Clustering analysis of regional reference evapotranspiration and its components based on climatic variables across northeast China, 1961–2010

Yuan Liu, Buchun Liu, Xiaojuan Yang and Wei Bai

ABSTRACT

Evapotranspiration integrates atmospheric demand and surface conditions. The Penman-Monteith equation was used to calculate annual and seasonal reference evapotranspiration (ET₀) and thermodynamic and aerodynamic components (ET_rad and ET_aero) at 77 stations across northeast China, 1961–2010. The results were: (1) annual ET_rad and ET_aero had different regional distribution, annual ET_rad values decreased from south to north, whereas the highest ET_aero values were recorded in the eastern and western regions, the lowest in the central region; (2) seasonal ET_aero distributions were similar to seasonal ET₀, with a south–north longitudinal pattern, while seasonal ET_rad distributions had a latitudinal east-west pattern; and (3) in the group for ET₀ containing 69 sampling stations, effects of climatic variables on ET₀ followed sunshine hours > relative humidity > maximum temperature > wind speed. Changes in sunshine hours had the greatest effect on ET_rad, but wind speed and relative humidity were the most important variables to ET_aero. The decline in sunshine duration, wind speed, or both over the study period appeared to be the major cause of reduced potential evapotranspiration in most of NEC. Wind speed had opposite effects on ET_rad and ET_aero, and therefore the effect of wind speed on ET₀ was not significant.

Key words | climatic variable, clustering analysis, northeast China, Penman-Monteith equation, reference evapotranspiration, thermodynamic and aerodynamic components

INTRODUCTION

The evapotranspiration rate from a reference surface (grass) is called the reference evapotranspiration and is denoted as ET₀ (Allen et al. 1998). ET₀ can be separated into thermodynamic (ET_rad) and aerodynamic (ET_aero) components. As an important factor in the hydrological cycle, ET₀ affects water availability, particularly for agriculture irrigation planning and water balances (Burn & Hesch 2007; Espadañor et al. 2011; Serrat-Capdevila et al. 2011; Feng et al. 2012). The value of ET₀, from the FAO Penman-Monteith (P-M) equation, was only affected by climatic variables at a specific location and during a certain period (Yu et al. 2002; Easterling et al. 2007; Zhang et al. 2011a), but does not consider crop characteristics and soil factors. ET₀ is a pivotal factor to calculate the crop reference evapotranspiration (Kite & Droegers 2000; Rana & Katerji 2000). However, ET₀ variation could affect precipitation as well as hydrological regimes, which have a direct impact on crop production by changing the agro-ecological water balance. To study the effects of ET₀ in northeast China (NEC), and understand drought risk in agriculture, requires analysis of the changes of ET₀ and meteorological factors in NEC.

Contrary to the expectation that a warmer climate will bring about an increase in evaporation, most studies have shown that calculated ET₀ is declining over the past decades at both the global (McVicar et al. 2007; Roderick et al. 2009) and regional scales (Chattopadhyay & Hulme 1997; Thomas 2000; Liu et al. 2004; Xu et al. 2006a) due to changes in climatic variables. A number of studies have shown that the
trend of ET₀ is not determined by one climatic variable alone (Ohmura & Wild 2002; Xu et al. 2006a). Roderick & Farquhar (2002) suggested that the decrease in observed potential pan-evaporation in the Northern Hemisphere was consistent with what would be expected from the observed large and widespread decreases in sunlight resulting from increasing cloud coverage and aerosol concentration. In China, declining ET₀ trends have been related mainly to decreased sunshine hours and slightly decreased precipitation (Thomas 2000; Gao et al. 2006). However, some literature has reported that there is no evidence of a relationship between ET₀ and change of wind speed (Guo et al. 2011; Zhang et al. 2011b), although Xu et al. (2006b) found that local land-cover change was the primary cause of decreased wind speed. Any change in climatic parameters also affects ET₀ to a greater or lesser extent. In the P-M multi-variable equation, different climatic variables have different dimensions and ranges of values; nevertheless, many studies have tried to determine the contribution of related climatic variables to expected ET₀ (Beres & Hawkins 2001). In the Yangtze basin, Gong et al. (2006) conducted a sensitivity analysis of key meteorological variables and derived the spatial variation of the sensitivity coefficients. To understand the relative importance of climatic variables in the P-M equation, a sensitivity analysis is required and the results are of vital significance in determining the effect of climate change on ET₀. However, previous analysis was restricted to the results at a single station or did not express the sensitivity of similar climatic variables at a regional scale (Gong et al. 2006; Irmak et al. 2006). Basically, a positive/negative coefficient for a climatic variable indicates that ET₀ will increase/decrease as the variable increases. Sensitivity analyses make it possible to determine the accuracy required when measuring the climatic variables used to estimate ET₀ at a significant level. Therefore, analysis on contributions of these meteorological variables to changes in ET₀ is essential to help discriminate the main driving forces causing variation in ET₀ across NEC. NEC is the most important agricultural region in China and has shown great sensitivity to shifts in climate. NEC has experienced a 0.38 °C 10a⁻¹ increase in mean air temperature over the past 50 years (Yang et al. 2007). Previous studies have focused on assessing the impacts of climate change on ET₀ in different fields or its effects on the irrigation schedule. Despite this, little effort has been expended on direct analysis of regional and seasonal ET₀ sensitivity to meteorological variables, especially on determining whether the two components of ET₀ have the same trends as ET₀ in NEC. An attribution analysis is then needed to quantify the contribution of each input variable in the FAO P-M equation to ET₀ variation regionally. Therefore, the aims of this study are: (1) to perform a quantitative analysis of changes in ET₀ and its components (ET_rad and ET_aero) at different spatio-temporal scales; and (2) to investigate how key climatic variables affect ET₀, ET_rad, and ET_aero and to identify similar regions in an attempt to understand the relative roles of the main climatic variables at a regional scale. The cause of spatio-temporal variations in ET₀ and its components in terms of energy balance and dynamics, which should help in accurately estimating regional water requirements and identify the spatial pattern of the dominant meteorological variables, is a vital component in assessing drought risk and guiding agricultural production in NEC.

