5-2010

Investigating Time-Scale Effects on Reference Evapotranspiration from Epan Data in North China

Yi Li
Northwest Agriculture and Forestry Sci-Tech University

Robert Horton
Iowa State University, rhorton@iastate.edu

Tusheng Ren
China Agricultural University

Chunyan Chen
Urumqi Observatory of Meteorology Bureau

Follow this and additional works at: https://lib.dr.iastate.edu/agron_pubs

Part of the Atmospheric Sciences Commons, Hydrology Commons, Plant Sciences Commons, and the Soil Science Commons

The complete bibliographic information for this item can be found at https://lib.dr.iastate.edu/agron_pubs/408. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
Investigating Time-Scale Effects on Reference Evapotranspiration from Epan Data in North China

Abstract
Reference evapotranspiration ($ET_o$) and pan evaporation ($E_{pan}$) are key parameters in hydrological and meteorological studies. The authors’ objectives were to evaluate the ratio of $ET_o$ to $E_{pan}$ ($k_p$) at daily and monthly scales and to predict average $ET_o$ in the following years using calibrated $k_p$ and observed $E_{pan}$ at the two time scales. Using 50 yr of data obtained at six typical sites in north China, daily and monthly $ET_o$ were calculated using the Food and Agriculture Organization estimation method (FAO-56) Penman–Monteith equation, and $k_p$ values were determined at the two time scales. Values of $k_p$ varied from 0.457 to 0.589 daily and from 0.392 to 0.528 monthly for the six sites. Both daily and monthly $k_p$ could be fitted as multilinear functions of longitude, latitude, elevation, and relative humidity. Relatively accurate predictions of daily mean $ET_o$ for the subsequent years following the calibration years at all six sites were obtained when the year number $L$ used for calibrating daily mean $k_p$ was sufficient (>38). In cases when large deviations occurred between average $k_p$ for the $L$ calibration years and the actual $k_p$ of the following ($L + 1$)th year, relatively large prediction errors resulted. For the monthly scale, soil heat flux $G$ fluctuated periodically. When variations of $G$ were included, the calculated monthly $ET_o$ values were smaller than the monthly $ET_o$ cumulated from daily $ET_o$. Thus, monthly $k_p$ values were smaller than daily $k_p$ values. Predictions of monthly $ET_o$ in 2001 for the six sites were relatively accurate with relative errors ranging from −11.9% to 12.1%. In conclusion, this method is simple and accurate with a small demand for weather data.

Disciplines
Atmospheric Sciences | Hydrology | Plant Sciences | Soil Science

Comments

Rights
© Copyright 2010 American Meteorological Society (AMS). Permission to use figures, tables, and brief excerpts from this work in scientific and educational works is hereby granted provided that the source is acknowledged. Any use of material in this work that is determined to be “fair use” under Section 107 of the U.S. Copyright Act or that satisfies the conditions specified in Section 108 of the U.S. Copyright Act (17 USC §108) does not require the AMS's permission. Republication, systematic reproduction, posting in electronic form, such as on a website or in a searchable database, or other uses of this material, except as exempted by the above statement, requires written permission or a license from the AMS. All AMS journals and monograph publications are registered with the Copyright Clearance Center (http://www.copyright.com). Questions about permission to use materials for which AMS holds the copyright can also be directed to the AMS Permissions Officer at permissions@ametsoc.org. Additional details are provided in the AMS Copyright Policy statement, available on the AMS website (http://www.ametsoc.org/CopyrightInformation).

This article is available at Iowa State University Digital Repository: https://lib.dr.iastate.edu/agron_pubs/408
Investigating Time-Scale Effects on Reference Evapotranspiration from $E_{\text{pan}}$ Data in North China

YI LI
College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry Sci-Tech University, Yangling, China

ROBERT HORTON
Agronomy Department, Iowa State University, Ames, Iowa

TUSHENG REN
Department of Soil and Water, China Agricultural University, Beijing, China

CHUNYAN CHEN
Urumqi Observatory of Meteorology Bureau in Xinjiang, Urumqi, China

(Manuscript received 1 October 2008, in final form 27 October 2009)

ABSTRACT

Reference evapotranspiration (ETo) and pan evaporation (Epan) are key parameters in hydrological and meteorological studies. The authors’ objectives were to evaluate the ratio of ETo to Epan ($k_p$) at daily and monthly scales and to predict average ETo in the following years using calibrated $k_p$ and observed Epan at the two time scales. Using 50 yr of data obtained at six typical sites in north China, daily and monthly ETo were calculated using the Food and Agriculture Organization estimation method (FAO-56) Penman–Monteith equation, and $k_p$ values were determined at the two time scales. Values of $k_p$ varied from 0.457 to 0.589 daily and from 0.392 to 0.528 monthly for the six sites. Both daily and monthly $k_p$ could be fitted as multilinear functions of longitude, latitude, elevation, and relative humidity. Relatively accurate predictions of daily mean ETo for the subsequent years following the calibration years at all six sites were obtained when the year number $L$ used for calibrating daily mean $k_p$ was sufficient (>38). In cases when large deviations occurred between average $k_p$ for the $L$ calibration years and the actual $k_p$ of the following ($L + 1$)th year, relatively large prediction errors resulted. For the monthly scale, soil heat flux $G$ fluctuated periodically. When variations of $G$ were included, the calculated monthly ETo values were smaller than the monthly ETo cumulated from daily ETo. Thus, monthly $k_p$ values were smaller than daily $k_p$ values. Predictions of monthly ETo in 2001 for the six sites were relatively accurate with relative errors ranging from −11.9% to 12.1%. In conclusion, this method is simple and accurate with a small demand for weather data.

1. Introduction

Crop water requirements (CWR) are important parameters in the design of irrigation systems, irrigation scheduling, water resources management, and water cycle research (e.g., Donatelli et al. 2006; Maule et al. 2006; Xu et al. 2006a,b). Direct measures of CWR are difficult because of equipment and funding limitations. CWR can be obtained from estimates of evapotranspiration (ET). The quantity ET is often estimated from measurements of free water evaporation or from calculated reference evapotranspiration (ETo). The quantity ETo is the evapotranspiration from the reference surface, which is a hypothetical grass reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s m$^{-2}$, and an albedo of 0.23, and closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (Allen et al. 1998). The quantity ETo can be considered to be an upper limit of actual ET.

Corresponding author address: Yi Li, College of Water Resources and Architectural Engineering, Northwest Agriculture and Forestry Sci-Tech University, Yangling, Shaanxi, 712100, China. E-mail: liyikitty@126.com

DOI: 10.1175/2009JAMC2130.1

© 2010 American Meteorological Society
The quantity ET₀ is useful for characterizing the climatic effects in soil–plant–atmosphere systems. It is important and widely used in agricultural water cycle studies, irrigation schedules, and applied meteorology. The ET₀ can be obtained by theoretical or empirical equations. Allen et al. (1998) modified the Penman–Monteith (PM) equation using a suite of reference land surface conditions, and the Food and Agriculture Organization adopted this as the standard ET₀ estimation method (herein denoted FAO-56). FAO-56 has been accepted worldwide as a good ET₀ estimator compared with other methods (Sumner and Jacobs 2005), both at the daily time step (Allen 1996; Allen et al. 1996, 2000; Liu et al. 1997; Garcia et al. 2004; Temesgen et al. 2005; Alexandris et al. 2006; Cai et al. 2007) and at the monthly scale (Allen et al. 1998; McVicar et al. 2005, 2007). To use FAO-56 requires maximum and minimum air temperature, relative humidity, solar radiation, and wind speed data. Gong et al. (2006) found that in the Changjiang (Yangtze) River basin in China, where ET₀ is primarily energy limited (average annual precipitation is greater than annual ET₀; Donohue et al. 2007), the calculated ET₀ was most sensitive to relative humidity, followed by shortwave radiation, air temperature, and wind speed.

Although FAO-56 was relatively accurate for calculating ET₀ (Gunston and Batchelor 1983; Sumner and Jacobs 2005), the required long-term and continuous meteorological datasets are often lacking. This makes it difficult to determine ET₀ for regions lacking complete historical climatic data. Therefore, many attempts have been made to estimate ET₀ using easily obtained and less costly information such as free water evaporation, or pan evaporation (E_pan). This is the rainfall-corrected evaporation observed by a special pan under sufficient water supply and is often linearly related with ET₀ characterized by a linear slope coefficient k_p. The relationship is written as

\[ ET₀ = k_p E_{pan}. \]  

In western countries, the class-A pan, 120.7 cm in diameter and 25 cm deep (Allen et al. 1998), is widely used for E_pan measurement (Allen 1996; Naoum and Tsanis 2003). However, in many Chinese weather stations, “micropans” of 20-cm diameter and 10-cm height, which are usually filled to a depth of 2 or 3 cm, have been used for a long time (Wang et al. 2006). The ratio of the area for heat transfer to the area for water vapor transfer is much greater for Chinese micropans than for class-A pans, resulting in lower k_p values for Chinese micropans compared to class-A pans (McVicar et al. 2007). McVicar et al. (2007) showed how k_p varies symmetrically in time (and space) in the Loess Plateau. Rotstayn et al. (2006) developed a physical model for pan evaporation and then Roderick et al. (2007) used this “Penpan” model in Australia to attribute trends in observed E_pan given trends in the forcing meteorological data in a water-limited context. Roderick et al. (2007) found that changes in temperature and humidity regimes were generally too small to impact pan evaporation rates and the observed decreases in pan evaporation were mostly due to decreasing wind speed with some regional contributions from decreasing solar irradiance.

Ultimately, our objective is to predict ET₀, for example, for local irrigation scheduling; this prediction requires accounting for the relationship between ET₀ and E_pan. Fan et al. (2006) showed that there were clear correlations between E_pan and ET₀ determined by the PM equation based on Loess Plateau climatic data. Further research is needed to determine how broadly applicable the linear relationship between E_pan and ET₀ is. When full climatic data are unavailable, using E_pan data can be a good approach to estimate ET₀ values (Gunston and Batchelor 1983; Allen et al. 1998).

### Table 1. Geographical and mean annual meteorological information of the selected stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Urumqi</th>
<th>Lhasa</th>
<th>Xining</th>
<th>Lanzhou</th>
<th>Huhehaote</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elev (m)</td>
<td>918</td>
<td>3649</td>
<td>2295</td>
<td>1517</td>
<td>1063</td>
<td>55</td>
</tr>
<tr>
<td>Lat (N)</td>
<td>43°47′</td>
<td>29°40′</td>
<td>36°43′</td>
<td>36°03′</td>
<td>40°50′</td>
<td>39°48′</td>
</tr>
<tr>
<td>Lon (E)</td>
<td>87°37′</td>
<td>91°08′</td>
<td>101°45′</td>
<td>103°53′</td>
<td>111°48′</td>
<td>116°28′</td>
</tr>
<tr>
<td>Air temperature (°C day⁻¹)</td>
<td>6.8</td>
<td>7.7</td>
<td>5.9</td>
<td>9.7</td>
<td>6.4</td>
<td>12.1</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹ day⁻¹)</td>
<td>2.4</td>
<td>1.9</td>
<td>1.8</td>
<td>0.9</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Relative humidity (% day⁻¹)</td>
<td>58</td>
<td>44</td>
<td>58</td>
<td>57</td>
<td>54</td>
<td>57</td>
</tr>
<tr>
<td>Pan evaporation (mm a⁻¹)</td>
<td>2177</td>
<td>2298</td>
<td>1633</td>
<td>1472</td>
<td>1809</td>
<td>1842</td>
</tr>
<tr>
<td>E_{pan} completeness (%)</td>
<td>99.5</td>
<td>96.3</td>
<td>99.9</td>
<td>99.9</td>
<td>99.9</td>
<td>99.9</td>
</tr>
</tbody>
</table>

### Table 2. Parameters reported in Chen et al. (2004).

<table>
<thead>
<tr>
<th>Station</th>
<th>Urumqi</th>
<th>Lhasa</th>
<th>Xining</th>
<th>Lanzhou</th>
<th>Huhehaote*</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>a₁</td>
<td>0.21</td>
<td>0.30</td>
<td>0.21</td>
<td>0.16</td>
<td>0.26</td>
<td>0.17</td>
</tr>
<tr>
<td>b₁</td>
<td>0.52</td>
<td>0.54</td>
<td>0.53</td>
<td>0.53</td>
<td>0.52</td>
<td>0.53</td>
</tr>
</tbody>
</table>

* Parameters of Huhehaote were referred to as Erlianhaote in Chen et al. (2004, their Table 1) with a longitude of 111°58′, latitude of 43°39′, and elevation of 965 m. For Huhehaote, the longitude was E111°48′, the latitude was N40°50′, and the elevation was 1063 m.
Research based on the PM method has focused on spatial distribution of \( k_p \) (McVicar et al. 2007), spatial and temporal trends (Gong et al. 2006), the effects of sensitivity coefficients on \( E_{\text{pan}} \) (Xu et al. 2006a,b), trends of \( E_{\text{pan}} \) (Roderick et al. 2009a,b), and sampling frequency effects (Hupet and Vanclooster 2001). Also of interest for \( E_{\text{pan}} \) and \( E_{\text{pan}} \) measurements and models in the context of a climate change (McVicar et al. 2005), widespread decreases in terrestrial midlatitude near-surface wind speeds in both the Northern (e.g., China: Xu et al. 2006a,b; Jiang et al. 2010; United States: Pryor et al. 2009) and Southern (e.g., Australia: McVicar et al. 2008) Hemispheres need to be accounted for. But there is still a need to compare \( k_p \) values at daily and monthly scales for less studied regions, to determine whether, and how, different time scales affect \( k_p \). It is unknown whether the simple method presented herein can successfully predict \( E_{\text{pan}} \). It is necessary to perform such research to determine how to use climatic data more efficiently. Our objectives were 1) to compare \( k_p \) values at daily and monthly scales, and 2) to predict \( E_{\text{pan}} \) with the calibrated \( k_p \) and observed \( E_{\text{pan}} \) at two time scales.

2. Materials and methods

a. Basic geographical and climatic conditions of the studied weather stations

The six weather stations (Urumqi, Lhasa, Xining, Lanzhou, Huhehaote, and Beijing) were selected from different climatic regions of north China. The data duration for all six stations was from 1955 to 2001. The smallest completeness of daily weather data (including maximum and minimum air temperature, relative humidity, wind speed, and sunshine hour) was 99.3%. The \( E_{\text{pan}} \) data of the six stations were almost complete (96.3%). The geographical and average climatic conditions of the six sites are presented in Table 1.

The land area maintained for all weather stations was 25 m by 25 m. The land area was leveled, and the plant cover was mown grass. Air temperature readings were made in a small screened box placed 2 m above the ground surface. The 20-cm-diameter micropan was located on a wooden platform 0.7 m above the ground. The relative humidity was measured with a barothermohygrograph 2.0 m above the ground. The sunlight hours were measured by a Jordan sunshine recorder at a height of 1.6 m above the ground. The wind speed was measured by an anemometer at a height of 10 m above the ground.

b. The standard reference evapotranspiration equation

The FAO-56 form of the Penman–Monteith equation is

\[
ET_o = \frac{0.408\Delta (R_n - G) + \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)},
\]

where \( ET_o \) is the reference evapotranspiration (mm day\(^{-1}\)), \( G \) is soil heat flux (MJ m\(^{-2}\) day\(^{-1}\)), \( T \) is mean air temperature at 2 m (°C), \( u_2 \) is wind speed at 2 m (m s\(^{-1}\)), \( e_s \) is saturation vapor pressure (kPa), \( e_a \) is actual vapor pressure (kPa), \( e_s - e_a \) is saturation vapor pressure deficit (kPa), \( \Delta \) is slope of vapor pressure curve (kPa °C\(^{-1}\)), \( \gamma \) is a psychrometric constant (kPa °C\(^{-1}\)), and \( R_n \) is net radiation (MJ m\(^{-2}\) day\(^{-1}\)). The net radiation \( (R_n) \) is the difference between the incoming net shortwave radiation \( (R_{ns}; \text{MJ m}^{-2} \text{day}^{-1}) \) and the outgoing net longwave radiation \( (R_{nl}; \text{MJ m}^{-2} \text{day}^{-1}) \), that is, \( R_n = R_{ns} - R_{nl} \). The values \( R_{ns} \) and \( R_{nl} \) are calculated by

\[
R_{ns} = \sigma \left( \frac{T_{\text{max}}^4 + T_{\text{min}}^4}{2} \right) (0.34 - 0.14 \sqrt{e_a}) (1.35 \frac{R_s}{R_{so}} - 0.35)
\]

and

\[
R_{nl} = (1 - \alpha) R_s,
\]

where \( R_s \) is solar radiation calculated with the Angstrom formula (Allen et al. 1998):
where \( \alpha \) is albedo assumed to be 0.23, \( R_a \) is extraterrestrial radiation (MJ m\(^{-2}\) day\(^{-1}\)), \( n \) is actual duration of sunshine (h), \( N \) is maximum possible duration of sunshine or daylight hours (h), \( n/N \) is relative sunshine duration, \( a_s \) is the regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days, and \( a_s + b_s \) is the fraction of extraterrestrial radiation reaching the earth on clear days (\( n = N \)). Prescott originally proposed \( a_s = 0.22 \) and \( b_s = 0.54 \). We used values reported by Chen et al. (2004) who presented \( a_s \) and \( b_s \) values for 46 sites in China. The values for our six sites taken from Chen et al. (2004) are presented in Table 2, and their sums are usually lower than the proposed sum of the FAO-56 values (0.75), which is due to high rates of air pollution reducing atmospheric transmittance and in agreement with previous results (McVicar and Jupp 1999).

As the magnitude of daily or 10-day soil heat flux beneath the grass reference surface is relatively small, it is ignored so \( G \) is assumed to be zero for a daily scale (Allen et al. 1998). This assumption could be a minor error source of \( \text{ET}_o \) calculation. For the monthly scale, \( G \) is calculated by

\[
R_s = (a_s + b_s \frac{n}{N}) R_a, \tag{5}
\]

**Fig. 2.** Linear relations between \( E_{pan} \) and \( \text{ET}_o \) for six stations at daily scale. Total data point number for the regression was 17,167. The slope of the line when forced through the origin was \( k_p \).
where subscripts $i+1$, $i$, and $i-1$ represent the number of month.

The other terms in Eq. (2) are derived from the methods given for daily scale and for monthly scale in Allen et al. (1998, chapters 3 and 4).

c. Pan evaporation method to evaluating ET$_o$

The pan evaporation measurements represent the comprehensive effects of aerodynamic and radiative items such as wind speed, sunlight hours, $e_s - e_a$, and net radiation (Rotstayn et al. 2006; Roderick et al. 2007), which are primary drivers of evapotranspiration. Air temperature is also important because it influences some of these drivers (e.g., $e_s - e_a$ and $R_n$ via $R_{LH}$) and other variables that control evapotranspiration.

The coefficient of linear relationship between ET$_o$ and $E_{pan}$ was affected by the environmental and meteorological conditions (McVicar et al. 2007). Although albedo may differ between locations, we assumed constant albedo for all of the locations. Assuming constant albedo may be a main environmental effect on $k_p$. For further discussion of environmental and meteorological effects, see McVicar et al. (2007) who performed a sensitivity analysis of $k_p$ to spatial interpolation and land surface parameterization. In addition, heat storage in the pan is assumed to be zero (Roderick et al. 2009a,b)
to simplify the calculation, which may be an issue when dealing with cloudy days immediately following sunny conditions. With such a small mass of water in a China micropan, this assumption will be less of an issue than for a class-A pan, which holds a greater volume of water. Pan evaporation data were compared with ET<sub>o</sub> for a class-A pan, which holds a greater volume of water.

**d. Estimation and prediction of average daily ET<sub>o</sub> for the following years**

The approach for predicting average daily ET<sub>o</sub> is based on Eq. (1). We use calibrated <i>k<sub>p</sub></i> values of early years and observed <i>E<sub>pan</sub></i> values of the following predicted year to obtain ET<sub>o</sub> values of the predicted year. With <i>M</i> is the year number for predicting, <i>M = 1, 2, ..., n = L, n</i> is the total year of the datasets, and <i>L</i> is the number of years used to calibrate the daily mean <i>k<sub>p</sub></i> values (<i>k<sub>p,cal</sub></i>), then

\[
\frac{\sum_{i=1}^{DN} k_p}{k_{p,cal}} = \frac{1}{DN},
\]

where DN is the total day number of days in <i>L</i> years. The daily mean <i>E<sub>pan</sub></i> of the (L + M)th year, \( E_{pan}^{L+M} \), is calculated as

\[
E_{pan}^{L+M} = \frac{\sum_{i=1}^{D} E_{pan}}{D},
\]

where \( D \) is the total number of days in the following year, that is, the (L + M)th year. According to Eq. (1), the predicted daily mean ET<sub>o</sub> of the (L + M)th year, \( ET_{o,pre}^{L+M} \), is

\[
ET_{o,pre}^{L+M} = k_{p,cal} L \times E_{pan}^{L+M}.
\]

As the time period for use of the prediction becomes larger (i.e., temporally extrapolating further away from an observation), there is greater potential for trends in the forcing meteorological data to alter the relationship we have developed for prediction.

