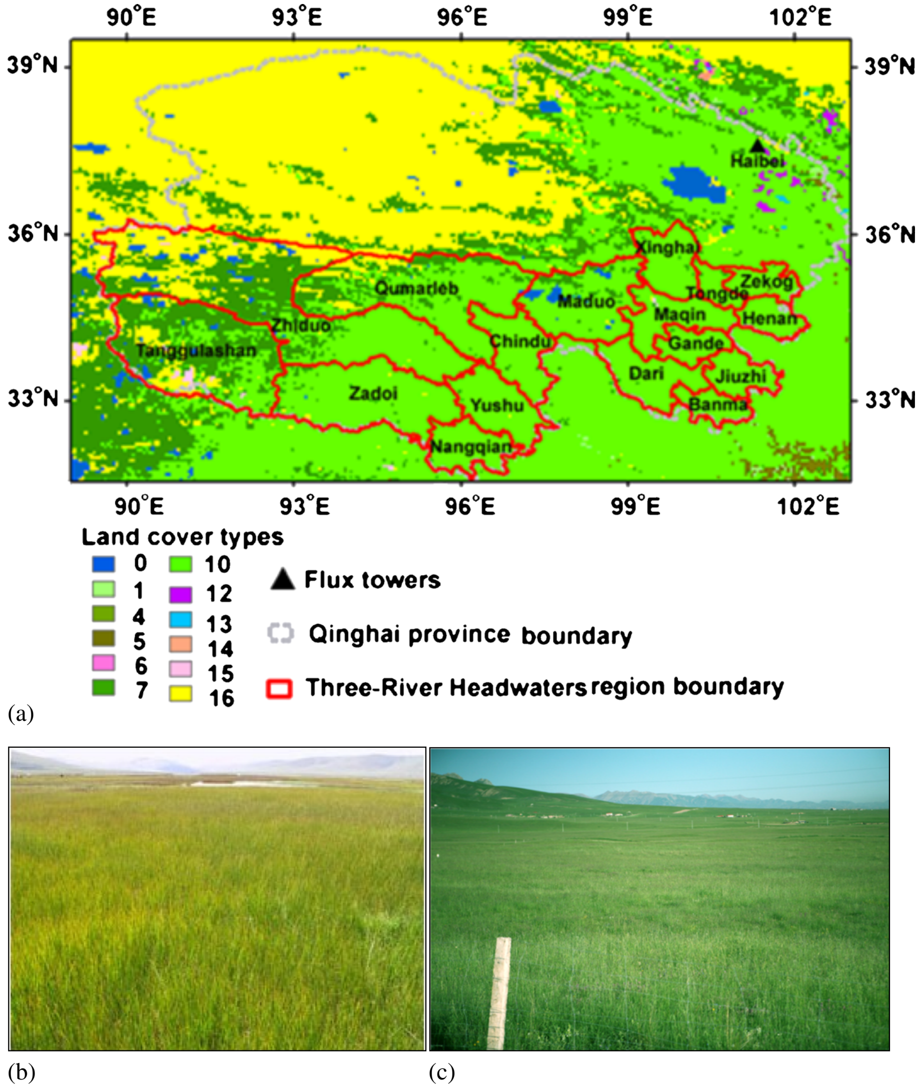

Figure 1. **(a)** Sketch map of the Three-River Headwaters region in the Qinghai–Tibetan Plateau (TP), China. IGBP land cover types are shown: 0: water body; 1: evergreen needleleaf forest; 2: evergreen broadleaf forest; 3: deciduous needleleaf forest; 4: deciduous broadleaf forest; 5: mixed forest; 6: closed shrubland; 7: open shrubland; 8: woody savanna; 9: savanna; 10: grassland; 11: permanent wetland; 12: crop land; 13: urban/build up; 14: crop land/natural vegetation mosaic; 15: snow/ice; and 16: barren lands. **(b)** Photo of alpine meadow for the Haibei site (photo source from Chinaflux: http://www.chinaflux.org/gczd/index.aspx?nodeid=86). **(c)** Photo of alpine meadow for the TRHR (photo source from Upper and Middle Yellow River Bureau: http://www.hhsb.gov.cn/news/9634).

AMSR–E *SM* data were interpolated into a resolution of 0.1°×0.1° using bilinear interpolation method.

2.3 *Methods*

Considering that the semi-empirical Penman LE (SEMI-Penman) algorithm, developed by Wang *et al.* (2010), includes the effects of WS on LE and can be used for detecting regional LE on decadal scales, its coefficients can be revised to assess the variation in LE in the TRHR and the algorithm can be written as:

$$LE_{es} = a_1(LE_E + LE_A) + a_2(LE_E + LE_A)^2, \quad (1)$$

$$LE_E = \frac{\Delta}{\Delta + \gamma} R_s[a_3 + a_4 NDVI + (1 - RH)(a_5 + a_6 NDVI)] \quad (2)$$

and

$$LE_A = \frac{\gamma}{\Delta + \gamma} WS[a_7 + (1 - RH) \times (a_8 + a_9 NDVI)] VPD, \quad (3)$$

where LE_{es} is the estimated LE. $a_1 = 0.819$, $a_2 = 0.0017$, $a_3 = 0.476$, $a_4 = 0.284$, $a_5 = -0.654$, $a_6 = 0.264$, $a_7 = 3.06$, $a_8 = -3.86$ and $a_9 = 3.64$. Δ is the slope of the saturated vapour pressure curve (KP_a/°C), γ is the psychrometric constant (KP_a/°C), *VPD* is the vapour pressure deficit

(KP_a). Considering that all empirical coefficients were calibrated using EC data at 64 globally distributed sites and these sites include a variety of land cover: grass, rangeland, pastures, crop fields, forests and mixed land cover, and considering that their locations also differ greatly from each other, we find these sufficiently representative for the purpose of estimating LE in the TRHR. In this study, we used a simple linear regression equation to recalibrate these empirical coefficients based on the statistical relationships between the estimated LE using the equation (1) and ground-measured LE at Haibei site and it can be expressed as:

$$LE_c = k \times LE_{es}, \tag{4}$$

where LE_c is the corrected LE using the EC data at the Haibei site and k is the linear regression coefficient. Since there are 3 years (2002–2004) of data available at Haibei flux tower site, we selected a three-fold cross-validation method to evaluate the performance of equation (4). We divided the samples into three groups with roughly equal numbers and each group having one year of data. Then equation (4) for each of the three groups was independently validated using the samples of the remaining two groups.

For water body, the Priestley–Taylor (PT) equation was then used to estimate LE of water evaporation (Priestley and Taylor 1972).

$$\mathrm{LE} = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G), \tag{5}$$

where α is the PT coefficient, which refers to evaporation arising from the atmospheric VPD and was set to 1.26 in this study.

3. Results and discussion

3.1 *Evaluation of algorithm performance in estimating LE*

The comparison of the measured and estimated daily LE at the Haibei flux tower site using equation (1) demonstrates that the original SEMI-Penman algorithm tends to underestimate LE

