Spatial Patterns and Influence Factors of Conversion Coefficients between Two Typical Pan Evaporimeters in China

Yanzhong Li 1,2, Changming Liu 1 and Kang Liang 1,*

1 Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; liyz_egi@163.com (Y.L.); liucm@igsnrr.ac.cn (C.L.)
2 University of Chinese Academy of Sciences, Beijing 100101, China
* Correspondence: liangk@igsnrr.ac.cn; Tel.: +86-10-6488-9083

Academic Editors: Tommaso Moramarco and Roberto Ranzi
Received: 18 July 2016; Accepted: 20 September 2016; Published: 27 September 2016

Abstract: Pan measurement is a reliable and efficient method for indicating the evaporative demand of the atmosphere. There are several types of pan evaporimeters worldwide, and the estimation of the conversion coefficients ($K_p$) between them is necessary in hydrologic research. In China, E601B pans were installed at all meteorological stations beginning in 1998. They replaced the 20 cm pans ($\phi_{20}$). To fully use the records from the two pans and obtain long-term pan evaporation, the spatial patterns of $K_p$ between $\phi_{20}$ and E601B and the factors that influence $K_p$ are investigated based on records from 573 national meteorological stations from 1998 to 2001. In this study, the results show that higher $K_p$ values are found in southwestern regions and lower values are found in northeastern regions during the warm seasons (from May to September), while $K_p$ values are lower during warm seasons than during cold seasons (from October to April the following year). In addition, net radiation was found to be the dominant climate factor that affects variations in $K_p$, followed by relative humidity and the vapor pressure deficit. This study can improve the benefit of not only the selection of appropriate evaporimeters by meteorological departments, but also of the study of temporal variability and trends in the evaporative demand.

Keywords: conversion coefficients; pan evaporation; eight climate regions in China; 20 cm diameter pan; E601B (E601); evaporative demand

1. Introduction

Evaporation is a key hydrological process [1]. It is an important nexus between the water cycle and energy budget and can further impact regional and global climate [2–4]. The atmospheric evaporative demand can be evaluated based on potential evapotranspiration [5,6] or evaporimeters [7,8] and is regarded as the upper limit of evaporation [9–11]. The evaporative demand of the atmosphere is controlled by radiative and aerodynamic factors, and it can be calculated using meteorological variables, such as radiation, wind speed, air temperature, and humidity [7,10]. However, these meteorological factors are not always available, especially radiation. Instead, a simple and efficient observational measurement device, the pan evaporimeter, is often adopted to accurately quantify local atmospheric evaporation [8,12–14]. Many types of pan evaporimeters have been installed in different countries to measure the evaporative demand [1,15], including Class A evaporimeters in the US and Australia [16], the GGI-3000 in Russia [17], the MO tank in Britain [18], and the 20 cm pan ($\phi_{20}$) and E601B in China [13,19]. These devices are used by meteorological and climate scientists, agricultural scientists, and hydrologists [12,20,21]. Although pan evaporation ($E_{pan}$) measured from various types of evaporimeters cannot completely represent the actual evaporation [22,23], it can provide in-depth...
Due differences between pan evaporimeters (for example, material type, geometric shape, and installation method), observed evaporation can vary greatly, even for evaporimeters in similar environments [27]. Pan evaporation values measured using different evaporimeters over the same time span, cannot be compared directly. Otherwise, considerable uncertainty would be introduced into the results. A conversion must be performed to make the values comparable. It is necessary to determine the conversion coefficient ($K_p$) between different measurements before using the values in studies of evaporation trends [28,29] or water resources [8]. A number of previous studies discussed $K_p$ related to pan evaporation at the point scale [15,30], regional scale [31,32], and catchment scale [33]. For example, Hong et al. [30] investigated two types of evaporimeters, one buried in the soil and one exposed to the air, at Nansi Lake Station. The results showed that the buried devices, such as E601 and GGI-3000, had larger $K_p$ values (ratio of the 20 m² evaporation tank to these evaporimeters, $K_p > 0.98$) compared to the $K_p$ values ($K_p < 0.88$) of an exposed ones, such as Class A and φ20. Fu et al. [15] compared the $K_p$ values of 15 types of evaporimeters to that of a 20 m² evaporation tank and found that the $K_p$ values of φ20 ($K_p = 0.60$) and E601B ($K_p = 1.07$) were distinctly different at the annual scale. Liang et al. [32] discussed the $K_p$ difference between $E_{\text{pan}}$ and reference evaporation ($ET_{\text{ref}}$) in the West Songnen Plain of China and found that it varied significantly in space (0.48–0.68) and time at an annual scale. Xu et al. [33] also studied the $K_p$ difference between $E_{\text{pan}}$ and $ET_{\text{ref}}$ in the Yangtze River basin. They observed higher $K_p$ values in the central region of the basin, which has a relatively lower vapor pressure deficit, and $K_p$ exhibited monthly variations in the three regions of the catchment. Due to the spatial and temporal variabilities in $K_p$, considerable uncertainties may be associated with using constant $K_p$ values in large regions when conducting climate change research [28,34]. The spatial patterns of $K_p$ and the dominant factors that control its variation must be determined. Revealing the spatial distribution of $K_p$ and its driving factors is imperative and can improve hydrometeorological studies.