The relative error RE is calculated as

\[
RE = \frac{ET_{o,act}^{L+M} - ET_{o,pre}^{L+M}}{ET_{o,act}^{L+M}} \times 100\%,
\]

where \( ET_{o,act}^{L+M} = \sum_{i=1}^{D} E_{o,act} / D \), which is the actual daily mean ET<sub>o</sub> [from Eq. (2)] of the <i>M</i> predicted year.

**e. Estimation and prediction of monthly ET<sub>o</sub>**

Although monthly ET<sub>o</sub> and <i>E<sub>pan</sub></i> change periodically, as long as Eq. (1) is statistically effective for monthly scale ET<sub>o</sub> and <i>E<sub>pan</sub></i> data to obtain <i>k<sub>p</sub></i> values, we can predict monthly ET<sub>o</sub> from monthly <i>E<sub>pan</sub></i>. The monthly ET<sub>o</sub> calculated with the FAO-56 equation (\( ET_{o,cal}^{i,j} \), \( i = 1, 2, \ldots, 12 \), representing month number) and the monthly <i>E<sub>pan</sub></i> cumulated from daily values (\( E_{pan}^{i,j} \)) were divided into 12 groups via months, respectively.

The calibrated monthly <i>k<sub>p</sub></i> values (<i>k_{p,cal}</i>) are obtained from the slope of \( E_{pan} \) versus ET<sub>o</sub> at the <i>i</i>th month for the early <i>L</i> years when forced through the origin. Predicted monthly ET<sub>o</sub> in the <i>i</i>th month of the (L + M)th year (\( ET_{o,pre}^{i,j} \)) is

\[
ET_{o,pre}^{i,j} = k_{p,cal} E_{pan}^{i,j} \times E_{pan}^{L+M},
\]

where \( E_{pan}^{L+M} \) is the cumulative daily <i>E<sub>pan</i></i> of the <i>i</i>th month in the (L + M)th year. Equation (10) is also used for determining REs of the predictions.

**3. Results**

**a. The periodic variation of ET<sub>o</sub> and <i>E<sub>pan</sub></i>**

Figure 1 shows the multiyear average monthly variations of ET<sub>o</sub> and <i>E<sub>pan</sub></i> for six sites. The maximum values of ET<sub>o</sub> and <i>E<sub>pan</sub></i> at Urumqi were largest among the six sites. The minimum values of ET<sub>o</sub> and <i>E<sub>pan</sub></i> at Lhasa were largest, while the smallest minimum values of ET<sub>o</sub> and <i>E<sub>pan</sub></i> were at Urumqi. The variations of monthly ET<sub>o</sub> and <i>E<sub>pan</sub></i> were generally similar. The maximum average monthly ET<sub>o</sub> and <i>E<sub>pan</sub></i> of Lhasa, Xining, Lanzhou,
and Beijing were around May, which agreed with McVicar et al. (2007), who reported May as having the maximum average monthly $E_{\text{pan}}$ on China’s Loess Plateau. For Huhehaote and Urumqi, the maximum $E_{\text{pan}}$ and $E_T$ occurred around July, which is likely a response to the differential Asian monsoon.

**b. Comparisons of $k_p$ at daily and monthly scales**

When we cumulated the calculated daily $E_T$ to 3-day, 10-day, 1-month, and 3-month scales, we obtained almost stable $k_p$ values for all six sites at these time scales. The ratios of $k_p$ at a larger time scale to $k_p$ at daily scale ranged from 1.01 to 1.04 for the six sites. The reasons could be from the assumption that zero heat storage in the water in the pan caused small errors. From our calculations, monthly $E_T$ values calculated using the FAO-56 equation were all smaller than those cumulated from daily $E_T$.

The linear relations in Eq. (1) between $E_{\text{pan}}$ and $E_T$ were fitted at daily and monthly scales. The illustrations of $E_{\text{pan}}$ via $E_T$ at the two scales for the six sites are presented in Figs. 2 and 3. There were obvious linear relations between $E_T$ and $E_{\text{pan}}$ at both daily and monthly scales for all sites. Mostly, $E_{\text{pan}}$ was larger than $E_T$. The data points showed increasing scatter as $E_{\text{pan}}$ values increased. Equation (1) fit the relations of $E_{\text{pan}}$ and $E_T$ with a lowest coefficient of determination of 0.740 at the daily