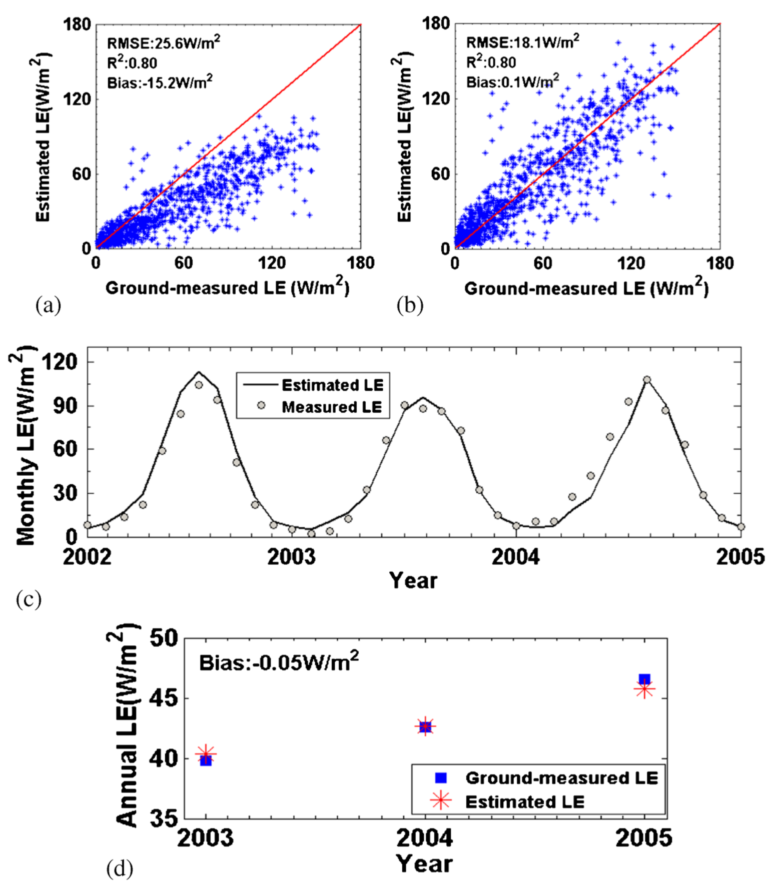

Figure 2. **(a)** Comparison of the daily LE observations for Haibei site and the corresponding estimated LE using the equation (1); **(b)** cross-validation of the daily LE observations for Haibei site and the corresponding estimated LE using the equation (4); **(c)** comparison of the monthly LE observations for Haibei site and the corresponding estimated LE using the equation (4); and **(d)** comparison of the annual LE observations for Haibei site and the corresponding estimated LE using the equation (4).

significantly for alpine meadow site (figure 2a). On average, the daily LE is estimated with a root mean square error (RMSE) of 25.6 W/m^2 and a bias of -15.2 W/m^2. The squared correlation coefficient (R^2) is 0.80 ($p < 0.01$).

To improve the performance of the SEMI-Penman algorithm for estimating LE in the TRHR dominated with mainly alpine meadow, we used the equation (4) and EC data at the Haibei site to revise the SEMI-Penman algorithm. Figure 2(b) shows the comparison between the daily LE observations and LE estimates using the equation (4) based on a three-fold cross-validation method for alpine meadow site. One can notice that the regression based on 2/3 of samples of the datasets successfully estimates the other 1/3 of the data and the SEMI-Penman algorithm has improved the accuracy of LE estimates for alpine meadow site by decreasing RMSE by 7 W/m^2 compared to the original algorithm.

Based on all meteorological variables and ground-observed EC data of Haibei site, equation (4) can be written as:

$$LE_c = 1.548 \times LE_{es}. \qquad (6)$$

Figure 2(c) presents a time series for monthly LE measurements and predictions at Haibei site using the equation (6). It is clear that equation (6) yields reasonable seasonal LE variations that are close to the ground-measured values. Figure 2(d) shows that the equation (6) offers the highest simulation accuracy for annual LE with a bias of -0.05 W/m^2, indicating the revised algorithm captures the observed seasonal and inter-annual variations in LE.

Because the original SEMI-Penman algorithm includes the variety of land cover (e.g., pastures, crop fields, forests) and the revised algorithm also considers the effects of the alpine meadow, we find the revised algorithm is sufficiently representative for the purpose of estimating terrestrial LE in the TRHR. In this study, the observed EC data is considered as accurately 'true' value to revise the LE algorithm, but approximately 20–50 W/m^2 of the EC measured errors and approximately 0.8 of energy closure ratio ($(LE+H)/(R_n - G)$) will also lead to large uncertainties when estimating LE in the TRHR (Wilson *et al.* 2002; Foken 2008; Mahrt 2010). The spatial resolutions of the AVHRR-NDVI and meteorological gridded datasets are all more than 8 km while the EC sites have a footprint of approximately 200 m (McCabe and Wood 2006; Yao *et al.* 2014a). This spatial mismatch between the flux tower site footprints and gridded footprints will also cause large uncertainties for LE estimation. In addition, error propagation through calculations, including EC energy closure correction, threshold filtering, gap filling and temporal interpolation, will amplify the errors for LE estimation (Wang and Dickinson 2012; Shi and Liang 2014; Yao *et al.* 2014b).

3.2 *Spatial patterns of terrestrial LE*

Based on equation (6) driven by AVHRR-NDVI and gridded meteorological data, we produced regional LE product in the TRHR with a spatial resolution of 0.1 degree during 1982–2010. The spatial distribution of the annual LE is consistent with the previous studies (Liu *et al.* 2008; Zhao *et al.* 2009). As shown in figure 3, the highest annual LE occurs in the south-east humid regions, whereas the north-west arid regions of the TRHR have the lowest annual LE due to the surface moisture limitations and their short growth seasons.

