On the attribution of changing pan evaporation in a nature reserve in SW China

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Abstract:

Negative trends of measured pan evaporation are widely reported. Studies of the factors that underlie this reduction in pan evaporation have not reached a consensus about the controlling factors. Most studies employ statistical analysis (correlation analysis or stepwise regression) to identify the controlling climatic variables; in contrast, few studies have employed physical-based theories. In addition, observations of pan evaporation and related climatic variables are reported to be influenced by anthropogenic activities. Consequently, the observed trends of climatic variables in a nature reserve would be useful for understanding regional climate change. The present study site is located in Ailaoshan National Nature Reserve, SW China, which is free of anthropogenic activity. In this study, we firstly applied the adjusted PenPan model to estimate the pan evaporation. Then, using this physical-based model, we identified a positive trend in pan evaporation, with a much larger increase in the dry season than in the wet season. The model results indicate that the change in the aerodynamic component is larger than that in the radiative component. In contrast to the reduction in wind speed and sunshine hours that has been reported in previous studies at various sites, we found that wind speed and sunshine hours have increased in recent decades, thereby explaining the increase of the pan evaporation rate. Wind speed made the greatest contribution to the change in pan evaporation, followed by sunshine duration. This study indicates that the potential evaporation has increased at this site despite the widely reported reduction in measured pan evaporation. During the dry season, the availability of water for agriculture and agroforestry could be threatened.

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KEY WORDS climate change; pan evaporation; adjusted PenPan model; Ailaoshan National Nature Reserve

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INTRODUCTION

One of the expected consequences of global warming is an increase in the rate of evaporation as a consequence of increased air temperature (Stocker et al., 2001). However, negative trends in measured pan evaporation have been reported in the United States (Hobbins et al., 2004), the former Soviet Union (Peterson et al., 1995), the Canadian prairies (Burn and Hesch, 2007), Australia (Roderick et al., 2007), New Zealand (Roderick and Farquhar, 2005), northeast India (Jhajharia et al., 2009), Thailand (Tebakari et al., 2005), and China (Xu et al., 2006; Wang et al., 2007; Zhang et al., 2007). However, positive trends have been reported in west Iran (Tabari and Marofi, 2011), north-eastern Brazil (da Silva, 2004), Israel (Cohen and Stanhill, 2002), and West Africa (Ogununde et al., 2006). Consequently, there is no consistency in the reported trends in pan evaporation measurements (Fu, 2009). Such contradictory trends in pan evaporation trends can even coexist in the same region (Wang et al., 2007; Ji and Zhou, 2011).

No consensus has been reached about the underlying causes of these changes in pan evaporation. The reduction in pan evaporation has predominantly been attributed to reduced solar irradiance in Russia (Peterson et al., 1995), the United States (Hobbins et al., 2004), China (Thomas, 2000; Liu et al., 2004; Gao et al., 2006; Wang et al., 2007), and Israel (Cohen and Stanhill, 2002), which is related to increased cloud coverage and enhanced aerosol concentrations (Roderick and Farquhar, 2002). Others have mainly attributed reductions in pan evaporation to changes in wind speed in Australia (Rayner, 2007; Roderick et al., 2007), the Tibetan Plateau (Chen et al., 2006; Zhang et al., 2007), and the Canadian prairies (Burn and Hesch, 2007); to changes in relative humidity in India (Chattopadhyay and Hulme, 1997) and the Chang Jiang Basin (Gong et al., 2006); and to changes in the maximum temperature in China (Cong and Yang, 2009). One key concern with current climate change is the impact of these changes on the hydro balance, which is largely determined by the potential evaporation (Cho et al., 2011; Kirono and Ken, 2011). Furthermore, changes in pan evaporation and the related climatic
variables are considered to be influenced by anthropogenic activities, such as urbanization and irrigation (Alpert et al., 2005; Alpert and Kishcha, 2008; Ji and Zhou, 2011). Moreover, previous understandings of factors that influence pan evaporation change were based on statistical analyses, such as correlation and stepwise regression (Chattopadhyay and Hulme, 1997; Chen et al., 2006; Cong and Yang, 2009; Jhajharia et al., 2009; Ji and Zhou, 2011). Consequently, a physically based estimate of pan evaporation in a nature reserve should be useful in understanding the natural change in pan evaporation.

