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Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiang (Yangtze River) catchment

Chong-yu Xu ^{a,b,*}, Lebing Gong ^{c,d}, Tong Jiang ^a, Deliang Chen ^{d,f},
V.P. Singh ^e

^a Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, China

^b Department of Geosciences, University of Oslo, Sem Saelands vei 1, P.O. Box 1047 Blindern, N-0316 Oslo, Norway

^c Department of Earth Sciences, Uppsala University, Sweden

^d Department of Earth Sciences, Gothenburg University, Sweden

^e Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana 70803-6405, USA

^f Laboratory for Climate Studies/National Climate Center, China Meteorological Administration, Beijing, China

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Summary In this study the Penman–Monteith reference evapotranspiration, pan evaporation measured by a 20 cm pan, and pan coefficient, i.e., the ratio of Penman–Monteith evapotranspiration to pan evaporation, at 150 meteorological stations during 1960–2000 in the Changjiang (Yangtze River) catchment in China are calculated, compared and regionally mapped. Their spatial distributions and temporal variations are examined and the causes for the variations are discussed. The spatial distributions of temporal trends in the reference evapotranspiration as well as in the meteorological variables that determine evapotranspiration are analyzed. The contributions of various meteorological variables to the temporal trend detected in the reference evapotranspiration and pan evaporation are then determined. The results show that: (1) the spatial distributions of reference evapotranspiration and pan evaporation are roughly similar. Spatial correlation coefficients between the reference evapotranspiration and the pan evaporation are high for both the seasonal and annual values. The temporal correlation between the two estimates is higher in the lower (humid) region than in the upper (semi-arid) region. The spatial distribution pattern of the pan coefficient is significantly influenced by wind speed and relative humidity in the region. Higher values of the pan coefficient were found in the central area of the catchment with a relatively high humidity (as compared with the upper area) and a very low wind speed (as compared with other areas); (2) for the whole catchment, there is a significant decreasing trend in both the reference evapotranspiration and the pan

* Corresponding author. Tel.: +47 22 855825; fax: +47 22 854215.
E-mail address: chongyu.xu@geo.uio.no (C.-y. Xu).

evaporation, which is mainly caused by a significant decrease in the net total radiation and to a lesser extent by a significant decrease in the wind speed over the catchment. No temporal trend is detected for the pan coefficient; (3) sensitivity analysis shows that the reference evapotranspiration is most sensitive to the net total radiation, followed by relative humidity, air temperature and wind speed.

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Introduction

Three terms are usually used in describing evaporation in the literature: (1) the term *free water evaporation*, ET_0 , is used for the amount of evaporation from open/free water surface, i.e., the water is returned to the atmosphere from lakes and reservoirs and, in some cases, from river channels in a river catchment; (2) the term actual evapotranspiration, ET_a , describes all the processes by which liquid water at or near the land surface becomes atmospheric water vapor under natural conditions; (3) the term potential evapotranspiration was first introduced in the late 1940s and 1950s by Penman (1948, 1956) and it is defined as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile". Note that in the definition of potential evapotranspiration, the evapotranspiration rate is not related to a specific crop, and there are many types of horticultural and agronomic crops that fit into the description of short green crops; (4) the reference evapotranspiration concept was introduced by irrigation engineers and researchers in the late 1970s and the early 1980s (e.g., Allen et al., 1998) to avoid ambiguities that existed in the definition of potential evapotranspiration. Reference evapotranspiration is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground". The Penman-Monteith method (Allen et al., 1998) overcomes shortcomings of the previous Penman method and provides reference values of potential evapotranspiration for a uniform grass reference surface worldwide and there is no need for a local calibration. In the reference evapotranspiration definition, the grass is specifically defined as the reference crop and this crop is assumed to be free of water stress and diseases. By adopting a reference crop (grass), it has become easier and more practical to select consistent crop coefficients and to make reliable actual crop evapotranspiration (ET_a) estimates in new areas. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect reference evapotranspiration rate, ET_{ref} . The only factors affecting ET_{ref} are climatic parameters. Consequently, ET_{ref} is a climatic parameter and can be computed from weather data.

There exists a multitude of methods for estimation of reference evapotranspiration, ET_{ref} , (e.g., Xu and Singh, 2002); the techniques for estimating ET_{ref} are based on one or more atmospheric variables, such as air tempera-

ture, solar or net total radiation and humidity, or some measurement related to these variables, like pan evaporation (ET_{pan}). Some of these methods are accurate and reliable; others provide only a rough approximation. Most of the methods were developed for use in specific studies and are most appropriate for use in climates similar to where they were developed (Penman, 1948; Jensen, 1973). The Penman-Monteith (P-M) approach was recommended by FAO (see Allen et al., 1998) as a standard to calculate reference evapotranspiration wherever the required input data are available.

Using pan evaporation for estimating reference evapotranspiration is another common method, especially in American and Asian countries (Golubev et al., 2001; Liu et al., 2004). The evaporation rate from pans filled with water is easily obtained. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth in that period. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open-water surface. Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce differences in loss of water from a water surface and from a cropped surface (e.g., Allen et al., 1998): "Reflection of solar radiation from water in the shallow pan might be different from the grass reference surface. Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime. There are also differences in turbulence, temperature and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance". Notwithstanding the difference between pan evaporation and evapotranspiration of cropped surfaces, the pan has proved its practical value and has been widely used to estimate reference evapotranspiration by applying empirical coefficients to relate ET_{pan} to ET_{ref} for periods of 10 days or longer (Allen et al., 1998).

Reference evapotranspiration is one of the most important things to consider when scheduling run times for an irrigation system, preparing input data to hydrological models of water balance study, assessing hydrological impact of changing climate conditions, etc. (Blaney and Criddle, 1950; Allen et al., 1998; Hobbins et al., 2001a,b; Xu and Li, 2003; Xu and Singh, 2005). This is because in the above mentioned activities, accurate spatial and temporal estimation of actual evapotranspiration is required. In a broad definition, the actual evapotranspiration is a combined process of both evaporation from soil and plant surfaces and transpiration through plant canopies. In practice, the estimation of actual evapotranspiration rate for a specific crop requires

first calculating potential or reference evapotranspiration (ET_p or ET_{ref}) and then applying the proper crop coefficients (K_c) to estimate actual crop evapotranspiration (ET_a). In conceptual hydrological modelling, the procedure for calculating actual evapotranspiration is also first to estimate ET_p or ET_{ref} based on meteorological factors, then compute the amount of that potential that is utilized by the actual evapotranspiration processes, given the current status of the plant- and soil-moisture-related characteristics. A general form of such functions can be shown as (Xu and Singh, 2004).

$$ET_a = ET_{ref} \cdot f\left(\frac{SMT}{SMC}\right) \quad (1)$$

where SMT is the actual soil moisture storage and SMC is the soil moisture storage at field capacity. Dyck (1983) provided a summary of some moisture extraction functions used by different investigators. Mintz and Walker (1993) also illustrated several moisture extraction functions. More discussions on the relationship between ET_{ref} and ET_a can be found in the work of Shuttleworth (1993) and Dingman (1994). Apparently, information on the spatial and temporal variations of ET_{ref} plays a vital role in regional hydrological studies. Considering that in China pan measurements are much denser than meteorological stations, and in order to make good use of pan evaporation data and provide reference data depicting spatial and temporal variations of reference evapotranspiration with a fine resolution, the spatial and seasonal variations of the pan coefficient for the catchment need to be determined with good accuracy.

Recognizing the above concerns an attempt is made in this paper to analyze, compare and regionally map the spatial and temporal variations of reference evapotranspiration, pan evaporation and pan coefficient in the Changjiang catchment so as to provide valuable information and database for regional hydrological studies and water resources planning and management. This key theme was divided into the following three sub-goals. The first goal was to evaluate the spatial distribution of the mean annual and seasonal ET_{ref} and ET_{pan} in the Changjiang catchment, and relate it to topographic and climatic variations in the region. The results provide both numerical and physical bases for the calculation and interpretation of pan coefficient variations in the catchment. The second goal was to analyze the long-term temporal distribution (trend) of mean annual and seasonal ET_{ref} and ET_{pan} in the Changjiang catchment, and quantify the contributions of meteorological variables to the trend. The results provide both numerical and physical bases for the study of hydrological impact of climate change and variability in the region. The third aim was to evaluate the spatial and temporal variations of the pan coefficient calculated as the ratio of reference evapotranspiration to pan evaporation. The results provide a reference data for future studies on calculating and depicting spatial and temporal variations of reference evapotranspiration with a fine resolution.

This paper presents the first results of ongoing research with the main objective of studying the impact of climate change on floods in the Changjiang (Yangtze River) basin in China. To provide an important input data base for the ongoing project and serve as a valuable reference data for the regional studies of hydrological modeling, irrigation

planning and water resources management, accurate spatial and temporal variations of reference evapotranspiration with a finer resolution than the national standard meteorological stations can provide need to be calculated for the Changjiang catchment. The ongoing research and the planned study include investigation and quantification of natural and human effects on the changing trend of meteorological variables, calculation and regional mapping of actual evapotranspiration in the catchment by using complementary relationship evaporation models and water balance models, investigation of the effect of the changes in evapotranspiration on flooding and the hydrological cycle in the region, etc.

Study region and data processing

The "Changjiang" in Chinese means "Long River" and is the longest river in Asia and the third longest in the world after the Amazon in South America and the Nile in Africa. The river is about 6380 km long and has a drainage area of 1.8×10^6 km² (Fig. 1). Originating from the Tibetan Plateau at an elevation higher than 5000 m, the Changjiang flows first south, then north and northeast, and finally east to reach the coast, 6300 km away from the starting point. The river basin is located in the subtropical and temperate climate zone. Monsoon winds, caused by differences in the heat-absorbing capacity of the continent and the ocean, dominate the climate of the region as well as the east part of China. Alternating seasonal air-mass movements and accompanying winds give rise to humid summer and dry winter. The advance and retreat of the monsoons determine to a large degree the timing of the rainy season and the amount of rainfall throughout the basin.

Data from 150 National Meteorological Observatory (NMO) stations including daily observations of maximum, minimum and mean air temperature, wind speed, relative humidity, sunshine hours, absolute vapour pressure, and pan evaporation of 20 cm diameter for the period of 1960–2000 were used in this study. They have been provided by the National Climatic Centre (NCC) of CMA (the China Meteorological Administration). The locations of these stations are also shown in Fig. 1.

In order to have a brief idea on the climate of the study region, the catchment is divided into three parts along the longitude from west to east, which corresponds well with the decrease in altitude (Fig. 1). The upper region has a mean altitude of 2551 m above sea level (m.a.s.l.), and the middle and lower regions have a mean altitude of 627 and 113 m.a.s.l., respectively. The classification of the upper, middle and lower regions of the catchment in this study is different from what is determined by the "Changjiang River Water Resources Commission (CWRC)" in China, where flood control is the main concern for the classification. According to CWRC, the section above Yichang station (where the Three Gorges Dam is located) is called the Upper Reach, 4500 km long, with a controlled catchment area of 1 m km² accounting for 70.4% of Yangtze's total area. From Yichang to Hukou is the Middle Reach, 955 km long with a catchment area of 680,000 km². The remaining part from Hukou to the estuary is called the Lower Reach, 938 km long with an inter-

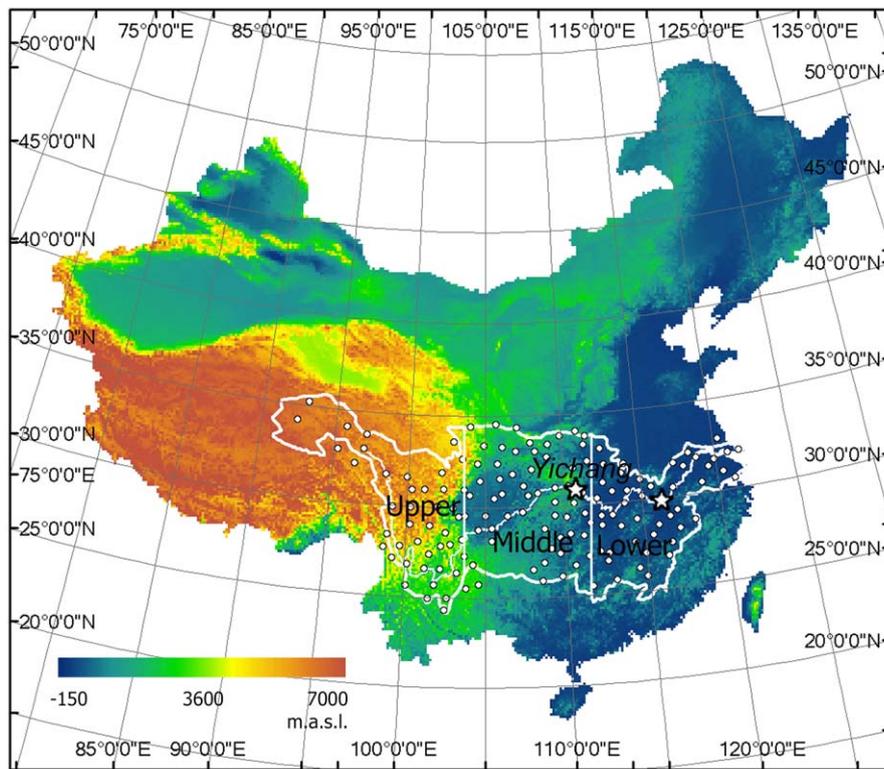


Figure 1 Location of Changjiang (Yangtze River) catchment and the meteorological stations (white dots).

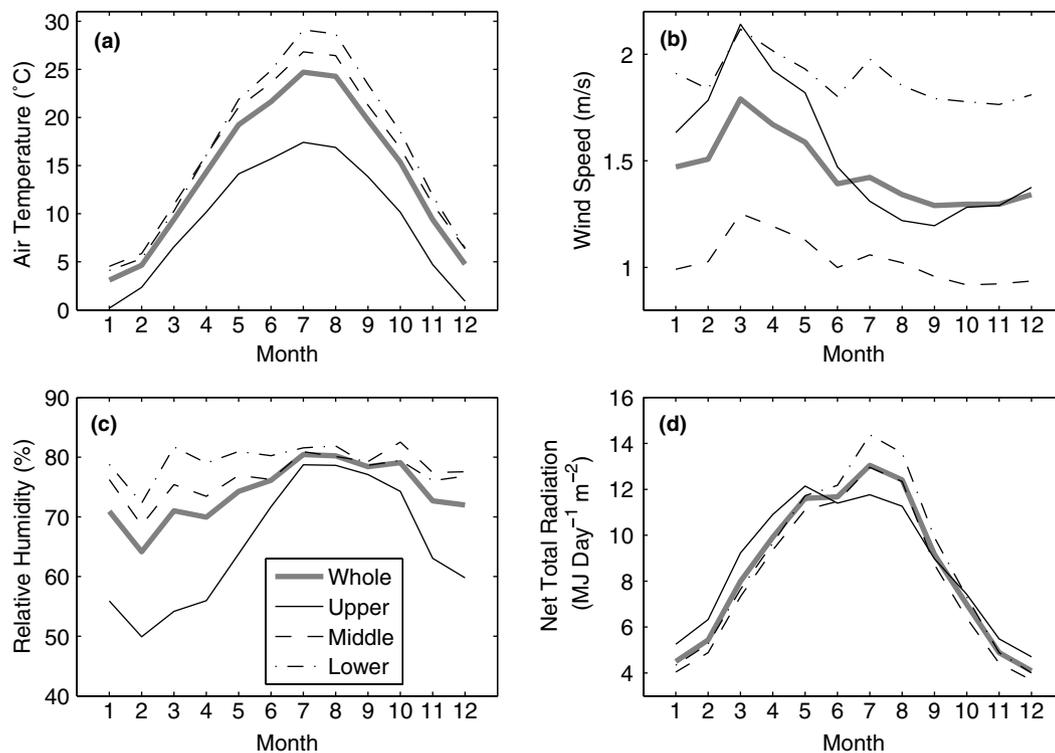


Figure 2 Mean monthly variations of the major meteorological variables for the upper region, middle region, lower region and the average of the catchment. The units for the variables are: relative humidity (%), solar radiation ($\text{MJ}/\text{m}^2/\text{d}$), temperature ($^{\circ}\text{C}$), vapour pressure (mbar), and wind speed ($0.1 \times \text{m/s}$).

val catchment area of 120,000 km². The mean monthly values of the major meteorological variables are plotted in Fig. 2 for the three regions (classified in this paper) and for the average of the catchment. It is seen from Fig. 2 that: (1) the monthly variation of relative humidity in the upper region is much bigger than that in other regions; (2) the maximum wind speed occurs in March for all the regions and the seasonal variation is much stronger in the upper region; (3) the strongest net total radiation is in May in the upper region, while it moves to July in other two regions.

Methods description

The P–M method

The P–M method has been recommended as the sole method for determining ET_{ref} by FAO (Allen et al., 1998) and is used in this study (Eq. (2)). The method has been selected because it is physically based and explicitly incorporates both physiological and aerodynamic parameters.

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_{ref} is the reference evapotranspiration (mm day⁻¹), R_n the net total radiation at the crop surface (MJ m⁻² day⁻¹), G is the soil heat flux density (MJ m⁻² day⁻¹), T the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m s⁻¹), e_s the saturation vapour pressure (kPa), e_a the actual vapour pressure (kPa), $e_s - e_a$ the saturation vapour pressure deficit (kPa), Δ the slope of the vapour pressure (kPa °C⁻¹), γ the psychrometric constant (kPa °C⁻¹).

The computation of all the data required for the calculation of the reference evapotranspiration followed the method and procedure given in Chapter 3 of the FAO paper 56 (Allen et al., 1998).

Pan evaporation and pan coefficient

In this study the pan evaporation measured with a diameter of 20 cm is used, which is one of the standard instruments at national meteorological stations in China. The pan coefficient was obtained by comparing the pan evaporation with the P–M method based reference evapotranspiration:

$$K_p = ET_{ref}/ET_{pan} \quad (3)$$

where ET_{ref} is the reference evapotranspiration (mm/day), K_p is the pan coefficient (dimensionless), and ET_{pan} the pan evaporation (mm/day).

Spatial interpolation

In this study, 11 commonly used interpolation methods were tested for their interpolation quality by the cross-validation method. The three best performed methods, Inverse Distance Weighted (Franke, 1982; Watson and Philip, 1985), Kriging with exponential variogram and Kriging with linear variogram, were selected for further testing on yearly interpolation of ET_{ref} , ET_{pan} and K_p . The correlation coefficients between the interpolated values of ET_{pan} , ET_{ref} and K_p and

Table 1 Comparison of interpolation quality of IDW (inverse distance weighted), Kriging (exponential) and Kriging (linear)

Methods	ET_{ref}	ET_{pan}	K_p
IDW	0.71	0.71	0.67
Kriging (exponential)	0.72	0.73	0.67
Kriging (linear)	0.73	0.73	0.67

Note: values in this table are correlation coefficients from the cross-validation tests.

the original values for the three best methods are shown in Table 1. The Kriging method with linear variogram was selected to use in the study for interpolating mean annual and mean seasonal values of the 150 stations into a grid of $0.25 \times 0.25^\circ$ in latitude and longitude since it has the highest correlation coefficient and is relatively simple.

Results and discussions

Spatial distribution of seasonal and annual reference evapotranspiration estimated by P–M method

The spatial distributions of seasonal and annual reference evapotranspiration are plotted in Fig. 3, which reflects a combined effect of all climatological factors. It can also be seen that the seasonal variations of the meteorological variables in different regions (see Fig. 2) caused the differences in the seasonal variations of ET_{ref} in different regions. In winter, the highest values are found in the southwest and lowest in the central part of the catchment. As can be seen in Fig. 2, the relative high net total radiation, wind speed and very low relative humidity are the main cause of the high ET_{ref} values in the upper region in the winter time. The low value in the central part as compared with lower part is mainly due to the low wind speed, since other three variables are similar as compared with the lower region (Fig. 2). In spring the spatial distribution of ET_{ref} is similar to that in the winter season, though the difference is smaller in most part of the catchment. The higher values found in the southwest region are due to relatively lower humidity and higher wind speed in the region, since, as can be seen from Fig. 2, the temperature in the upper region is lower and the net total radiation is similar as compared with other two regions. In summer the spatial distribution changes to a very different pattern where the highest values are found in the eastern part (lower region) while the lowest values in the western part (upper region). A clearly east-west gradient is shown, indicating the dominant role by the temperature and the net total radiation; while the difference in relative humidity is the smallest in the season. Compared with other seasons, autumn has a fairly homogeneous spatial distribution except at a few isolated points. The annual distribution has a rich spatial structure with a relatively low area in the central part of the catchment and high areas in southwest and southeast.

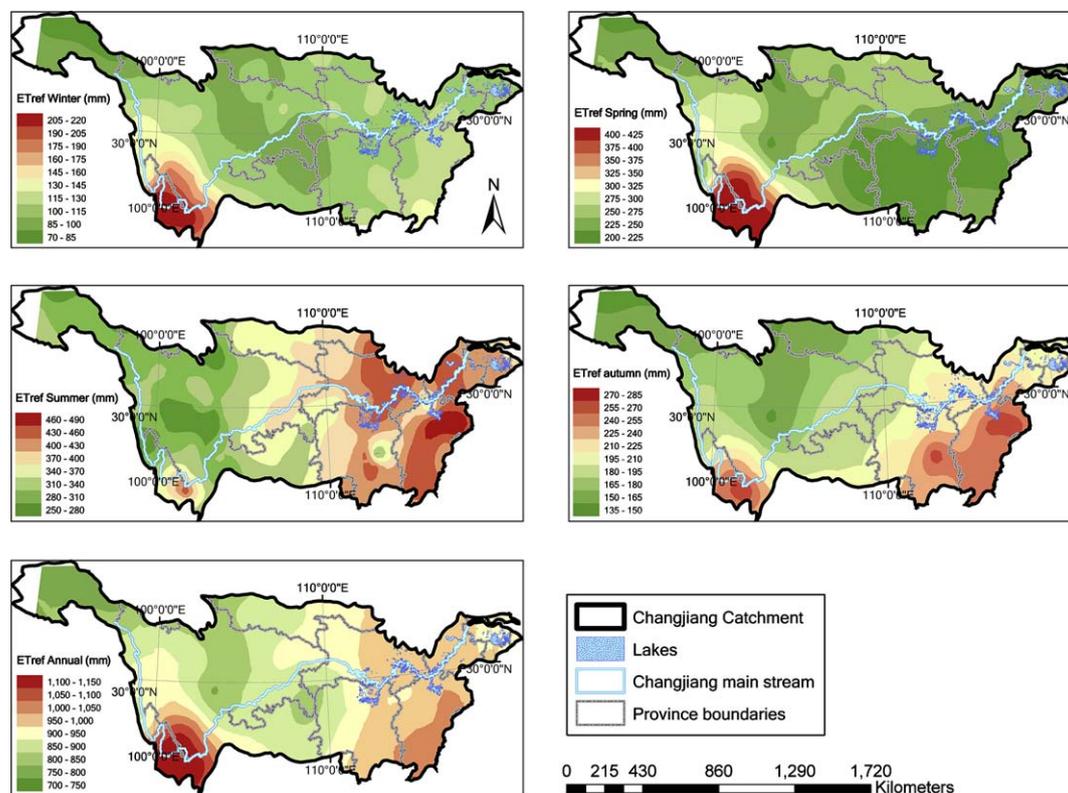


Figure 3 Spatial distribution of mean seasonal and annual reference evapotranspiration for the Changjiang catchment.

These spatial distribution maps provide valuable information in water resources planning and management in the catchment, since spatial distribution of annual and seasonal values of ET_{ref} is an important driving force in the hydrological cycle. In wet seasons it provides an upper limit for the actual evapotranspiration and in dry seasons and in dry areas it is an evaporative power for ET_a . Combining the spatial distribution maps of ET_{ref} with the spatial distribution of meteorological variables will provide an important background and physical interpolation for climate change studies in the region. Changing a meteorological variable in different seasons or areas will have a different effect on the reference evapotranspiration, and in turn, on the actual evapotranspiration and the hydrological cycle.

Spatial distribution of seasonal and annual pan evaporation

The spatial distribution of seasonal and annual pan evaporation is shown in Fig. 4. Comparing Figs. 4 and 3 it is clear that pan evaporation has a roughly similar spatial distribution pattern as has reference evapotranspiration and a consistent positive difference between pan evaporation and reference evapotranspiration exists over all different seasons and regions. Similar distribution patterns and systematic differences make pan measurements a suitable substitute for the reference evapotranspiration, provided that a proper correction factor (pan coefficient) is determined. In fact, this kind of measurements has been widely

used in hydrological applications (e.g., Guo et al., 2002). In addition, some other applications, such as water requirement estimate for a crop, require the reference evapotranspiration as defined by FAO. Therefore, a correction of the pan measurement by multiplying the pan coefficient would also be required in order to yield a better estimate of the reference evapotranspiration.

Spatial and temporal correlations of ET_{ref} and ET_{pan}

In order to quantify the spatial and temporal similarity and consistency between ET_{pan} and ET_{ref} , spatial and temporal correlations between the two were calculated. In Table 2 the results of spatial regression equations with ET_{ref} being the dependent variable and ET_{pan} being the independent variable are shown for each season. It is seen that good correlations exist for all the seasons; the negative intercepts and slope larger than unity indicate a positive bias between ET_{pan} and ET_{ref} . This is expected since pan measurements are made for the water surface of a small area. In Fig. 5 the spatial distribution of the temporal correlation coefficient is shown. It is obtained by first calculating the temporal correlation coefficient of annual time series of ET_{pan} and ET_{ref} at each station and then interpolating the coefficient to the whole catchment. The results show that seasonal (not shown) and annual correlation coefficients (Fig. 5) are all positive, which means that temporal variation in pan measurements follows that of the Penman–Monteith estimates. For most regions the correlations are fairly high, indicating that the pan measurement simulates the change in all relevant meteorological condi-

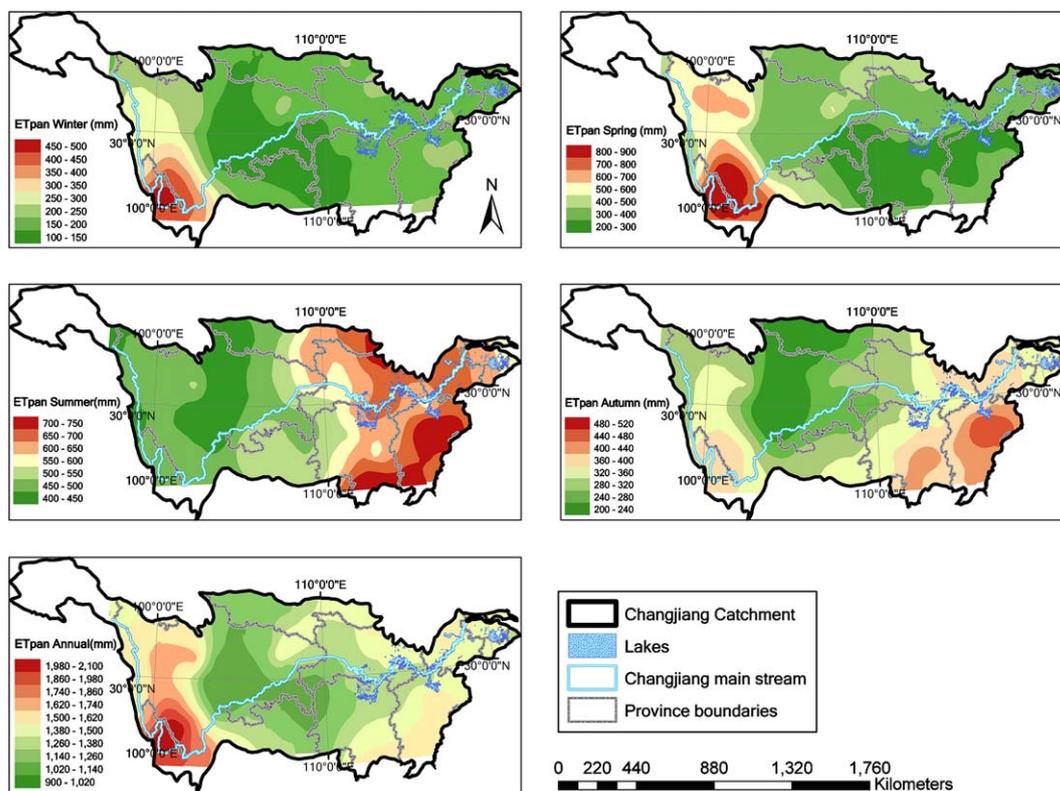


Figure 4 Spatial distribution of mean seasonal and annual pan evaporation for the Changjiang catchment.

Table 2 Regression relationships between pan evaporation and reference evapotranspiration

Season	Slope	Intercept	R^2
Winter	2.73	-120.13	0.79
Spring	3.11	-385.14	0.88
Summer	1.78	-98.19	0.78
Autumn	2.08	-91.53	0.76
Annual	2.36	-803.84	0.66

$ET_{ref} = \text{intercept} + \text{slope} \times ET_{pan}$.

tions fairly well. This may not be surprising, as pan evaporation measures the integrated effect of radiation, wind, temperature and humidity on evaporation from an open-water surface. The high correlation and a systematic difference provide the pan coefficient with a physical base. Lower val-

ues of the correlation coefficient between reference evapotranspiration and pan evaporation in the upper region of the catchment confirms the finding of Brutsaert and Parlange (1998) that "in non-humid environments, measured pan evaporation is not a good measure of potential evaporation".

Spatial distribution of seasonal and annual pan coefficients

Although the spatial variation of the reference evapotranspiration and pan evaporation has roughly a similar pattern, the K_p values, the ratio of reference evapotranspiration to pan evaporation, are not a constant over space and season (Fig. 6). Unlike the cases for ET_{ref} and ET_{pan} (Figs. 3 and 4) where a clear difference of the spatial variation of seasonal reference evapotranspiration and pan evaporation values is shown, the spatial variations of the seasonal K_p values

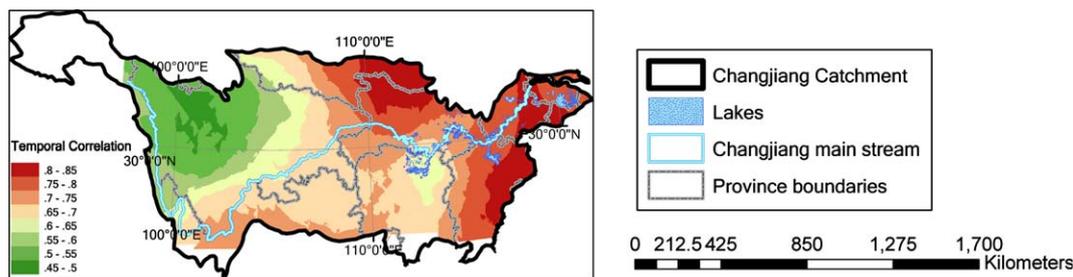


Figure 5 Spatial variation of the temporal correlation coefficient between (yearly time series of) reference evapotranspiration and pan evaporation.

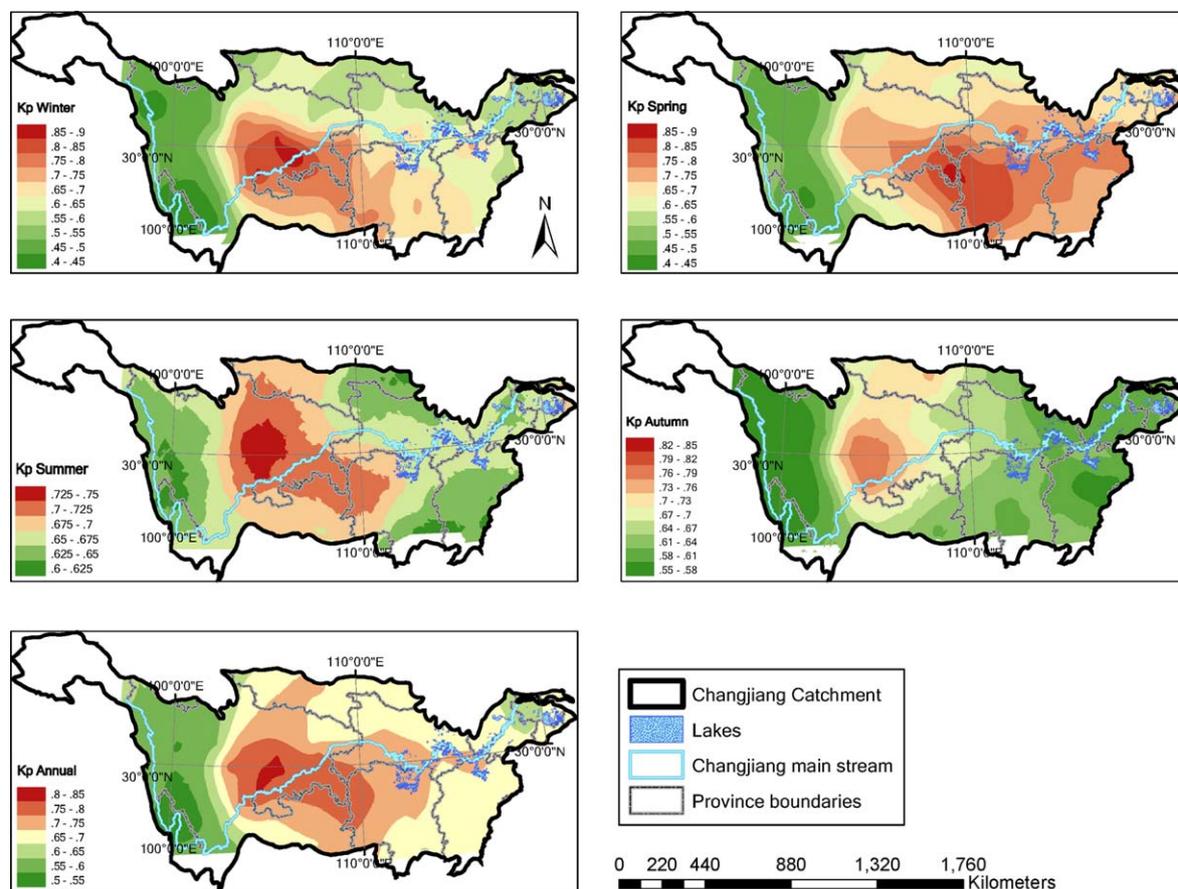


Figure 6 Spatial distribution of seasonal and annual pan coefficient, K_p for the whole catchment.

are quite similar for all the seasons, where the lowest values are in the south-west part of the catchment (which means a bigger relative difference between ET_{ref} and ET_{pan}), the highest values are in the central area (means a smaller relative difference between ET_{ref} and ET_{pan}), and the eastern part (lower reach) of the river catchment has a middle range. As a whole, the ratio varies between 0.51 and 0.94 for the basin with an average of 0.69 and a standard deviation of 0.089 values.

The spatial variations of annual and seasonal K_p values clearly reflect the physical characteristics of the pan coefficient. According to FAO (Allen et al., 1998), the variation of pan coefficient depends on: (1) the type of the pan used; (2) the pan environment (fallow or cropped area); (3) the climate (humidity and wind speed). The K_p value is high (low) if: (1) the pan is placed in a fallow area (cropped area); (2) the humidity is high (low); (3) the wind speed is low (high). The higher value of K_p in the central area of the catchment is due to, as can be seen from Fig. 2, the fact that the central area has a relatively high humidity (as compared with upper area) and a very low wind speed (as compared with other areas).

For illustrative purposes, the monthly variation of the K_p values in the catchment is plotted in Fig. 7 for the three regions. It is seen that: (1) the seasonal variation of the K_p values is the biggest in the upper region of the catchment, with the smallest value of 0.50 being in winter to 0.70 being in summer; (2) the variation of the K_p values in

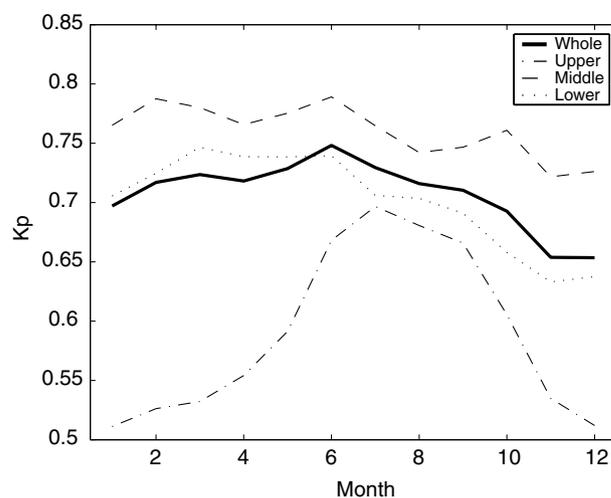


Figure 7 Monthly variation of pan coefficient, K_p for the upper, middle, lower regions of the catchment as well as the mean value for the whole catchment.

the middle and lower regions of the catchment have a similar pattern, but in the lower region the K_p values are smaller than those in the middle region by approximately 0.1; (3) for the average of the catchment, the mean monthly K_p values vary from about 0.66 in December to 0.74 in June. The spatially interpolated seasonal K_p values will be used in the

following studies to convert the pan evaporation measurements into reference evapotranspiration in places where there are no meteorological data available for calculating reference evapotranspiration.

Trend analysis of mean annual ET_{ref} , ET_{pan} , K_p and main meteorological variables for the whole catchment

The time series of annual ET_{ref} , ET_{pan} and K_p from 1960 to 2000 averaged over the whole catchment are plotted in Fig. 8. A decreasing trend is clearly seen for ET_{ref} and ET_{pan} (Fig. 8(a) and (b)). In order to test the significance of the trend existing in the ET_{ref} and ET_{pan} series, both parametric T -test and non-parametric Mann–Kendall test

(Kendall, 1975; Mann, 1945) are performed. The parametric test consists of two steps, fitting a linear simple regression equation with the time t as independent variable and the meteorological variable, Y as dependent variable (in this case the evapotranspiration), and testing the statistical significance of the slope of the regression equation. The basic principle of the Mann–Kendall method is to test the significance of Kendall’s tau and the procedure is presented in many standard statistical books (e.g., Helsel and Hirsch, 1992).

The results of trend analysis of the pan evaporation and the reference evapotranspiration are shown in Table 3 (row 1 and row 2). It is seen that the hypothesis of no trend is rejected by both parametric T -test and the nonparametric Mann–Kendall tau test. In other words, the decreasing

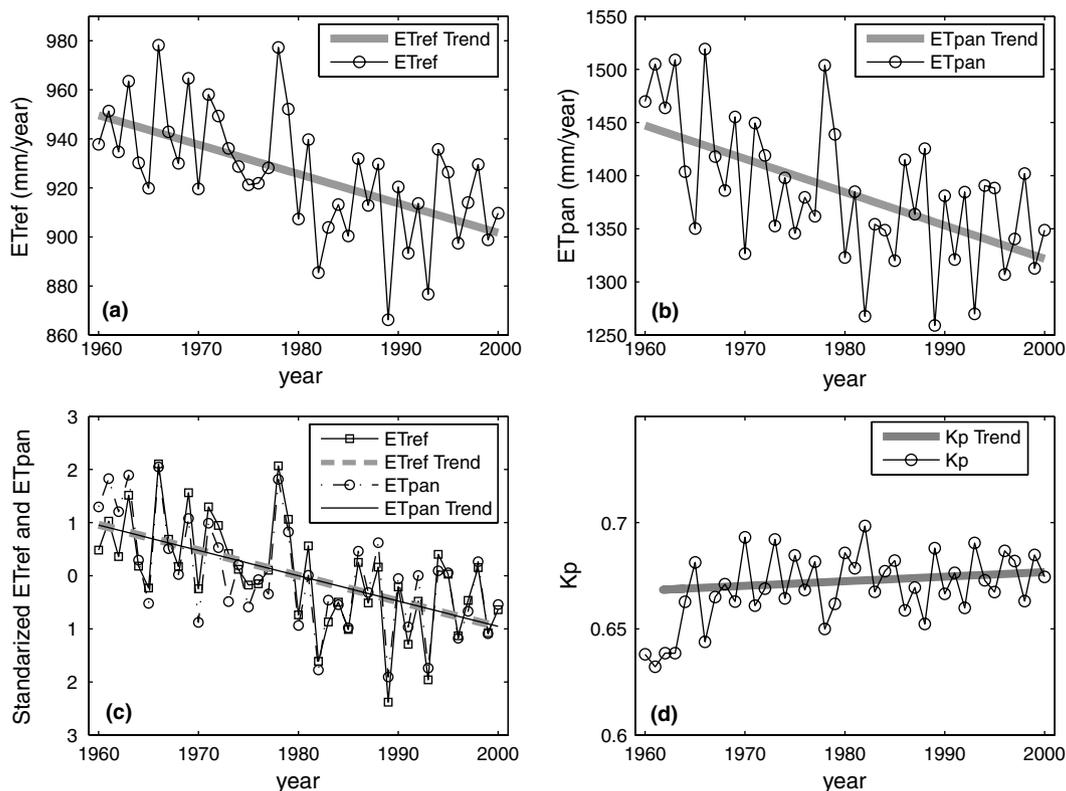


Figure 8 Inter-annual variation of the pan evaporation (a), the reference evapotranspiration (b), standardized ET_{pan} and ET_{ref} (c), and the K_p (d) for the catchment for the period 1960–2000.

Table 3 Test the trend for ET_{ref} , ET_{pan} , K_p and other meteorological variables

No.	Variable	Parametric T -test				Nonparametric Mann–Kendall test			
		Slope	T	T_c	H_0	Kendall’s Tau	Z	Z_c	H_0
1	ET_{ref}	−1.24	−4.02	2.02	R	−0.39	−3.54	1.96	R
2	ET_{pan}	−3.09	−4.27	2.02	R	−0.38	−3.47	1.96	R
3	K_p	2.1E-4	1.19	2.02	N.R.	0.12	1.01	1.96	N.R.
4	Air temperature	0.01	2	2.02	N.R.	0.16	1.47	1.96	N.R.
5	Wind speed	−0.01	−12.14	2.02	R	−0.74	−6.77	1.96	R
6	Relative humidity	0	0.85	2.02	N.R.	0.07	0.66	1.96	N.R.
7	Net Solar radiation	−0.01	−6.46	2.02	R	−0.54	−4.93	1.96	R

Note: H_0 , no trend; R, reject; N.R., not reject; $T_c = t_{\alpha/2, n-2}$ and $Z_c = Z_{\alpha/2}$ and $\alpha = 5\%$ significance level.

tendency of ET_{ref} and ET_{pan} is significant at the 5% significance level. The slope value shown in Table 3 reflects the amount of evaporation decreasing per year and the larger slope value for ET_{pan} as compared with that of ET_{ref} is due to the fact that the values of ET_{pan} are larger than ET_{ref} . As can be seen in Fig. 8(c) the slopes for ET_{pan} and ET_{ref} are actually the same when standardized values are plotted together. Fig. 8(d) and Table 3 (row 3) show that there is no decreasing or increasing trend for K_p , except that the first four values of K_p are remarkably small which are caused by the relatively high values of ET_{pan} for the period. The reason for these outliers found in ET_{pan} is yet to be investigated in a future study.

The temporal trend detected in Fig. 8 and Table 3 reveals a combined effect of all the meteorological variables, of which all, except relative humidity, have a positive effect on ET. In order to analyze the main causes of the decreasing trend existing in the measured pan evaporation and the calculated reference evapotranspiration, the same trend analysis procedure is performed on the major meteorological variables that determine the magnitude of the evaporation values. The meteorological parameters that are examined include air temperature, relative humidity, wind speed and net total radiation. The results of the trend analysis of the meteorological variables are shown in Table 3 (rows 4–7). It is noted that both tests show that two out of four variables, i.e., wind speed and net total radiation have a significant decreasing trend over the past 41 years. Annual time series of the two are plotted in Fig. 9, which clearly shows a strong decreasing trend. As for the decreasing trend found in the net total radiation, previous studies have shown that the decrease in the global radiation (sunshine duration) is the most likely cause, which is a regional phenomenon. By examining the global total radiation measurements in eastern China, Zhang et al. (2004) came to the conclusion that the global total radiation is decreasing, which is due to the increased air pollution in the area. Another study by Liu et al. (2004) also found that unlike other

parts of the world, the decrease in solar irradiance in China was not always accompanied by an increase in cloud cover and precipitation. Therefore they speculate that aerosols may play a critical role in the decrease of solar irradiance in China. This study also shows that there is no increasing or decreasing trend in the relative humidity. The decreased wind speed is a complicated issue and has not been discussed in the literature. In our ongoing research, we are trying to explore the possible causes of the wind speed decrease by: (1) identifying and comparing the stations located in the city's centre and in rural areas; (2) comparing the observed wind speed with publicly available Reanalyses data sets (NCEP and/or ERA40) over the region and implying wind trends derived from these data (in relative terms) for the region or the sub-regions, etc. The results will be reported in the near future.

Quantitative estimation of the influence of net total radiation and wind speed on the decreasing trend in evapotranspiration

In order to quantify the contributions of net total radiation and wind speed to the decreasing trend of evapotranspiration, the following steps are performed: (1) removing the decreasing trend in wind speed and net total radiation to make them as stationary time series; (2) recalculating the reference evapotranspiration by using, in each time, the detrended data series for wind speed or net total radiation and using original data for other variables; (3) comparing the result with the original evapotranspiration and the difference is considered as the influence of the trend by that variable.

Simple linear regression method is again used to establish trends (Fig. 10(a) and (b)). The detrended series are also shown in figure. In Fig. 10(c) three lines are shown. It is seen from Fig. 10(c) that: (1) a large difference exists between the original reference evapotranspiration and the recal-

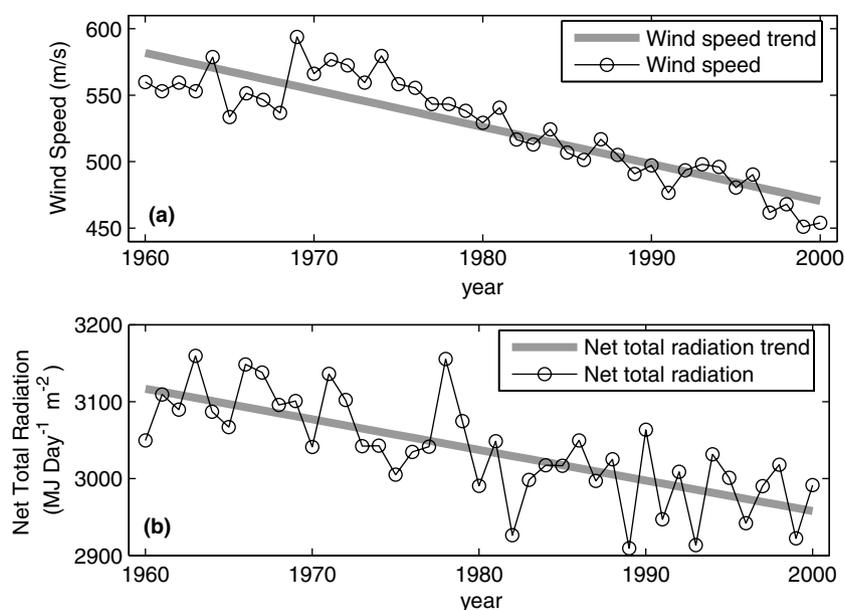


Figure 9 Annual variation of the wind speed (a) and the net total radiation (b) and their long term trends for the catchment.