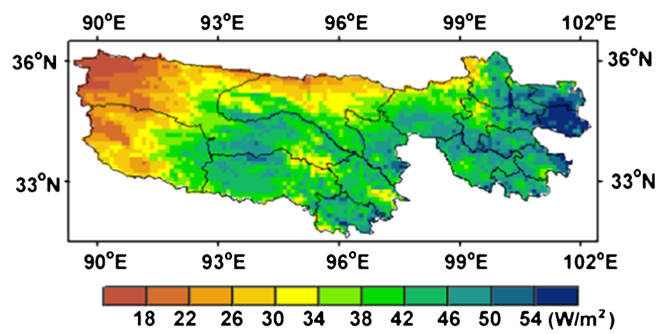

Figure 3. Spatial patterns of mean annual terrestrial LE in the TRHR from 1982 to 2010.

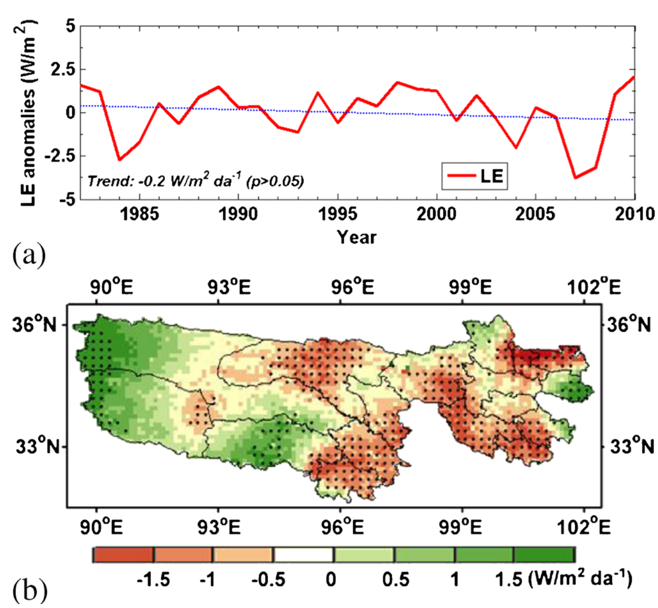

Figure 4. (**a**) Inter-annual variability of the terrestrial LE anomaly and (**b**) spatial distribution of the terrestrial LE trends in the TRHR. The dashed lines refer to the linear trends for 1982–2010. The black solid dots refer to grids with 95% confidence.

The mean annual land LE value for the TRHR during 1982–2010 is approximately 38.8 W/m^2 (35–40.8 W/m^2), which is higher than the values of other studies (Liu *et al.* 2008; Zhang *et al.* 2010). For example, Liu *et al.* (2008) reported the mean annual ET between 1980 and 2000 in the TRHR was 217.8 mm (or 16.9 W/m^2) based on the water and heat balance (WHB) equation. Zhang *et al.* (2010) used the Penman–Monteith (PM) algorithm to estimate ET during 2006–2007 in the TRHR and found the mean annual ET for steppe was 275.4 mm (or 21.4 W/m^2). The primary cause of this discrepancy in estimating annual LE may be a deficiency of observations modifying the parameters of the previous WHB and PM methods.

3.3 *Variation in terrestrial LE over the past three decades*

Our terrestrial LE estimate of the TRHR, derived from remote sensing and gridded meteorological observations, demonstrates that the linear trend in terrestrial LE has been found to be slightly negative, at about −0.2 W/m^2 per decade for 1982–2010, and the trend is not statistically significant (p >0.05) (figure 4). The negative LE trend with no significant confidence is opposite to the previous findings due to the expected accelerated hydrological cycle associated with rising temperature (Liu *et al.* 2008; Zhang *et al.* 2010). Indeed, for the same time period, terrestrial LE over the west region (west of 95°E) of the TRHR slightly increased on average by 0.5 W/m^2 per decade. However, there is no significant correlation between inter-annual variability in T_a and LE variability. We wondered whether variability in P could be the reason for the rising of LE trend over the west region (west of 126°E) of the TRHR, which belongs to the semi-arid and arid regions. Figure 5 shows the strong coherence between 1982–2010 LE trends derived from satellite data, and trends in the independent gridded P over the west region of the TRHR in which surface moisture is expected to affect LE. Overall, the correlation coefficient between the annual anomalies of LE and P over the west region of the TRHR was 0.60 ($p < 0.05$). In theory, *SM* trends are more consistent with LE trends because *SM* is a better proxy for moisture supply of LE and inter-annual variability in *SM* correlates well with P variability (Jung *et al.* 2010; Zeng *et al.* 2014) (figure 6). In arid and semi-arid regions, scarce P leads to dry soil and LE becomes restricted by *SM* and P. Yet, the relatively short time period (2003–2010) of AMSR–E *SM* data fails to detect the variation in *SM* over the past three decades.