This study was undertaken at a site in a nature reserve in south-west China, and the objective of the study was to answer the following questions: (1) ‘What changes in pan evaporation are occurring in this nature reserve?’ and (2) ‘What are the main factors contributing to these changes in pan evaporation?’

MATERIALS AND METHODS

Study site

The Ailaoshan Station for Subtropical Forest Ecosystem Studies (ASSFES; 24°32′N, 101°01′E; 2480 m a.s.l.) of the Chinese Academy of Sciences is located in Jingdong County, Yunnan Province (Figure 1). A standard meteorological station operated by ASSFES has been in operation at the site since 1981. Based on long-term meteorological observations from that station, the annual mean temperature is 11.0 °C, with a monthly mean temperature of 5.2 °C in the coldest month (January) and 15.2 °C in the warmest month (July). The average annual rainfall is 1902 mm, with 1630 mm falling during the wet season (May–October) and 272 mm during the dry season (November–April). The average annual pan evaporation (Φ20 cm) is 1297 mm: 583 mm in the wet season and 714 mm in the dry season.

Estimation of pan evaporation

The PenPan model was derived from Penman’s combination equation (Penman, 1948) and then developed by Roderick et al. (2007). The pan evaporation \( E_p \) is separated into radiative \( (E_{p,R}) \) and aerodynamic \( (E_{p,A}) \) components (Equation (1)).

\[
E_p = E_{p,R} + E_{p,A} = \left( \frac{\Delta}{\Delta + \gamma} \right) \frac{R_e}{\gamma} + \left( \frac{\Delta}{\Delta + \gamma} f_q(U_2) VPD \right)
\]  

(1)

\( \Delta (k \text{ Pa}^\circ \text{C}^{-1}) \) refers to the slope of the saturation vapour pressure \( (e_s, \text{ k Pa}) \) with temperature \( (T, ^\circ \text{ C}) \) (Equation (2)), \( R_e (\text{J m}^{-2}) \) refers to the net radiation (Equation (7)), \( \gamma (= 2.4 \text{ here}) \) is the ratio of the effective surface area for heat and vapour transfer, \( \lambda (= 2.45 \text{ MJ kg}^{-1}) \) is the latent heat of vaporization, \( \gamma (\text{k Pa}^\circ \text{C}^{-1}) \) is the psychrometric constant adjusted for elevation (Equation (3)), \( f_q(U_2) \) is a function based on the wind speed at a height of 2 m (Equation (4)), and \( U_2 (\text{m s}^{-1}) \) is calculated from the wind speed at a height of 10 m and an empirical coefficient from the wind profile function (Equation (5)). \( VPD (\text{k Pa}) \) is the vapour saturation deficit (Equation (6)) between the actual vapour pressure \( (e_s, \text{ k Pa}) \) and the saturation vapour pressure \( (e_s, \text{ k Pa}) \). \( T_a \) and \( T_w \) in Equation (6) are the temperatures of the dry bulb and wet bulb, respectively.

Establishment of pan evaporation

The net radiation \( (R_n) \) in Equation (1) was estimated with Equation (7), which differs from the process used by Roderick et al. (2007). \( S_t (\text{hours of sunshine}) \) is the actual duration of sunshine, recorded with a dark-tube recorder. \( N (\text{h}) \) is the maximum possible duration of sunshine, and \( R_e \) is the extra-terrestrial radiation \( (\text{MJ m}^{-2} \text{day}^{-1}) \). \( a \) (= 0.25 here) and \( b \) (= 0.5 here) are empirical constants (Allen et al., 1998). \( \sigma \) is the Stefan–Boltzmann constant \( (4.903 \times 10^{-8} \text{MJ K}^{-1}) \). \( T_{\text{max}} \) and \( T_{\text{min}} \) are the maximum and minimum temperatures, respectively.

\[
R_n = 0.77 \times \left( \frac{a + b}{N} \right) R_s - \sigma \left[ \frac{T_{\text{max}}^4 + T_{\text{min}}^4}{2} \right] \times (0.34 - 0.14 \sqrt{e_a}) \times \left( 1.35 \frac{a + b}{a + b} - 0.35 \right)
\]  

