Point-by-point responses to Referee #1

This paper attempts to quantify relative importance of different climate drivers on dryness trends over continental East Asia. The authors find that the drying trends in arid regions are mostly explained by reduced precipitation but it is due to the increase in atmospheric water holding capacity in humid areas. While the topic that aims at understanding influence of different aspects of the climate on dryness is interesting, this paper has number of problems and is not of the quality acceptable for publication. My main concern is related to methods used in the study.

[Reply] We appreciate your critical reviews and technical comments. Detailed responses to individual specific comments are presented below.

1. It is unclear how the computation is conducted. In particular, how did the author derive the numbers used in Fig. 1? Did they computed the station values first and then average over the region for PET and P separately or did they compute PET/P at individual station and then average over the region? The order of calculation would have an impact on the time series used to plot Fig 1a.

[Reply] These variables are calculated at each station, then averaged over a region to construct regional means. Except for directly measured variables (surface air temperature, precipitation, 10m wind speed, sunshine duration, and relative humidity), all variables are computed at each station based on daily observation. The annual-mean values, climatologies, and corresponding anomalies are calculated at each station using the daily values. The station values are averaged over each hydro-climate regimes to compute regional means. We have added descriptions about the order of computation in the revised manuscript.

Lines 81-82: We compute daily *PET* and *PET/P*, and then estimated annual-mean values at individual weather sites.

Lines 88-89: To identify the climate variable that contributed most significantly to the observed *PET/P* trends, relative influences of changes in *P*, *Rn*, *WS*, *Ta*, and *RH* on the *PET/P* trends are computed at individual weather sites.

Lines 115-116: Note that the temporal variations are average of *PET/P* anomalies at 56, 50, and 51 weather sites located in the regions of arid, transitional, and humid climate regimes.

2. It is unclear how the statistical significance of the change point in Fig. 1 was determined. What kind of test for statistical significance was employed for equation (6)? Would the error term epsilon in (5) follow a Gaussian distribution? More importantly, as the authors moving i in (4), the authors are

conducting multiple tests. This means that the statistical significance would be incorrect if multiple testing (which the author did not mention) is not explicitly considered. Additionally, Fig. 1 does show long-term trend but the model (5) only considered a step function which is not correct. If a linear trend is considered in (5), would the authors still find a change point around 1980? Note that if there is a long-term trend in the series and if that trend is not considered in the change-point detection, one would always detect a change point in the middle of the time series. This is not useful and it seems that this is what the authors were doing. There is a body of climate literature discussing proper models and tests for the detection of change point but authors do not seem to be aware such studies.

5. Fig. 1 does not support the use of step regression of (5). It looks more like a long term trend with the last few years reversed that trend rather than an abrupt change in the 1980s. This would also invalidate the subsequent analyses regarding different impacts of precipitation and temperature change before and after 1980 as discussed in the paper.

[Reply] Our answers below apply to both the second and fifth comments because these two comments are related to the long-term trend in temporal variation of *PET/P*.

As commented, there is a significant trend in temporal variations in *PET/P* ($p < 0.05$) for 1961-2010 shown in figure 1a of the original manuscript because the trends in *PET/P* are negative at 86.7% of the weather sites examined in this study (Fig. S1a). However, for most stations, *PET/P* trends for 1961-2010 are below the 95% confidence level except for some stations in the northwestern China (Fig. S1a). A few stations show significant trends over the monsoon region (> 100ºE) for which we focus on. This spatial distribution of the *PET/P* trends is more similar the *P* trends than the *PET* trends (Fig. S1). The spatial patterns of the *P* trends are well-known in previous studies: significant increases in *P* over the northwestern China (Zhai et al., 2005; Shi et al., 2007; Piao et al., 2010) and insignificant trends over the monsoon region (Wang and Ding, 2006; Piao et al., 2010). Figure S1 is added to the revised manuscript as figure 3 in order to show that the trends in *PET/P* and *P* over the monsoon regions are not significant for the 1961-2010.

In this study, we separate the monsoon region into three regions based on the 50-year climatology of *PET/P*: arid (*PET/P*>2), transitional (1<*PET/P*<2), and humid (*PET/P*<1). Figure S2 shows the temporal anomalies of annual-mean *PET/P* for 1961-2010 over the three regions in the monsoon region. Because the temporal variations of *PET/P* are much larger in the arid region, figure 1 in the original manuscript may not well show the variations of *PET/P* in the transitional and humid regions. In addition, the linear trend in *PET/P* variations is not significant in the arid and humid regions ($p > 0.1$ for the both regions). Only the transitional region shows a significant trend in the PET/P variation ($p < 0.05$). Thus, we conclude that the time series shown in original figure 1 gives incomplete (and can be misleading) information to readers. We removed the original figure 1 and added figure S2 to the revised manuscript as figure 4.

There are numerous studies about decadal variations in the atmospheric circulation and rainfall over the monsoon region around 1980 (Gong and Ho, 2002; Zhou et al., 2008; Ding et al., 2008; Ha et al., 2012). Based on both insignificant trends in *PET/P* over the monsoon region for 1961-2010 (figure S1) and the background assessments on the decadal variations of monsoon circulation, we can assume that an abrupt change exists in the temporal changes in *PET/P* over the monsoon region around 1980. Thus, the change-point method is used to examine a year reasonable to divide the analysis period into the pre- and post-transition periods. In the revised manuscript, three change-point methods are used to estimate a timing of an abrupt change in the temporal variation of *PET/P* in each climate regime: 1) detection of change-point based on cumulative sum (Pettitt, 1980), 2) detection of change-point based on simple linear regression model (Lund and Reeves, 2002), and 3) detection of shifts in the mean values between two periods (Beaulieu et al., 2012). Also, the statistical significance of change-points is determined.

At first, we try to find the change-point of the *PET/P* variations for the three regions when a cumulative sum for the *PET/P* variations for the ith year (C_i) is greatest (Pettitt, 1980). The cumulative sum C_i is calculated as follows:

$$C_0 = 0 \qquad \text{(S1)}$$

$$C_i = C_{i-1} + (X_i - \bar{X}) \qquad \text{(S2)}$$

where X_i is the *PET/P* anomaly in year i, and $\bar{X}$ is the averaged *PET/P* for the whole analysis period. The year of abrupt change in *PET/P* is 1983, 1980, and 1980 in arid, transitional, and humid regions, respectively. For the transitional region, we apply this method after removing the linear trend, but the result remains the same. A simple bootstrap analysis is used to determine the confidence level (Taylor, 2000). A difference of the maximum and minimum of cumulative sum is computed as the following equation:

$$C_{diff} = C_{max} - C_{min} \qquad \text{(S3)}$$

where C_{max} and C_{min} are the maximum and minimum of cumulative sum. Next, we generate a bootstrap sample of 50 units by randomly reordering values of the original time series. We compute C_{diff}^0 based on the bootstrap sample by performing the same processor following equations (S1), (S2), and (S3) to determine whether C_{diff} is less than C_{diff}^0 or not. If the number of bootstrap sample is N, the confidence level of the change-point γ is defined as the following equation:

$$\gamma = \frac{x}{N} \qquad \text{(S4)}$$

where x is a number of bootstraps which satisfies $C_{diff}^0 < C_{diff}$. We use 5000 bootstrap samples to determine the confidence level of the year of abrupt change. The determined confidence levels are 0.613, 0.996, and 0.954 for the arid, transitional, and humid regions, respectively.

The second change-point method is based on the linear regression model (Lund and Reeves, 2002). Previously, we adopt a method used in Elsner et al. (2000), however, this method can overestimate change-points (Lund and Reeves, 2002). The method uses two simple linear regression models written as the following equation:

$$X_i = \begin{cases} a_1 + b_1 i + e_t, & 1 \le i \le c \\ a_2 + b_2 i + e_t, & c < i \le n \end{cases} \qquad \text{(S5)}$$

where X_i is time series of the *PET/P* variations, a_1 and a_2 are intercepts, b_1 and b_2 are the trends before and after the time of abrupt change c. e_t is the error of the linear regression model.

For the time c $(2 \le c \le n-1)$, the parameters of the regression model can be computed based on a least squares estimation as the following equations:

$$\hat{b}_1 = \frac{\sum_{i=1}^{c}(i-\overline{\iota_1})(X_i-\overline{X_1})}{\sum_{i=1}^{c}(i-\overline{\iota_1})^2}, and\ \hat{b}_2 = \frac{\sum_{i=c+1}^{n}(i-\overline{\iota_2})(X_i-\overline{X_2})}{\sum_{i=c+1}^{n}(i-\overline{\iota_2})^2} \qquad \text{(S6)}$$

$$\hat{a}_1 = \overline{X_1} - \hat{b}_1\overline{\iota_1}, and\ \hat{a}_1 = \overline{X_2} - \hat{b}_2\overline{\iota_2} \qquad \text{(S7)}$$

where $\overline{X_1}$ and $\overline{X_2}$ are the averages of X_i, and $\overline{\iota_1}$ and $\overline{\iota_2}$ are the averages of i before and after time c, respectively. The test statistic F_c is represented as the following equation:

$$F_c = \frac{(SSE_R - SSE_F)/2}{SSE_F/(n-4)} \qquad \text{(S8)}$$

where

$$SSE_F = \sum_{i=1}^{c}\left(X_i - \hat{a}_1 - \hat{b}_1 i\right)^2 + \sum_{i=c+1}^{n}\left(X_i - \hat{a}_2 - \hat{b}_2 i\right)^2 \qquad \text{(S9)}$$

$$SSE_R = \sum_{i=1}^{n}\left(X_i - \hat{a}_R - \hat{b}_R i\right)^2 \qquad \text{(S10)}$$

$$\hat{a}_R = 12\frac{\sum_{i=1}^{n}(X_i-\bar{X})\, i}{n(n+1)(n-1)}, and\ \hat{b}_R = \frac{1}{n}\sum_{i=1}^{n}(X_i - \hat{a}_R i) \qquad \text{(S11).}$$

If $c = 1$, the first term in the right-hand side of Equation (S9) is set to zero; for $c = n$, the second summation of Equation (S9) is set to zero. The time when the maximum value F_c exceeds the critical values of the F_{max} percentiles (5.91 and 6.92 for 90% and 95% confidence level, respectively; Table 1 in Lund and Reeves, 2002) is selected as the change point. Figure S3 shows the distribution of the statistic F_c over the arid, transitional, and humid regions. Based on the F_c values, only the transitional region shows an abrupt change of *PET/P* around 1980. Thus, we can conclude that there is a trend shift around 1980 in the transitional region. No significant shifts in the *PET/P* trends are fount for the arid and humid regions.

In addition to the two kinds of change-point methods, we used another method which detects shifts in the mean values between two periods to account for the decadal variations in monsoon circulation and rainfall over the analysis region. This method can be expressed as:

$$X_i = \begin{cases} m_1 + e_t, & 1 \le i \le c \\ m_2 + e_t, & c < i \le n \end{cases} \qquad \text{(S12)}$$

where m_1 and m_2 are the means before and after the time c (Beaulieu et al., 2012). For all c from 1 to n, the difference between m_1 and m_2 (Δm_c) is calculated. The abrupt change is determined at the time r at which $\Delta m_r = \max(\Delta m_c)$. The years of abrupt change based on this method are 1983, 1980, and 1970 over the arid, transitional, and humid regions, respectively. The significance test of these years is conducted using student's t-test. The test statistic T is expressed as following:

$$T = \left| \frac{m_{1r} - m_{2r}}{\sqrt{\sigma_{1r}^2/r + \sigma_{2r}^2/(n-r)}} \right| \qquad \text{(S13)}$$

where m_{1r} and m_{2r} are the means; σ_{1r}^2 and σ_{2r}^2 are the variance before and after the time r. Values of T are 1.870 ($p < 0.1$), 4.744 ($p < 0.01$), and 2.106 ($p < 0.05$) over the arid, transitional, and humid regions, respectively. The same analysis is applied to the temporal variations in the *PET/P* of the transitional region after removing the long-term trend. In this case, the time of abrupt change is 1980 with the T value of 2.383 ($p < 0.05$).

As mentioned above, the decadal variation of the monsoon circulation around 1980 is a well-known climate shift over the monsoon region. In addition, the three detection methods pick up similar years of abrupt change in *PET/P* over the three climate regions that are generally consistent with the year of climate shift due to decadal variability of the monsoon circulation. Thus, we conclude that separating of the whole analysis period into 1961-1983 and 1984-2010 is reasonable for quantifying the impacts of climate variables on *PEP/P* trends.

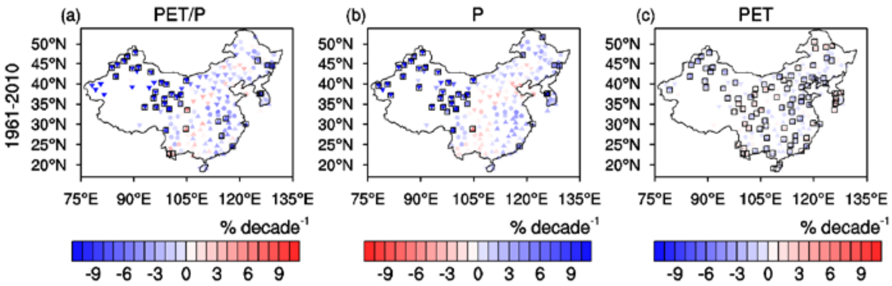

Figure S1. Spatial distributions of the trends in *PET/P*, *P*, and *PET* over continental East Asia. a−c: The spatial distribution of trends in the annual-mean *PET/P* (a), *P* (b), and *PET* (c) for the period of 1961−2010. Inverse triangles, circles, and triangles represent stations classified as arid, transitional, and humid regions, respectively. The open squares indicate that the trend is significant at the 95% confidence level.

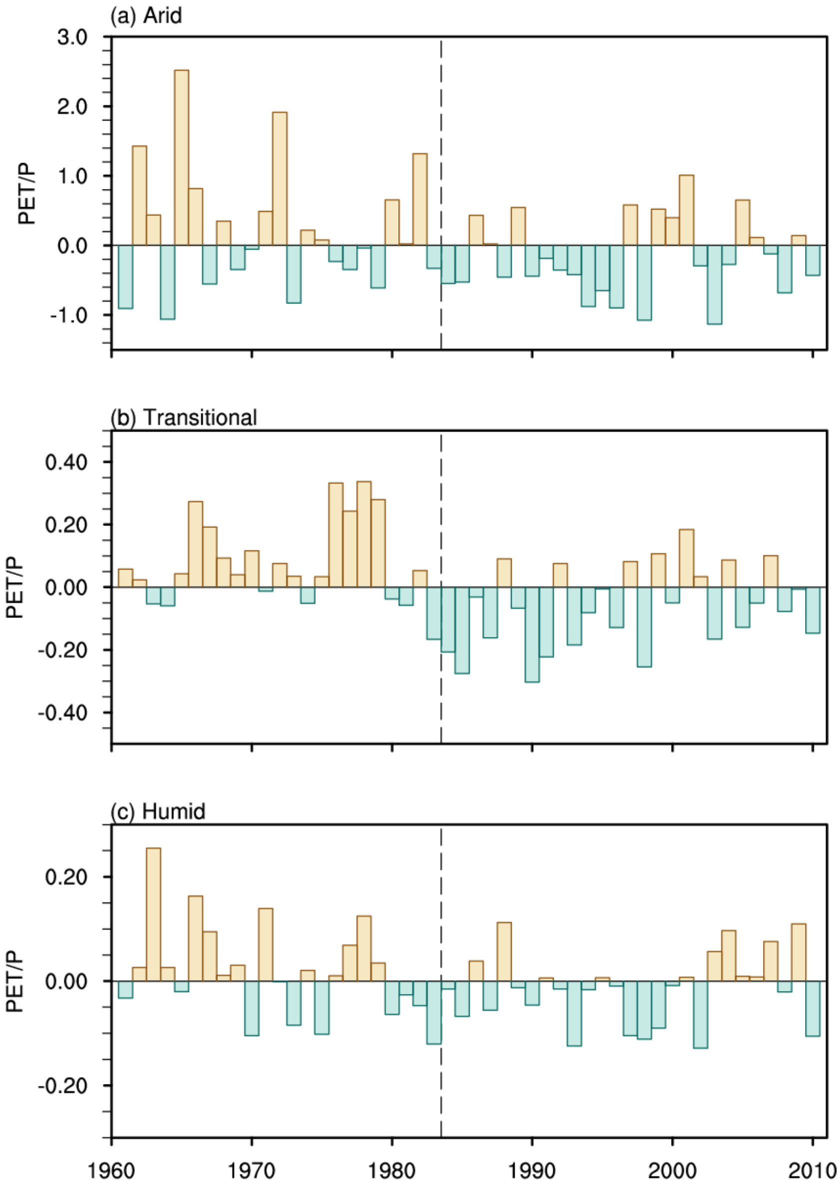

Figure S2. Interannual variations of the annual-mean *PET/P* over the (a) arid, (b) transitional, and (c) humid regions located to the east of 100ºE. Yellow and blue bars indicate the positive and negative anomalies for *PET/P*, respectively.

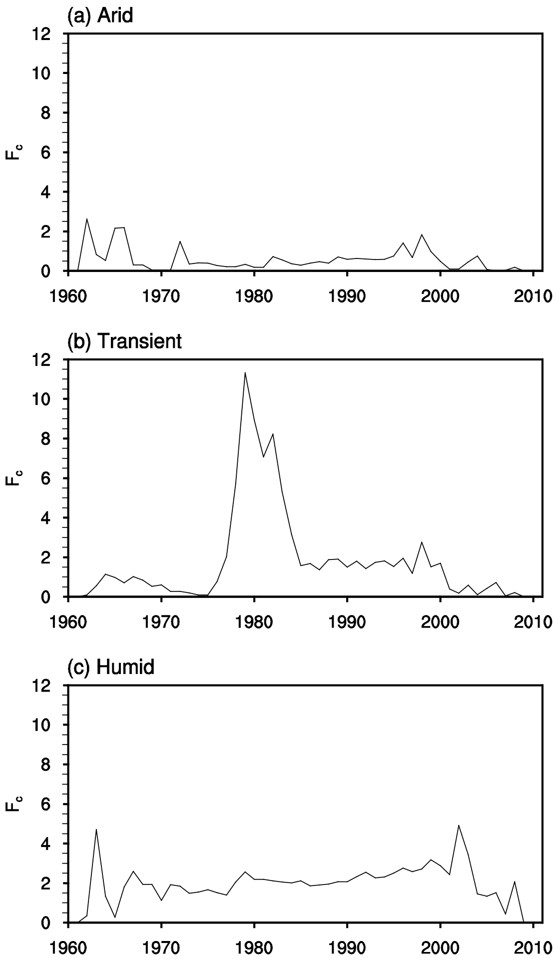

Figure S3. The F_c statistics for the temporal variations of the annual-mean *PET/P* over the (a) arid, (b) transitional, and (c) humid regions.

3. The PET calculation (1) involves non-linear interactions among different drivers in particular wind, vapor pressure, and temperature. However, in order to derive the relative importance of different drivers, the authors simplified such interaction by using a linear regression (8). Is such simplification justified? Are the interactions among different drivers too small to be ignored? A proof or references supporting this approach is required. Also, are the regression estimated for individual stations separately or on the regional mean series? These details need to be clearly described for the work to be reproducible. Even

if the interaction term among different variables to be small, the variables in (8) may not be independent (e.g., there must be some correlation between radiation and temperature, between temperature and humidity because a day of clear sky would correspond to high radiation, high temperature, and low relative humidity). So how did the authors test the significance of regression?

[Reply] Equation (8) in the original manuscript looks too simple considering the nonlinear relationship between *PET* and climate parameters derived in Equation (1) of the original manuscript. However, there are several studies using this linear regression method to determine the most important climate variable for the response of *PET* to climate changes (Chattopadhyay and Hulme, 1997; Yin et al., 2010; Dinpashoh et al., 2011; Han et al., 2012). Thus, the linear regression equation can be used to divide the impact of four climate parameters on *PET* changes.

To test the significance of the regression equation, we computed partial correlation coefficients between *PET* and the four parameters, *Rn*, *WS*, *Ta*, and *RH* at 189 stations for the period 1961–1983 and 1984–2010 (Fig. S4). Regardless of the analysis periods, *Rn*, *WS*, and *Ta* are positively correlated with *PET*, whereas the partial correlation coefficient for *RH* is negative. For all four variables, partial correlation coefficients are significant at the 95% confidence level for most stations, indicating that these fields are closely correlated with *PET*. Also, the significance of partial correlation coefficients suggest that the regression equation does not suffer from multicollinearity of each climate parameters. This strongly supports the significance of the regression equation and ignore the interaction between climate parameters.

