Recent changes in pan-evaporation dynamics in China

Xiaomang Liu, Yuzhou Luo, Dan Zhang, Minghua Zhang and Changming Liu

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[1] Pan-evaporation \( (E_{\text{pan}}) \) as the indicator of atmospheric evaporative demand has decreased worldwide with climate change in the last decades, which is called “Pan Evaporation Paradox”. This study investigates the recent changes in \( E_{\text{pan}} \) dynamics in China using the observed \( E_{\text{pan}} \) records for the period 1960–2007. The results show that \( E_{\text{pan}} \) decreased in China from 1960 to 1991 by \(-5.4 \text{ mm yr}^{-2}\). The attribution results show that the significant decreases \((P < 0.001)\) in wind speed and solar radiation offset the effect of increasing air temperature and led to the decrease in \( E_{\text{pan}} \). However, the observed \( E_{\text{pan}} \) has increased since 1992 by \(7.9 \text{ mm yr}^{-2}\). From 1992 to 2007, the amplitude of increase in air temperature rose seriously, while the amplitude of decrease in wind speed declined and solar radiation even increased insignificantly \((P > 0.1)\). The results show that increasing air temperature dominated the change in \( E_{\text{pan}} \), which offset the effect of wind speed and led to the increase in \( E_{\text{pan}} \). Citation: Liu, X., Y. Luo, D. Zhang, M. Zhang, and C. Liu (2011), Recent changes in pan-evaporation dynamics in China, Geophys. Res. Lett., 38, L13404, doi:10.1029/2011GL047929.

1. Introduction

[2] Decreases in pan-evaporation \( (E_{\text{pan}}) \) over the last decades have been reported in many regions of the world associated with climate change [e.g., Peterson et al., 1995; Roderick and Farquhar, 2002; Liu et al., 2004]. The decrease in \( E_{\text{pan}} \) associated with the increasing near-surface air temperatures is called “Pan Evaporation Paradox” [Brutsaert and Parlange, 1998]. Various interpretations have been presented to explain the “Paradox” in different regions. As \( E_{\text{pan}} \) is an integrated effect of climate variables, increases in air temperature should lead to increases in \( E_{\text{pan}} \). However, this effect could be offset by decreases in vapor pressure deficit, wind speed and solar radiation which lead to decreasing rates of \( E_{\text{pan}} \). Therefore, observed decreases in solar radiation and/or wind speed are considered the causing factors of decreasing \( E_{\text{pan}} \) in different regions of the world [e.g., Roderick et al., 2009a, 2009b]. Recently, the decrease in wind speed is widely considered as the dominant factor contributing to the decreases in \( E_{\text{pan}} \) [e.g., Rayner, 2007; Roderick et al., 2007; Zheng et al., 2009].

[3] Decreases in \( E_{\text{pan}} \) from the 1950s to around 2000 were also reported in China, and decreases in solar radiation and wind speed were considered the driving forces [e.g., Liu et al., 2004, 2010]. However, most of the \( E_{\text{pan}} \) time series ended in 2001 and those studies focused on trend estimation directly, while analysis on the abrupt change in \( E_{\text{pan}} \) was not available. In addition, nationwide quantitative attribution of changes in \( E_{\text{pan}} \) to climate variables was also not available in the literature. In this study, the updated data (1960 to 2007) from the weather station network in China were used and the abrupt changes in \( E_{\text{pan}} \) were analyzed nationwide. Attribution analysis was performed using the Penman-Monteith formulation to quantify the contributions of climate variables to overall trends in \( E_{\text{pan}} \). Our results focus on the recent changes and attribution of \( E_{\text{pan}} \) dynamics in China.

2. Data and Methods

2.1. Data

[4] Monthly meteorological records of 518 national meteorological stations from 1960 to 2007 from the National Climatic Centre (NCC) of China Meteorological Administration (CMA) were used in the study (Figure 1). Crop reference evapotranspiration was calculated based on the mean values of daily maximum, minimum and air temperatures \( (T_{\text{max}}, T_{\text{min}}, T_{a}) \) at 2 m height, wind speed measured at 10 m height, vapor pressure \( (VP) \) at 2 m height and sunshine duration [Allen et al., 1998]. Wind speed was adjusted to 2 m height \((U)\) using Allen et al.’s [1998] wind profile relationship. Solar radiation \( (R_{s}) \) was available at 51 stations. \( E_{\text{pan}} \) was measured using a metal pan, 20 cm in diameter and 10 cm high, installed 70 cm above the ground on a wooden platform. The pan was filled to 2 cm, or sometimes 3 cm, depending on local daily evaporative rates [McVicar et al., 2007].