(7)

To evaluate the estimated \( R_n \), the observed water surface \( R_n \) in the evaporator was calculated with Equation (8). Global radiation \( (Q) \) was observed by a pyranometer.
(CM11, Kipp & Zonen, Delft, Holland). We used \( \alpha = 0.14 \) as the albedo of the water surface in the evaporator (Linacre, 1992; Rost et al., 2006). \( R_t \) is the net long-wave irradiance of the pan. In this study, \( R_t \) was simply considered a fixed value of 40 W m\(^{-2}\) during cloudless periods (Linacre, 1994).

\[
R_n = (1 - \alpha) \times Q + R_t
\]

(8)

The performances of the estimated \( R_n \) and \( E_p \) were evaluated with Equation (9). \( x_i \) refers to the observed records; \( \bar{x} \) refers to the modelled values. \( n \) is the sample months of the observations. In this study, the PenPan model was evaluated for the 36-month observation of \( E_{601} \) (2008–2010) and the 23-year observation of the \( \Phi \)20-cm pan (1983–1990, 1996–2010).

\[
RSME = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x}_i)^2}{n}}
\]

(9)

Attribution of the change in pan evaporation

The change in pan evaporation \( \left( \frac{dE_p}{dt} \right) \) was separated into the change in the radiation component \( \left( \frac{dE_{p,R}}{dt} \right) \) and the change in the aerodynamic component \( \left( \frac{dE_{p,A}}{dt} \right) \) (Equation (10)). The change in the radiation component (Equation (11)) could be attributed to the changes in the temperature \( (T^\#) \), the minimum temperature \( (T_{\min}^\#) \), the maximum temperature \( (T_{\max}^\#) \), the sunshine hours \( (S_t^\#) \), and the actual vapour pressure \( (e_a^\#) \). The change in the aerodynamic component (Equation (12)) could be attributed to the changes in the wind speed \( (U^\#) \), the saturation vapour pressure deficit \( (VPD^\#) \), and the temperature \( (T^\#) \). When calculating the contribution of each variable, the other variables were assumed to remain constant at their long-term means.

\[
\frac{dE_{p,R}}{dt} \approx \frac{\partial E_{p,R}}{\partial T} \frac{dT}{dt} + \frac{\partial E_{p,R}}{\partial T_{\min}} \frac{dT_{\min}}{dt} + \frac{\partial E_{p,R}}{\partial T_{\max}} \frac{dT_{\max}}{dt}
\]

\[
\frac{dE_{p,A}}{dt} \approx \frac{\partial E_{p,A}}{\partial U} \frac{dU}{dt} + \frac{\partial E_{p,A}}{\partial VPD} \frac{dVPD}{dt} + \frac{\partial E_{p,A}}{\partial T} \frac{dT}{dt}
\]

(10)

\[
T^\# = T_{\min}^\# + T_{\max}^\# + S_t^\# + e_a^\#
\]

\[
\frac{dE_{p,R}}{dt} \approx \frac{\partial E_{p,R}}{\partial u} \frac{du}{dt} + \frac{\partial E_{p,R}}{\partial VPD} \frac{dVPD}{dt} + \frac{\partial E_{p,R}}{\partial T} \frac{dT}{dt}
\]

\[
= U^\# + VPD^\# + T^\#
\]

(11)

(12)

Trend analysis

The trend for each meteorological variable was analysed with the Mann–Kendall test (Mann, 1945). Mann–Kendall’s tau values and the non-parametric Sen’s slopes were calculated with the ‘Kendall’ package (McLeod, 2009) and ‘zyp’ package (Bronaugh, 2009), respectively, in the R environment (R Development Core Team, 2010). A positive tau value indicated an increasing trend, and a negative tau indicated a decreasing trend. The slope of each variable was computed by simple linear regression against the year.

RESULTS

Model performance

We first estimated \( R_n \) over 36 months (2008–2010) with Equation (7). The estimated \( R_n \) was then compared with the observed value calculated with Equation (8). The agreement between the estimated \( R_n \) and observed \( R_n \) was excellent (Figure 2). We then extended the estimation of \( R_n \) to the rest of the years (before 2008), and the modelled \( E_p \) was calculated with the estimated \( R_n \). Figure 3 shows that the modelled \( E_p \) had conversion coefficients of 0.691 and 1.046 for the simultaneous observations of the \( \Phi \)20-cm pan and \( E_{601} \), respectively.

