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:

\[ C_{\text{diff}} = C_{\text{max}} - C_{\text{min}} \quad (S1) \]

where \( C_{\text{max}} \) and \( C_{\text{min}} \) 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 \( C_{\text{diff}}^0 \) based on the bootstrap sample by performing the same processor following equation (1), (2), and (S1) and determine whether \( C_{\text{diff}} \) is less than \( C_{\text{diff}}^0 \) or not. If the number of bootstrap sample is \( N \), the confidence level of the change-point \( \gamma \) is defined as the following equation:

\[ \gamma = \frac{x}{N} \quad (S2) \]

where \( x \) is a number of bootstraps which satisfies \( C_{\text{diff}}^0 < C_{\text{diff}} \). 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:

\[ X_i = \begin{cases} a_1 + b_1 i + e_i, & 1 \leq i \leq c \\ a_2 + b_2 i + e_i, & c < i \leq n \end{cases} \quad (S3) \]

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 \( c \). \( e_i \) is the error of the linear regression model.

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

\[ \hat{b}_1 = \frac{\sum_{i=1}^{c}(i - \bar{t}_1)(X_i - \bar{X}_1)}{\sum_{i=1}^{c}(i - \bar{t}_1)^2}, \text{and} \hat{b}_2 = \frac{\sum_{i=c+1}^{n}(i - \bar{t}_2)(X_i - \bar{X}_2)}{\sum_{i=c+1}^{n}(i - \bar{t}_2)^2} \quad (S4) \]
where $\bar{X}_1$ and $\bar{X}_2$ are the averages of $X_i$, and $\bar{i}_1$ and $\bar{i}_2$ are the averages of $i$ before and after time $c$, respectively. The test statistic $F_c$ is represented as the following equation:

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

where

$$SSE_F = \sum_{i=1}^{c} (X_i - \hat{\alpha}_1 - \hat{\beta}_1 i)^2 + \sum_{i=c+1}^{n} (X_i - \hat{\alpha}_2 - \hat{\beta}_2 i)^2$$

and

$$SSE_R = \sum_{i=1}^{c} (X_i - \hat{\alpha}_R - \hat{\beta}_R i)^2$$

$$\hat{\alpha}_R = 12 \frac{\sum_{i=1}^{n} (X_i - \bar{X}) i}{n(n+1)(n-1)}, \text{ and } \hat{\beta}_R = \frac{1}{n} \sum_{i=1}^{n} (X_i - \hat{\alpha}_R i)$$

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:

$$X_i = \begin{cases} m_1 + e_i, & 1 \leq i \leq c \\ m_2 + e_i, & c < i \leq n \end{cases}$$

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 $m_2$ ($\Delta m_r$) can be calculated. The abrupt change is determined at time $r$, which satisfies $\Delta m_r = \max(\Delta m_r)$. 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:

$$T = \frac{m_{1r} - m_{2r}}{\sqrt{\sigma_{1r}^2/r + \sigma_{2r}^2/(n-r)}}$$

where $m_{1r}$ and $m_{2r}$ are the means; $\sigma_{1r}^2$ and $\sigma_{2r}^2$ 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 PET/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


Han, S., Xu, D., and Wang, S.: Decreasing potential evaporation trends in China from 1956 to 2005:


