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

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S1. Algorithm for calculating daily PET

Daily *PET* values are calculated from 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:

$$PET = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} \frac{c_1(1 + c_2 U_2)(e_s - e_a)}{\lambda} \qquad (S1)$$

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

S2. Change-point methods

Three change-point methods are used to find the change-point of the temporal variation of *PET/P* for the three hydro-climate regimes illustrated in figure 4. One method defines the change-point when cumulative sum of the *PET/P* variation for the ith year (C_i) is greatest (Pettitt, 1980). The cumulative sum C_i is calculated as follows:

$$C_0 = 0 \qquad \text{(S2)}$$

$$C_i = C_{i-1} + (X_i - \bar{X}) \qquad \text{(S3)}$$

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 again with removing long-term 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 defined as the following equation:

$$C_{diff} = C_{max} - C_{min} \qquad \text{(S4)}$$

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 *PET/P* variations. We compute C_{diff}^{0} based on the bootstrap sample by performing the same processor following equation (S2), (S3), and (S4) 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:

$$\gamma = \frac{x}{N} \qquad \text{(S5)}$$

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). This method uses two simple linear regression models written as the following equation:

$$X_i = \begin{cases} a_1 + b_1 i + e_t, & 1 \le i \le c \\ a_2 + b_2 i + e_t, & c < i \le n \end{cases} \quad \text{(S6)}$$

where X_i is a time series of the *PET/P* anomalies, 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:

$$\hat{b}_1 = \frac{\sum_{i=1}^{c}(i-\overline{\iota_1})(X_i-\overline{X_1})}{\sum_{i=1}^{c}(i-\overline{\iota_1})^2}, and\ \hat{b}_2 = \frac{\sum_{i=c+1}^{n}(i-\overline{\iota_2})(X_i-\overline{X_2})}{\sum_{i=c+1}^{n}(i-\overline{\iota_2})^2} \quad \text{(S7)}$$

$$\hat{a}_1 = \overline{X_1} - \hat{b}_1\overline{\iota_1}, and\ \hat{a}_1 = \overline{X_2} - \hat{b}_2\overline{\iota_2} \quad \text{(S8)}$$

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:

$$F_c = \frac{(SSE_R - SSE_F)/2}{SSE_F/(n-4)} \quad \text{(S9)}$$

where

$$SSE_F = \sum_{i=1}^{c}\left(X_i - \hat{a}_1 - \hat{b}_1 i\right)^2 + \sum_{i=c+1}^{n}\left(X_i - \hat{a}_2 - \hat{b}_2 i\right)^2 \quad \text{(S10)}$$

$$SSE_R = \sum_{i=1}^{n}\left(X_i - \hat{a}_R - \hat{b}_R i\right)^2 \quad \text{(S11)}$$

$$\hat{a}_R = 12\frac{\sum_{i=1}^{n}(X_i-\bar{X})\,i}{n(n+1)(n-1)}, and\ \hat{b}_R = \frac{1}{n}\sum_{i=1}^{n}(X_i - \hat{a}_R i) \quad \text{(S12).}$$

If $c = 1$, the first term in the right-hand side of Equation (S10) is set to zero; for $c = n$, the second summation of Equation (S10) 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 S1 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, 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, the other method, which detects shifts in the mean values between two periods, is used to account for the decadal variations in monsoon circulation and rainfall over the analysis region. This method can be expressed as:

$$X_i = \begin{cases} m_1 + e_t, & 1 \le i \le c \\ m_2 + e_t, & c < i \le n \end{cases} \qquad \text{(S13)}$$

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:

$$T = \left| \frac{m_{1r} - m_{2r}}{\sqrt{\sigma_{1r}^2/r + \sigma_{2r}^2/(n-r)}} \right| \qquad \text{(S14)}$$

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 ($p < 0.05$).

The determined years of abrupt change in *PET/P* over three climate regimes based on two detection methods of undocumented change are generally consistent with the well-known climate shift over monsoon regions, late 1970s or early 1980saround 1980, due to decadal variability of East Asian 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.