**Study area**

NEC is an important agricultural and economic region (NBSC, 2001–2008). There are 77 China Meteorological Agency weather stations in the study region (Figure 1). NEC is influenced by the East Asian Monsoon, and the regional climate can be characterized as semi-humid, with annual air temperature ranging between −4.2 °C and 10.9 °C during the past 50 years. Annual precipitation decreases from the southeast (1,084 mm) to the northwest (380 mm). Annual sunshine hours have decreased by 40.7 h per decade over the past 50 years (Table 1). NEC plays a vital role in China’s economic development due to its fertile land. It is one of the most important production areas for maize, rice, and soybeans. This region uses a one-crop-per-year farming system (Yang et al. 2007). Recently, drought has become a dominant factor limiting regional agricultural and economic development under the combined impacts of climate change and intensified human activities.
Data collection

Daily meteorological data were collected from 77 meteorological stations across NEC from January 1961 to December 2010, which display an appropriate geographical distribution as shown in Figure 1. Eight meteorological variables were recorded: mean daily temperature (T$_{avg}$, °C), maximum temperature (T$_{max}$, °C), minimum temperature (T$_{min}$, °C), precipitation (R, mm), sunshine hours (SH, h), pressure (P, kPa), mean wind speed (WS, m s$^{-1}$), and relative humidity (RH, %). The data were provided by the China Meteorological Administration, and sunshine duration was converted into daily solar radiation using the Ångström formula (Jones 1992).

Table 1 | Yearly mean air temperature, precipitation and sunshine hours and their trends in northeast China between 1961 and 2010

<table>
<thead>
<tr>
<th>Mean temperature</th>
<th>Precipitation</th>
<th>Sunshine hours</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average (°C)</strong></td>
<td><strong>Trend (°C 10$^{-1}$)</strong></td>
<td><strong>Average (mm)</strong></td>
</tr>
<tr>
<td>-4.2 $\sim$ 10.9</td>
<td>0.3</td>
<td>380 $\sim$ 1,084</td>
</tr>
<tr>
<td>-90 $\sim$ 1,000</td>
<td>2,909.6</td>
<td></td>
</tr>
</tbody>
</table>