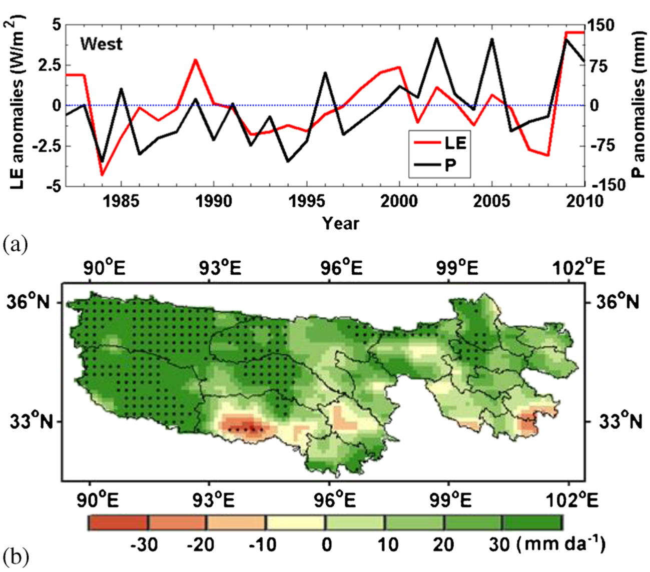

Figure 5. (**a**) Inter-annual variability of the terrestrial LE and P anomaly in the west region of the TRHR. (**b**) Spatial distribution of the terrestrial P trends for 1982–2010 in the TRHR. The black solid dots refer to grids with 95% confidence.

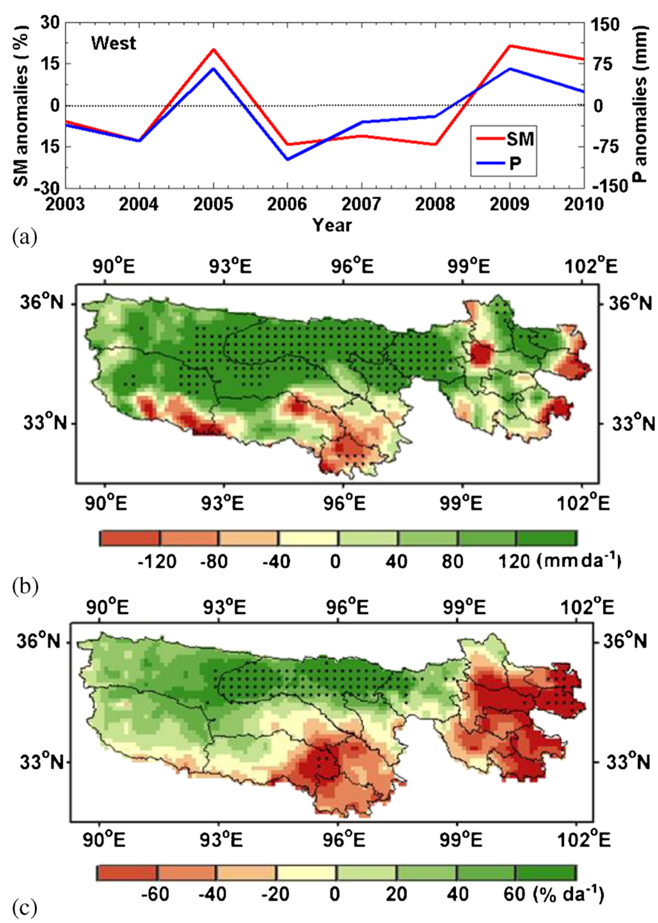

Figure 6. (**a**) Inter-annual variability of the terrestrial P and AMSR–E SM anomaly in the west region of the TRHR. Spatial distribution of the terrestrial (**b**) P and (**c**) AMSR–E trends for 2003–2010 in the TRHR. The black solid dots refer to grids with 95% confidence.

The pattern of increasing LE matched by a P rising illustrates that increasing P is the main mechanism, contributing to the rising LE trend over the west region of the TRHR during 1982–2010 (Jung *et al.* 2010; Yao *et al.* 2014b).

