Change-point methods

At first, we try to find change-point of PET/P variations using cumulative sum for three regions following equations (2) and (3) of the original manuscript. The year of abrupt change in PET/P is 1983, 1980, and 1980 in arid, transient, and humid regions, respectively. In the transient region, we apply this method to the detrended time series due to the significant trend, but the result is not changed. In the main body, we omitted the significant test for the results. A simple bootstrap analysis is used to determine a confidence level (Taylor, 2000). Before performing the bootstrap analysis, a difference of the maximum and minimum of cumulative sum as the following equation:

$$C_{diff} = C_{max} - C_{min} \qquad \text{(S1)}$$

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 (1), (2), and (S1) and 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:

$$\gamma = \frac{x}{N} \qquad \text{(S2)}$$

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

The second change-point method is based on linear regression model (Elsner et al., 2000). However, we change the second method to the other method concerning about the possible overestimation of change-point (Lund and Reeves, 2002). The newly adopted method use two simple linear regression model written as the following equation:

$$X_i = \begin{cases} a_1 + b_1 i + e_t, & 1 \le i \le c \\ a_2 + b_2 i + e_t, & c < i \le n \end{cases} \qquad \text{(S3)}$$

where X_i is a time series of PET/P variations, a_1 and a_2 are the intercepts, b_1 and b_2 are the trend 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 least squares estimation as the following equations:

$$\hat{b}_1 = \frac{\sum_{i=1}^{c}(i - \bar{\iota}_1)(X_i - \overline{X_1})}{\sum_{i=1}^{c}(i - \bar{\iota}_1)^2}, and\ \hat{b}_2 = \frac{\sum_{i=c+1}^{n}(i - \bar{\iota}_2)(X_i - \overline{X_2})}{\sum_{i=c+1}^{n}(i - \bar{\iota}_2)^2} \qquad \text{(S4)}$$

$$\hat{a}_1 = \overline{X_1} - \hat{b}_1 \overline{\iota_1}, and\ \hat{a}_1 = \overline{X_2} - \hat{b}_2 \overline{\iota_2} \qquad \text{(S5)}$$

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:

$$F_c = \frac{(SSE_R - SSE_F)/2}{SSE_F/(n-4)} \qquad \text{(S6)}$$

where

$$SSE_F = \sum_{i=1}^{c} \left(X_i - \hat{a}_1 - \hat{b}_1 i\right)^2 + \sum_{i=c+1}^{n} \left(X_i - \hat{a}_2 - \hat{b}_2 i\right)^2 \qquad \text{(S7)}$$

$$SSE_R = \sum_{i=1}^{n} \left(X_i - \hat{a}_R - \hat{b}_R i\right)^2 \qquad \text{(S8)}$$

$$\hat{a}_R = 12 \frac{\sum_{i=1}^{n} (X_i - \bar{X})\, i}{n(n+1)(n-1)}, and\ \hat{b}_R = \frac{1}{n} \sum_{i=1}^{n} (X_i - \hat{a}_R i) \qquad \text{(S9).}$$

If $c = 1$, the first term in right-hand side of equation (S7) is set to zero. For $c = n$, the second summation of equation (S7) is set to zero. The change-point is determined the time when the maximum value F_c is sufficiently large to exceed 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). Figure S3 shows the distribution of the statistic F_c over the arid, transient, and humid regions, respectively. Based on the values of F_c, the only transient region shows an abrupt changes in PET/P around 1980. Thus, we can conclude that this method is not suitable to determine abrupt change in PET/P over the monsoon regions.

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

$$X_i = \begin{cases} m_1 + e_t, & 1 \le i \le c \\ m_2 + e_t, & c < i \le n \end{cases} \qquad \text{(S10)}$$

where m_1 and m_2 are the means before and after the time c (Beaulieu et al., 2012). As the time c is changed from 1 to n, the difference between m_1 and m_2 (Δm_c) can be calculated. The abrupt change is determined at time r, which satisfies $\Delta m_r = \max(\Delta m_c)$. The year of abrupt change is 1983, 1980, and 1970 over the arid, transient, 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:

$$T = \left| \frac{m_{1r} - m_{2r}}{\sqrt{\sigma_{1r}^2/r + \sigma_{2r}^2/(n-r)}} \right| \qquad \text{(S11)}$$

where m_{1r} and m_{2r} are the means; σ_{1r}^2 and σ_{2r}^2 are the variance before and after the time p.

Values of T are 1.870 (p > 90%), 4.744 (p > 99%), and 2.106 (p > 95%) in over the arid, transient, and humid regions, respectively. Considering the significant trend in the transient region, the same analysis is applied to temporal variations in PET/P of the transient region with removing long-term trend. In this change, the change-point is 1980 and the value test statistic is 2.383 (p > 95%).

As we mentioned above, the decadal variation of monsoon circulation around 1980 is a well-known climate shift over monsoon regions. In addition, determined years of abrupt change in PET/P over three climate regimes based on detection methods of undocumented change are generally consistent with the year of climate shift due to decadal variability of monsoon circulation. Thus, we can conclude that separating analysis period into 1961-1983 and 1984-2010 is reasonable to quantify the impacts of climate variables on PEP/P trends. Of course, we approve that descriptions about the methods and background study about the decadal variation of East Asian monsoon circulation are not enough in the original manuscript. We will add sufficient explanations in the revised manuscript.

References

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.

Ding, Y., Wang Z., and Sun Y.: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences, Int. J. Climatol., 28, 1139–1161, doi:10.1002/joc.1615 2008.

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.

Elsner, J. B., Jagger, T., and Niu, X.-F.: Changes in the rates of North Atlantic major hurricane activity during the 20th century, Geophys. Res. Lett., 27, 1743-1746, doi:10.1029/2000GL011453, 2000.

Gong, D.-Y. and Ho, C.-H.: Shift in the summer rainfall over the Yangtze River valley in the late 1970s, Geophys. Res. Lett., 29, 78-1, doi:10.1029/2001GL014523, 2002.

Ha, K.-J., Heo, K.-Y., Lee, S.-S., Yun, K.-S., and Jhun, J.-G.: Variability in the East Asian Monsoon: a review, Met. Apps., 19, 200-215, doi:10.1002/met.1320, 2012.

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.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., and Fang, J.: The impacts of climate change on water resources and agriculture in China, Nature, 467, 43–51, doi:10.1038/nature09364, 2010.

Shi, Y., Shen, Y., Kang, E., Li, D., Ding, Y., Zhang, G., and Hu, R.: Recent and Future Climate Change in Northwest China, Climatic Change, 80, 379-393, doi:10.1007/s10584-006-9121-7, 2007.

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

Wang, B. and Ding, Q.: Changes in global monsoon precipitation over the past 56 years, Geophys. Res. Lett., 33, L06711, doi:10.1029/2005GL025347, 2006.

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.

Zhai, P. M., Zhang, X. B., Wan, H., and Pan, X. H.: Trends in total precipitation and frequency of daily precipitation extremes over China, J. Clim. 18, 1096–1108, doi:10.1175/JCLI-3318.1, 2005.

Zhou, T., Zhang, L., and Li, H.: Changes in global land monsoon area and total rainfall accumulation over the last half century, Geophys. Res. Lett., 35, L16707, doi:10.1029/2008GL034881, 2008.