Penman-Monteith (FAO) method

The FAO56 equation is recommended as the sole method for determining reference evapotranspiration (ET$_0$). Most of the parameters can be measured or readily calculated from weather data. The equation is (Allen et al. 1998):

$$ET_0 = ET_{rad} + ET_{aero}$$

$$= \frac{0.408\Delta (R_n - G)}{\Delta + \gamma (1 + 0.34U_2)} + \frac{900}{\Delta + \gamma (1 + 0.34U_2)} \frac{U_2 (e_a - e_s)}{t}$$

where ET$_0$ is the reference evapotranspiration (mm d$^{-1}$). In this paper, ET$_0$ is separated out into a thermodynamic term (ET$_{rad}$) and an aerodynamic term (ET$_{aero}$), R$_n$ is the net radiation at the surface (MJ m$^{-2}$ d$^{-1}$), G is the soil heat flux (MJ m$^{-2}$ d$^{-1}$), which is ignored in the daily calculation due to its relatively small magnitude, t is the average air temperature at 2 m height (°C), U$_2$ is the wind speed at 2 m height (m s$^{-1}$), e$_s$ is the saturation vapor pressure (kPa), e$_a$ is the actual vapor pressure (kPa), (e$_a$ - e$_s$) is the saturation vapor pressure deficit (kPa), $\Delta$ is the slope of the saturated water-vapor pressure curve (kPa °C$^{-1}$), and $\gamma$ is the psychometric constant (kPa °C$^{-1}$). The seasonal and annual values were calculated from the daily ET$_0$ values.
Statistical analysis

Linear regression analysis and testing

Generally, the linear trend of a time series can be estimated by the least-squares method and can be expressed as:

\[ \hat{y}(t) = at + b \] (2)

where the slope (a) is the estimated rate of change in ET\(_0\), ET\(_{rad}\) or ET\(_{aero}\) on a yearly or seasonal basis, t is the time (the year), \(\hat{y}(t)\) contains the annual or seasonal values of ET\(_0\), ET\(_{rad}\) or ET\(_{aero}\), and b is a constant. The magnitude of a trend is represented by the slope of the linear trend and expressed on a decadal scale. If a < 0, the trend is negative, and if a > 0, then the trend is positive.

Statistical test analysis

To detect the presence of trends in a long-term time series of ET\(_0\), ET\(_{rad}\), and ET\(_{aero}\), Student’s t-test was applied at 95 or 99% statistical significance. This method was used to estimate the slope of trends, and is widely used for trend testing of hydrological and meteorological data (Espadafor et al. 2011; Tabari et al. 2011; Tabari & Aghajanloo 2012).

Linear stepwise regression

The effects of key climatic variables on ET\(_0\), ET\(_{rad}\), and ET\(_{aero}\) were analyzed by linear stepwise regression. Each ET\(_0\) and its components served as a dependent variable and the eight climatic variables as predictors. The key climatic variables, which attained the \(P < 0.05\) criterion, were chosen for the final linear regression model using linear stepwise regression analysis. The contribution of each significant variable was determined by the explained variance (\(R^2\)).

Cluster analysis

Cluster analysis is sometimes useful in an analysis of variance to split the variables into reasonably homogeneous groups. This approach is illustrated for several sets of data, and a likelihood ratio test is developed for judging the significance of differences among the resulting groups. The number of climatic variables significantly contributing to ET\(_0\) or its components differed at 77 stations over NEC. In order to reduce the number of important factors and similar regional classifications, the selected key climatic variables were placed into clusters on the basis of their similarity or dissimilarity. The similarity of two objects was determined using the degree of similarity, which was based on the sensitivities of similar climatic variables in the study region (Edwards & Cavalli-Sforza 1965). Then sub-samples of the resulting clusters (two and four classes) were collected so that any uncertainty in the data could be represented. All statistical analyses were carried out at a regional scale over the past 50 years using SPSS 17.0.

Spatial interpolation

To evaluate the spatial distribution and trends of ET\(_0\), ET\(_{rad}\), and ET\(_{aero}\), the linear trends were used to interpolate the variables using the inverse weighted distance (IWD) method. IWD interpolation is characterized by fitting a smooth and continuous surface to the observation points, and does not need a preliminary estimate for the structure of temporal variance and statistical hypotheses (Zhu et al. 2005) and so was used in this study.

RESULTS

Variations in ET\(_0\) and its components

Annual variations

Monsoons are very complex, which means that the study region contains a wide variety of micro-climates which affect crop growth and developments. Figure 2(a)–2(c) show the spatial distributions of average annual ET\(_0\) and its components across NEC for 1961–2010. The mean annual ET\(_0\) over NEC was 836 mm, with a range from 592 mm (Mohe in Heilongjiang) to 1,084 mm (Chaoyang in Liaoning). Mean annual ET\(_0\) decreased slightly from southeast to northwest, showing a longitudinal trend
Mean annual ETrad was 517 mm, ranging from 636 mm in the south to 409 mm in the north (Figure 2(b)), and declined in a latitudinal pattern (east-west). The mean annual ETaero was 319 mm (Figure 2(c)), with the maximum ETaero (514 mm) occurring at Tongyu in Jilin and the minimum ETaero (150 mm) at Linjiang in Jilin, expressing a longitudinal change in the study region. Generally, the contribution of the annual radiation component was about 1.8 times that of the ETaero component (Table 2).