China is an ideal location to study $K_p$ patterns and the factors that influence $K_p$. Among the various evaporation pans used in China [15,19,35,36], the two most common are the φ20 and E601B pans (Figure 1 and Table 1). In 1998, the E601B pans were first installed at all meteorological stations across China, with the aim of replacing the φ20 pan. To maintain comparability between the two evaporimeters, simultaneous observations were collected from 1998 to 2001. By 2002, the φ20 pans were successfully replaced by E601B pans at all stations, and E601B became the standard evaporimeter for measuring evaporation in China. To effectively use the records from the two pan evaporation devices in long-term studies of evaporation trends (the φ20 pan records date to approximately 1951), the $K_p$ value between them must be determined. In addition, China can be divided into eight climatic regions [13,37] due its large spatial extent. There are significant differences in climate between the regions [38]; for example, the temperature increases from north to south, and precipitation increases from northwest to southeast (Table 1). Ren et al. [35] compared the monthly and annual mean $K_p$ values between the two evaporimeters in different provinces from 1998 to 2001. Additionally, Liu et al. [36] compared the $K_p$ values between E601 (similar to E601B) and φ20 in several typical cities from 1986 to 1995. However, few studies have focused on $K_p$ differences in different climatic conditions, which may considerably affect $K_p$. Mapping the spatial distribution of $K_p$ between the two evaporimeters and determining the driving factors of $K_p$ can allow the pan evaporation records in China to be fully used and provide an understanding of the underlying mechanisms of $K_p$ variability.
To address these issues, we compare the spatial distribution and temporal variability (monthly for one year) of $K_p$ and investigate the factors that influence $K_p$ between the E601B and φ20 pans in China. The main objectives of this paper are as follows: (1) investigate the monthly variation and spatial distribution of $K_p$ for the two pan evaporations during the warm (May–September) and cold seasons (October–April); and (2) determine the contributions of several key climatic factors to the variation in $K_p$. The results of this study can improve the selection of the appropriate pan in different climate regions and provide information for hydrologic research, especially studies of evaporation trends. This study is structured as follows: in Section 2, the datasets and methods used in our study are described; in Section 3, the spatial distribution of $K_p$ is mapped during the warm and cold seasons. Furthermore, the factors that influence $K_p$ are also investigated in this section. The uncertainties and conclusions are shown in Sections 4 and 5.

This paper reports the initial stage of ongoing research work. The ongoing research and planned studies are as follows: (1) constructing a long-term series of pan evaporation records (from the

---

**Figure 1.** Four types of evaporation evaporimeters: Class A from the USA (a); GGI-3000 from Russia (b); and φ20 (c) and E601B (d) from China.

**Table 1.** Detailed information regarding the four types of evaporimeters.

<table>
<thead>
<tr>
<th>Evaporimeter Name</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class-A</td>
<td>Area: 12.56 ft$^2$ (diameter: 4 ft)&lt;br&gt;Depth: 10 in</td>
<td>Supported by a wood frame and the bottom is 5 cm higher than ground, popular in USA.</td>
</tr>
<tr>
<td>GGI-3000</td>
<td>Area: 3000 cm$^2$&lt;br&gt;Depth: 60 cm (cylinder) C + 8.7 cm (circular cone)</td>
<td>Buried in the ground with rim about 7.5 cm above the ground level, popular in Russian.</td>
</tr>
<tr>
<td>φ20</td>
<td>Area: 314 cm$^2$ (diameter: 20 cm)&lt;br&gt;Depth: 10 cm</td>
<td>Rim is 70 cm from the ground, in every meteorological station in China.</td>
</tr>
<tr>
<td>E601B</td>
<td>Same as GGI-3000</td>
<td>Buried like GGI-3000, fiberglass material, surrounded by water and soil circle. Installed in every meteorological station from 1998.</td>
</tr>
</tbody>
</table>
1950s–present) and investigating the trends in pan evaporation across the country in the context of climate change [5,13]; (2) performing experiments regarding the pan evaporation of φ20 and E601B and developing some novel approaches or formulations to explain the mechanisms of KP [20,39]; and (3) investigating and quantifying the effects of various climatic factors on KP using a modified PenPan model [27] and a partial differential method [6].

2. Data and Methods

2.1. Information and Measurements from Different Evaporimeters

Different types of evaporimeters have been used to measure the evaporative demand of the atmosphere [15]. Two typical pans are recommended by the World Meteorological Organization [40]: Class A from the USA (Figure 1a) and GGI-3000 from Russia (Figure 1b). However, these two evaporimeters are not widely installed in China, but the φ20 and E601B (Figure 1c,d) evaporimeters are commonly used. Additional information regarding the evaporimeters is listed in Table 1.

The φ20 pan with a screen to prevent bird drinking is made of metal and placed at a height of 70 cm (Figure 1c). This evaporimeter is weighed at 20:00 each day using a high-precision weighbridge, and it is then refilled with water to a depth of 20 mm. The daily evaporation rate can be calculated from the following equation:

\[ E = \frac{W_1 - W_2}{31.4} + P \]  

where \( E \) is the pan evaporation rate (mm·day\(^{-1}\)); \( W_1 \) and \( W_2 \) are the pan weights of the previous and current measurements, respectively (g·day\(^{-1}\)); \( P \) is the total precipitation (mm·day\(^{-1}\), including rain and snow); and 31.4 is the weight of 1 mm of water in the pan (g·mm\(^{-1}\)). The E601B is made of fiberglass and has a relatively lower heat transfer to the surrounding area. The evaporation from this evaporimeter should be relatively close to the evaporation recorded from a moderately-sized water body (such as a 20 m\(^2\) evaporation tank) [15,19]. The daily evaporation rate can be calculated using Equation (2):

\[ E = P + (H_1 - H_2) \]  

where \( E \) and \( P \) are the same as in Equation (1); and \( H_1 \) and \( H_2 \) are the water depths of E601B on the previous and current day, respectively. The water depths of \( H \) can be read directly from the indicator installed on the stylus holder (Figure 1d).

2.2. Meteorological and Evaporation Data

Daily meteorological data and evaporation data from the evaporimeters at 573 national meteorological stations were obtained from the China Meteorological Administration (CMA, Figure 2) for a four-year period (January 1998–December 2001). The data were quality controlled. Records that were missing for less than three consecutive days were interpolated based on the nearest data. For gaps of more than three days, the missing data were replaced using a simple linear regression based on the nearest stations. Finally, 573 of the 756 meteorological stations with continuous records were selected. Monthly data, which were summed from daily values, were used in the following sections.

To identify the effects of different climatic factors on the KP values of the two pans, the entire region was divided into eight climatic regions [13,37]: northwest (NW), north center (NC), North China plain (NCP), northeast (NE), east (E), southeast (SE), southwest (SW), and Tibet plateau (TP). According to the aridity index (AI, Table 2), NW, NC, NCP, and NE are humid regions (AI > 1.0), while E, SE, and SW are non-humid regions (AI < 1.0). The climate characteristics of each region are listed in Table 2. Pan evaporation is an integrated process affected by various climate factors, such as the net radiation (\( R_n \)), wind speed (\( U_2 \)), air temperature (\( T_{\text{mean}} \)), vapor pressure deficit (VPD), relative humidity (RH), and elevation (Elev) [19,21,41]. The \( U_2 \) at a height of 2 m was derived from a height of 10 m according to a logarithmic wind speed profile. \( R_n \) was calculated from the difference between the incoming net shortwave radiation (\( R_{ns} \)) and the outgoing net longwave radiation (\( R_{nl} \)) [21].
The coefficients, $a_s$ and $b_s$, recommended by Allen et al. [21] to calculate the solar radiation ($R_s$) were not used. The optimized coefficients calibrated using the 116 solar radiation stations were adopted in our paper. These coefficients can significantly reduce the uncertainty associated with radiation [42].

![Locations of meteorological stations in China. The eight regional abbreviations are shown in the figure. This map was modified from Liu et al. [13].](image)

**Figure 2.** Locations of meteorological stations in China. The eight regional abbreviations are shown in the figure. This map was modified from Liu et al. [13].

**Table 2.** Climate factor characteristics in the eight climatic regions from 1998 to 2001.

<table>
<thead>
<tr>
<th>Region</th>
<th>VP (kPa)</th>
<th>T (°C)</th>
<th>$U_2$ (m/s)</th>
<th>$R_s$ (MJ/m²/Day)</th>
<th>$P_{pr}$ (mm/a)</th>
<th>$ET_{ref}$ (mm/a)</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW ($n = 57$)</td>
<td>0.76</td>
<td>8.45</td>
<td>1.65</td>
<td>15.60</td>
<td>137.03</td>
<td>1078.22</td>
<td>7.87</td>
</tr>
<tr>
<td>NC ($n = 39$)</td>
<td>0.82</td>
<td>9.12</td>
<td>1.72</td>
<td>15.99</td>
<td>265.80</td>
<td>1088.08</td>
<td>4.09</td>
</tr>
<tr>
<td>NCP ($n = 119$)</td>
<td>1.04</td>
<td>9.12</td>
<td>1.91</td>
<td>13.95</td>
<td>494.26</td>
<td>938.91</td>
<td>1.90</td>
</tr>
<tr>
<td>NE ($n = 48$)</td>
<td>0.80</td>
<td>2.52</td>
<td>2.14</td>
<td>13.45</td>
<td>442.05</td>
<td>779.81</td>
<td>1.76</td>
</tr>
<tr>
<td>E ($n = 83$)</td>
<td>1.71</td>
<td>16.43</td>
<td>1.62</td>
<td>11.96</td>
<td>1164.64</td>
<td>902.78</td>
<td>0.78</td>
</tr>
<tr>
<td>SE ($n = 67$)</td>
<td>2.17</td>
<td>20.35</td>
<td>1.30</td>
<td>11.85</td>
<td>1728.42</td>
<td>948.11</td>
<td>0.55</td>
</tr>
<tr>
<td>SW ($n = 103$)</td>
<td>1.70</td>
<td>16.27</td>
<td>1.16</td>
<td>12.02</td>
<td>1179.91</td>
<td>886.25</td>
<td>0.75</td>
</tr>
<tr>
<td>TP ($n = 57$)</td>
<td>1.32</td>
<td>11.78</td>
<td>0.95</td>
<td>15.34</td>
<td>1035.75</td>
<td>941.24</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Notes: VP is the vapor pressure; $T$ is the air mean temperature; and $U_2$ is the wind speed; All of these parameters are taken at a height of 2 m above the ground. $R_s$ is the solar radiation; $P_{pr}$ is the precipitation; $ET_{ref}$ is the reference evapotranspiration calculated using the Penman-Monteith method [21,43]; and AI is the aridity index derived from the ratio of $ET_{ref}$ to $P_{pr}$.

Evaporation data for the E601B pan are not available during the winter in most northern regions in China because the water in the pan freezes. Thus, the year was divided into a warm season (May–September) and a cold season (October–April). This is reasonable because the warm season accounted for most of the annual evaporation (>60%), even in the southern areas; therefore, these months were the most important.

### 2.3. Calculations and Analysis Method for the $K_p$

$K_p$ is defined as the ratio of the E601B evaporation to the $φ20$ pan evaporation:

$$K_p = \frac{E_{E601B}}{E_{20}}$$

where $E_{E601B}$ is the monthly evaporation rate of the E601B pan; and $E_{20}$ is the $φ20$ evaporation rate for the same month. Spatial interpolation using the Kriging method was performed in ESRI ArcGIS 10.0.
software (Redlands, CA, USA) with the spatial analysis toolbox [6,44] to obtain the spatial distributions of monthly and annual $K_p$ values.

A Pearson's correlation analysis, multiple stepwise regression analysis, and our knowledge of the potential physical driving factors ($T_{\text{mean}}$, RH, VPD, $U_2$, Elev, and $R_n$) were used to analyze the potential factors that influence $K_p$ variation. The Pearson's correlation coefficients between $K_p$ and selected climatic factors were calculated using SPSS Statistics 20 (SPSS Inc., Chicago, IL, USA). Stepwise multiple linear regressions were developed between $K_p$ and the potential dominant factors to find the best predictors and the independent explanatory ability of each selected climatic factor based on the spatial variation in $K_p$.

3. Results and Analysis

3.1. Spatial Patterns of $K_p$ for the Two Pan Evaporimeters

3.1.1. Spatial Distribution of Pan Evaporation during the Warm Season

The spatial distributions of $\phi20$ and E601B evaporation during the warm season from 1998 to 2001 at the national scale are shown in Figure 3a,b, respectively. When the characteristics of the eight climatic regions were combined (Table 2), the differences between the two pan evaporations were spatially related to the variations in meteorological factors. For the warm season from 1998 to 2001, there were statistically significant differences ($p < 0.001$) between the $\phi20$ and E601B pan evaporations, and the annual values were 1014 mm and 597 mm, respectively (Table 3). The spatial distributions of the pan evaporations of $\phi20$ and E601B generally exhibited the same spatial pattern: a clear decreasing trend from northwest to southeast. The highest values were found in the NW region, while the lowest values were found in the TP, NW and NE regions. The $\phi20$ pan evaporation varied from 739 mm to 5573 mm with an average of 1613 mm, and the E601B pan evaporation varied from 470 mm to 2831 mm with an average of 921 mm.

![Spatial distributions of $\phi20$ and E601B evaporation; the determination coefficient $R^2$; and the conversion coefficient $K_p$.](image)

**Figure 3.** Spatial distributions of $\phi20$ (a) and E601B (b) evaporation; the determination coefficient $R^2$ (c); and the conversion coefficient $K_p$ (d) between the two pan evaporations during the warm season (May–September).
Table 3. Statistical information regarding E601B and φ20 pan evaporation (E_E601B, E_20), the determination coefficient (R^2), and the conversion coefficient (K_p) between the two pans in eight climatic regions during the warm season and three regions in the cold season. The minimum and maximum values are given in parentheses.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Regions</th>
<th>E_20</th>
<th>E_E601B</th>
<th>R^2</th>
<th>K_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm</td>
<td>NW</td>
<td>1613 (739, 5573)</td>
<td>921 (470, 2831)</td>
<td>0.89 (0.67, 0.97)</td>
<td>0.58 (0.50, 0.67)</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>1363 (832, 2382)</td>
<td>814 (477, 1436)</td>
<td>0.94 (0.86, 0.99)</td>
<td>0.61 (0.51, 0.70)</td>
</tr>
<tr>
<td></td>
<td>NCP</td>
<td>1123 (648, 2166)</td>
<td>635 (386, 1107)</td>
<td>0.91 (0.52, 0.98)</td>
<td>0.57 (0.47, 0.92)</td>
</tr>
<tr>
<td></td>
<td>NE</td>
<td>1004 (641, 1425)</td>
<td>543 (329, 803)</td>
<td>0.91 (0.68, 0.98)</td>
<td>0.55 (0.46, 0.62)</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>872 (645, 1236)</td>
<td>524 (401, 792)</td>
<td>0.87 (0.67, 0.97)</td>
<td>0.60 (0.51, 0.75)</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>847 (468, 1033)</td>
<td>526 (304, 740)</td>
<td>0.89 (0.74, 0.97)</td>
<td>0.62 (0.53, 0.77)</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>752 (498, 1159)</td>
<td>472 (323, 708)</td>
<td>0.87 (0.57, 0.98)</td>
<td>0.63 (0.49, 0.89)</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>890 (521, 1766)</td>
<td>620 (328, 1288)</td>
<td>0.84 (0.48, 0.97)</td>
<td>0.62 (0.51, 0.74)</td>
</tr>
<tr>
<td></td>
<td>National</td>
<td>1014 (468, 5573)</td>
<td>597 (304, 2831)</td>
<td>0.89 (0.46, 0.99)</td>
<td>0.60 (0.46, 0.92)</td>
</tr>
<tr>
<td>Cold</td>
<td>E</td>
<td>543 (402, 681)</td>
<td>345 (278, 419)</td>
<td>0.93 (0.83, 0.98)</td>
<td>0.66 (0.55, 0.80)</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>666 (403, 1224)</td>
<td>444 (250, 819)</td>
<td>0.90 (0.74, 0.97)</td>
<td>0.68 (0.58, 0.80)</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>692 (312, 1466)</td>
<td>440 (218, 889)</td>
<td>0.92 (0.76, 0.99)</td>
<td>0.67 (0.49, 0.80)</td>
</tr>
<tr>
<td></td>
<td>Humid</td>
<td>664 (312, 1466)</td>
<td>427 (218, 921)</td>
<td>0.92 (0.74, 0.99)</td>
<td>0.66 (0.49, 0.81)</td>
</tr>
</tbody>
</table>

3.1.2. Spatial Distribution of the Correlation Coefficient during the Warm Season

To quantify the performance of the E601B pan in capturing the spatial distribution and temporal variation of the φ20 pan evaporation, the temporal determination coefficients (R^2) of the two pan evaporation series during the warm season were calculated at each station, and the spatial distributions of R^2 were mapped using the Kriging interpolation method [44]. The results showed that the two pan evaporations had high R^2 values in each region (Figure 3c) and varied significantly in one month (Figure 4). The mean value of R^2 in China can reach 0.89, indicating that the E601B values capture the variation in φ20 fairly well. This is not surprising because the two pans were influenced by the same meteorological conditions, such as solar radiation, wind speed, temperature, etc. Thus, it may be reasonable to convert φ20 evaporation values to E601B evaporation values by multiplying a constant.

Figure 4. Monthly variation in the coefficient of determination (R^2) values of E601B and φ20 pan evaporation in the eight climate regions. The R^2 values in the three humid regions (E, SE, and SW) are illustrated by dotted lines, and the R^2 values in the four non-humid regions and TP region are illustrated by solid lines during the warm season (May–September). The national R^2 is illustrated by the solid black line with open star symbols.
Despite the overall high $R^2$ between $\phi 20$ and E601B in China, large differences were also found in the eight climatic regions. The $R^2$ values in the northern regions were generally higher than those in the southern regions, which indicated that the variabilities in the two evaporimeters became more uniform as evaporation increased. The average values of $R^2$ ranged from 0.89 to 0.94 in the northern regions. $R^2$ was highest in the NC region, and it varied between 0.86 and 0.99, with an average of approximately 0.94 (Table 3). By contrast, the average values of $R^2$ in the southern regions (E, SE, and SW) ranged from 0.87 to 0.89 with smaller deviations. The monthly $R^2$ values in the southern regions were high in the cold season and low in the warm season. The $R^2$ values in Northern China were high and stable in the warm season. The lowest average $R^2$ value (0.84) was found in the TP region, and it exhibited a decreasing trend from May to September (Figure 4). This $R^2$ value in TP may be caused by special climatic conditions. For example, the TP region is the highest plateau in the world with an average elevation of 4000 m, and it is also known as the “Third Pole” of the earth [45].

3.1.3. Spatial Distribution of $K_p$ during the Warm Season

The spatial distribution of $K_p$ during the warm season is shown in Figure 3d. $K_p$ was calculated at each meteorological station independently, and the spatial distribution was obtained using the Kriging interpolation method [44]. The results show that the two pan evaporations exhibited the same spatial distribution (Figure 3a,b), while $K_p$ exhibited significant spatial differences. Overall, $K_p$ varied from 0.46 to 0.92 in China, with an average of approximately 0.60 and a standard deviation of 0.056 (Table 3). $K_p$ was lower in the non-humid northern regions ($K_p < 0.60$) than in the humid southern regions ($K_p > 0.60$), which indicated that the bias in the evaporations of the two pan evaporations was smaller in the humid area during the warm season. Thus, the pan $K_p$ between the two evaporimeters varied substantially, and this variation was larger at low latitudes and smaller at high latitudes. Researchers have documented that the additional heat absorbed by the pan wall has an important effect on $K_p$ [46,47]. Additionally, the $\phi 20$ device can intercept more solar radiation at high latitudes (e.g., NE and NW) than at low latitudes (e.g., SW and SE) due to the solar zenith angle difference. The extra absorbed heat is subsequently transferred into the water through the pan wall, which increases the evaporation rate of the $\phi 20$ pan. The $K_p$ pattern (Figure 3d) generally reflected this process. Additionally, pronounced differences between $K_p$ values in the eight climatic regions were also detected. The smallest $K_p$ values were found in the NE region, and the average $K_p$ ranged from 0.46 to 0.62 with an average of 0.55. The largest values were observed in the SW and TP regions, both with averages of 0.63. The spatial distribution of $K_p$ was similar to that noted by Chen, Gao [19], who compared $\phi 20$ evaporation to reference evapotranspiration in China. Therefore, the regional differences in $K_p$ must be considered to obtain accurate evaporation data series when the evaporation values from the two pans are adopted to determine evaporation trends.

3.1.4. Monthly Variation in $K_p$ during the Warm Season

In addition to the spatial differences, the $K_p$ values of the two evaporimeters also exhibited significant temporal variability. The variation in $K_p$ in eight regions during the warm season is shown in Figure 5. The results are as follows: (1) overall, the monthly average values of $K_p$ in China increased during the warm season from approximately 0.58 in May to 0.63 in September, and the increase was especially rapid from June to August; (2) except in humid regions, $K_p$ varied throughout the warm season with a similar increasing pattern (solid line); (3) in the humid regions, $K_p$ decreased from May to June and then increased until August or September (dotted line), which confirmed the finding of Allen et al. [21] that $K_p$ was high in humid environments; and (4) the lowest values of the entire warm season ($K_p = 0.54$) occurred in the NE region with mean monthly variation from 0.51 to 0.58. The largest values varied from the SW region in May to the TP region in June and July and to SW region again in August and September.
Figure 5. Monthly variation in the conversion coefficient ($K_p$) of E601B and $\phi$20 pan evaporation in the eight climate regions. The $K_p$ values in the three humid regions (E, SE, and SW) are illustrated by dotted lines, and the $K_p$ values in the four non-humid regions and TP region are illustrated by solid lines during the warm season (May–September). The national $K_p$ is illustrated by the solid black line with open star symbols.

3.1.5. Spatial Pattern and Temporal Variability of $K_p$ in Humid Regions during the Cold Season

In humid regions (E, SE, and SW), the annual precipitation is larger than 1000 mm and the aridity index is less than 1.0 (Table 2). Due to the relatively high minimum temperature, there are no frozen periods throughout the whole year. Therefore, the evaporation records of E601B are still available during the cold season (October–April). The spatial pattern of evaporation ($E_20$, $E_{E601B}$) and the $R^2$ and $K_p$ between the two pans during the cold seasons are shown in Figure 6. As was the case in the warm season (Figure 3), the evaporation from the two pans exhibited similar spatial patterns during the cold season in humid areas, increasing from the central to marginal regions (Figure 6a,b) and averaging 664 mm and 427 mm annually for the $\phi$20 and E601B pans, respectively (Table 3). The $R^2$ values also increased from the central to marginal regions and were relatively high, with an average of 0.92. This trend indicated that the E601B evaporimeter could capture the variation in $\phi$20 better during the cold season than during the warm season.

Although the two pan evaporations had similar spatial patterns, the spatial variations in $K_p$ during the cold season were not constant. The highest values occurred in the northwest and southeast parts of the humid region, indicating larger differences between the two evaporations, while the lowest values occurred in the northeast and southwest areas, indicating smaller differences between the two evaporations. Overall, the $K_p$ values ranged from 0.49 to 0.81 (with a mean of 0.66 ± 0.057) in the humid regions. These values were significantly different from those during the warm season ($p < 0.001$). Of the three regions, the $K_p$ values in the E region were significantly lower than those in the others regions ($p < 0.01$), and there was no significant difference between the values in the SE and SW regions. The highest $K_p$ values appeared in the SW region during the warm season and in the SE region during the cold season.

The $K_p$ between the two pans varied significantly during the cold season (October–April of the following year): (1) the $K_p$ increased from October to the maximum value ($K_p \approx 0.71$) in December or January of the following year, and then decreased until April ($K_p \approx 0.58$); and (2) in the three regions, $K_p$ exhibited the same pattern of variations. The variation of $K_p$ at the annual timescale showed an increase from approximately May to December and then a decrease until April. The monthly variation pattern was most similar to that found by Fu et al. (2009), whose study was conducted at an experimental evaporation station in the E region. The average value of $K_p$ during the cold
season (0.66 ± 0.057) was greater than that during the warm season (0.62 ± 0.047), indicating a smaller difference between the two pan evaporations during the cold season. The average value of $K_p$ in all months in the humid regions was 0.64, with a standard deviation of 0.057.

As noted above, except for in the TP region, the monthly variability in $K_p$ exhibited a similar pattern in both the warm and cold seasons, which indicated that some specific factors may control the variability in the $K_p$ value. Therefore, meteorological factors were quantitatively explored to identify those that made the greatest contributions to $K_p$ variability.

### 3.2. Potential Factors That Influence $K_p$

The Pearson correlation coefficients ($r$) and significance levels between $K_p$ and several climatic factors are listed in Table 4. $K_p$ was generally negatively correlated with $R_n$, VPD, $U_2$, Elev, and $T_{\text{mean}}$. The relationships between $K_p$ and the climatic factors were similar to those noted by Xu et al. [33] in the Yangtze River basin, China. They investigated the $K_p$ of $\phi 20$ and the Penman-Monteith reference evapotranspiration; and found that a high conversion coefficient was associated with a relatively high RH and low $U_2$. At the national scale, $K_p$ was significantly negatively correlated ($p < 0.01$) with $R_n$ ($r = -0.4$) and VPD ($r = -0.33$), and positively correlated with RH ($r = 0.33$) (Table 4). As climate change has occurred in recent decades [48], the pan evaporation paradox [12,13] associated with the variation in solar radiation has gained increasing attention at the global [49,50] and regional scales [51,52]. The change in net radiation ($R_n$) is expected to strongly affect $K_p$ because of the high correlation between $K_p$ and $R_n$; therefore, it should be considered in studies of evaporation trends that use different pan measurements. However, at the regional scale, the $r$ values exhibited a significant geographic distribution. In five of the eight climatic regions, NCP, NE, E, SE, and SW, the $K_p$ values had the highest correlation with $R_n$, followed by RH and VPD. In the other three regions, the $K_p$ values

![Figure 6. Spatial distributions of $\phi 20$ (a) and E601B (b) evaporation; the correlation coefficient $R^2$ (c); and the conversion coefficient $K_p$ (d) between E601B and $\phi 20$ evaporation in the cold season (October–April).]
were more associated with RH (especially in the NC and TP regions, with $r$ values of 0.46 and 0.42, respectively), and the following factors were found in VPD and $T_{mean}$ (Table 4). Therefore, further analysis must be performed to quantitatively separate the effects of different climate variables on $K_p$ values.

Table 4. Pearson’s correlation between the conversion coefficients ($K_p$) and various climate factors, and the independent explanatory powers of each variable based on $K_p$ variation derived from the stepwise multiple linear regressions ($\%$, in parentheses). $T_{mean}$ is the mean air temperature, RH is the relative humidity, VPD is the vapor pressure deficit, $U_2$ is the wind speed at a height of 2 m, Elev is the elevation, and $R_n$ is the net radiation. The dominant factors are highlighted in bold.

<table>
<thead>
<tr>
<th>Variables and Regions</th>
<th>$T_{mean}$</th>
<th>RH</th>
<th>VPD</th>
<th>$U_2$</th>
<th>Elev</th>
<th>$R_n$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW ($n = 1528$)</td>
<td>−0.04</td>
<td>0.34 a</td>
<td>−0.14 a</td>
<td>−0.04</td>
<td>−0.12 a</td>
<td>−0.12 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(0.3)</td>
<td>(11.2)</td>
<td>(0.5)</td>
<td>(0.8)</td>
<td>(1.4)</td>
<td>(1.2)</td>
<td>(15.2)</td>
</tr>
<tr>
<td>NC ($n = 984$)</td>
<td>−0.21 a</td>
<td>0.46 a</td>
<td>−0.4 a</td>
<td>−0.04</td>
<td>0.1 b</td>
<td>−0.36 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(3.3)</td>
<td>(21)</td>
<td>(0.1)</td>
<td>(4.5)</td>
<td>(5.8)</td>
<td>(5.5)</td>
<td>(32)</td>
</tr>
<tr>
<td>NCP ($n = 3065$)</td>
<td>−0.03</td>
<td>0.21 a</td>
<td>−0.19 a</td>
<td>−0.04 b</td>
<td>−0.08 a</td>
<td>−0.24 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(0.8)</td>
<td>(0.4)</td>
<td>(0.5)</td>
<td>(0.5)</td>
<td>(5.5)</td>
<td>(10.4)</td>
<td></td>
</tr>
<tr>
<td>NE ($n = 973$)</td>
<td>0.04</td>
<td>0.22 a</td>
<td>−0.16 a</td>
<td>−0.16 a</td>
<td>−0.04</td>
<td>−0.3 a</td>
<td>(8.8) (17.7)</td>
</tr>
<tr>
<td></td>
<td>(8.6)</td>
<td>(6.6)</td>
<td>(6.6)</td>
<td>(6.6)</td>
<td>(8.8)</td>
<td>(17.7)</td>
<td></td>
</tr>
<tr>
<td>E ($n = 3858$)</td>
<td>−0.3 a</td>
<td>0.17 a</td>
<td>−0.33 a</td>
<td>−0.15 a</td>
<td>0.04 b</td>
<td>−0.43 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(3)</td>
<td>(0.9)</td>
<td>(2.8)</td>
<td>(0.4)</td>
<td>(18.1)</td>
<td>(25.2)</td>
<td></td>
</tr>
<tr>
<td>SE ($n = 3207$)</td>
<td>−0.33 a</td>
<td>−0.03</td>
<td>−0.23 a</td>
<td>0.06 b</td>
<td>0.01</td>
<td>−0.35 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(0.3)</td>
<td>(1.1)</td>
<td>(0.3)</td>
<td>(0.4)</td>
<td>(12.2)</td>
<td>(14.5)</td>
<td></td>
</tr>
<tr>
<td>SW ($n = 4688$)</td>
<td>−0.23 a</td>
<td>0.25 a</td>
<td>−0.32 a</td>
<td>−0.11 a</td>
<td>−0.05 a</td>
<td>−0.35 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(0.5)</td>
<td>(3.9)</td>
<td>(2.2)</td>
<td>(0.3)</td>
<td>(12.2)</td>
<td>(19.1)</td>
<td></td>
</tr>
<tr>
<td>TP ($n = 1408$)</td>
<td>0.3 a</td>
<td>0.42 a</td>
<td>−0.21 a</td>
<td>−0.06 b</td>
<td>−0.21 a</td>
<td>0.06 b</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(17.7)</td>
<td>(17.7)</td>
<td>(17.7)</td>
<td>(17.7)</td>
<td>(17.7)</td>
<td>(17.7)</td>
<td></td>
</tr>
<tr>
<td>National ($n = 19,848$)</td>
<td>−0.17 a</td>
<td>0.33 a</td>
<td>−0.33 a</td>
<td>−0.15 a</td>
<td>−0.06 a</td>
<td>−0.4 a</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(0.2)</td>
<td>(4.4)</td>
<td>(4.4)</td>
<td>(4.4)</td>
<td>(15.5)</td>
<td>(23.1)</td>
<td></td>
</tr>
</tbody>
</table>

Notes: * Significant at the 0.01 level; ** significant at the 0.05 level; - is no value.

The percent contributions of each climate factor to $K_p$ variation were analyzed using multiple stepwise regression with $K_p$ as the dependent variable and the six climatic factors as the independent variables (Table 4). The climate factors together explained approximately one quarter of the $K_p$ variation in China. Of the six climatic factors, $R_n$ had the most explanatory power, with an independent explanation percentage of 15.5%, followed by RH and VPD (4.4% and 1.4%, respectively). The combined explanation percentage was 23.1%, which implied that more complicated mechanisms affect the variations in $K_p$. Similar to the $r$ values, the highest explanatory percentages in five of the eight regions were found at the relatively low heat capacity, the water temperature of $\phi 20$ increases faster during the day and also decreases faster at night than that of the E601B pan. This phenomenon may be significant in regions with high temperature differences, such as the NE and NW regions (Table 3). By contrast, the E601B, compared to the $\phi 20$, has no effect because it was buried in the ground and surrounded by
water (Figure 1). Similarly, Lim et al. [47], based on an energy balance experiment, found that the $K_p$ between a Class A pan and steady state lake evaporation was mainly dependent on the additional radiation absorbed by the pan wall. The wall of the $\phi 20$ also had a large area based on the ratio of the wall to the water surface (Figure 1c). Thus, the wall absorbed additional radiation and transferred heat to the water, which increased the evaporation [27]. In addition, on nights without solar radiation, the appreciable storage of heat within the pan wall (Class A or $\phi 20$) may have caused additional evaporation [27], while E601B had a relatively small evaporation because it was buried in the soil. A negative correlation between $K_p$ and $R_n$ was found in this paper (Table 4), and this finding has also been confirmed by previous experimental data [15,41,53]. In addition, wind speed can decline rapidly with decreasing height due to higher surface roughness and friction near ground [21]. Therefore, a small $\phi 20$ evaporimeter located at a higher elevation and exposed to the faster wind speed should have more evaporation than the E601B evaporimeter, resulting in a small $K_p$. This condition can be amplified by regional differences in wind speed. For example, the average wind speed is high in the NE and NCP regions (Table 2); thus, the $\phi 20$ evaporation could be larger than that of E601, resulting in smaller $K_p$ values than in other regions during the warm season (Table 3).

In conclusion, several factors, including water temperature, vapor pressure, wind speed, turbulence, heat transfer, and heat storage, can affect pan evaporation. The combined influence of various factors produces different spatial patterns and monthly variations in $K_p$. However, further analysis of the contribution of each factor to $K_p$ requires rigorous experimental investigation of the physics of pan evaporation [47,53] or more reasonable evaporation models [14].

4. Uncertainties

Uncertainties of the spatial distribution and monthly variation of $K_p$ existed in this study, as well as the explanatory powers of the climatic factors. First, although the spatial distribution of $K_p$ is useful for evaporation studies, it should be noted that only larger $R^2$ values indicate a high confidence of converting the $\phi 20$ evaporation to E601B evaporation. Therefore, in combination with the spatial distribution of $R^2$ (Figures 3a and 4), it was reasonable to obtain E601B evaporation by multiplying $K_p$ by the $\phi 20$ evaporation in the northern part of China, such as in the NC, NCP, and NE regions. However, there are uncertainties in the TP and NW regions due to the relatively sparse distribution of monitoring stations in such large areas (Figure 2); thus, $K_p$ should be used cautiously in these regions. Second, the $K_p$ value was calculated based on the assumption that $K_p$ remains constant over time. This may not be true in some places, and its further testing of the inter-annual variability is required. In addition, the climatic factors that were selected to explain $K_p$ may not be independent. For example, VPD is a function of RH and temperature [21].

Despite these uncertainties, this study presented the spatial distribution of $K_p$ and investigated the dominant climatic factors. Our findings were similar to those of previous studies [19,33,41,53]. Therefore, more attention should be paid to the spatial and temporal variations in $K_p$ before using evaporation data from different evaporimeters. Some researchers have documented that evaporation from Class A (Figure 1a), GGI-3000 (Figure 1b), and $\phi 20$ (Figure 1c) evaporimeters had relatively small $K_p$ values compared to those of 20 m$^2$ evaporation tanks [8,15,30]. By contrast, E601B evaporation had a high value of $K_p$ and was close to the free water surface evaporation [15]. Researchers have compared various types of evaporimeters at the station scale in the E and NCP regions of China [15,30]. They found that the E601B, compared to other evaporimeters, had a larger conversion coefficient and smaller coefficient of variation with 20 m$^2$ evaporation tanks, indicating that the evaporation from E601 was much closer to evaporation from the free water surface. The Class A and $\phi 20$ pans, which are exposed to the air and can absorb additional radiation via the wall, had small conversion coefficients with 20 m$^2$ evaporation tanks [8,47]. Therefore, it is reasonable to substitute E601B for $\phi 20$ in China, not only because of its stability in different climate regions but also because of its relatively small difference relative to evaporation from large water bodies.
5. Conclusions and Suggestions

This paper analyzed the spatial distribution, correlation coefficient ($R^2$), and conversion coefficient ($K_p$) of evaporation from two typical pans in eight climate regions in China. The main conclusions are as follows:

1. During the warm season, the spatial evaporation patterns of the two pans were similar and showed increasing trends from the southeastern to northwestern regions of China. The $R^2$ values were relatively high and ranged from 0.48 to 0.99 with an average of 0.89, which indicates that the E601B pans accurately captured the variation in $\phi_20$ evaporation. The $K_p$ values showed significant spatial variability across China and varied from 0.46 to 0.92 with a mean of 0.60. The highest and lowest $K_p$ values were found in the southwestern (SW and TP) and NE regions, respectively. Generally, $K_p$ increased from May to September in all of the regions, especially during the summer (June, July and August). In the humid regions (the E, SE, and SW regions), the values of $R^2$ and $K_p$ were higher during the cold season (means of 0.92 and 0.66, respectively) than during the warm season. The monthly $K_p$ values at the annual scale had a unimodal distribution. They increased from May to December or January the following year, and then decreased until April.

2. The Pearson correlations and the explanatory powers of the variables were calculated using the multiple stepwise regression method. $R_n$ was the dominant climatic factor for the variation in $K_p$, exhibiting the best correlation ($r \approx 0.4, p < 0.01$) and highest independent explanatory power (approximately 15%) in five of the eight regions, followed by RH and VPD. The combined explanation percentage of all of the variables was 23.1%, and significant differences in explanation percentages were observed in the eight climate regions.

Although the contributions of climate factors to $K_p$ variability were identified by the stepwise multiple linear regression method, the selected factors in this study had relatively weak explanatory powers. Further experiments must be performed to investigate the other potential mechanisms that affect $K_p$, such as the water vapor pressure at the surface and in the air, pan size, wind speed [53], and the energy balance around evaporation meters [47]. Based on this initial stage of this research, ongoing research and planned experiments, new approaches and evaporation equations [14,41] will be explored using the large and valuable meteorological records available in China. Quantification of the contributions of climatic factors to $K_p$ and determination of the mechanisms of $K_p$ variability can improve the understanding of long-term trends in pan evaporation across China.

Acknowledgments: This research was financially supported by Natural Science Foundation of China (No. 41330529, 41501032, 41571024). We will give many thanks to Wilfried Brutsaert and Guobin Fu for their good suggestions to the manuscript.

Author Contributions: This paper was designed and performed by all the authors. Yanzhong Li wrote the draft of the paper. Changming Liu provided the data and financial support. Kang Liang provided the idea and detailed directed the writing.

Conflicts of Interest: The authors declare no conflict of interest.

References


11. Donohue, R.J.; McVicar, T.R.; Roderick, M.L. Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. J. Hydrol. 2010, 386, 186–197. [CrossRef]


23. Liu, W.; Wang, L.; Zhou, J.; Li, Y.; Sun, F.; Fu, G.; Li, X.; Sang, Y.F. A worldwide evaluation of basin-scale evapotranspiration estimates against the water balance method. J. Hydrol. 2016, 538, 82–95. [CrossRef]


