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Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin

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Summary Sensitivity analysis is important in understanding the relative importance of climatic variables to the variation of reference evapotranspiration (ET_{ref}). In this study, a non-dimensional relative sensitivity coefficient was employed to predict responses of ET_{ref} to perturbations of four climatic variables in the Changjiang (Yangtze River) basin. ET_{ref} was estimated with the FAO-56 Penman–Monteith equation. A 41-year historical dataset of daily air temperature, wind speed, relative humidity and daily sunshine duration at 150 national meteorological observatory stations was used in the analysis. Results show that the response of ET_{ref} can be precisely predicted under perturbation of relative humidity or shortwave radiation by their sensitivity coefficients; the predictive power under perturbations of air temperature and wind speed depended on the magnitude of the perturbation, season and region. The prediction errors were much smaller than the seasonal and regional variation of their sensitivity coefficients. The sensitivity coefficient could also be used to predict the response of ET_{ref} to co-perturbation of several variables. The accuracy of the prediction increases from the lower to the upper region. Spatial variations of long-term average monthly and yearly sensitivity coefficients were obtained by interpolation of station estimates. In general, relative humidity was the most sensitive variable, followed by shortwave radiation, air temperature and wind speed. The actual

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rank of the four climatic variables in terms of their sensitivity varied with season and region. The large spatial variability of the sensitivity coefficients of all the climatic variables in the middle and lower regions of the basin was to a large extent determined by the distinct wind-speed patterns in those two regions.

Introduction

Reference evapotranspiration (ET_{ref}), defined as the potential evapotranspiration of a hypothetical surface of green grass of uniform height, actively growing and adequately watered, is one of the most important hydrological variables for scheduling irrigation systems, preparing input data to hydrological water-balance models, and calculating actual evapotranspiration for a region and/or a basin (Blaney and Criddle, 1950; Dyck, 1983; Hobbins et al., 2001a,b; Xu and Li, 2003; Xu and Singh, 2005). ET_{ref} is a measure of the evaporative demand of the atmosphere independent of crop type, crop development and management practices. Only climatic factors affect ET_{ref}. Consequently, ET_{ref} is a climatic parameter and can be computed from meteorological data (Allen et al., 1998). Different categories of methods have been developed in attempts to model ET_{ref}, including (Xu and Singh, 2002): (1) water budget (e.g., Guitjens, 1982), (2) mass-transfer (e.g., Harbeck, 1962), (3) combination (e.g., Penman, 1948), (4) radiation (e.g., Priestley and Taylor, 1972), and (5) temperature-based (e.g., Thornthwaite, 1948; Blaney and Criddle, 1950) equations. The Penman—Monteith (P—M) method is recommended by FAO as the sole method to calculate reference evapotranspiration wherever the required input data are available (e.g., Allen et al., 1998; Droogers and Allen, 2002). The FAO method is a physically-based approach that can be used globally without any need for additional adjustments of parameters. Xu et al. (2006a,b) and Chen et al. (2005) studied the Penman—Monteith ET_{ref} in the Changjiang basin in detail and found that the spatial pattern and temporal trend of ET_{ref} agreed with pan evaporation.

A major drawback to apply the P—M method is its relatively high data demand. The method requires, apart from site location, air temperature, wind speed, relative humidity, and shortwave radiation data. The number of meteorological stations where all of these parameters are observed is limited in many areas of the globe. The number of stations where reliable data for these parameters exist is even smaller, especially in developing countries (Droogers and Allen, 2002). A sensitivity analysis of ET_{ref} to perturbations (all sorts of data errors or, actual climatic changes) associated with one or more climatic variables is important to improve our understanding of the connections between climatic conditions and ET_{ref} variability, and between data availability and estimation accuracy of ET_{ref}.

Studies on regional and seasonal behaviour of the sensitivity of reference evapotranspiration to climatic variables are rare in the literature, and no study has been done for the Changjiang basin. A recent study of the sensitivity of ET_{ref} was reported by Hupet and Vanclooster (2001) at a single station in a moderate humid climatic zone in Belgium. Because of different approaches used in parameterising ET models, there are different definitions of the sensitivity coefficients and the different spatial-temporal scales in previous studies (e.g., McCuen, 1974; Saxton, 1975; Coleman and DeCoursey, 1976; Beven, 1979; Ley et al., 1994; Rana and Katerji, 1998; Qiu et al., 1998). This makes it difficult to compare literature results. In addition, these studies are often suffering from sparse station data and limited temporal coverage. Thus, a common framework for sensitivity analysis of ET_{ref} with long-term spatially dense dataset would be useful in connecting the spatial variability of sensitivity with regional climate conditions. The aim of the present study was to provide reliable sensitivity coefficients of ET_{ref} for the Changjiang basin based on meteorological data of 150 National Meteorological Observatory (NMO) stations for the period 1960—2000. This paper presents results of an on-going study of the impact of climate change on floods in the Changjiang (Yangtze River) basin in China. The ongoing and planed research 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 basin by using the complementary-evaporation approach (Xu and Singh, 2005) and water-balance models, investigation of effects of changes in evapotranspiration on flooding and the hydrological cycle in the region. ET_{ref} provides a measure of the integrated effect of radiation, wind, temperature and humidity on evapotranspiration. In humid climate, reference evapotranspiration provides an upper limit for actual evapotranspiration and in an arid climate it indicates the total available energy for actual evapotranspiration. Quantitative estimation of the effect of different meteorological variables on reference evapotranspiration is also an important step in studying the impact of climate change on evapotranspiration and water-balance components.

Study area, data and method

The Changjiang basin

The Changjiang River is about 6380 km long with a drainage area of 1.8×10^6 km^2 (Fig. 1). Originating from the Tibetan Plateau, the terrain of the basin is shaped like a ladder with three stairs. The Qinghai-Tibet Plateau in the west, the highest stair, has an average elevation of over 3000 m above sea level; the second stair, where the Sichuan basin is located, has an average elevation of 1000 m; the third stair in east China Plain has an average elevation of about 100 m. In this study, the basin is divided into three sub-regions that correspond to the three stairs, the upper the middle and the lower regions, respectively. The classification of the upper, middle and lower regions of the basin in this

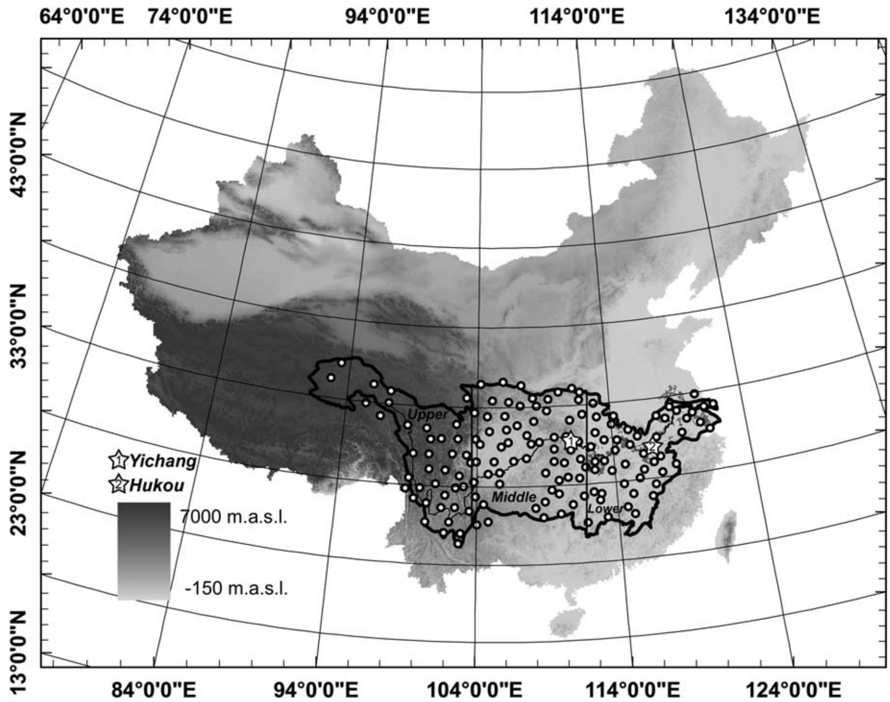

Figure 1 Location of the Changjiang (Yangtze River) basin and the meteorological stations used in this study (white dots).

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 million km^2 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 km^2. The remaining part from Hukou to the estuary is called the Lower Reach, 938 km long with a catchment area of 120,000 km^2.

Meteorological stations

A data set of 150 National Meteorological Observatory stations (Fig. 1) with daily observations of maximum, minimum and average air temperature at 2 m height, wind speed measured at 10 m height, relative humidity (2 m height) and daily sunshine duration for the period 1960–2000 was used in this study. Data were provided by the National Climatic Centre (NCC) of China Meteorological Administration (CMA). The wind-speed measurements were transformed to wind speed at 2 m height by the wind profile relationship introduced in Chapter 3 of the FAO paper 56 (Allen et al., 1998). The Changjiang basin climate is characterised by (1) a seasonal variation of relative humidity in the upper region that is much greater than those in the 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 highest shortwave radiation is in May in the upper region, and in July in the other two regions; (4) the upper region is distinct from the rest in its significantly lower temperature and relative humidity. The major difference between the middle and the lower regions is that the latter has a significantly higher wind speed (Fig. 2).

Penman–Monteith reference evapotranspiration and the sensitivity coefficient

The FAO Penman–Monteith method

The P–M method for calculating daily reference evapotranspiration (Allen et al., 1998) is:

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

where: $\mathrm{ET_{ref}}$ is reference evapotranspiration (mm day^{-1}), R_n net radiation at the crop surface (MJ m^{-2} day^{-1}), G soil heat flux (MJ m^{-2} day^{-1}), T_A average daily air temperature at 2-m height (°C), u_2 wind speed at 2-m height (m s^{-1}), e_s saturation vapor pressure (kPa), e_A actual vapor pressure (kPa) and $(e_s - e_A)$ saturation vapor pressure deficit (kPa), Δ is slope of the saturated water–vapor-pressure curve (kPa °C^{-1}), and γ is psychrometric constant (kPa °C^{-1}). The computation of all 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).

Original measurements of air temperature (TA), wind speed (WD), and relative humidity (HD) were chosen for sensitivity analyses. The forth variable that was analysed is shortwave radiation (*RS*). This is because shortwave radiation is one of the input variables in a number of semi-physical and semi-empirical equations that are used to derive the net energy flux required by the Penman method. Following the procedure described by Allen et al. (1998), *RS* can be estimated with the Angstrom formula that relates surface shortwave radiation to extraterrestrial radiation and daily sunshine duration:

$$RS = \left(a_s + b_s\frac{n}{N}\right)R_a \quad (2)$$

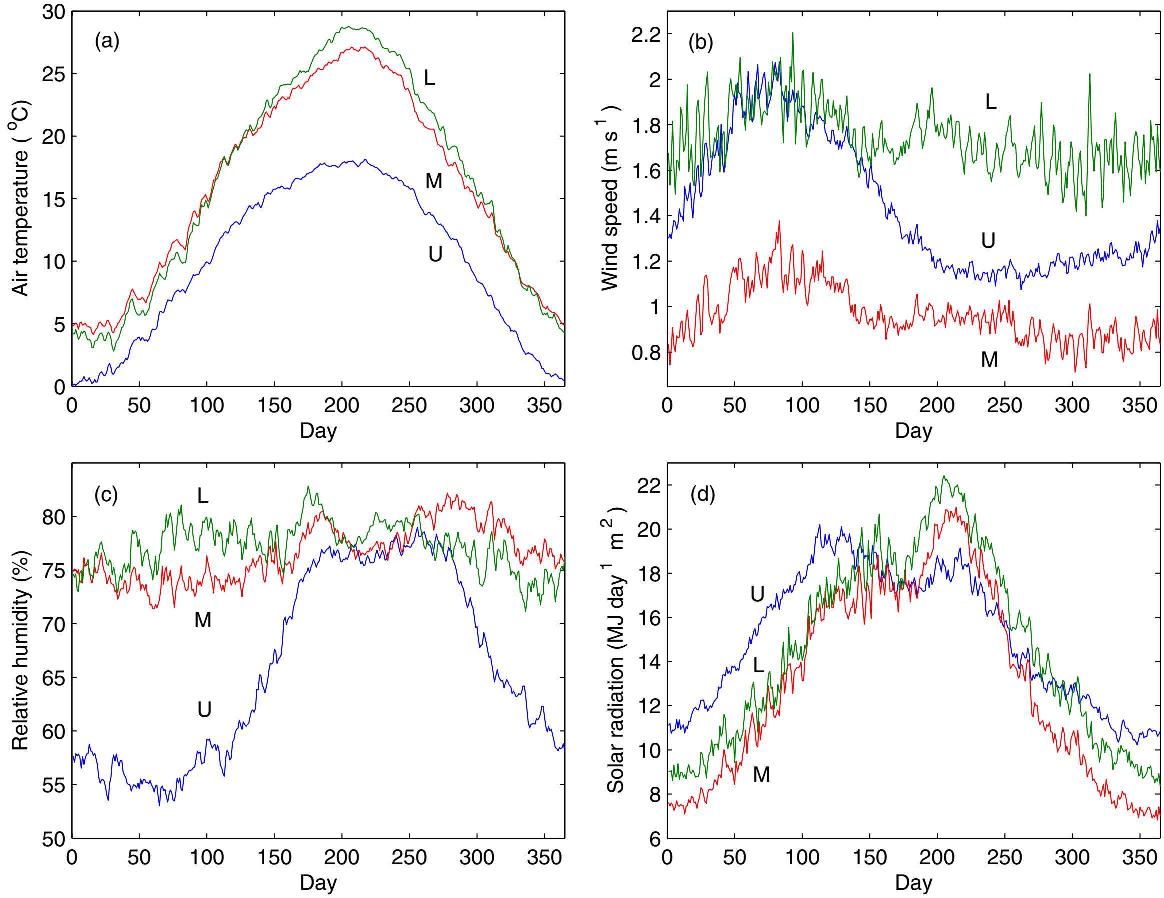

Figure 2 Mean daily variations of the major climatic variables in the upper (U), middle (M) and lower regions (L) of the Changjiang basin.

where RS is solar or shortwave radiation (MJ m^{-2} day^{-1}), n is daily sunshine duration (h), N is maximum possible duration of sunshine or daylight hours (h), n/N is relative sunshine duration, R_a is extraterrestrial radiation (MJ m^{-2} day^{-1}), a_s and b_s are regression constants. The recommended values $a_s = 0.25$ and $b_s = 0.50$ were used in this study.

The sensitivity coefficients

In evaporation studies (e.g., McCuen, 1974; Saxton, 1975; Coleman and DeCoursey, 1976; Beven, 1979), as well as in other hydrological (e.g., Anderton et al., 2002) and ecological (e.g., Beres and Hawkins, 2001) applications, a number of sensitivity coefficients have been defined depending on the purpose of the analyses. A simple but practical way of presenting a sensitivity analysis is to plot relative changes of a dependent variable against relative changes of an independent variables as a curve (e.g., McKenney and Rosenberg, 1993; Singh and Xu, 1997; Goyal, 2004), denoted as the ''*sensitivity curve* method'' in the following text. More often, however, a mathematically defined *sensitivity coefficient* (e.g., McCuen, 1974; Saxton, 1975; Coleman and DeCoursey, 1976; Beven, 1979; Rana and Katerji, 1998; Qiu et al., 1998; Hupet and Vanclooster, 2001) is used to characterise sensitivity. For multi-variable models (e.g., the P—M method), different variables have different dimensions and different ranges of values, which makes it difficult to compare the sensitivity by partial derivatives. Consequently, the partial derivative is transformed into a non-dimensional form (e.g., Beven, 1979):

$$S_{V_i} = \lim_{\Delta V_i \to 0} \left(\frac{\Delta \mathrm{ET_{ref}}/\mathrm{ET_{ref}}}{\Delta V_i/V_i} \right) = \frac{\partial \mathrm{ET_{ref}}}{\partial V_i} \cdot \frac{V_i}{\mathrm{ET_{ref}}} \quad (3)$$

S_{V_i} is sensitivity coefficient and V_i is the ith variable. The transformation that gives the ''non-dimensional relative sensitivity coefficient'' (denoted as ''*sensitivity coefficient*'' in the following text), was first adopted by McCuen (1974) and is now widely used in evapotranspiration studies (e.g., Coleman and DeCoursey, 1976; Beven, 1979; Rana and Katerji, 1998; Qiu et al., 1998; Hupet and Vanclooster, 2001). Basically, a positive/negative sensitivity coefficient of a variable indicates that $\mathrm{ET_{ref}}$ will increase/decrease as the variable increases. The larger the sensitivity coefficient, the larger effect a given variable has on $\mathrm{ET_{ref}}$. In graphical form, the sensitivity coefficient is the slope of the tangent at the origin of the sensitivity curve. Practically, the coefficient is accurate enough to represent the slope of the sensitivity curve within a certain ''linear range'' around the origin. The width of the range depends on the degree of non-linearity of the sensitivity curve. If a sensitivity curve is linear, the sensitivity coefficient is able to represent the change in $\mathrm{ET_{ref}}$ caused by any perturbation of the variable concerned. A sensitivity coefficient of 0.2 for a variable would in this case mean that a 10% increase of that variable, while all other variables are held constant, may increase ET_{ref} by 2%. If the sensitivity curve is significantly non-linear, the predictive power of the sensitivity coefficient will be limited to small perturbations only.

Sensitivity coefficients were calculated on a daily basis for air temperature, wind speed, relative humidity and shortwave radiation. Monthly and yearly average sensitivity coefficients were obtained by averaging daily values. Representative regional sensitivity coefficients were obtained by averaging station values. Spatial patterns of monthly and yearly sensitivity coefficients were obtained by interpolating station values to the whole basin in ArcGIS. The partial derivatives, needed for the determination of the sensitivity coefficients, were calculated analytically by means of symbolic calculation of Matlab™. The analytical expressions can be found in the online supplementary materials alongside the electronic version of the article.

The transmitting curve and the predictive power of sensitivity coefficients

The predictive power of sensitivity coefficients may be limited by the non-linearity of the sensitivity curve. It is thus useful to provide the sensitivity coefficients together with their predictive power. The predictive power of the coefficients was studied by a simple transformation of the sensitivity curve. Each point on the sensitivity curve relates the relative change of a climatic variable to ET_{ref}. The transformation was done by dividing each point on the sensitive curve, except at the origin, by its x-coordinate. If the sensitivity curve has the form $y = f(x)$, the resulting curve has the form $y' = f(x)/x$. Each point on the resulting curve (defined as the transmitting curve) relates the relative change of a climatic variable (x-coordinate) to a ''transmitting factor'' (y-coordinate). By multiplying the relative change of the climatic variable and its transmitting factor, the relative change of ET_{ref} was obtained. The origin of the transmitting curve, which was left blank in the transformation, can be filled by the sensitivity coefficient S_{V_i}. The transmitting factor, which is a function of the magnitude of perturbation itself, transmits perturbation of climatic variables to changes in ET_{ref} in a more precise way than the sensitivity coefficients themselves. At the same time, the flatness of the transmitting curve provides a direct way of measuring the predictive power of the sensitivity coefficients. The flatter the transmitting curve, the more representative the sensitive coefficient becomes, and therefore the larger its predictive power.