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Figure 2(d)–2(f) map the negative and positive trends of annual ET₀ and its components, with the significance levels shown by different-sized black dots. The mean annual ET₀ declined over large central areas of NEC between 1961 and 2010. The mean rate of decline was −4.7 mm 10⁻¹, with the maximum ET₀ variation (18.7 mm 10⁻¹) occurring at Tahe in Heilongjiang and the minimum value (−50.5 mm 10⁻¹) occurring at Jinzhou in Liaoning. Nineteen stations reached the 99% significance level, and 12 stations reached the 95% significance level. The trends for the remaining stations were not significant (Figure 2(d)). As for the decomposition into two components, positive ETrad trends were found in most areas of NEC (60 stations). These trends varied between 0.3 mm 10⁻¹ (Youyan in Liaoning) and 20.3 mm 10⁻¹ (Hulin in Heilongjiang), with most trends remaining well below 10 mm 10⁻¹. Thirty-four stations reached 99% significance, and nine stations attained 95% significance (Figure 2(e)). In contrast, the annual mean trends for ETaero (−9.7 mm 10⁻¹) were negative for 63 stations. Negative rates of change ranged from −34.1 mm 10⁻¹ (Chaoyang in Liaoning) to −0.5 mm 10⁻¹ (Shangzhi in Heilongjiang). These variations also showed significant spatial trends. The trends at 41 stations reached the 99% significance level, and 30 stations reached the 95% significance level.

**Seasonal variations**

Seasonal spatial distributions for ET₀ and its components across NEC for 1961–2010 are shown in Figure 3(a)–3(l).
The seasonal ET\textsubscript{0} distributions had similar patterns to seasonal ET\textsubscript{aero}, with both showing longitudinal variation, whereas the seasonal ETrad distributions had a latitudinal pattern.

Area-averaged ET\textsubscript{0} was 272 mm in spring and accounted for 33\% of annual ET\textsubscript{0}, ranging from 187 mm (Mohe in Heilongjiang) to 373 mm (Chaoyang in Liaoning). The highest spring ET\textsubscript{0} occurred in the southwestern part of NEC, whereas the lowest spring ET\textsubscript{0} was recorded in the northern mountain regions (Figure 3(a)). The mean ETrad value was 142 mm (41\% of annual ET\textsubscript{0}), with a decreasing latitudinal distribution from south to north (Figure 3(c)).

The ET\textsubscript{aero} spatial distribution showed a longitudinal trend similar to the spring ET\textsubscript{0} distribution, although with smaller values than ET\textsubscript{0} and representing only 27\% of annual ET\textsubscript{0} (Figure 3(c)).

The summer months (June, July, and August) were characterized by high ET\textsubscript{0} values (Thomas 2000). Spatial distributions of summer ET\textsubscript{0}, ETrad and ET\textsubscript{aero} over the past 50 years are shown in Figure 3(d)–3(f). Area-averaged ET\textsubscript{0} in summer was 364 mm, and the highest value was 433.8 mm, in the western part of NEC. The lowest value was 306 mm, in the eastern part of NEC (Figure 3(d)). Summer ET\textsubscript{0} accounted for 44\% of the total annual value, a result comparable to those reported by Tong et al. (2004), with percentage values varying from 52\% at Wushtaoing to 57\% at Minqin. The contour bands showed longitudinal variation and gradually changed along an east-west axis, which implied that both elevation gradients and latitude differences produce fluctuations in ET\textsubscript{0}. Most of the mean summer ETrad values ranged from 270 to 300 mm (54\% of annual ETrad). The highest value appeared in the western part of Liaoning. Variability was low across most of the study region (Figure 3(e)). Most summer ET\textsubscript{aero} values remained below 100 mm, with the highest values (exceeding 125 mm) occurring in the western parts of Jilin and Heilongjiang (Figure 3(f)).