2.2. Methods

[5] The rank-based non-parametric Mann–Kendall statistical test [Mann, 1945; Kendall, 1975] has been commonly used for trend detection due to its robustness for non-normally distributed data, which are frequently encountered in hydro-climatic time-series. Assuming normal distribution at the significant level of \( P = 0.05 \), a positive Mann-Kendall statistics \( Z \) larger than 1.96 indicates an significant increasing trend, while a negative \( Z \) lower than \(-1.96 \) indicates a significant decreasing trend. Critical \( Z \) values of \( \pm 1.64, \pm 2.58 \) and \( \pm 3.29 \) were used for the probabilities of \( P = 0.1, 0.01 \) and 0.001, respectively. Spatially, China is divided into eight climatic regions (Figure 1), which are generally consistent with those defined by Liu et al. [2004]. Nationwide and regional averages of \( E_{\text{pan}} \) and climate variables were first calculated. Temporal trends and change points of the average \( E_{\text{pan}} \) and climate variables were then quantified by the linear regression and Pettitt’s [1979] test, respectively.

[6] The differentiation equation method [Zheng et al., 2009] was used to attribute the change in \( E_{\text{pan}} \). It is widely accepted that there exists a good linear relationship
between $E_{\text{pan}}$ and reference evapotranspiration ($ET_{\text{ref}}$), expressed as:

$$ E_{\text{pan}} = K_p \times ET_{\text{ref}} + K_c $$

(1)

where $K_p$ and $K_c$ are regression coefficients. $ET_{\text{ref}}$ is the crop reference evapotranspiration of a hypothetical surface estimated by the Penman-Monteith formula [Allen et al., 1998]. The calculating processes and results of $ET_{\text{ref}}$ and $R_e$ are summarized in Text S1, Table S1, and Figure S1 of the auxiliary material. Following the Penman-Monteith formula, contributions of changes in climate factors to $ET_{\text{ref}}$ trend can be approximately estimated as the following [Zheng et al., 2009]:

$$ \frac{dET_{\text{ref}}}{dt} = \frac{\partial ET_{\text{ref}}}{\partial R_e} \frac{dR_e}{dt} + \frac{\partial ET_{\text{ref}}}{\partial T_a} \frac{dT_a}{dt} + \frac{\partial ET_{\text{ref}}}{\partial U} \frac{dU}{dt} + \frac{\partial ET_{\text{ref}}}{\partial VP} \frac{dVP}{dt} + \delta $$

(2)

where $\delta$ is the error item. The detailed formulas and calculating results of differential items are summarized in Text S1 and Tables S2 and S3 of the auxiliary material. With the relationship between $E_{\text{pan}}$ and $ET_{\text{ref}}$ shown in equation (1), the contributions of climate factors to the long-term trend in $E_{\text{pan}}$ can be expressed as:

$$ \frac{dE_{\text{pan}}}{dt} = K_p \frac{\partial ET_{\text{ref}}}{\partial R_e} \frac{dR_e}{dt} + K_p \frac{\partial ET_{\text{ref}}}{\partial T_a} \frac{dT_a}{dt} + K_p \frac{\partial ET_{\text{ref}}}{\partial U} \frac{dU}{dt} + K_p \frac{\partial ET_{\text{ref}}}{\partial VP} \frac{dVP}{dt} + \varepsilon $$

(3a)

or simplified as:

$$ C_E E_{\text{pan}} = C_s (R_e) + C_s (T_a) + C_s (U) + C_s (VP) + \varepsilon $$

(3b)

where $C_E E_{\text{pan}}$ is the calculated long-term trend in $E_{\text{pan}}$. $C_s (R_e)$, $C_s (T_a)$, $C_s (U)$ and $C_s (VP)$ are individual contributions to the long-term trend in $E_{\text{pan}}$ due to the change in $R_e$, $T_a$, $U$ and $VP$ respectively. $\varepsilon$ is the error item between $C_E E_{\text{pan}}$ and observed $E_{\text{pan}}$ trend ($O_E E_{\text{pan}}$).

### 3. Results

#### 3.1. $E_{\text{pan}}$ Trend

Figure 2a shows the variation of annual $E_{\text{pan}}$ for nationwide average from 1960 to 2007. A change point for $E_{\text{pan}}$ series was identified around the year 1992. $E_{\text{pan}}$ decreased significantly ($P < 0.001$) at $5.4 \text{ mm yr}^{-2}$ from 1960 to 1991, while $E_{\text{pan}}$ increased significantly ($P < 0.001$) at $7.9 \text{ mm yr}^{-2}$ from 1992 to 2007. For all the eight climatic regions, change points of annual $E_{\text{pan}}$ series were observed in early 1990s. The regional variations of $E_{\text{pan}}$ and climate

![Figure 1](image1.png)

**Figure 1.** The spatial distribution of the 518 meteorological stations in China. The red circles indicate the 51 stations which have observed solar radiation data. Regional abbreviates are provided in the figure. The latitudes to define the 8 regions are about 44°N, 36°N, 35°N and 28°N from North to South respectively and the longitude are 100°E and 110°E from West to East respectively.