Similar to other computed variables, the regression equation also estimates for each station at first, then relative influences are computed as illustrated in figure 6 in the revised manuscript.

Details about computing relative influences of climate parameters are described in Section 3 in supplementary information. We add references for the regression equation of *PET*. Also, we describe the order for computing regional mean and test of significance and multicollinearity of the regression equation. Please see the relevant section in supplementary information.

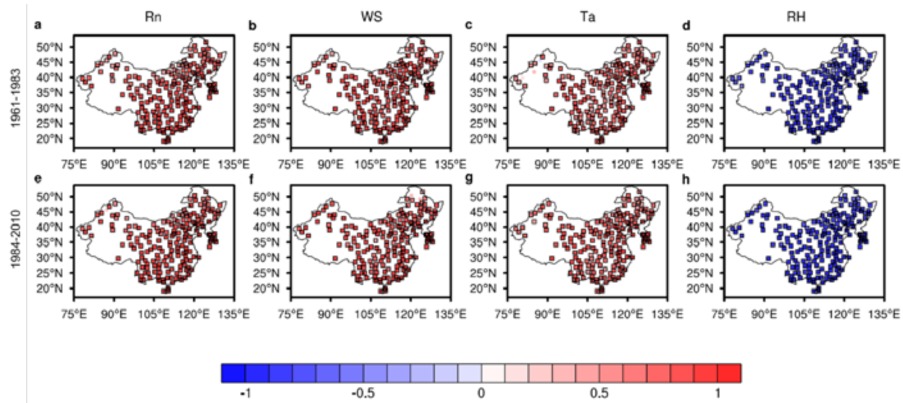

Figure S4. Spatial distribution of partial correlation coefficients over continental East Asia for 1961–1983 and 1984–2010 between *PET* and four parameters such as *Rn*, *WS*, *Ta*, and *RH*. Squared markers indicate that the coefficients are significant at 95% significance level.

4. How did the authors estimate the confidence interval in Fig. 3?

[Reply] The 95% confidence interval is calculated as below:

$$\left(\bar{x} - 1.96\frac{s}{\sqrt{n}}, \qquad \bar{x} + 1.96\frac{s}{\sqrt{n}}\right) \qquad \text{(S14)}$$

where, $\bar{x}$ and s is the mean and standard deviation of relative contributions of each climate variable, respectively. n is the number of stations located in arid (56), transitional (50), and humid regions (51), respectively.

We add the above description about computing the confidence level in section 3 of supplementary information.

List of relevant changes made in the manuscript following comments

1. Lines 81-82. We add sentences about computation of daily mean *PET* and *PET/P* as following:

We computed the daily *PET* and *PET/P*, and then estimated the annual-mean values at individual weather sites.

2. Lines 82-85. We mention about three kinds change-point method applied to temporal variation of *PET/P* as following:

Due to the decadal variation of East Asian monsoon circulation (Ding et al., 2008; Ha et al., 2012), the whole analysis period is divided into two sub-periods, 1961-1983 and 1984-2010, by applying three change-point methods to the temporal variations of *PET/P* (Pettitt, 1980; Lund and Reeves, 2002; Beaulieu et al., 2012, see section 2 of supplementary information for details).

3. Lines 88-89. We add sentences about computation of relative influences of each climate parameters on *PET/P* trends as following:

To identify the climate variables that contribute most significantly to the observed *PET/P* trends, relative influences of changes in *P*, *Rn*, *WS*, *Ta*, and *RH* on the *PET/P* trends are computed at individual weather sites.

4. Lines 104-110. We add a new figure illustrating spatial distribution of *PET/P* trends for 1961-2010 (figure 3) and relevant descriptions as following:

The annual-mean *PET/P* is decreased over most of analysis domain (86.7% of total weather stations) during 1961-2010 by both increase in *P* and decrease in *PET* (Fig. 3). Note that the scale of the *P* trends (Fig. 3b) is reversed in order to represent drying and wetting trends as red and blue colors, respectively. The negative trends in *PET/P* are large and significant at 95% significance level ($p > 0.95$) over the northwestern China (< 100ºE), whereas the eastern part of the analysis domain (> 100ºE), classified by monsoon climate zone, shows small and insignificant trends in *PET/P* (Fig. 3a). The spatial pattern of the trends in *P* is similar to that of *PET/P* with opposite sign (Figs. 3a and 3b). At more than half of the sites, the trends in *PET* is significant, but the magnitude of *PET* trends is small (Fig. 3c).

5. Lines 113-118. We remove the original figure 1, instead, we add a new time series illustrating annual anomalies of *PET/P* over the arid, transitional and humid regimes (figure 4). Descriptions about this figure are following paragraph:

Figure 4 depicts the temporal variation in the mean *PET/P* for the arid, transitional, and humid regimes over monsoon regions (> 100ºE) expressed as annual mean anomalies. Note that the temporal variations are the averages of *PET/P* anomalies at 56, 50, and 51 weather sites located on arid, transitional, and humid climate regimes, respectively. For all three climate regimes, the *PET/P* anomalies show abrupt changes in early 1980s (see supplementary for details). Also, the trends in *PET/P* anomalies are not significant in the arid and humid regimes. Thus, the analysis of *PET/P* changes over the monsoon regions needs a separation of the analysis period.

6. Lines 161-162. We mention about the confidence interval of regional averaged relative influences as following:

The confidence interval is computed at the 95% significance level based on relative influences of five variables at 56, 50, and 51 stations of arid, transitional, and humid climate regimes.

7. Supplementary section 2. We describe explanations and results of each change-point methods, also significant tests of determined time of abrupt change.

8. Supplementary section 3. We explain how to compute the relative influences of five climate parameters on *PET/P* trends. In this section, we test significance and multicollinearity of the regression equation of *PET*. Also, we describe the calculation of confidence intervals of relative influences in same section.

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Point-by-point responses to Referee #2

1. Authors needs to bring sense of using their study at regional scale where opinion 'dry gets drier, wet gets wetter' does not fit. It cannot be a generalised statement as it is proved over some other regions.

[Reply] Thank you for your comments. We removed the sentence in abstract. Instead, we added a new sentence, lines 53-55, as:

Further, changes in the hydrological cycle over East Asia is not consistent with a well-known paradigm "dry regions drier, wet regions wetter" in spite of significant warming trend (Greve et al., 2014).

2. How about role of precipitation on humid region is it only evapotranspiration which is controlling?

[Reply] In the humid region, the precipitation change always acts to decrease dryness in both analysis periods (1961-1983 and 1984-2010). We describe the role of precipitation on dryness trends over the humid area at section 3.2. In the early period, the influence of precipitation is much larger than other climate variables whereas precipitation is a second important variable for the dryness change in the later period. Based on this, we highlight the importance of evapotranspiration over the humid regime in the later period.

3. 'Our results suggest that enhanced atmospheric water demands caused by warming can threaten water resources in wet monsoon areas and possibly in other warm and water-sufficient regions' - This process is well understood based on physical laws- then why authors want to claim it that way.

[Reply] As pointed out, warming-induced atmospheric water demand increases are well known process. However, we attempt to analyze the influence of warming on long-term changes in the dryness over the wet monsoon region. "**Over the monsoon region, dryness increases associated with warming has not been analyzed in previous studies on dryness trends due to large variations of precipitation"**. Our results first emphasize the increase in the atmospheric water demand due to warming as the main cause of the dryness trends over the East Asian monsoon region based on station observations, especially in the humid region. We changed the last sentence of Abstract as following:

"Our results show significant drying influences of the warming over the humid monsoon region in recent decades; this also supports the drying trends over the warm and water-sufficient regions in future climate."

4. All set of equations are from published work and hence need not to part of the main text and can go

in the supplementary material. If so, then methodology needs to be simpler for better understanding of common researcher.

[Reply] Thank you for your suggestions, we describe the *PET* calculation algorithm based on Penman-Monteith Method, change-point methods, and computation of relative influences of climate parameters on *PET/P* trends in section 1, 2, and 3 of supplementary information, respectively.

Overall this work though using important data, but looks more of reporting the finding over the region of study and lacks in providing comprehension on the physical processes leading to such changes. I am sorry that I can’t recommend this paper.

[Reply] We cordially disagree with this comment. The main novelty of this study is the attribution of the drying trends to specific climate variables and land-atmosphere interaction, which resulted in a conclusion “In contrast, the increase in potential evapotranspiration due to increased atmospheric water-holding capacity, a secondary impact of warming, works to increase aridity over the humid monsoon region despite enhanced water supply and relatively less warming.”. In our opinion, this level of detailed analysis is not common (e.g., Feng and Fu, 2013). Also, using site observation data is distinguished point from previous studies, which use grid reconstructed data.

List of relevant changes made in the manuscript following comments

1. Abstract. We remove the sentence “Recent studies reveal that spatial patterns of continental dryness trends are in contrast to the “dry gets drier, wet gets wetter” paradigm.

2. Abstract. We change the last sentence as following:

Our results show significant drying effects of the warming over the humid monsoon region in recent decades; this also supports the drying trends over the warm and water-sufficient regions in future climate.

3. Lines 53-55. We describe inconsistency of ‘dry get drier, wet gets wetter’ paradigm over East Asia as following:

Further, changes in the hydrological cycle over East Asia is not consistent with a well-known paradigm “dry regions drier, wet regions wetter” in spite of significant warming trend (Greve et al., 2014).

4. Method and data. We change this section moving equation sets to supplementary information as following:

To compute the aridity index, *PET/P*, climate data for the period 1961−2010 are obtained from 179 and 10 meteorological sites in mainland China and South Korea, respectively. Quality of these data is controlled by the National Meteorological Center of the China Meteorological Administration and Korea Meteorological Administration. Data include daily precipitation, daily mean air temperature, 10-m wind speed, relative humidity, and sunshine duration. The last four variables are used to compute daily *PET* following the Penman-Monteith method (Allen et al., 1998; see section 1 in supplementary information for details). We computed daily *PET* and *PET/P*, and then estimated their annual-mean values at individual weather sites. Due to the decadal variation of East Asian monsoon circulation around 1980 (Ding et al., 2008; Ha et al., 2012), the entire analysis period is divided into two sub-periods, 1961-1983 and 1984-2010, by applying three change-point methods to temporal variation of *PET/P* (Pettitt, 1980; Lund and Reeves, 2002; Beaulieu et al., 2012, see section 2 of supplementary information for details). The data at each meteorological sites satisfy the following criteria: 1) all climate parameters in the year 2010 exist, 2) sufficient records for at least 10 years for the two sub-periods (i.e., 1961–1983 and 1984–2010).