The spatial distributions of autumn ET\textsubscript{0}, ETrad, and ET\textsubscript{aero} are shown in Figure 3(g)–3(i). The ET\textsubscript{0} distribution patterns were similar to spring patterns, but the values were lower in autumn than in spring. The mean value was 155 mm and represented 18.5\% of annual ET\textsubscript{0}, which was higher than in winter (about 5\% of annual ET\textsubscript{0}). The maximum autumn ET\textsubscript{0} and ET\textsubscript{aero} values for the region both occurred at Dalian (243 and 136 mm), whereas the minimum values (80 and 31 mm) occurred in the northern part of Heilongjiang (Figure 5(g) and 5(i)). The autumn ETrad values varied between 43 mm (Tahe in Heilongjiang) and 111 mm (Kuandian in Liaoning) and accounted for 23\% of the total annual value (Figure 5(h)).

Figure 3(j)–3(l) show that the mean ET\textsubscript{0} value was 45 mm in winter, which was rather low. Furthermore, the spatial distributions were fairly homogeneous and accounted for only 5\% of annual ET\textsubscript{0}. The highest ET\textsubscript{0} value was recorded in the southwestern part of NEC (109 mm at Dalian). Figure 5(k)–5(l) also show that ETrad and ET\textsubscript{aero} varied only slightly in the central part of NEC. Generally, at a seasonal scale, the contribution of the spring and autumn radiation components was about 1.3 times that of the aerodynamic component. In contrast, the ratio between the radiation and aerodynamic components was about 4.0 in summer, but only 0.5 in winter (Table 2).

In Figure 4, the white area represents negative trends and the gray area positive trends for seasonal ET\textsubscript{0} and its components between 1961 and 2010. As before, the trends which were significant at the 95 or 99\% levels are marked with different sizes of black dots. In general, seasonal

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>ETrad/ET\textsubscript{0} (%)</th>
<th>ET\textsubscript{aero}/ET\textsubscript{0} (%)</th>
<th>Ratio of ETrad and ET\textsubscript{aero}</th>
</tr>
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<tr>
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<td>Annual</td>
<td>61.0</td>
<td>39.0</td>
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</tr>
<tr>
<td></td>
<td>Spring</td>
<td>51.0</td>
<td>49.0</td>
<td>1.10</td>
</tr>
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<td></td>
<td>Summer</td>
<td>75.4</td>
<td>24.6</td>
<td>3.33</td>
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<td></td>
<td>Autumn</td>
<td>48.0</td>
<td>52.0</td>
<td>0.97</td>
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<tr>
<td></td>
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<td>74.6</td>
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<td>Winter</td>
<td>31.3</td>
<td>68.7</td>
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<tr>
<td>Average of NEC</td>
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<td>Winter</td>
<td>39.8</td>
<td>60.2</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 2 | Proportional contributions made by ETrad and ET\textsubscript{aero} to ET\textsubscript{0} in NEC from 1961–2010
Figure 3 | Regional spatial distribution of seasonal ET₀, ETₐero and ETₐero means across NEC, 1961–2010. Figures (a)–(c) show the ET₀, ETₐero and ETₐero respectively, changes in spring, (d)–(f) show the respective changes in summer, (g)–(i) show the respective changes in autumn and (j)–(l) show the respective changes in winter.
Figure 4: Spatial distribution of seasonal temporal trends in ET₀, ETₓₑ, and ETₓₑₑ across NEC, 1961–2010. Figures (a)–(c) show the ET₀, ETₓₑ, and ETₓₑₑ changes in spring, (d)–(f) show the changes in summer, (g)–(i) show the changes in autumn, and (j)–(l) show the changes in winter. Stations with temporal trends that were significant at the 95 and 99% levels are marked with different sized black dots. Stations symbols with concentric circles had non-significant linear trends.
ET\textsubscript{aero} values declined, and these declines were more pronounced than any positive trends. However, seasonal ET\textsubscript{rad} values increased. The seasonal distributions of ET\textsubscript{rad} and ET\textsubscript{aero} were similar to their annual values.

In spring, ET\textsubscript{rad} values averaged 0.5 mm 10\textsuperscript{a-1} and exhibited a certain amount of spatial variation, reaching 1.1 mm 10\textsuperscript{a-1} in Heilongjiang. Thirty-seven stations reached the 99% significance level and nine the 95% level. ET\textsubscript{aero} values averaged -0.2 mm 10\textsuperscript{a-1} and declined across the whole region. Significant trends were concentrated in Liaoning and Jilin (35 stations). The average trend in spring ET\textsubscript{0} was -0.1 mm 10\textsuperscript{a-1}, ranging from -0.5 mm 10\textsuperscript{a-1} (Linjiang in Jilin) to 0.3 mm 10\textsuperscript{a-1} (Mohe in Heilongjiang), with most trends remaining well below zero (Figure 4(a)–4(c)).