However, in the eastern humid regions (east of 95°E) of the TRHR, terrestrial LE significantly decreased on average by 0.7 W/m^2 per decade from 1982 to 2010; which was consistent with the variation in R_s (figure 7), offsetting the increased LE over the west region of the TRHR caused by the increased P. Statistically significant ($p < 0.05$) positive correlations between annual LE and R_s were found in 78% of the east region of the TRHR. The strong spatial consistency of the patterns in the estimated LE and R_s trends indicates that decreasing R_s in the eastern humid regions of the TRHR is the primary contributor to the variation in terrestrial LE because the east region is an energy-limited environment. Other mechanisms that could be responsible for a decreasing LE seem to be less important because of the weak correlations between the variation in LE and other climate factors. Many scientists reported that decreasing R_s trend may be caused by the steadily increasing aerosol optical depth (AOD) in the eastern and central Tibetan Plateau (TP) or in the surrounding regions over the past decades, especially after 1980 (Liang and Xia 2005; You *et al.* 2013). However, Tang *et al.* (2011) supported the view that the importance of cloud changes in altering R_s may be comparable to that of the aerosol changes. The detailed causes of the variation in R_s still remain uncertain. Based on our results, we argue that variations in both P and R_s, rather than $T_{a,}$ are the most climate variables to alter the trend in LE in the TRHR. Because the significance of these trends is limited by the relatively short time period of the satellite record, it is difficult to assess whether this is normal climate oscillation or a climate-change signal associated with carbon sink and regional atmosphere feedback.

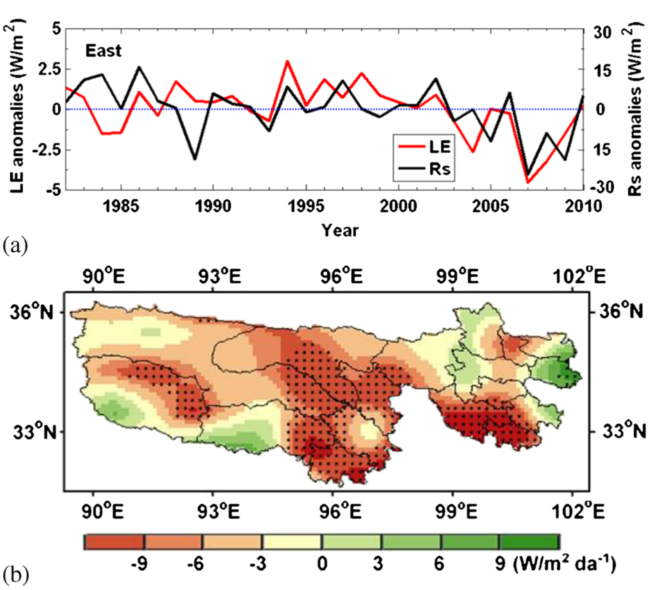

Figure 7. (**a**) Inter-annual variability of the terrestrial LE and R_s anomaly in the east region of the TRHR. (**b**) Spatial distribution of the terrestrial R_s trends for 1982–2010 in the TRHR. The black solid dots refer to grids with 95% confidence.

4. Conclusions

We estimated the spatio-temporal change in terrestrial LE in the TRHR from 1982 to 2010 using a semi-empirical Penman LE algorithm based on ground eddy covariance (EC) observations from an alpine grass site in this study. The mean annual land LE value for the TRHR during 1982–2010 is approximately 38.8 W/m^2 (35–40.8 W/m^2), which is higher than the values of other studies due to the deficiency of observations modifying the parameters of the previous WHB and PM methods. In contrast to the concurrent increasing trends in LE in the TRHR due to the global warming, we have provided satellite evidence that there is no statistically significant change in annual LE from 1982 to 2010. However, we also found that terrestrial LE over the east region of the TRHR significantly decreased on average by 0.7 W/m^2 per decade due to the decreasing R_s, offsetting the increased LE over the west region of the TRHR due to the rising P.

There are a few problems that deserve further study. Our revised semi-empirical Penman LE algorithm was modified by EC data of an alpine grass site, which ignores the revision for other land cover types and suffers from a 'space for time' substitution hypothesis. The effects of rising atmospheric CO_2 concentrations were also ignored in our algorithm, which causes additional uncertainties. In the future, we will focus on the impacts of the land use change and increasing CO_2 on terrestrial LE in the TRHR over the past several decades.

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