![Figure 2](image2.png)

**Figure 2.** (a) Variation of annual $E_{\text{pan}}$ for nationwide average from 1960 to 2007. The blue line shows the five year moving average and the red dotted lines are the linear trends fitted to corresponding periods. Trends in annual $E_{\text{pan}}$ for the 518 meteorological stations in China during the periods (b) 1960 to the early 1990s and (c) the early 1990s to 2007 ($E_{\text{pan}}$ trends for the stations were calculated before and after the change points of the corresponding climatic regions). S and NS in the figure legend indicate significance and insignificance at $P = 0.05$, respectively. The numbers given after S or NS indicate the number of stations out of 518 stations in these categories.
factors are summarized in Table S4 and Figure S2 of the auxiliary material. Annual $E_{\text{pan}}$ in all the eight regions decreased before early 1990s and increased since then. $E_{\text{pan}}$ trends for the 518 stations were calculated before and after the corresponding regional change points. As shown in Figures 2b and 2c, annual $E_{\text{pan}}$ in most stations decreased from 1960 to the early 1990s and increased from the early 1990s to 2007.

### 3.2. $E_{\text{pan}}$ Attribution

[8] The contributions of changes in climate factors to the long-term trend in annual $E_{\text{pan}}$ were estimated by equation (3) at all the stations. The calculated $E_{\text{pan}}$ trends ($C_{\text{E}_{\text{pan}}}$) fit well with the observed $E_{\text{pan}}$ trends ($O_{\text{E}_{\text{pan}}}$) for the 518 stations with $R^2 = 0.93$ and 0.91 before and after the early 1990s respectively (see Figure S3 of the auxiliary material). For the country average, the overall relative errors between $C_{\text{E}_{\text{pan}}}$ and $O_{\text{E}_{\text{pan}}}$ were $-7\%$ and $-9\%$ for the two periods, respectively (Table 1). For the eight climatic regions, the maximum relative error from 1960 to the early 1990s was $-12\%$ which occurred in the Tibet Plateau. The maximum relative error from the early 1990s to 2007 was $-16\%$ which occurred in the North Center. The good agreement between $C_{\text{E}_{\text{pan}}}$ and $O_{\text{E}_{\text{pan}}}$ suggested that it was reasonable to use equation (3) to estimate contributions of individual climate factors to the long-term trend in $E_{\text{pan}}$.

[9] Table 1 shows the contribution of each climate factor to the trend in annual $E_{\text{pan}}$. For the nationwide average, from 1960 to 1991, $T_a$ increased significantly ($P < 0.05$) at 0.011°C yr$^{-1}$, and the increases in $T_a$ should have led to an increase in $E_{\text{pan}}$ at 1.3 mm yr$^{-2}$. However, both $U$ and $R_S$ decreased significantly ($P < 0.001$) at $-0.012$ m s$^{-1}$ yr$^{-1}$ and $-0.023$ MJ m$^{-2}$ day$^{-1}$ yr$^{-1}$ respectively, and decreases in $U$ and $R_S$ should have led to a decrease in $E_{\text{pan}}$ at $-3.5$ mm yr$^{-2}$ and $-2.7$ mm yr$^{-2}$, respectively. VP increased insignificantly ($P > 0.1$) and led to a decrease in $E_{\text{pan}}$ at $-0.1$ mm yr$^{-2}$. The combined effects of the four climate factors resulted in a decrease in $E_{\text{pan}}$ at $-5.0$ mm yr$^{-2}$, and the absolute and relative error compared to $O_{\text{E}_{\text{pan}}}$ was $0.4$ mm yr$^{-2}$ and $-7\%$, respectively. It is clear that the increasing $T_a$ had a positive effect on $E_{\text{pan}}$, but the effect had been offset by decreasing $U$ and $R_S$.