Summer ET\textsubscript{rad} values showed very minor negative changes (Figure 4(e)), with the exception of the southwestern part of NEC. The mean ET\textsubscript{rad} trend was 0.1 mm 10\textsuperscript{a-1}, the minimum trend occurred at Qianan (-0.4 mm 10\textsuperscript{a-1}) and the maximum at Kaiyuan (0.5 mm 10\textsuperscript{a-1}). Twenty-seven stations reached the 99% significance level. Summer ET\textsubscript{aero} trends increased slightly in the eastern part of NEC (Figure 4(f)). Most changes were negative, ranging from -0.6 mm 10\textsuperscript{a-1} at Zhangdang to 0.7 mm 10\textsuperscript{a-1} at Songjiang. Twenty-four stations reached the 99% significance level. The summer ET\textsubscript{0} trend was close to zero and insignificant (60 stations), but increased in the northeastern part of NEC and declined in the southwest.

The spatial patterns of autumn ET\textsubscript{rad} and ET\textsubscript{aero} trends were similar to those in summer. The maximum change in autumn ET\textsubscript{rad} occurred at Zhangwu (2.2 mm 10\textsuperscript{a-1}), and more than half the stations reached the 95% significance level (Figure 4(h)). ET\textsubscript{aero} values declined across the whole NEC, with the most strongly negative changes occurring at Qingyuan (-1.5 mm 10\textsuperscript{a-1}) (Figure 4(i)). Autumn ET\textsubscript{0} values showed both negative and positive trends, depending on the area, but only 18 stations were above the 95% significance level (Figure 4(g)). The positive trends were particularly strong in the central part of NEC.

The ET\textsubscript{rad} mean value was 2.5 mm 10\textsuperscript{a-1} in winter, and its trends were slightly positive, with the maximum trend occurring at Baicheng (8.2 mm 10\textsuperscript{a-1}). Most stations reached high levels of significance. ET\textsubscript{aero} showed mostly negative trends in winter, with the rates of change in ET\textsubscript{aero} ranging between -1.9 mm 10\textsuperscript{a-1} (Qingyuan, Liaoning) and 2.0 mm 10\textsuperscript{a-1} (Changbai, Jilin). Largely positive trends in winter ET\textsubscript{0}, ranging from -0.8 mm 10\textsuperscript{a-1} to 2.0 mm 10\textsuperscript{a-1}, were observed, but most stations did not record significant values.

Relationship between components

The changes in ET\textsubscript{rad}/ET\textsubscript{0} and ET\textsubscript{aero}/ET\textsubscript{0} contributions with latitude and longitude are shown in Figure 5. Due to the decline in ET\textsubscript{rad} from south to north (Figure 2(b)), the proportion contributed by ET\textsubscript{rad} to ET\textsubscript{0} tended to increase with latitude, although the maximum ratio occurred around Linjiang and Kuandian. The proportion contributed by ET\textsubscript{aero}/ET\textsubscript{0} tended to decrease and showed a spatial
pattern opposite to the $ET_{rad}/ET_0$ proportional contribution (Figure 5(a)). The $ET_{rad}/ET_0$ proportion ranged from 50 to 80%, whereas the $ET_{aero}/ET_0$ proportion ranged from 20 to 50%. The trends in the $ET_{rad}$ and $ET_{aero}$ proportional contributions were similar to the results for the $ET_{rad}/ET_0$ ratio (Figure 5(a)), decreasing with longitude (Figure 5(b)), but increasing with latitude. On average, the last two proportions were close to 1:1 in the central areas, which are located around 45° N and 125° E (Figure 5(a)–5(b)).

**Cluster analysis to climatic variables affecting $ET_0$ and its components**

Despite rising temperatures in China, $ET_0$ has been decreasing across most parts of NEC. To identify how much changes in meteorological variables affect $ET_0$ and its components, stepwise regression and cluster analyses were performed with climatic factors as independent variables. Cluster analysis was used to reflect the influence of key regional climatic variables on other variables whose changes in turn have an impact on $ET_0$, while still being able to predict $ET_0$ responses accurately.