To identify the climate variable that contributed most to the observed *PET/P* trends, relative influences of changes in *P*, *Rn*, *WS*, *Ta*, and *RH* on the *PET/P* trends are computed at each individual weather sites based on the derivative of *PET/P* with respect to time as following:

$$\frac{d}{dt}\left(\frac{PET}{P}\right) = -\frac{PET}{P^2}\frac{dP}{dt} + \frac{1}{P}\frac{dPET}{dt} \qquad (1)$$

The first and second terms on right-hand side indicate temporal changes in the aridity index due to the changes in *P* and *PET*. *PET* can be decomposed into *Rn*, *WS*, *Ta*, and *RH* four climate parameters using multilinear regression (Chattopadhyay and Hulme, 1997; Yin et al., 2010; Dinpashoh et al., 2011; Han et al., 2012see section 3 in supplementary information for details). Then, the equation (1) is written as follows:

$$\frac{d}{dt}\left(\frac{PET}{P}\right) \approx -\frac{\overline{PET}}{\bar{P}^2}\frac{dP}{dt} + \frac{1}{\bar{P}}\left(a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt}\right) \qquad (2)$$

where the terms on the right-hand side are the trend in *PET/P* considering changes in *P*, *Rn*, *WS*, *Ta*, and *RH*, indicate the relative effects of *P*, *Rn*, *WS*, *Ta*, and *RH*, resoectively. $\bar{P}$ and $\overline{PET}$ are the average of the annual-mean *P* and *PET* for the analysis period, respectively.

Dominance of climate warming effects on recent drying trends over wet monsoon regions

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Abstract

Understanding changes in ~~continental surface~~background dryness over the land is key information for adapting to climate change because of the critical socioeconomic consequences. ~~Recent studies reveal that spatial patterns~~However, causes of continental dryness ~~trends are in contrast to the “dry gets drier, wet gets wetter” paradigm. Causes of the complexity in dryness trends~~changes remain uncertain because various climate parameters control ~~continental~~ dryness. Here, we ~~quantify the relative effects of~~verify dominant climate ~~drivers on~~variables determining dryness trends over continental East Asia, which is characterized by diverse hydro-climate regimes ranging from arid to humid ~~to arid~~, by ~~analyzing~~quantifying the relative effects of changes in precipitation, solar radiation, wind speed, surface air temperature, and relative humidity on trends in aridity index based on observed data from 189 weather stations for the period of 1961-2010. ~~Since~~Before the early 1980s~~, monsoon~~ (1961-1983), change in precipitation is a primary condition for determining aridity trends. In the later period (1984-2010), dominant climate ~~zones (east of 100°E) have been getting significantly drier, but the related mechanisms vary~~parameter on aridity trends varies according to the hydro-climate regime. Drying trends in arid regions are mostly explained by reduced precipitation. In contrast, ~~in humid areas,~~ the increase in potential evapotranspiration due to increased atmospheric water-holding capacity, a secondary impact of warming, ~~is the primary condition for the~~ works to increase ~~in dryness. This drying impact of atmospheric moisture deficiency is much stronger in~~ aridity over the humid ~~areas than in arid areas. Our results suggest that~~monsoon region despite enhanced ~~atmospheric~~ water ~~demands caused by~~supply and relatively less warming ~~can threaten water resources in wet monsoon areas and possibly in other~~. Our results show significant drying effects of the warming over the humid monsoon region in recent decades; this also supports the drying trends over the warm and water-sufficient regions~~.~~ in future climate.

1 Introduction

The ~~mechanism behind~~background dryness over the land varies as climate changes, but major climate parameter driving dryness changes remains unclear in ~~continental fundamentally differs from that over the ocean because of limited surface moisture availability (Hoekstra and Mekonnen, 2012; Greve et al., 2014;~~ many regions (Sherwood and Fu, 2014; Hegerl et al., 2015). In ~~many~~previous assessments, precipitation (*P*), the amount of water supply, is regarded as a key variable for understanding variations in dryness, particularly in humid regions such as Asian monsoon regions (Wang et al., 2012; Kitoh et al., 2013; Liu and Allan, 2013). For example, in East Asia, dryness changes are generally summarized as "the dry ~~western~~northwestern region (west of 100°E and north of 30°N) is getting wetter, the dry northern region (east of 100°E and north of 35°N) is getting drier, and the wet southeastern region (east of 100°E and south of 35°N) is getting wetter" based on changes in annual mean *P* (Wang and Ding, 2006; Piao et al., 2010). In addition, a decrease in *P* leads to drying trends over the northern and central-east regions of India, part of the South Asian monsoon region (Zhou et al., 2008; Roxy et al., 2015). However, climate change ~~significantly~~also varies potential evapotranspiration (*PET*~~)~~), the amount of atmospheric moisture demand (Liu et al., 2010; Han et al., 2012; Shan et al., 2012~~), the amount of atmospheric moisture demand.~~). *PET* variations largely affect dryness trends that are in turn closely related to the occurrence of droughts, water scarcity, and tree mortality (Westerling et al., 2006; Park Williams et al., 2013; Dai, 2013). Drying impacts of *PET* increase are usually emphasized in water-limited regions (Westerling et al., 2006; Estes et al., 2014); however, humid areas are also expected to experience severe aridification in the 21st century because of a continuous increase in *PET* (Feng and Fu, 2013; Cook et al., 2014). Thus, the processes involved in the variability of dryness need to be examined over various hydro-climate regimes to better understand continental dryness changes.

This study aims to elucidate the mechanisms of dryness trends in continental East Asia through the analysis of observed climate data at 179 and 10 weather stations in mainland China and South Korea, respectively, for the period 1961−2010. The long-term trend in dryness is a critical concern for continental East Asia, as it is a region of massive populations, widely varying hydro-climate regimes, fragile ecosystems, and significant agricultural activities (Piao et al., 2010; Geng et al., 2014; Jeong et al., 2014). Also, the analysis region has recently experienced abrupt climate changes (Gong and Ho 2002; Yue et al., 2013). For example, northeast China experienced severe warming by 0.36 ºC decade^{-1} for the period of 1960-2006 (Piao et al. 2010). Rainfall intensity has significantly increased over southeastern China (Zhai et al., 2005). Further, changes in the hydrological cycle over East Asia is not consistent with a well-known paradigm "dry regions drier, wet regions wetter" in spite of significant warming trend (Greve et al., 2014).

Previous assessments ~~of~~on trends in surface dryness show contradictory results over continental East Asia. Assessments based on grid reanalysis data generally suggest that continental East Asia is getting drier due to an increase in *PET* accompanied by an increase in the vapor pressure deficit (VPD) (Feng and Fu, 2013; Greve et al., 2014; Huang et al., 2016). On the contrary, the other studies using site observations reported that more than half of the stations over mainland China show negative trends in both *PET/P* and *PET*, indicating a decrease in surface dryness, following a decrease in solar irradiance and wind speed despite continuous warming (Wu et al., 2006; Zhang et al., 2009; Huang et al., 2016). Thus, a quantitative analysis is needed to explain the contradiction between previous assessments regarding surface dryness over continental East Asia.

In this study, an aridity index, *PET/P*, defined as *PET* based on the Penman–Monteith ~~equation (Penman, 1948;~~ method (Allen et al., 1998) divided by *P*, is employed to assess surface dryness and its trends (Middleton et al., 1997; Estes et al., 2014; Greve et al., 2014). Over the land surface, the amount of actual evaporation (*AET*) is constrained by the amount of *P*, which is also generally less than *PET* because of limited available water at the ~~land~~ surface (Fu and Feng, 2014; Greve et al., 2014). Thus, the *PET/P* ratio is more suitable for measuring the degree of water deficiency or surplus for a certain climate condition. If the value of *PET/P* is less than unity, the location is classified as a wet region, and vice versa. Likewise, as the aridity index decreases, the land surface becomes wetter, and vice versa. By the definition of the aridity index, trends in surface dryness can be resolved by combining the effects of changes in five climate parameters: *P*, net radiation (*Rn*), wind speed (*WS*), surface air temperature (*Ta*), and relative humidity (*RH*). Furthermore, we classify the analysis domain into three hydro-climate regimes based on the 50-year climatology of *PET/P*: arid (*PET/P* ≥ 2), transitional (1 ≤ *PET/P* < 2), and humid (*PET/P* < 1) (Geng et al., 2014) (Fig. ~~S1~~1). The ratio *PET/P* and regional classification allow the identification of climate parameters that are important for trends in surface dryness over the three hydro-climate regimes.

2 Methods and data

~~2.1 Climate dataset~~

~~Climate~~To compute the aridity index, *PET/P*, climate data for the period 1961−2010 are obtained from 179 and 10 meteorological sites in mainland China and South Korea, respectively. ~~Data include daily mean air temperature,~~

~~precipitation, wind speed at a height of 10 m, relative humidity, and sunshine duration. The quality of this~~Quality of these data is controlled by the National Meteorological Center of the China Meteorological Administration and Korea Meteorological Administration. ~~The~~Data include daily precipitation, daily mean air temperature, 10-m wind speed, relative humidity, and sunshine duration. The last four variables are used to compute daily *PET* following the Penman-Monteith method (Allen et al., 1998; see section 1 in supplementary information for details). We computed the daily *PET* and *PET/P*, and then estimated their annual-mean values at individual weather sites. Due to the decadal variation of East Asian monsoon circulation (Ding et al., 2008; Ha et al., 2012), the entire analysis period is divided into two sub-periods, 1961-1983 and 1984-2010, by applying three change-point methods to the temporal variations of *PET/P* (Pettitt, 1980; Lund and Reeves, 2002; Beaulieu et al., 2012, see section 2 of supplementary information for details). The data at each meteorological sites satisfy the following criteria: 1) ~~the existence of~~ all climate parameters in the year 2010 exist, 2) sufficient records for at least 10 years for the two ~~analysis~~ sub-periods (i.e., 1961–1983 and 1984–2010).