S3. Estimation of relative influences of climate parameters on *PET/P* trends

The derivative of the aridity index with respect to time is written using the following equation:

$$\frac{d}{dt}\left(\frac{PET}{P}\right) = -\frac{PET}{P^2}\frac{dP}{dt} + \frac{1}{P}\frac{dPET}{dt} \qquad \text{(S15)}$$

The first and second terms on right-hand side indicate temporal changes in the aridity index due to changes in P and PET. PET can be decomposed into four climate parameters using multilinear regression:

$$PET = a_{Rn}R_n + a_{WS}WS + a_{Ta}T_a + a_{RH}RH + b \qquad (S16)$$

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. This linear regression method is widely used 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). We obtain the time derivative of Equation (S16) as follows:

$$\frac{dPET}{dt} = a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt} \qquad \text{(S17).}$$

where each term on the right-hand side indicates trends in *PET* with respect to changes in each climate variable individually. Finally, Equation (S15) is written as follows:

$$\begin{aligned}\frac{d}{dt}\left(\frac{PET}{P}\right) &= -\frac{PET}{P^2}\frac{dP}{dt} + \frac{1}{P}\left(a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt}\right) \\ &\approx -\frac{\overline{PET}}{\bar{P}^2}\frac{dP}{dt} + \frac{1}{\bar{P}}\left(a_{Rn}\frac{dR_n}{dt} + a_{WS}\frac{dWS}{dt} + a_{Ta}\frac{dT_a}{dt} + a_{RH}\frac{dRH}{dt}\right) \qquad \text{(S18)}\end{aligned}$$

where the terms on the right-hand side are the trend in *PET/P* considering changes in *P*, *Rn*, *WS*, *Ta*, and *RH*, indicating relative influences of *P*, *Rn*, *WS*, *Ta*, and *RH* sequentially. $\bar{P}$ and $\overline{PET}$ are the average of P and PET for the analysis period, respectively. Relative influences of each climate parameters are computed at individual weather stations, and then averaged over the arid, transitional, and humid regions of monsoon climate zones.

The confidence intervals relative influences of each climate parameters for the arid, transitional, and humid regions are calculated by the following equation:

$$\left(\bar{x} - 1.96\frac{s}{\sqrt{n}}, \quad \bar{x} + 1.96\frac{s}{\sqrt{n}}\right) \qquad \text{(S19)}$$

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.

The significance of the regression equation (S16) is tested. 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. S2). 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 prove that the regression equation does not suffer from multicollinearity of climate parameters. This strongly supports the significance of equation (S16) and ignore the interaction between climate parameters.

S4. Supplementary Tables

		P	*Rn*	*WS*	*Ta*	*RH*
1961-1983	Arid	1.15 (9.25)	−0.66 (0.91)	0.14 (1.76)	0.44 (0.32)	0.55 (0.98)
	Transitional	0.39 (7.93)	−0.85 (1.42)	0.23 (1.48)	0.12 (0.41)	0.13 (0.68)
	Humid	−4.52 (6.56)	−2.06 (1.79)	−0.64 (1.26)	−0.02 (0.28)	0.46 (1.61)
1984-2010	Arid	3.27 (8.31)	−1.01 (1.20)	−0.75 (1.56)	1.28 (0.62)	1.05 (1.26)
	Transitional	2.02 (5.68)	−0.34 (1.36)	−0.48 (1.44)	0.97 (0.40)	0.99 (1.16)
	Humid	−1.08 (4.15)	−0.70 (1.39)	0.03 (1.29)	0.79 (0.45)	1.81 (1.15)

Table S1. Averaged relative influences of five climate parameters over three hydro-climate regimes for two analysis period. Averaged relative influences of each climate parameters are computed for arid, transitional, and humid regions located on east of 100°E, respectively. Values in parentheses are standard deviations for each climate parameters for both specific region and period.