**Cluster analysis to $ET_0$**

From a stepwise regression analysis, the climatic variables that reached the 95% significance level were selected. The effects of changes in these climatic variables on $ET_0$ were analyzed by cluster analysis using two classifications. The classifications were based on climatic-variable quality characteristics and their sensitivity to $ET_0$. The 77 sampling sites were placed into two groups using a classification in which each group contained sites with statistically similar characteristics. The distribution of climatic variable sensitivities in NEC is shown in Figure 6(a)–6(c).

After stepwise regression analysis, climatic variables of similar sensitivity were classified into four types. Figure 6(a) shows that all the sampling sites in Group 4-1, with 41 sampling sites, were sensitive mainly to SH, RH, $T_{max}$, and WS. The climatic variables made varying levels of contribution to $ET_0$. Group 4-3 contained 28 sampling sites and showed a different sequence in the effects of $T_{max}$ and WS compared to Group 4-1. Group 4-2 contained only three stations (Tahe, Suihua, and Yanji), which were sensitive mainly to pressure. Group 4-4 contained four sites where $ET_0$ was affected mainly by precipitation. The sampling sites in Groups 4-1 and 4-3 were located mainly in the central and southern areas of NEC.

When clustering into two classes, 74 sites were classified into Group 2-1 and three sites into Group 2-2. Most sampling sites in Group 2-1 were sensitive to SH, RH, $T_{max}$, and WS. However, the climatic variables did not affect $ET_0$ uniformly in Group 2-2 (Figure 6(b)).

**Cluster analysis to $ET_{rad}$ and $ET_{aero}$**

Similarly, cluster analysis into two groups was used to analyze the sensitivity of the effect of changes in climatic variables on $ET_{rad}$ and $ET_{aero}$, as shown in Figure 7. The analysis showed that in all groups, changes in SH always
had the most important effect on ET_rad. The 40 sites in Group 4–1 were located mainly in Heilongjiang, whereas 20 stations from Jilin made up Group 4–2, and 14 stations were in Group 4–3. The maximum contribution to ET_rad was made by SH, WS, and T_max, but these variables were differently arranged in different groups. The remaining three stations were included in Group 4–4, where RH had less effect (Figure 7(a)). In Group 2–1, containing 60 stations, SH, WS, and T_max made equal contributions to ET_rad. The remaining 17 stations were clustered in Group 2–2, which was slightly more affected by relative humidity (Figure 7(b)). Generally, relative humidity had little effect on ET_rad.

When the stations were clustered into four types, WS had the most important effect on ET_aero (Figure 7(c)–7(d)). There was a clear distinction between Group 4–1 and the other three types. WS, RH, and T_max had the greatest effects in Group 4–1, containing 65 stations. These stations were located mainly in Heilongjiang. When the results were clustered into two groups, the major difference was whether air pressure had a significant impact on ET_aero. In Group 2–1, all the variables had similar correlations (69 stations). The greatest effects were due to WS and RH, similarly to Group 4–1.

DISCUSSION

In this study, ET_0 and its thermodynamic (ET_rad) and aerodynamic (ET_aero) components across NEC had been thoroughly analyzed. The analysis was restricted to Liaoning, Jilin and Heilongjiang provinces in the extreme northeast of China, which is one of China’s most susceptible areas to climate change. Daily meteorological data from 1961–2010 for 77 standard meteorological stations were

Figure 7  Distributions of climatic variables that effect ET_rad and ET_aero based on a cluster analysis across NEC.
used in the investigation. Multiple statistical analysis was applied to examine important sensitivity rates of climatic factors on ET₀ at the regional scale. Different maps of temporal ET₀ and its components provided valuable information for regional management of cropping systems, evaluation of agricultural water use and agro-climatic zoning.

By comparing ETₐ and ETₐ₀ as calculated by the P-M equation and their contributions to ET₀, annual and seasonal values were obtained for each station and used to predict the situation across the whole study region.

It is important to identify the major climate factors with key roles in the changes of ET₀ and its components in NEC. China, having the world’s largest population, has been self-sufficient in food production during recent decades, although agriculturally suitable areas account for only 10% of the national territory (Thomas 2000). Any major shift in temporal or spatial ET₀ patterns could have positive or negative consequences for China’s food supplies and in turn for the world economy (Harris 1996). Only climatic variables (e.g., sunshine hours, wind speed, relative humidity, and temperature) are normally used to model the evaporative process in the P-M model. From a practical point of view, knowledge about the relative importance of contributing factors helps to determine which of the ET₀, ETₐ, and ETₐ₀ estimates requires collecting the least amount of data and is therefore best suited for use in regions.