~~**2.2 Calculation of daily PET**~~

~~Daily *PET* values are calculated from~~To identify the ~~Penman-Monteith approach, which is one of the credible methods for estimating atmospheric water demand (Sheffield et al., 2012). The formulation of daily *PET* following the Penman-Monteith approach is written as:~~

$$\cancel{PET = \frac{\Delta}{\Delta+\gamma}R_n + \frac{\gamma}{\Delta+\gamma}\frac{c_1(1+c_2U_2)(e_s - e_a)}{\lambda} \qquad (1)}$$

~~where Δ is the slope of the vapor pressure curve (kPa K^{-1}) at a certain temperature, γ is the psychrometric constant (kPa K^{-1}), R_n is the net radiation at the surface (mm day^{-1}), c_1 is 6.43 MJ kPa^{-1} day^{-1}, c_2 is 0.536 s m^{-1}, U_2 is the wind speed at a height of 2 m (m s^{-1}), e_s is the saturation vapor pressure of the air (kPa), e_a is the actual vapor pressure (kPa), and λ is the latent heat of vaporization (MJ mm^{-1}) (Allen et al., 1998; Sheffield et al., 2012). This *PET* equation is a simplified form of the FAO Penman-Monteith equation that neglects stomatal conductance and heat flux from the ground. All of the~~ climate variables ~~are computed using the station-based climate data following an equation set that is described in the FAO56 report (Allen et al., 1998). The wind speed at a height of 2 m is computed from station-~~that contribute most to the observed ~~wind speed at 10 m using a wind profile relationship (Han et al., 2012). Station elevations are computed by linear interpolation and Global 30 Arc-Second Elevation (GTOPO30) of the United States Geological Survey to estimate the net radiation based on sunshine duration. There are differences between the interpolated elevation and actual elevation due to the~~

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~~limitation of spatial resolution, but the temporal variation of *PET* or the relative influence of climate parameters cannot be changed with the elevation differences.~~

~~2.3 Change-point analysis~~

~~We use two methods to find the change-point of the temporal variation of~~ *PET/P*~~. One method defines the change-point when cumulative sum of *PET/P* variation for the ith year (C_i) is greatest (Pettitt, 1980). The cumulative sum C_i is provided as follows:~~

$$C_0 = 0 \qquad (2)$$

$$C_i = C_{i-1} + (X_i - \bar{X}) \qquad (3)$$

~~where X_i is the *PET/P* anomaly in year i, and $\bar{X}$ is the averaged *PET/P* for the whole analysis period. In the other change-point model (Elsner et al., 2000), X_i is the same, *PET/P* of the ith year. Y_i is defined as $\log_{10}(X_i + 1)$. The step variable T_i is defined for an integer p that changes from 2 to $q = N - 1$ as follows:~~

$$T_i(p) = \begin{cases} 0, & i < p \\ 1, & i \geq p \end{cases} \qquad (4)$$

~~where N is the total number of years of the analysis period 1961–2010. Using the step variable T_i, a simple linear first-order regression model is suggested for an integer p as follows:~~

$$Y_i = \alpha_0(p) + \alpha_1(p)T_i(p) + \epsilon_i(p) \qquad (5)$$

~~where $\alpha_0(p)$ is the intercept, $\alpha_1(p)$ the slope and $\epsilon_i(p)$ the error of residual at Y_i for a fixed p. In addition, the value of $P(p)$ is computed by~~

$$P(p) = \hat{\alpha}_1(p)/\mathrm{se}[\hat{\alpha}_1(p)] \qquad (6)$$

~~where $\mathrm{se}[\hat{\alpha}_1(p)]$ is the standard error of $\alpha_1(p)$. Let $P(p_1) = max\{|P(2)|, |P(3)|, \ldots, |P(q)|\}$. The p_1 can be a change-point if the $P(p_1)$ is statistically significant.~~

~~2.4 Estimation of the~~ trends, relative influences of ~~climate parameters~~

~~The~~ changes in *P*, *Rn*, *WS*, *Ta*, and *RH* on the *PET/P* trends are computed at individual weather sites based on the derivative of ~~the aridity index~~ *PET/P* with respect to time ~~is written using the~~as following ~~equation:~~:

$$\frac{d}{dt}\left(\frac{PET}{P}\right) = -\frac{PET}{P^2}\frac{dP}{dt} + \frac{1}{P}\frac{dPET}{dt} \qquad (\cancel{7}1)$$

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The first and second terms on right-hand side indicate temporal changes in the aridity index due to the changes in *P* and *PET*. *PET* can be decomposed into *Rn*, *WS*, *Ta*, and *RH* four climate parameters using multilinear regression~~:~~ (Chattopadhyay and Hulme, 1997; Yin et al., 2010; Dinpashoh et al., 2011; Han et al., 2012; see section 3 in supplementary information for details). Then, the equation (1) is written as follows:

$$PET = a_{Rn}R_n + a_{WS}WS + a_{Ta}T_a + a_{RH}RH + b \qquad (8)$$

~~where a_{Rn}, a_{WS}, a_{Ta}, and a_{RH} are the regression coefficients of *Rn*, *WS*, *Ta*, and *RH*, respectively, and the constant b is the intercept. We obtain the time derivative of Eq. (8) as follows:~~

$$\frac{dPET}{dt} = a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt} \qquad (9).$$

~~where each term on the right-hand side indicates trends in *PET* with respect to changes in each climate variable individually. Finally, Eq. (7) is written as follows:~~

$$\frac{d}{dt}\left(\frac{PET}{P}\right) = -\frac{PET}{P^2}\frac{dP}{dt} + \frac{1}{P}\left(a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt}\right)$$
$$\approx -\frac{\overline{PET}}{\overline{P}^2}\frac{dP}{dt} + \frac{1}{\overline{P}}\left(a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt}\right) \qquad (10)$$

$$\frac{d}{dt}\left(\frac{PET}{P}\right) \approx -\frac{\overline{PET}}{\overline{P}^2}\frac{dP}{dt} + \frac{1}{\overline{P}}\left(a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt}\right) \qquad (2)$$

where the terms on the right-hand side ~~indicate~~are the trend in ~~the aridity index~~*PET/P* considering changes in *P*, *Rn*, *WS*, *Ta*, and *RH*, ~~sequentially~~indicate the relative effects of *P*, *Rn*, *WS*, *Ta*, and *RH*, respectively. $\overline{P}$ and $\overline{PET}$ are the average of the annual-mean *P* and *PET* for the analysis period, respectively.

3 Results

3.1 ~~Changes~~Trends in ~~dryness trends~~ *PET/P*, *P*, and *PET* over continental East Asia ~~during 1961-2010~~

Figure ~~1 depicts temporal variations in~~ 2 shows climatology of annual-mean *PET/P*, *P*, and *PET* ~~for~~of all analysis stations ~~expressed as annual mean anomalies. For~~ over continental East Asia for the ~~entire~~ period~~, *PET/P* decreases at a rate of -2.30% decade^{-1} due to both increases in *P* (2.44% decade^{-1}) and decreases in *PET* (−0.52% decade^{-1}), implying reduced dryness caused by increased water supply as well as decreased atmospheric water demands. However, the temporal variation in *PET/P*~~ of 1961-2010. *PET/P* is ~~not monotonic. The change-point of the long-~~

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~~term trend in *PET/P* is 1983 based on two change-point analyses. This change-point is significant at the 99% confidence level. The trend in *PET/P* is negative (-1.81% decade^{-1}) for 1961–1983~~significantly varied by regions: getting larger to northwestern direction and ~~positive (1.66% decade^{-1}) for 1984–2010~~smaller to southeastern direction (Fig~~. 1a). The decrease in *PET/P* before the early 1980s is due mainly to the relatively large increase in *P* (4.56% decade^{-1}) rather than the decrease in *PET* (-0.95% decade^{-1})~~ 2a). This spatial pattern of *PET/P* is caused by both northwest-southeast patterns of *P* and small regional variation of *PET* (Figs. ~~1a~~2b and ~~1b). In contrast, the~~ 2c). The annual-mean *PET/P* is decreased over most of analysis domain (86.7% of total weather stations) during 1961-2010 by both increase in *PET* ~~(1.22% decade^{-1}) largely contributes to the increase~~*P* and decrease in *PET*~~/P during the later period (Figs. 1a and 1c).~~

~~The spatial distributions of *PET/P*, *P*, and *PET* trends are consistent with those of the overall changes in both periods~~ (Fig. ~~2~~3). Note that the scale of the *P* trends (~~Figs. 2b and 2e~~Fig. 3b) is reversed in order to represent drying and wetting trends as red and blue colors, respectively. The negative trends in *PET/P* are large and significant at 95% confidence level over the northwestern China (< 100ºE), whereas the eastern part of the analysis domain (> 100ºE), classified by monsoon climate zone, shows small and insignificant trends in *PET/P* (Fig. 3a). The spatial pattern of the trends in *P* is similar to that of *PET/P* with opposite sign (Figs. 3a and 3b). At more than half of the sites, the trends in *PET* is significant, but the magnitude of *PET* trends is small (Fig. 3c).

The wetting trends over the arid northwestern China are caused by significant increase in *P* rather than the decrease in *PET* (Fig. 3), also consistent with previous assessments (Zhai et al., 2005; Shi et al., 2007; Piao et al., 2010). However, over monsoon climate regions, more detailed analysis is needed due to the decadal variation in large-scale atmospheric circulation and rainfall (Ding et al., 2008; Piao et al., 2010). Figure 4 depicts the temporal variation in the mean *PET/P* for the arid, transitional, and humid regimes over monsoon regions (> 100ºE) expressed as annual mean anomalies. Note that the temporal variations are the averages of *PET/P* anomalies at 56, 50, and 51 weather sites located on arid, transitional, and humid climate regimes, respectively. For all three climate regimes, the *PET/P* anomalies show abrupt changes in early 1980s (see section 2 of supplementary information for details). Also, the trends in *PET/P* anomalies are not significant in the arid and humid regimes. Thus, the analysis of *PET/P* changes over the monsoon regions needs a separation of the analysis period.

The spatial distributions of *PET/P* trends show considerable changes between both analysis periods (Figs. 5a and 5d). For the earlier period, about 60% of the total number of stations show decreasing trends in *PET/P*, particularly in the arid (northwestern and northern China) and humid regions (southeastern China) (Fig. ~~2a~~5a). Increasing trends in *PET/P*, with relatively small magnitudes, occur mainly in the transitional region (northeastern and southwestern China). The spatial pattern of the *P* trend is similar to that of the *PET/P* trend but with the opposite sign, suggesting that the changes in *P* are directly linked to changes in *PET/P* for most of the analysis region (Figs. ~~2a~~5a and ~~2b~~5b). Decreasing trends in *PET* appear in more than three-quarters of the analysis domain, but these are significant only in humid regions because of their small magnitudes (Figs. ~~2a~~5a and ~~2c~~5c).