Attribution of changing pan evaporation

The analysis of the trends in the climatic variables is shown in Table I. Positive trends were observed in temperature, sunshine hours, and wind speed, and their increases in the dry season were greater than those in the wet season. \( VPD \) did not show an obvious trend but increased slightly in the dry season and decreased slightly in the wet season.

Table II shows the partitioning of \( E_p \) in the dry season, the wet season, and the whole year. The modelled \( E_p \) increased with a trend of 4.54 mm a\(^{-2}\) in the last 30 years, and the increase in \( E_p \) was predominantly attributable to its increase in the dry season. Changes in the aerodynamic component accounted for 56.68% of the \( E_p \) change in the dry season. However, in the wet season, the radiative component accounted for 89.02% of the change in \( E_p \).

Figure 2. The linear relationship between the estimated and observed net radiation \( (R_n) \).
The increase in $E_{p,A}$ was mainly contributed by an increase in the wind speed, and the increase in $E_{p,R}$ was mainly contributed by an increase in the number of sunshine hours. In summary, the change in $E_p$ was predominantly attributed to the change in wind speed, followed by the change in sunshine hours (Table II).

**DISCUSSION**

**PenPan model performance and uncertainties**

Fu et al. (2004) calculated the conversion coefficients between various evaporation pans and a 20-m² evaporation tank, yielding coefficients of about 0.6 for the Φ20-cm pan and 1.07 for $E_{601}$. In addition, Xu et al. (2006) reported a conversion coefficient of 0.7 for Φ20-cm pan evaporation compared with reference evapotranspiration in the Yangtze River catchment. Consequently, the PenPan model showed an excellent performance in this study because the conversion coefficients for the Φ20-cm pan and $E_{601}$ were similar to those in the studies listed above (Figure 3).

However, several uncertainties in the PenPan model must be improved. For example, the albedo cannot be constant under field conditions (Roderick et al., 2007), and the current variables inadequately represent the actual variation in solar irradiance. Changes in atmospheric aerosols could not be detected by the current dark-tube recorder; however, such changes could have influenced the pan evaporation trend.
Table II. The modelled pan evaporation rate \((dE_p/dt, \text{ in mm a}^{-1})\) and its components

<table>
<thead>
<tr>
<th></th>
<th>Dry</th>
<th>Wet</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated (E_p)</td>
<td>4.12</td>
<td>0.42</td>
<td>4.54</td>
</tr>
<tr>
<td>Radiation (dE_p/dt)</td>
<td>1.78</td>
<td>0.38</td>
<td>2.16</td>
</tr>
<tr>
<td>Radiation partition (T^*_p)</td>
<td>0.55</td>
<td>0.11</td>
<td>0.66</td>
</tr>
<tr>
<td>(T_{\text{min},p})</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(T_{\text{max},p})</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(S)</td>
<td>1.23</td>
<td>0.26</td>
<td>1.50</td>
</tr>
<tr>
<td>(ea^*)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Aerodynamic (dE_p/dt)</td>
<td>2.33</td>
<td>0.05</td>
<td>2.38</td>
</tr>
<tr>
<td>Aerodynamic partition (T^*_a)</td>
<td>–0.17</td>
<td>–0.01</td>
<td>–0.18</td>
</tr>
<tr>
<td>(U^*)</td>
<td>1.87</td>
<td>0.68</td>
<td>2.55</td>
</tr>
<tr>
<td>VPD*</td>
<td>0.64</td>
<td>–0.63</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Moreover, the PenPan model does not consider the heat storage component; consequently, it is only applicable to weekly or monthly input data (Thom et al., 1981).