[10] From 1992 to 2007, $T_a$ increased significantly ($P < 0.01$) with a much larger amplitude of 0.064°C yr$^{-1}$ and the increases in $T_a$ should have led to an increase in $E_{\text{pan}}$ at 7.4 mm yr$^{-2}$. Meanwhile, $U$ decreased with a smaller rate of $-0.007$ m s$^{-1}$ yr$^{-1}$ ($P < 0.05$), while $VP$ decreased insignificantly and $R_S$ increased significantly ($P > 0.1$). Decrease in $U$ should have led to a decrease in $E_{\text{pan}}$ at $-2.0$ mm yr$^{-2}$, while increase in $R_S$ and decrease in VP should have led to an increase in $E_{\text{pan}}$ at 0.2 and 1.7 mm yr$^{-2}$ respectively. The combined effects of the four climate factors resulted in an increase in $E_{\text{pan}}$ at 7.2 mm yr$^{-2}$, and the absolute and relative error compared to $O_{\text{E}_{\text{pan}}}$ was $-0.7$ mm yr$^{-2}$ and $-9\%$, respectively. Decreasing $U$ could not offset the effects of increasing $T_a$, and $E_{\text{pan}}$ increased since 1992.

[11] For the eight climatic regions, from 1960 to the early 1990s, decreases in $U$ dominated the decreases in $E_{\text{pan}}$ in the northern and central parts of China such as Northwest, North Center, Northeast, North China Plain and Tibet Plateau, while decreases in $R_S$ dominated the decreases in $E_{\text{pan}}$ in the southern part of China such as Southeast, East, and Southwest. From the early 1990s to 2007, increases in $T_a$ dominated the increases in $E_{\text{pan}}$ in all the climatic regions except Northeast, where significant decrease ($P < 0.05$) in VP dominated the increase in $E_{\text{pan}}$.

### 4. Discussion

[12] The differentiation equation method based on the Penman-Monteith formula was used to quantify the contribution of climate variables to overall trends in $E_{\text{pan}}$. The errors between $C_{\text{E}_{\text{pan}}}$ and $O_{\text{E}_{\text{pan}}}$ could come from the...

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### Table 1. Contributions of Climate Factors to the Trends in Annual $E_{\text{pan}}$ in the Eight Climatic Regions and the Whole China$^a$

<table>
<thead>
<tr>
<th>Region</th>
<th>$C_{\text{E}_{\text{pan}}}$</th>
<th>$C_{\text{U}}$</th>
<th>$C_{\text{VP}}$</th>
<th>$C_{\text{R}_S}$</th>
<th>$C_{\text{E}_{\text{pan}}}$</th>
<th>OBS</th>
<th>$\epsilon$</th>
<th>$\rho(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nation(92)</td>
<td>1.3</td>
<td>-3.5</td>
<td>-0.1</td>
<td>-2.7</td>
<td>-5.0</td>
<td>-5.4</td>
<td>0.4</td>
<td>-7</td>
</tr>
<tr>
<td>NW(94)</td>
<td>1.8</td>
<td>-7.5</td>
<td>-1.6</td>
<td>-0.8</td>
<td>-8.2</td>
<td>-7.7</td>
<td>0.6</td>
<td>7</td>
</tr>
<tr>
<td>NC(91)</td>
<td>2.2</td>
<td>-7.3</td>
<td>-0.1</td>
<td>-1.5</td>
<td>-6.6</td>
<td>-7.2</td>
<td>0.6</td>
<td>-8</td>
</tr>
<tr>
<td>NE(93)</td>
<td>3.1</td>
<td>-4.3</td>
<td>-0.9</td>
<td>-0.9</td>
<td>-3.0</td>
<td>-3.3</td>
<td>0.3</td>
<td>-10</td>
</tr>
<tr>
<td>NCP(92)</td>
<td>2.1</td>
<td>-5.6</td>
<td>-0.4</td>
<td>-2.6</td>
<td>-6.4</td>
<td>-7.2</td>
<td>0.8</td>
<td>-11</td>
</tr>
<tr>
<td>TP(92)</td>
<td>0.7</td>
<td>-3.2</td>
<td>-0.7</td>
<td>0.0</td>
<td>-3.2</td>
<td>-3.6</td>
<td>0.4</td>
<td>-12</td>
</tr>
<tr>
<td>SE(95)</td>
<td>0.7</td>
<td>-1.6</td>
<td>0.3</td>
<td>-4.0</td>
<td>-4.6</td>
<td>-4.1</td>
<td>-0.4</td>
<td>10</td>
</tr>
<tr>
<td>E(92)</td>
<td>-0.7</td>
<td>-2.2</td>
<td>1.0</td>
<td>-5.1</td>
<td>-7.0</td>
<td>-6.6</td>
<td>-0.4</td>
<td>6</td>
</tr>
<tr>
<td>SW(92)</td>
<td>0.0</td>
<td>-0.8</td>
<td>0.1</td>
<td>-3.8</td>
<td>-4.5</td>
<td>-4.9</td>
<td>0.4</td>
<td>-8</td>
</tr>
</tbody>
</table>