In the later period, the spatial patterns of the *PET/P*, *P*, and *PET* trends change drastically over the monsoon climate regions (~~east of 100°E) (~~Figs. ~~2d–2f~~5d–5f). The trends in *PET/P* shift from negative to positive values in both the humid (southeastern China) and arid (northern and northeastern China) regions (Figs. ~~2a~~5a and ~~2d~~5d). These notable alterations of the *PET/P* trend ~~lead to an increasing trend of overall mean~~ are explained by changes in *P* and *PET*~~/*P* after~~ trends. After the early 1980s ~~(Figs. 1a and 2d). Trends in *P* also change significantly:~~, positive trends of *P* are reversed in the arid regions, and the magnitude of the increasing ~~trend~~trends in *P* decreases in the humid regions (Figs. ~~2b~~5b and ~~2e). The~~ 5e). These changes in *P* trends are consistent with ~~the~~those in *PET/P* trends ~~in~~over the arid ~~region~~regions but not in the humid area (Figs. ~~2d~~5d and ~~2e~~5e). Significant increases in *PET* ~~explain~~leads to the ~~inconsistency between the~~positive trends in *PET/P* ~~and *P*~~ in the humid area despite the increase in *P* (Figs. ~~2d and 2f~~5d–5f).

The ~~trend shifts that occur around the early 1980s~~different spatial patterns of *PET/P* trends between both analysis periods are consistent with regional patterns of changes in climate variables ~~in~~over East Asian monsoon regions. The variations of *P* are directly associated with the decadal variability of the East Asian monsoon circulation. As monsoon circulation weakened, both meridional circulation and southerlies in lower atmosphere decreased over the East Asian monsoon region; hence, moisture transport is concentrated over southern China (Ding et al., 2008). These changes create favorable conditions for rainfall over the southern China (humid monsoon region) but opposite situations over the northern China (arid monsoon region~~.~~). Since the late 1970s, weakening of monsoon circulation has led to significant decreases and increases in *P* over arid and humid monsoon regions, respectively (Ding et al., 2008; Piao et al. 2010). The increasing trend in *P* over the humid area decreases or reverses as a result of the reduction in monsoon rainfall related to the recovery of monsoon circulation after the early 1990s (Liu et al., 2012; Zhu et al., 2012). As a consequence of changes in the monsoon circulation, the decreasing trends in *P* in the arid region are greater than the increasing trends in the humid area (Fig. ~~2e~~5e). Changes in other climate fields are linked to the positive *PET* trends (Fig. ~~2f~~5f). For example, the warming trend becomes more severe in the later period (Ge et al., 2013; Yue et al., 2013) (Figs. ~~S2c~~S3c and ~~S2g~~S3g). The trend in absorbed solar radiation changed from dimming to brightening, particularly in the humid region (Tang et al., 2011) (Figs. ~~S2a~~S3a and ~~S2e~~S3e). Consequently, the combined impacts of changes in climate parameters resulted in the increase in *PET/P*~~.~~ for 1984-2010.

3.2 Relative influences of five climate parameters on changes in dryness trends

~~To identify the climate variable that contributed most significantly to the observed *PET/P* trends, we computed the relative influences of changes in *P*, *Rn*, *WS*, *Ta*, and *RH* on the *PET/P* trends over three hydro-climate regimes (Table S1). Figure 3 displays the averaged effects of five climate parameters and their confidence intervals over the three hydro-climate regimes for the two analysis periods. Here, positive values of a particular variable indicate increasing rates of *PET/P* with respect to changes in that variable only, and vice versa.~~Figure 6 shows spatial distribution of the relative influences of five climate variables over the continental East Asia for 1961-1983 and 1984-2010. Here, positive values of a particular variable indicate increasing rates of *PET/P* with respect to changes in that variable only, and vice versa. Overall, *PET/P* trends are strongly affected by changes in *P* in both analysis periods. Influences of other four variables are generally small, but in part comparable to those of *P*. In the early period, changes in *P* decrease *PET/P* in the arid (northwestern China and Inner Mongolia) and humid regions (southeastern China), also increase *PET/P* over a part of the transitional (Shandong Peninsula) and arid (Bohai Bay) (Fig. 6a). Changes in *PET/P* due to other climate parameters are negligible except relatively large influences of *Rn* over the humid regions (Figs. 6b-6e). In the later period, *P* shows positive influences over the northeastern China (arid and transitional regions are co-existed), but reduces *PET/P* over the arid (northwestern China) and humid regions (southeastern China) (Fig. 6f). Relative influences of *Rn* shows similar magnitudes to that of *P* over the transitional area (Shandong Peninsula) (Figs. 6f and 6g). Over the humid regions (southeastern China), positive influences of *RH* are on a par with the negative influences of *P* (Figs. 6f and 6j).

The spatial patterns of relative effects of climate parameters are significantly different according to the analysis periods and regions, indicating that the mechanisms involved in changing *PET/P* trends operate differently. Figure 7 displays the averaged effects of five climate parameters over the three hydro-climate regimes for the two analysis periods. The confidence intervals are computed at the 95% significance level based on relative influences of five variables at 56, 50, and 51 stations of arid, transitional, and humid climate regimes (see section 3 in supplementary information for details). Note that this analysis focuses on the monsoon region, which shows significant variability in the trends of *PET/P*. Stations located in western China (west of 100°E) are excluded. The mean climate of western China is distinctly different from the monsoon ~~climate[8].~~climate (Piao et al., 2010). Furthermore, the dryness trends in these regions are more strongly associated with variations in *P* for both analysis periods than with other climate variables (Fig. ~~S3).~~6, and Zhai et al., 2005; Shi et al., 2007).

~~The relative effects of climate parameters are significantly different according to the analysis period and the hydro-climate regime, indicating that the mechanisms involved in changing *PET/P* trends operate differently (Fig. 3).~~ Over the arid region, the positive effects of *P*, *Ta*, and *RH* (1.15%, 0.44%, and 0.55% decade^{-1}, respectively) increase the ~~aridity~~*PET/P* before the early 1980s (Fig. 7a). Large~~3a). In addition, the large~~ confidence range of *P* indicates a substantial impact of *P* on the *PET/P* trends locally (Fig. ~~S3a~~6a). In the later period, the change in *P* provides the largest influence (3.27% decade^{-1}), at least twice the magnitude of any other climate parameter. These results imply that the decrease in *P* is the main cause of the significantly increasing trend in *PET/P* over the arid region. In the transitional region, the negative influence of *Rn* (-0.85% decade^{-1}) appears to be the largest in the earlier period (Fig. ~~3b~~7b), but the wide confidence interval of *P* suggests that *PET/P* trends vary spatially according to the changes in *P* (Fig. ~~S3a~~6a). In the later period, *PET/P* increased because of the positive influences of changes in *P*, *Ta*, and *RH* (2.02%, 0.97%, and 0.99% decade^{-1}, respectively), despite the negative effects of *Rn* and *WS* (-0.34% and -0.48% decade^{-1}, respectively). Thus, the increasing trend of *PET/P* in the transitional region is largely a consequence of surface warming (i.e., *Ta*) and decreases in *P* and *RH*. Over the humid area, negative effects of both *P* and *Rn* (-4.52% and -2.06% decade^{-1}, respectively) lead to the decrease of *PET/P* in the earlier period (Fig. ~~3c~~7c). The contribution from each of the other three variables is much smaller. In contrast, in the later period, the positive influences of *Ta* and *RH* (0.79% and 1.81% decade^{-1}, respectively) are somewhat larger than the negative influences of *P* and *Rn* (-1.08% and -0.70% decade^{-1}, respectively). Thus, the increasing trend in *PET/P* over the humid region is mainly caused by the warming and subsequent increase in atmospheric water demand.

4 Discussions and Conclusions

The present study suggests that trends in surface dryness reverse from wetting to drying around the early 1980s over both arid and humid monsoon regions. In addition, major climate parameters determining dryness trends vary by both the analysis period and ~~by region~~hydro-climate regime. For the period of 1961-1983, trends in surface dryness are mostly attributed to changes in *P*, regardless of region. A significant decrease in *Rn* reinforces wetting trends over the humid area by decreasing *PET*. Large influences of *P* and *Rn* on dryness trends are consistent with the results of previous studies on trends in aridity and *PET* using daily observations of weather (Wu et al., 2006; Han et al., 2012).

In the later period, changes in *P*, *Ta*, and *RH* lead to drying trends over the monsoon regions. Figure ~~4~~8 illustrates the impacts of the three variables on the dryness trend in the arid and humid monsoon regions, respectively. Over the arid monsoon region, *PET/P* is greatly increased by the positive effects of the three variables, whereas the humid monsoon region shows relatively small increases in *PET/P* because the positive effects of *Ta* and *RH* are offset by the negative effects of *P*. In contrast to the importance of the effect of evaporative potential on surface dryness in other water-limited regions (Westerling et al., 2006; Estes et al., 2012), the decrease in *P* plays a dominant role in the increasing *PET/P* trends in the arid monsoon region. In the humid monsoon area, the decrease in *RH* shows the largest effect on the *PET/P* trend, despite the relatively small magnitude of warming. The relationship between air temperature and saturation vapor pressure (e_s) (e.g., the Clausius–Clapeyron equation) explains the large influence of the decrease in *RH*. Due to high mean temperatures in the humid monsoon region (shades of the map in Fig. ~~4~~8), warming leads to a steep increase in e_s, and a subsequent decrease in *RH*, resulting in a large increase in evapotranspiration.

Our results based on point observations already include various anthropogenic impacts such as land use/land cover changes (LULCC) and increased aerosol emissions, which can influence climate and further surface dryness (Menon et al., 2002; Guo et al., 2013). For example, in the later period, positive influences of *P* are generally inconsistent with negative influences of *Rn* (Fig. 3a) because of the decrease in *P* is favorable condition for the increase in *Rn*, which can result in positive influences of *Rn* on the surface dryness trend. We anticipate that aerosols can play an important role in the decrease in *Rn* in the arid region by absorbing and scattering solar irradiance. Furthermore, additional heating due to urbanization may cause different trends in atmospheric water demands between urban and rural areas (Han et al., 2012; Ren and Zhou, 2014). However, examining the effects of LULCC and aerosols on trends in surface dryness lies beyond scope of the present study.