NEC shows a wide range of evapotranspiration rates (Figure 2) due to its complex topography and the influence of regional monsoon circulation branches (Thomas 2000). On a regional basis, ET₀ trends over NEC were similar to long-term ETₐ₀ trends between 1961–2010, but they gave rise to large spatial and temporal variations in sensitivity to a number of physical variables. Annual ETₐ and ETₐ₀ values had different regional distribution patterns. Annual ETₐ showed a latitudinal, decreasing trend from south to north in NEC, whereas the highest values of ETₐ₀ were recorded in the eastern and western regions of NEC, and the lowest values were recorded in the central region. Therefore, the ET₀ distribution pattern overlaps the ETₐ and ETₐ₀ distributions and declines in a southwest to northeast direction. The analysis presented here shows that for NEC as a whole, ET₀ decreased every year between 1961–2010, except for the northern and western parts of NEC. Furthermore, the ET₀ values showed a significant rain-zonal trend. The mean annual ETₐ and ETₐ₀ values also declined across NEC. The seasonal ET₀ distributions showed similar longitudinal trend patterns to the seasonal ETₐ₀ distributions, but the seasonal ETₐ distributions formed latitudinal patterns (Figure 3). The values of ET₀ and its components varied over the seasons. These distribution patterns provide valuable information that can be used to estimate crop coefficients (e.g., maize, rice) for regional crop water studies because they are among the most important factors determining actual regional evapotranspiration, which in turn is a key parameter for regional irrigation water planning and management (Doorenbos & Pruitt 1977). In NEC, if observed precipitation and ET₀ trends remain unchanged, future agricultural production will have to cope with decreasing water availability during the growing season.

Climate change has the potential to affect all of these factors in a combined way. In a warming climate scenario, the most common argument is that a warmer atmosphere will be able to hold more water, and evaporation will therefore increase. However, despite globally rising temperatures, most studies have shown that measured pan evaporation and calculated reference evapotranspiration are declining at both the global (Roderick et al. 2009) and regional scales (Chattopadhyay & Hulme 1997; Thomas 2000; Liu et al. 2004). Several studies have reported mostly decreasing ET₀ trends across China (Thomas 2000; Gao et al. 2006; Zhang et al. 2011a). However, the spatio-temporal variability of these changes is considerable, with trends changing sign even over short distances. A decrease in ET₀ clearly points to changes in atmospheric water and therefore to changes in the climatic parameters that drive evapotranspiration. Declining ET₀ rates appear to be due to decreases in solar radiation and wind speeds, whereas temperature actually has a smaller than expected effect at the single-station level (Thomas 2000, especially in China (Gao et al. 2006). Although Xu et al. (2006b) found that local land-cover change was the primary cause of decreasing wind speeds, it is still uncertain whether genuine large-scale regional changes in global circulation are taking place. Knowledge of which climatic variables influence the evaporative environment on a regional scale is currently limited, especially in NEC. Therefore, sensitivity analysis is
important for understanding the relative impact of changes in climatic variables on regional variation. Cluster analysis was performed in this investigation to identify changes in the meteorological variables that affect ET₀ and its components. The 77 sampling sites were classified by placing them into two or four groups with similar characteristics. For ET₀, the regional sensitivity ranking was SH > RH > T_max > WS. SH had the most important effect on ET_rad over the whole region, whereas WS and RH had the most important effects on ET_aero. Previous studies have suggested that south of 35°N, sunshine appears to be most strongly associated with evapotranspiration changes, whereas wind speed, relative humidity, and maximum temperature are the primary factors in NEC (Thomas 2000).

CONCLUSIONS

On a regional basis, the annual ET_rad and ET_aero had opposite regional distribution patterns. Annual ET_rad decreased with increasing latitude from south to north, whereas ET_aero was highest in the eastern and western regions of NEC. Seasonal ET₀ distributions were similar to seasonal ET_aero distributions and exhibited a longitudinal east-west trend, whereas seasonal ET_rad distributions had a latitudinal south-north trend. The 77 sampling sites were placed into similar groups according to similarities in driving forces based on climatic variables. There were 69 sampling sites in Group 2–1 for ET₀, while the variable change sensitivity followed the order SH > RH > T_max > WS. Sunshine (SH) was always the most important variable affecting ET_rad, whereas WS and RH primarily affected ET_aero. Wind speed had opposite effects on ET_rad and ET_aero, so the effect of wind speed on ET₀ was not significant.

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