S5. Supplementary Figures

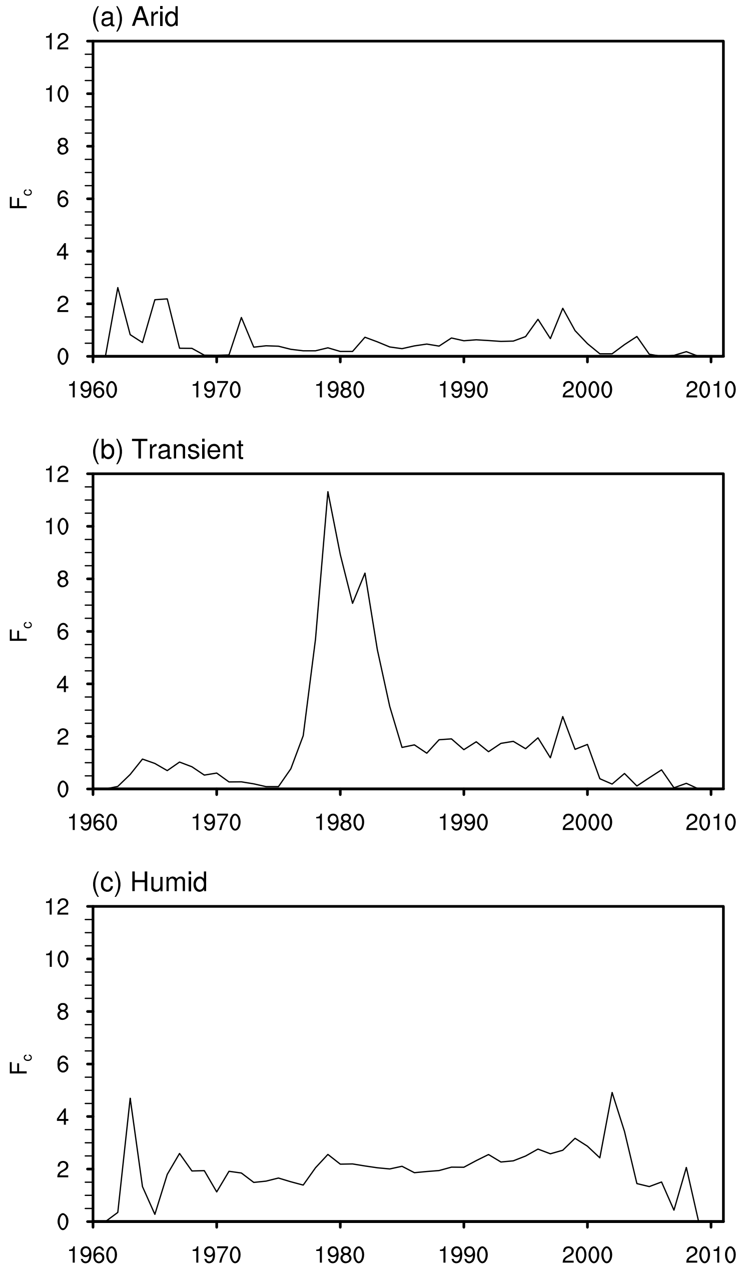

Figure S1. The F_c statistics for the temporal variations of the annual-mean *PET/P* over the (a) arid, (b) transitional, and (c) humid regions.

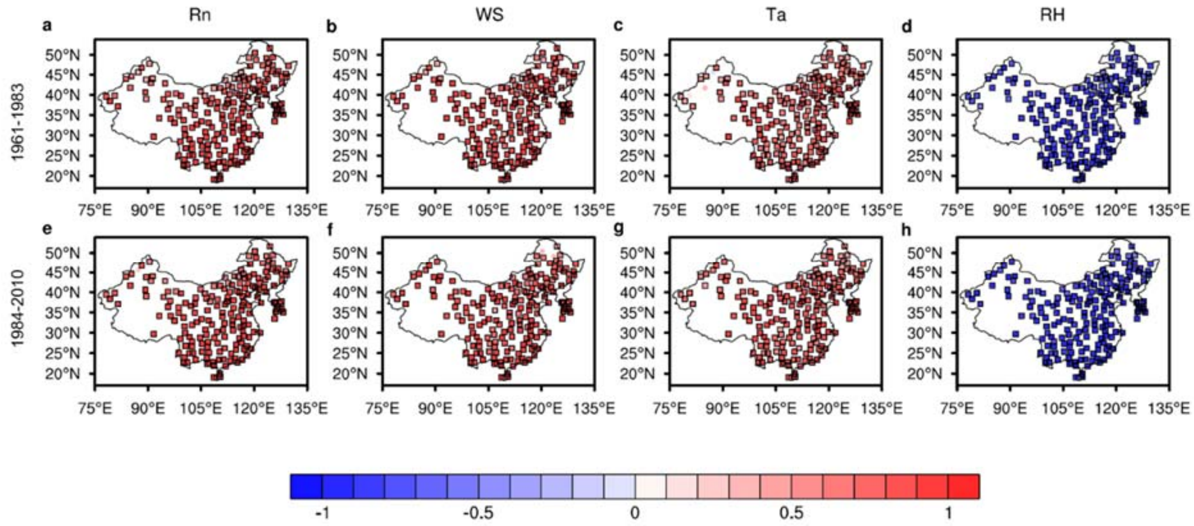

Figure S2. Spatial distribution of partial correlation coefficients over continental East Asia for 1961–1983 and 1984–2010 between *PET* and four parameters such as *Rn*, *WS*, *Ta*, and *RH*. Squared markers indicate that the coefficients are significant at 95% significance level.