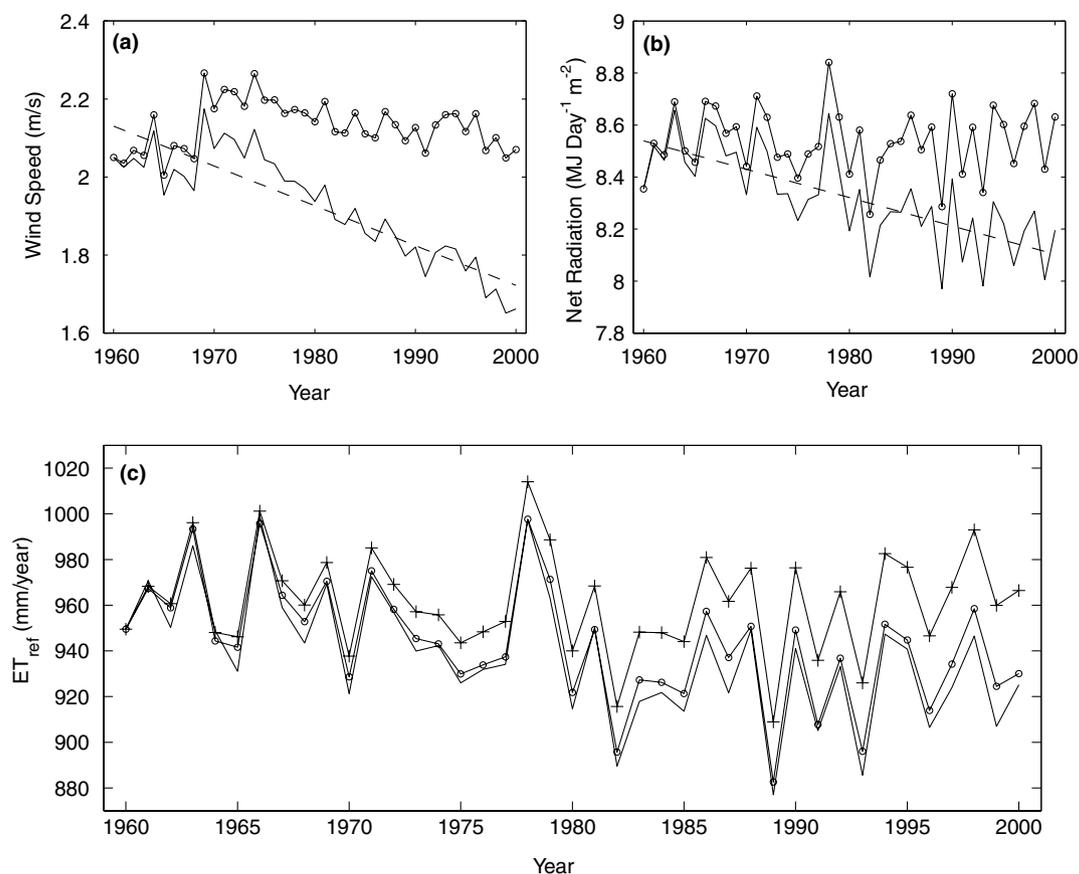


Figure 10 The plot of the original annual values, the trend and the recovered stationary series for wind speed (a) and net radiation (b), (c) shows the comparison of the original mean annual reference evapotranspiration with the recalculated evapotranspiration. The solid line at the bottom is the reference evapotranspiration calculated by using original data for all meteorological variables; the line with circle is the reference evapotranspiration calculated by using the wind speed data with trend removed and original data for other variables; and the line with cross is the reference evapotranspiration calculated by using the net radiation data with trend removed and original data for other variables.

lated evapotranspiration with detrended net total radiation; (2) a smaller but still remarkable difference is obtained between the original reference evapotranspiration and the recalculated evapotranspiration with detrended wind speed. This result reveals that the decreasing trend in the net total radiation is the main cause of the decreasing trend found in the reference evapotranspiration, while the decreasing trend in wind speed contributes to much a smaller magnitude.

Sensitivity of the reference evapotranspiration to meteorological variables

From Fig. 9 and Table 3 it is clear that decreasing trends in wind speed and net total radiation are significant at the 5% level, while Fig. 10 shows that the decrease in the net total radiation contributes most to the decreasing trend in the reference evapotranspiration. To better understand the result obtained in the previous sections, sensitivity analysis of the reference evapotranspiration to the meteorological variables is performed. A simple but practical way of sensitivity analysis is to calculate and plot the relative changes of an input variable against the resultant relative change of

the output variable as a curve (i.e., the 'sensitivity curve'), then the corresponding relative change of the outcome can easily be read from the sensitivity curve for a certain relative change of the variable. This method has been used by many authors (Paturel et al., 1995; Xu and Vandewiele, 1994; Goyal, 2004).

In this study, seven scenarios are generated for each meteorological variable using the following equation:

$$X(t) = X(t) + \Delta X \quad \Delta X = 0, \pm 10\%, \pm 20\%, \pm 30\% \text{ of } X(t) \quad (4)$$

where X is the meteorological variable, and t is the time in day.

Fig. 11 shows the result of the sensitivity study. It is seen that the two most sensitive variables are relative humidity and net total radiation, followed by air temperature and wind speed. The combination of Fig. 11 and Table 3 explains the result in Fig. 10. For example, on one hand, the decreasing trend in wind speed is strongest among those in the four meteorological variables (Table 3). On the other hand, it is the least sensitive variable on the annual basis (Fig. 11). Thus its contribution to the decreasing trend in the reference evapotranspiration is much smaller than that from the net

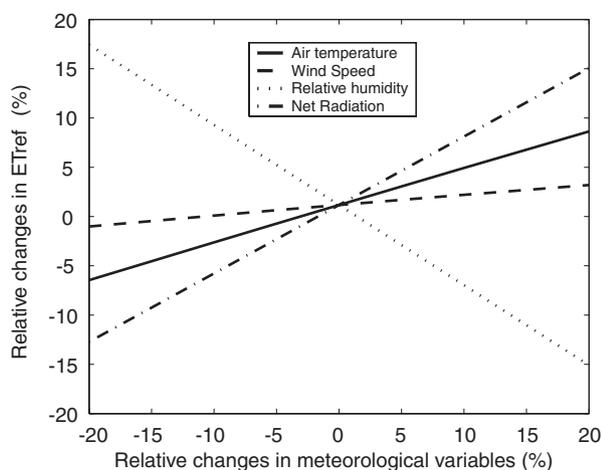


Figure 11 The sensitivity of the reference evapotranspiration to the four major meteorological variables.

total radiation (Fig. 10). Another example is that although relative humidity is the most sensitive variable, it has no contribution to the decreasing trend in the reference evapotranspiration, because the relative humidity over the whole catchment has no significant decreasing or increasing trend (regression slope equals zero in Table 3). The net total radiation is the main cause of the decreasing trend in the reference evapotranspiration because it is not only one of the most sensitive variables (Fig. 11), but also a variable with significant decreasing trend (Fig. 9 and Table 3).

Summary and conclusions

In this study, we evaluated and compared reference evapotranspiration, pan evaporation and pan coefficient for the Changjinag (Yangtze River) catchment. Daily meteorological data from 1960 to 2000 for 150 standard meteorological stations were used in the investigation. By comparing the reference evapotranspiration calculated by the P–M method with the pan measurement, the monthly, seasonal and annual pan coefficients were obtained for each station and then interpolated for the catchment.

The following conclusions may be drawn from the study: (1) the reference evapotranspiration and pan evaporation have similar regional distribution patterns in the catchment both with the highest values being in the upper region of the catchment and the lowest values being in the middle region. This distribution pattern provides valuable information for regional hydrological studies since it is one of the most important factors determining regional actual evapotranspiration, which, in turn, is a key parameter in regional water resources assessment and water management. In the humid region reference evapotranspiration is the upper boundary for actual evapotranspiration, while in the arid area it is a drying force for the actual evapotranspiration; (2) for the whole catchment, there is a significant and similar decreasing trend in the reference evapotranspiration and pan evaporation. The main cause of this decreasing trend is the net total radiation followed by wind speed both having a significant decreasing trend in the region for the study period; (3) the pan coefficient, K_p , varies both regionally and seasonally.

Smallest K_p values are found in the upper reach (western part) of the basin, meaning that the relative difference between the reference evapotranspiration and pan evaporation is the biggest in the region, the largest K_p values are obtained in the central area of the catchment. As discussed earlier, this spatial variation pattern is determined by the spatial variation of the wind speed and relative humidity in the catchment since other factors (pan type, measurement environment) influencing K_p values are the same; (4) sensitivity analysis shows that the most sensitive variable for the reference evapotranspiration is the relative humidity followed by the net total radiation, air temperature and wind speed. The actual contribution of each variable to the decreasing trend in the reference evapotranspiration and pan evaporation is a combined effect of the sensitivity of evapotranspiration to the variable and the actual temporal change of the variable. In the Changjiang catchment, the most important predictor for the decreasing trend in the reference evapotranspiration and pan evaporation is the net total radiation followed by wind speed; since they are not only sensitive variables in determining ET_{ref} and ET_{pan} , but also decreasing significantly in the catchment. Recent studies (Zhang et al., 2004; Liu et al., 2004) have shown that the decreasing trend in the net total radiation is mainly due to increased air pollution in the area, which is a regional phenomenon. The reason for the decreasing trend in wind speed is yet to be quantified in a future study.

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