**FIG. 5.** Comparisons of $k_{p, \text{cal}}$ and $k_{p, L+1}$: $k_{p, \text{cal}}$ is the calibrated daily mean $k_p$ in total $L$ years, while $k_{p, L+1}$ is the daily mean $k_p$ of the $(L+1)$th year.
scale and 0.626 at the monthly scale. At the daily scale, $k_p$ ranged from 0.457 to 0.589; $k_p$ at Lanzhou was the largest, while $k_p$ at Urumqi was the lowest. At the monthly scale, $k_p$ decreased compared to the daily scale and ranged from 0.392 to 0.528. The seasonal $k_p$ values reported by Xu et al. (2006a,b) ranged between 0.51 and 0.94 for the Yangtze River basin, and they were generally larger than ours. The seasonal $k_p$ of McVicar et al. (2007) reported in their Fig. 11 for central China ranged from 0.4 to 0.7 and had a larger range relative to our values. The ratios of monthly–daily $k_p$ were 0.87 for Urumqi, 0.96 for Lhasa, 0.68 for Xining, 0.90 for Lanzhou, 0.97 for Huhehaote, and 0.93 for Beijing. A very low (or high) pan coefficient may be caused by some geological and climatic factors such as elevation, relative humidity, wind speed, air temperature, and so on.

There was no single function between $k_p$ and the climatic and geographical elements such as longitude, latitude, altitude, and relative humidity. The coefficient $k_p$ was affected not by a single geographical or climatic element but by several factors. Two multivariable linear functions obtained for $k_p$ and the related influence factors were as follows:

for daily scale,

$$k_p = -0.041 - 2.0 \times 10^{-5} \varphi - 0.01 \delta - 0.002L + 0.012 \text{RH},$$

(12)
for monthly scale,

$$k_p = 1.082 - 5.1 \times 10^{-5} \varphi - 0.011 \delta - 0.001L - 0.004\text{RH},$$  
(13)

where $\varphi$ is longitude, $\delta$ is latitude, $L$ is elevation (m), RH is relative humidity (%), the correlation coefficient of the multivariable regression (multir) for daily scale was 0.978, and that for monthly scale was 0.780. Monthly $k_p$ was much lower than daily $k_p$ at Xining, which decreased the value of multir.

c. Prediction of daily mean $ET_o$

Based on the calibrated daily mean $k_p$ of the early $L$ years and the calculated daily mean $E_{\text{pan}}$ of the $(L + M)$th year, the daily mean $ET_o$ of the $(L + M)$th year ($ET_{0,\text{pre}}^{L+M}$) was predicted (see section 2d). The daily mean $ET_{0,\text{pre}}^{L+M}$ is compared with the estimated FAO-56 daily mean $ET_o$ of the $(L + M)$th year (Fig. 4). Estimated and predicted $ET_o$ values were similar when $ET_o$ was smaller than 3.2 mm day$^{-1}$. Above 3.2 mm day$^{-1}$ several points deviated from the 1:1 line. The $ET_{0,\text{pre}}^{L+M}$ values of Xining, Lanzhou, Huhehaote, and Beijing were relatively close to the 1:1 line in comparison with Urumqi and Lhasa, especially when daily mean $ET_o$ values were relatively small.

From Eq. (9), the errors for $ET_{0,\text{pre}}^{L+M}$ came from both $k_{p,\text{cal}}^{L+M}$ and $E_{\text{pan}}^{L+M}$. While $E_{\text{pan}}^{L+M}$ was obtained from the observed daily $E_{\text{pan}}$ values, despite observation errors, it should not be the main error source of $ET_{0,\text{pre}}^{L+M}$. So the main error source for $ET_{0,\text{pre}}^{L+M}$ was most likely from $k_{p,\text{cal}}^{L+M}$.
to $k_p^{L+1}$ were larger. The $k_p^{L+1}$ curve fluctuated around $k_p^{L, \text{cal}}$ for most sites. The deviations of $k_p^{L, \text{cal}}$ to $k_p^{L+1}$ became smaller when the year number used to determine $k_p^{L, \text{cal}}$ increased. That was the main reason RE of $ET_{0, \text{pre}}$ were low when the year number used to determine $ET_{0, \text{pre}}$ was greater than 38. Generally, the curves of $k_p^{L, \text{cal}}$ were flat and could be treated as a constant value for predicting $ET_o$ at the selected six sites.