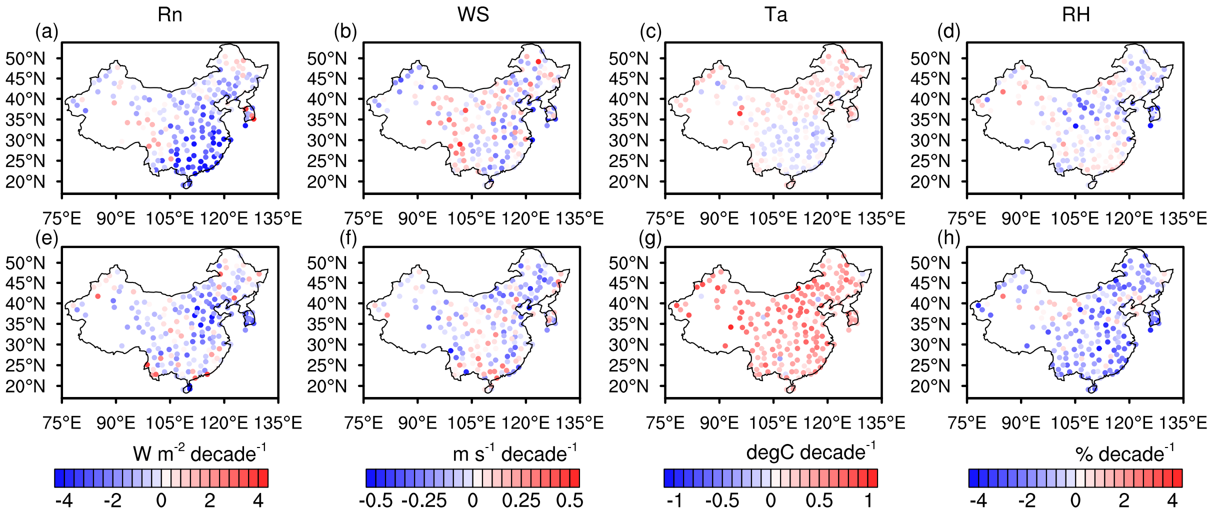

Figure S3. Spatial distributions of the trends in *Rn*, *WS*, *Ta*, and *RH* over continental East Asia. a−d, The spatial distribution of trends in the annual-mean *Rn* (a), *WS* (b), *Ta* (c), and *RH* (d) for the period of 1961−1983. e−h, as a−d, but for the period 1984−2010.

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration–guidelines for computing crop water requirements–FAO Irrigation and drainage Paper 56, FAO, 1998.

Beaulieu, C., Chen, J., and Sarmiento, J. L.: Change-point analysis as a tool to detect abrupt climate variations, Phil. Trans. R. Soc. A., 370, 1228-1249, doi:10.1098/rsta.2011.0383, 2012.

Chattopadhyay, N., Hulme, M.: Evaporation and potential evapotranspiration in India under conditions of recent and future climate change, Agric. Forest Meteorol., 87, 55-73, 1997.

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V. P., and Kahya, E.: Trends in reference crop evapotranspiration over Iran, J. Hydrology, 399, 422-423, doi:10.1016/j.jhydrol.2011.01.021, 2011.

Han, S., Xu, D., and Wang, S.: Decreasing potential evaporation trends in China from 1956 to 2005: Accelerated in regions with significant agricultural influence?, Agric. Forest Meteorol., 154-155, 44–56, doi:10.1016/j.agrformet.2011.10.009, 2012.

Lund, R., Reeves, J.: Detection of undocumented changepoints: A revision of the two-phase regression model, J. Clim., 2547-2554, 2002.

Pettitt, A. N.: A simple cumulative sum type statistic for the change-point problem with zero-one observation, Biometrika, 67, 1, 79–84, 1980.

Sheffield, J., Wood, E. F., and Roderick, M. L.: Little change in global drought over the past 60 years, Nature, 491, 435-438 doi:10.1038/nature11575, 2012.

Taylor, W. A.: Change-Point Analysis: A Powerful New Tool For Detecting Changes, WEB: http://www.variation.com/cpa/tech/changepoint.html, 2000.

Yin, Y., Wu, S., Chen, G., and Dai, E.: Attribution analyses of potential evapotranspiration changes in China since the 1960s, Theor. Appl. Climatol., 101, 19-28, doi:10.1007/s00704-009-0197-7, 2010.