The results of measured pan evaporation studies are inconsistent, partly because of differences in the measuring instruments used. For example, the PenPan model was developed to harvest energy more efficiently than other pan evaporators (McVicar et al., 2007), and the fraction of vapour condensing from the air to the water surface in the evaporators, which occurs when the water temperature is below the dew point (mainly during the rainy season), cannot be detected by the current method. Therefore, the change in pan evaporation could be influenced by many factors, meaning that it may not accurately represent the changes in potential evaporation. The positive trend in pan evaporation estimated with the PenPan model in this study is consistent with the increasing pan evaporation and potential evaporation on the Tibetan Plateau and in south-west China (Thomas, 2000; Xu et al., 2005; Chen et al., 2006; Gao et al., 2006; Cong and Yang, 2009). In addition, Cong and Yang (2009) reported that most stations in China have shown positive trends in pan evaporation since 1986. Liu et al. (2011) reported an increase of pan evaporation in China from 1992 to 2007. Consequently, the study concludes that potential evaporation and water evaporation demand could have increased in the post-1981 period. Further studies at the regional level are needed to confirm this finding.

According to the physical theory of water vaporization, potential evaporation is more sensitive to relative humidity than to other climatic variables, which means that a small change in relative humidity could result in a large change in potential evaporation (Gong et al., 2006; Yin et al., 2010). This could be the reason that the correlation coefficient for relative humidity is higher than that for any other climatic variable (Ji and Zhou, 2011). However, when the slope of relative humidity is considered, its contribution to pan evaporation may differ (because the contribution is obtained by multiplying the coefficient by the slope). In this study, the slope of VPD change was low (Table I), so the change in VPD made a limited contribution to the change of pan evaporation. Physically, \(T_{\text{max}}, T_{\text{min}},\) and \(e_a\) may have a strong influence on the water evaporation rate. These factors were used to estimate the net radiation in this study. Based on the coefficients for these factors in Equation (7), their contributions to the change in net radiation was very small. Consequently, the model results indicate that these factors made a minor contribution to the change in pan evaporation.

Climate change at the nature reserve site

Observed changes in climatic variables can be influenced by anthropogenic activities. For example, urbanization can change the surface roughness and consequently reduce the measured wind speed around the meteorological station (Ren et al., 2008; Jiang et al., 2010). The increase in aerosols in the atmosphere, deriving from the industrialization of recent decades, can reduce the availability of sunlight (Alpert et al., 2005). Irrigation around the meteorological station could have changed the vapour pressure deficit in rural area. As a result, observations in a nature reserve are more precise in representing the natural trends of climatic variables.

Contrary to the widely reported negative trends in sunshine hours and wind speed, this nature reserve site showed positive trends in both sunshine hours and wind speed (Table I). This is possibly attributable to the absence of anthropogenic influences in this area. A slight increase in wind speed has recently been reported in south-west China (Jiang et al., 2010). Guo et al. (2010) also reported that the wind speed in Yunnan Province increased in spring and summer during the period 1991–2005. Given that previous studies have reported reduced precipitation (Wang and Ding, 2006) and vapour supply (Yao et al., 2008), it is postulated that more energy is partitioned to sensible heat, thereby increasing the air current momentum (McVicar et al., 2012). In addition, the positive trend in sunshine hours observed in this study is consistent with the study of Zheng et al. (2010), who reported a positive trend in sunshine hours in rural and high-elevation mountain areas of the Yunnan–Guizhou Plateau, and consistent with Qian et al. (2006) who reported that cloud cover has decreased over China.

CONCLUSIONS AND IMPLICATIONS

Contrary to the widely reported reduction in pan evaporation, this study has shown a positive trend in pan evaporation, which is consistent with the increase in potential evaporation reported in south-west China (Thomas, 2000; Xu et al., 2005; Chen et al., 2006; Gao et al., 2006). The increase is much more pronounced in the dry season than in the wet season. Consequently, if there has been no simultaneous change in precipitation, the water available for agriculture and afforestation could be threatened.

The present results show that change of wind speed has contributed most of the change in pan evaporation, followed by sunshine hours. In terms of seasonal patterns, the change of the aerodynamic component is dominant
over the change of $E_p$ in the dry season, and the change of the radiative component is dominant over the change of $E_p$ in the wet season. Consequently, water evaporation demand could be predicted more efficiently based on the current trends of climatic variables. These results were derived in a nature reserve, and the fact that the trends in pan evaporation, wind speed, and sunshine hours of the present study are inconsistent with those reported previously indicates that further study is required to consider the nature of anthropogenic effects on the widely reported negative trends in pan evaporation.

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