For further analyses, we compared the predicted and estimated daily mean $ET_o$ values of the latter predicted years using the calibrated $k_p^{L, \text{cal}}$ of the early $L$ ($L = 38, \ldots, 46$) years (Fig. 6). Only small differences were found between the predicted and estimated $ET_o$ values for all six stations. The RE (%) of the predictions ranged from $-4.4$ to $11.2$ for Urumqi, from $0.6$ to $4.8$ for Lhasa, from $-10.8$ to $10.4$ for Xining, from $-4.1$ to $10.9$ for Lanzhou, from $-3.4$ to $8.2$ for Huhehaote, and from $-5.8$ to $5.6$ for Beijing. Relatively large differences between calibrated $k_p$ and actual $k_p$ of the predicted year caused a relatively large RE. The RE decreased when increasing the time of predictions, and if there was a relatively large calibration period then RE decreased. Small differences were found between the predicted and estimated daily mean $ET_o$. 

Fig. 9. The predicted and calculated monthly $ET_o$ (from meteorological data) values in 2001 at the indicated stations.
d. Prediction of monthly ET\(_o\) from 2001

Soil heat flux \(G\) was small relative to net radiation \(R_n\) (Allen et al. 1998, chapter 3), but \(G\) was an important parameter when we calculated monthly ET\(_o\) using the FAO-56 equation. Figure 7 illustrates the variations of daily mean monthly \(G\) for the six sites from January 1999 to December 2000. There were generally similar fluctuations and ranges of monthly \(G\) for most of the sites, but monthly \(G\) for Lhasa fluctuated less and ranged from \(-0.46\) to \(0.44\) MJ m\(^{-2}\) day\(^{-1}\). Monthly \(G\) at Urumqi fluctuated more than the monthly \(G\) at the other sites. The lowest \(G\) occurred in October at Urumqi (0.91 MJ m\(^{-2}\) day\(^{-1}\), having an upward direction) and the highest \(G\) occurred around April (\(-0.89\) MJ m\(^{-2}\) day\(^{-1}\), having a downward direction) at Urumqi, which followed the obvious fluctuation of air temperature.

A key factor for predicting monthly ET\(_o\) is to calibrate monthly \(k_p\). From the prediction of daily ET\(_o\), it was known that using as many years as possible for data of calibration enhanced prediction accuracy. So when calibrating monthly \(k_p\) values we selected the early 45 yr of data for the six sites. Similar to the daily scale, the monthly average \(k_p\) (or the calibrated \(k_p\)) tended to be stable when the length of years for calibration increased. Figure 8 shows the variation of the calibrated monthly \(k_p\) for the six sites. Monthly \(k_p\) generally had periodic variations with the maximum occurring in July or August.

Figure 9 shows the predicted monthly ET\(_o\) in 2001 for the six sites. In general, the periodic changes of the predicted monthly ET\(_o\) were similar to the calculated values. The ET\(_o\) values from July to September were predicted with a relatively large RE in comparison with the other months.

The RE for the prediction of monthly ET\(_o\) in 2001 are presented in Table 3. The RE at Lhasa and Beijing were generally low relative to the other sites. The RE values for January, March, October, and November were generally larger than the monthly RE of the other months. Similar to the daily scale, low RE values were mainly due to accurately calibrated monthly \(k_p\). The coefficient of determination for calibrating monthly \(k_p\) ranged from 0.830 to 0.898 for Lhasa and Beijing and from 0.683 to 0.879 for the other sites.

Since the prediction procedure is not complicated and it only needs \(E_{\text{pan}}\) observations and the historical average \(k_p\) values, this method is promising for simply and accurately predicting daily average ET\(_o\) and monthly ET\(_o\).

### 4. Conclusions

The relatively good correlation between \(E_{\text{pan}}\) and ET\(_o\) makes it possible to use the pan coefficient \(k_p\) to predict ET\(_o\) from the observed \(E_{\text{pan}}\) for selected stations. Values of \(k_p\) at the daily scale ranging from 0.457 to 0.589 were generally larger than \(k_p\) at the monthly scale ranging from 0.392 to 0.528 for the six sites. Accurate prediction of daily average ET\(_o\) for the years following calibration was possible especially when the actual \(k_p\) of the predicted year was similar to the calibrated \(k_p\). The predictions of monthly ET\(_o\) were relatively accurate. This method for predicting average ET\(_o\) is operable because of its simplicity.

**Acknowledgments.** This work was funded by China National Natural Science Foundation (50709028). We thank the anonymous reviewers and Robert Ewing for providing insightful comments that helped us to improve the paper.

**REFERENCES**