$^a$The numbers in brackets after regional names mean the change dates of each region. OBS: observed trends; CALC: calculated trends by equation (3); the unit is given in mm yr$^{-2}$; $\epsilon$ and $\rho(\%)$ mean error and relative error to observed trends, respectively. See Figure 1 for descriptions of climatic regions.
assumption of differential equations (equation (3)). The four climate factors impacted each other and they were not totally independent. However, the differential equations assumed that they were independent. In addition, the majority of errors between $C_{E_{\text{pan}}}$ and $O_{E_{\text{pan}}}$ were negative (Table 1), which partly because the four climate factors could not completely capture the changes in $E_{\text{pan}}$. Other factors such as aerosol and dust etc. could also impact the radiation and further impact the evaporation process.

[13] Serious decrease in $U$ contributed to the decrease in $E_{\text{pan}}$ from 1960 to the early 1990s in the northern and central parts of China. Such results were also found in the United States [Hobbs, 2004] and Australia [e.g., Rayner, 2007; Roderick et al., 2007; McVicar et al., 2008; Donohue et al., 2010]. Meanwhile, $U$ decreased at $\sim 0.012$ m s$^{-1}$ yr$^{-1}$ for China average, which is almost identical to the trends reported in Australia [Roderick et al., 2007] and many Northern Hemisphere countries [Vautard et al., 2010].

The dominant factor in the $E_{\text{pan}}$ trend had regional differences, despite $U$ being the dominant factor for nationwide average. The amplitude of decrease in $R_h$ in the southern part of China was larger than that in the northern and central part of China, and decrease in $R_h$ played a more important role in the decrease in $E_{\text{pan}}$ in southern part of China. Xu et al. [2006] also found that decrease in $E_{\text{pan}}$ in Yangtze River catchment (located in the southern part of China) was mainly caused by the decrease in $R_h$ and to a lesser extent by the decrease in $U$.

[14] Globally, the observed increase in $T_a$ rose dramatically since the 1990s and the warmest 11 years from 1850 all occurred between 1995 and 2007 [World Meteorological Organization, 2007]. For China average, the annual increase in $T_a$ was 0.064°C yr$^{-1}$ from 1992 to 2007, about six times higher than that of 0.011°C yr$^{-1}$ from 1960 to 1991. Effect of sharply increasing $T_a$ dominated the changes in $E_{\text{pan}}$ and led to the reversal of $E_{\text{pan}}$ trends. In addition, the impacts of increasing $T_a$ led to increase in $E_{\text{pan}}$ that could be partitioned in to two components, aerodynamic component and radiative component (see Text S1 of the auxiliary material). Increasing $T_a$ led to 5.6 mm yr$^{-2}$ increase in aerodynamic component and 1.8 mm yr$^{-2}$ increase in radiative component from 1992 to 2007. Increasing $T_a$ were impacting aerodynamic component more than radiative component of $E_{\text{pan}}$.

5. Conclusion

[15] The recent changes in $E_{\text{pan}}$ dynamics in China were investigated based on measurements at 518 stations. Annual $E_{\text{pan}}$ for the China average decreased significantly ($P < 0.001$) at $-5.4$ mm yr$^{-2}$ from 1960 to 1991 and increased significantly ($P < 0.001$) at 7.9 mm yr$^{-2}$ from 1992 to 2007. The increasing $T_a$ had a positive effect on $E_{\text{pan}}$, but the effect had been offset by decreasing $U$ and $R_h$ from 1960 to 1991. Since 1992, serious increases in $T_a$ dominated the changes in $E_{\text{pan}}$ and led to the increase in $E_{\text{pan}}$—Regionally, change points of annual $E_{\text{pan}}$ series were observed in the early 1990s for all the eight climatic regions. Decreasing $U$ dominated the decreases in $E_{\text{pan}}$ in the northern and central parts of China, while decreasing $R_h$ dominated the decreases in $E_{\text{pan}}$ in the southern part of China from 1960 to the early 1990s. Increasing $T_a$ dominated the increases in $E_{\text{pan}}$ in all the climatic regions except Northeast, where decrease in $VP$ dominated the increase in $E_{\text{pan}}$ from the early 1990s to 2007.

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C. Liu, X. Liu, and D. Zhang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

Y. Luo and M. Zhang, Department of Land, Air and Water Resources, University of California, One Shield Ave., Davis, CA 95616, USA. (mhzhang@ucdavis.edu)