The effects of *Ta* and *RH*, which act to dry land surfaces, increased significantly in recent decades in all regions (~~Fig. 3~~Figs. 6 and 7). Moreover, over the humid monsoon region, increases in *RH* show a greater influence on trends in surface dryness than increases in *P*. This is an unusual situation considering the large variability of summer monsoon rainfall over continental East Asia. The large influence of *RH* is supported by steep warming over the humid monsoon area after the early 1980s. This kind of drying mechanism is consistent with that suggested in assessments dealing with changes in surface dryness during the 20th and 21st centuries using reconstructed data and future climate projections (Sherwood and Fu, 2014). Thus, our study could be an observed precursor of the projected drying trends over the humid areas in 21st century (Cook et al., 2014; Yin et al., 2015). The present results also indicate that drying of the land surface in response to warming is already in progress, not simply a future risk. Therefore, water management planning must consider the increased water demands associated with warming in order to mitigate water scarcity, even in the wet monsoon regions.

Code and data availability

Codes of NCAR Command Language version 6.3.0, Python, and Interactive Data Language for calculation and climate data are available upon request to the correspondence author Su-Jong Jeong (waterbell@gmail.com).

Author Contributions

C.-E. P. conceived and designed the study, analysed data, and wrote the paper. S.-J. J. helped conceive of the study, and wrote the paper. C.-H. H. wrote the paper. H. P. analysed data, and wrote the paper. S. P., J. K., and S. F. helped conceive of the study and wrote the paper.

Competing interests

The authors declare no competing financial interest.

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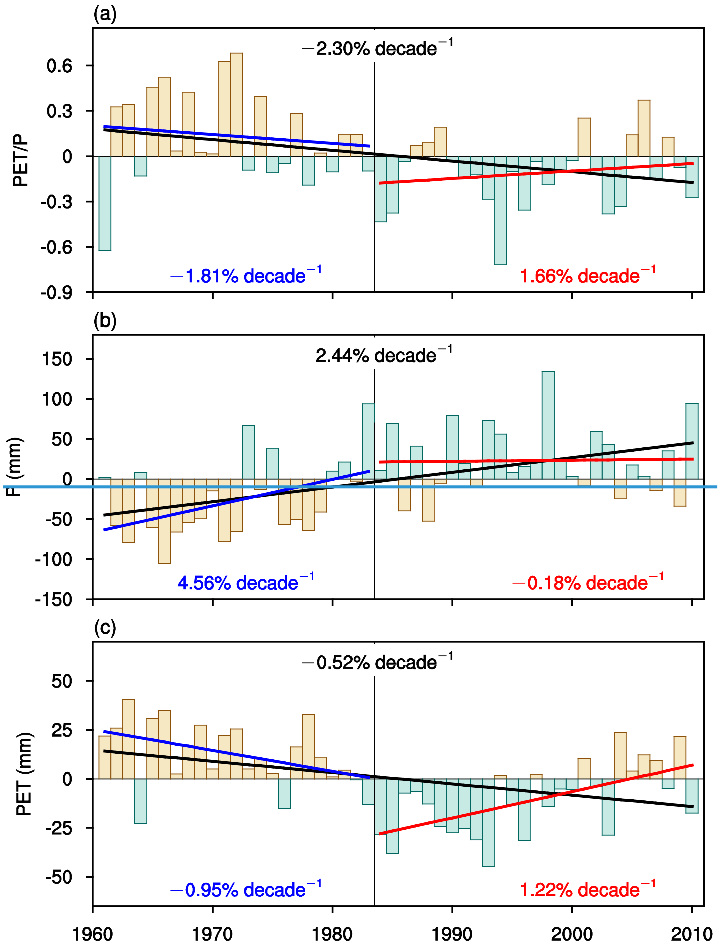
Figures



~~Figure 1: Temporal variations of annual-mean *PET/P* (a), *P* (b), and *PET* (c) in continental East Asia. Yellow and blue bars indicate the positive and negative anomalies for *PET/P* and *PET*, respectively, but negative and positive anomalies for *P*, respectively. Black, blue, and red lines are linear regression lines (% decade^{-1}) for the periods 1961–2010, 1961–1983, and 1984–2010, respectively.~~

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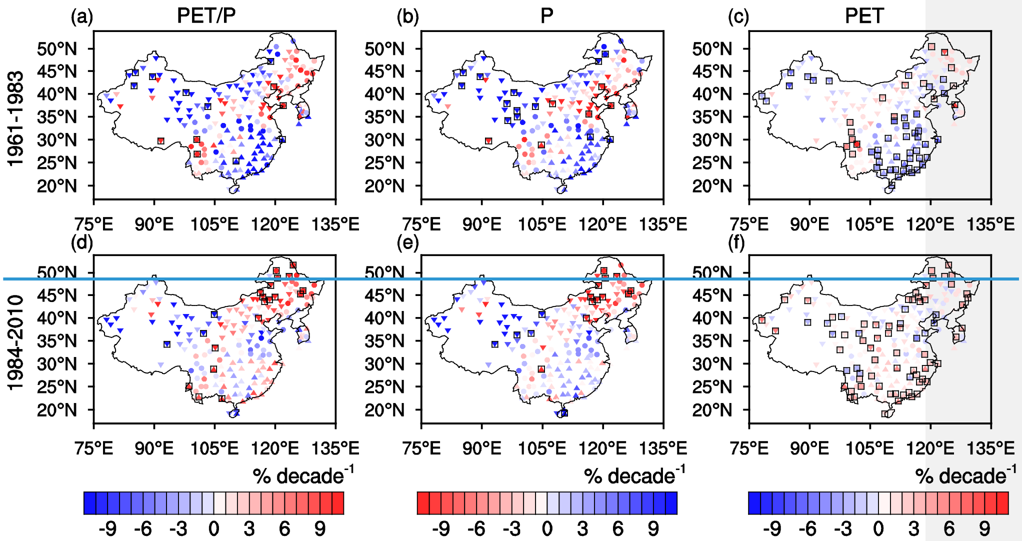

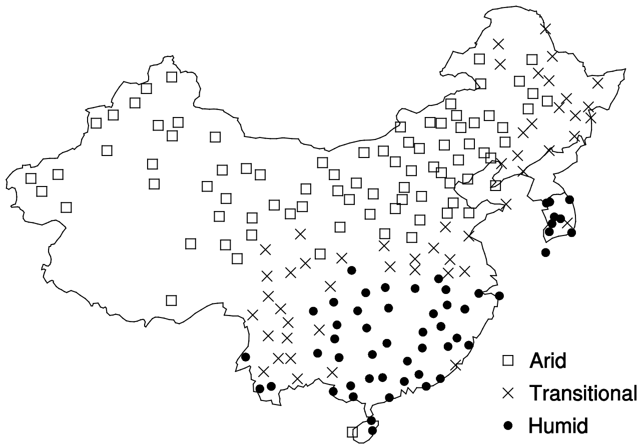

Figure 1. Spatial distribution of 189 meteorological stations in analysis domain. Spatial locations of 179 and 10 meteorological sites of Mainland China and South Korea. Empty squares, crosses and filled circles indicate stations that classified by arid, transitional, and humid regimes based on 50-year climatological *PET/P* for the period of 1961-2010.

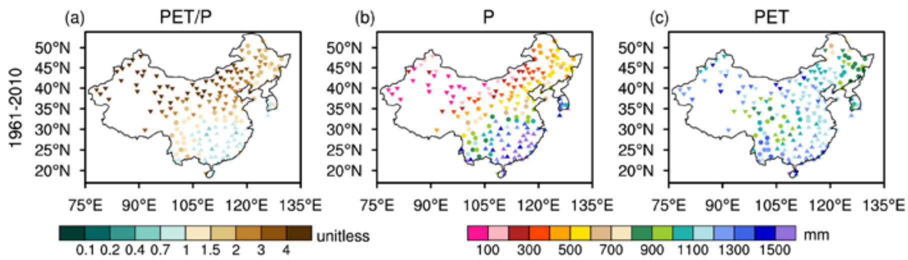

Figure 2: Spatial distributions of the climatologies of *PET/P* (a), *P* (b), and *PET* (c) over continental East Asia for the period of 1961-2010. Inverse triangles, circles, and triangles represent stations classified as arid, transitional, and humid regions, respectively.

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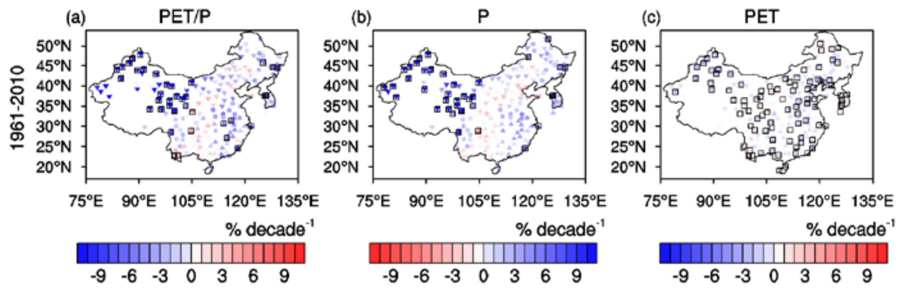

Figure 3. Spatial distributions of the trends in *PET/P*, *P*, and *PET* over continental East Asia. a–c: The spatial distribution of trends in the annual-mean *PET/P* (a), *P* (b), and *PET* (c) for the period of 1961–2010. Inverse triangles, circles, and triangles represent stations classified as arid, transitional, and humid regions, respectively. The open squares indicate that the trend is significant at the 95% confidence level.

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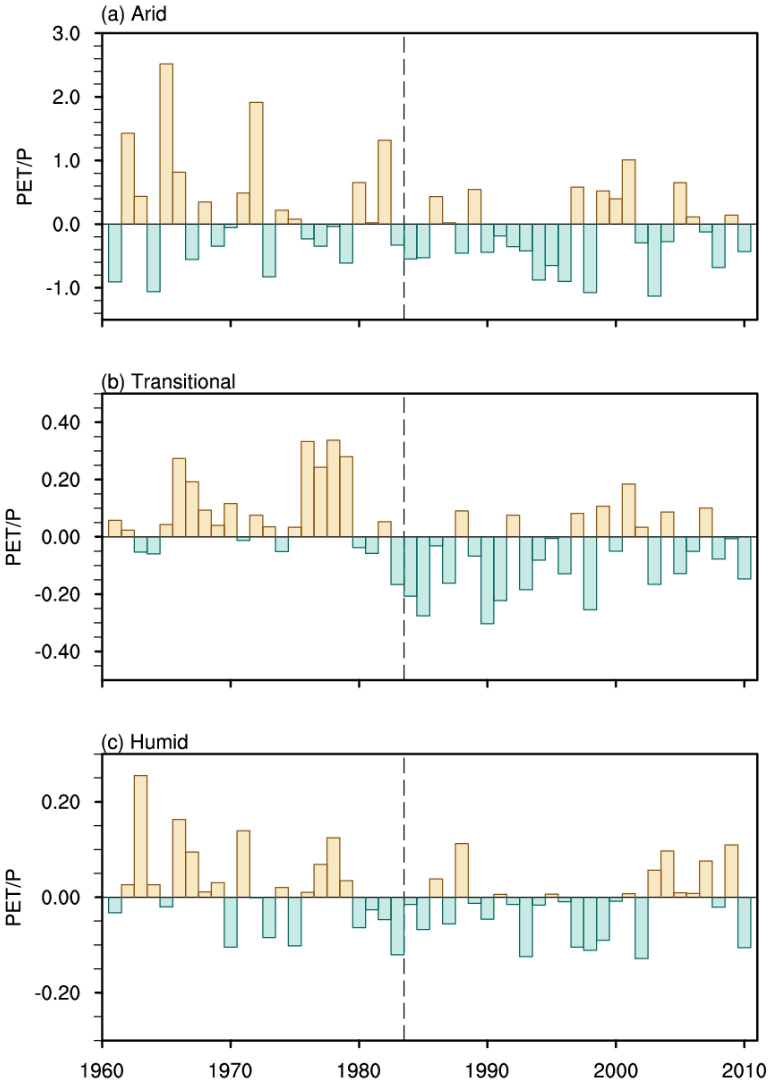

Figure 4. Interannual variations of the annual-mean *PET/P* over the (a) arid, (b) transitional, and (c) humid regions located to the east of 100ºE. Yellow and blue bars indicate the positive and negative anomalies for *PET/P*, respectively.

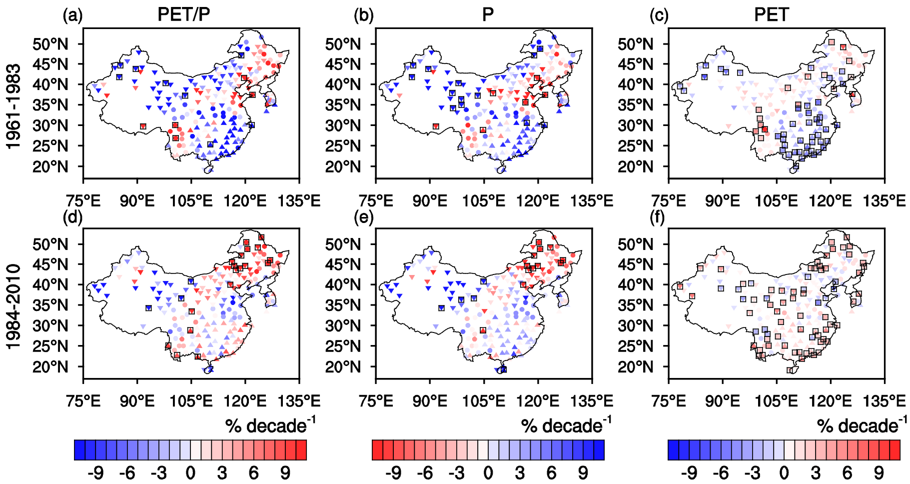

Figure 5: Spatial distributions of the trends in *PET/P*, *P*, and *PET* over continental East Asia. a−c: The spatial distribution of trends in the annual-mean *PET/P* (a), *P* (b), and *PET* (c) for the period of 1961−1983. d−f: as a−c, but for the period 1984−2010. Inverse triangles, circles, and triangles represent stations classified as arid, transitional, and humid regions, respectively. The ~~empty square indicates~~open squares indicate that the trend is significant at the 95% confidence level.

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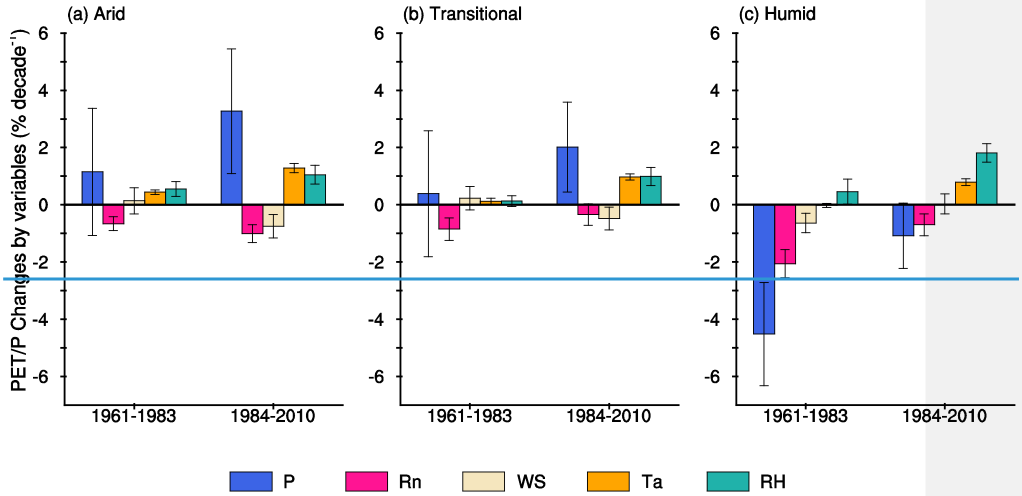
(a) Arid
(b) Transitional
(c) Humid
PET/P Changes by variables (% decade⁻¹)
6
4
2
0
-2
-4
-6
1961-1983
1984-2010
P
Rn
WS
Ta
RH

~~Figure 3~~

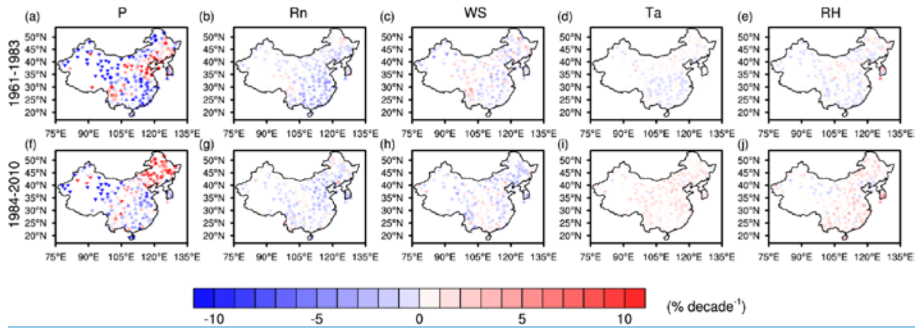

Figure 6. Spatial distributions of the relative influences of five climate parameters on the *PET/P* trends. a-e, The spatial distribution of relative influences of the changes in *P* (a), *Rn* (b), *WS* (c), *Ta* (d), and *RH* (e) on the *PET/P* trends for the period of 1961-1983. f-j, as a-e, but for the period of 1984-2010. Inverse triangles, circles, and triangles represent stations classified as arid, transitional, and humid regions, respectively.

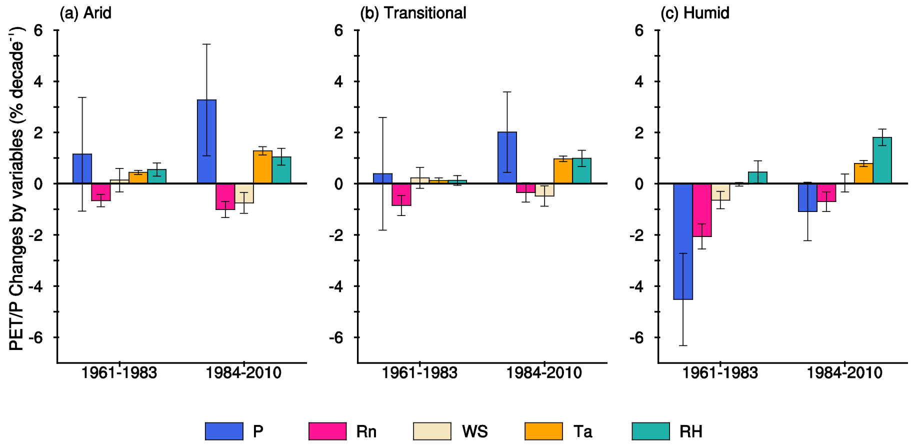

Figure 7: Relative influences (% decade^{-1}) of five climate parameters averaged over the three hydro-climate regimes: arid (a), transitional (b), and humid (c). The influences are computed for the two analysis periods: 1961−1983 and 1984−2010. Blue, pink, beige, orange, and cyan bars represent the respective influences of *P*, *Rn*, *WS*, *Ta*, and *RH*. Error bars represent confidence intervals at the 95% confidence level.

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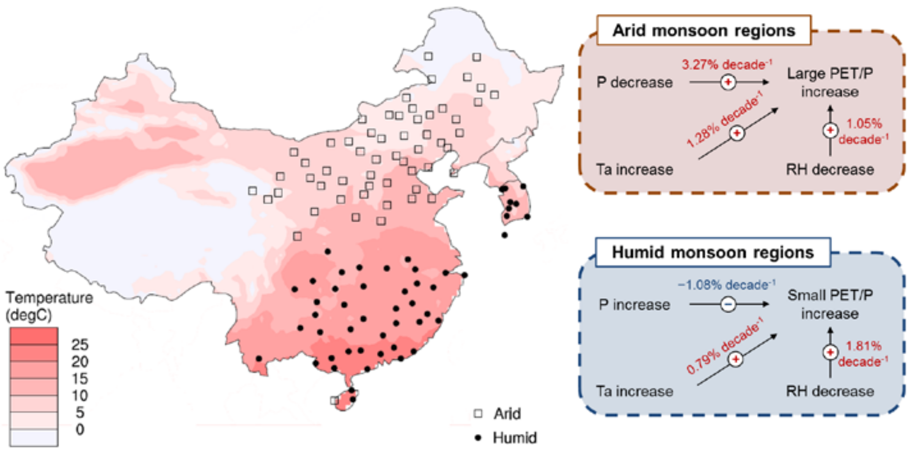

Figure 48: Schematic diagram of the contributions of *P*, *Ta*, and *RH* on the *PET/P* trends in arid and humid monsoon regions for the period of 1983−2010. Diagrams of the influences of *P*, *Ta*, and *RH* on the trend in *PET/P* over arid and humid monsoon regions in 1983−2010 are located to the right of annual-mean temperature over continental East Asia for 1961−2010 (°C). Empty squares and filled circles are stations classified as arid and humid monsoon regions (east of 100°E), respectively.

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