The predictive power of the sensitivity coefficient for each meteorological variable was examined for each station and each month (obtained by averaging daily values), under a one-at-a-time perturbation (i.e., one variable was changed while all others were held constant). It is well established in sensitivity studies that significant effects can be produced by a pair of variables acting in concert (Burgman et al., 1993). Such combined effects can be larger than the sum of the individual effects of the two variables. However, the applications of the sensitivity coefficient in evaporation studies are always limited in the ''one-at-a-time'' case. Perturbations of more than one variable are likely to happen at the same time in real life. In this work, the predictive power of sensitivity coefficients for co-perturbation of all climatic variables was tested in three climatically distinct regions of the Changjiang basin. A Monte-Carlo simulation based on the definition of the sensitivity coefficient (S_{V_i}) was implemented for this purpose. The test simulation consisted of four steps: (1) Perturbated climatic data were generated. For each of the 150 stations, 100 random perturbation scenarios were generated for TA, WD, HD and RS, respectively. The range of perturbation was between (−20%, 20%) for each variable; (2) In each scenario, the actual response of ET_{ref} was obtained by recalculating ET_{ref} using the perturbed data with the Penman–Monteith equation; (3) The predicted change in ET_{ref} was calculated by summing up the sensitivity-coefficient-estimated perturbation of ET_{ref}, i.e.,

$$\left(\frac{\Delta ET_{ref}}{ET_{ref}}\right) \cong \left(\frac{\Delta TA}{TA}\right)\cdot S_{TA} + \left(\frac{\Delta WD}{WD}\right)\cdot S_{WD} + \left(\frac{\Delta HD}{HD}\right)\cdot S_{HD} + \left(\frac{\Delta RS}{RS}\right)\cdot S_{RS} \quad (4)$$

(4) The 100 pairs of actual and estimated responses of ET_{ref} were plotted for each station and their coefficients of determination (R^2) were calculated.

Results

Daily variation of the sensitivity coefficients

Daily sensitivity coefficients exhibit large fluctuations during the year (Fig. 3). The same feature has also been reported by Hupet and Vanclooster (2001). Daily variation patterns of S_{TA} agree with those of air temperature. ET_{ref} is insensitive to TA in winter and the sensitivity gradually increases and achieves its maximum value in summer (Fig. 3a). ET_{ref} is significantly less sensitive to air temperature in the upper region compared to the other two regions throughout the year. For the middle and lower regions, the sensitivity is similar in winter and early spring, but it achieves a much higher value in summer in the lower region. The similar patterns of S_{TA} and TA indicate that TA determines the extent of the seasonal variation of S_{TA}. Fig. 3b shows that ET_{ref} is most sensitive to wind in winter time. Relatively strong negative sensitivity coefficients were obtained for relative humidity (Fig. 3c). There was also a considerable difference among the three sub-regions. Strong negative sensitivity coefficients indicated that increases in relative humidity greatly reduce the evapotranspiration potential. Similar results are obtained in previous studies, where relative humidity is a major limiting factor. Zeng and Heilman (1997) conclude that the impact of climate change may be minimal if warming is accompanied by higher humidity. Daily variation patterns of S_{RS} were very similar throughout the basin; minimum and maximum values were found in winter and summer, respectively (Fig. 3d). Like air temperature, the sensitivity coefficient for shortwave radiation also showed a pronounced seasonal cycle, similar to the seasonal cycle of the measured shortwave radiation. A decrease in the energetic term appeared to be associated with an increased significance of the aerodynamic term, which led to the decrease of the sensitivity coefficients for the shortwave radiation corresponded to an increase in the sensitivity coefficient for the wind speed at the end of

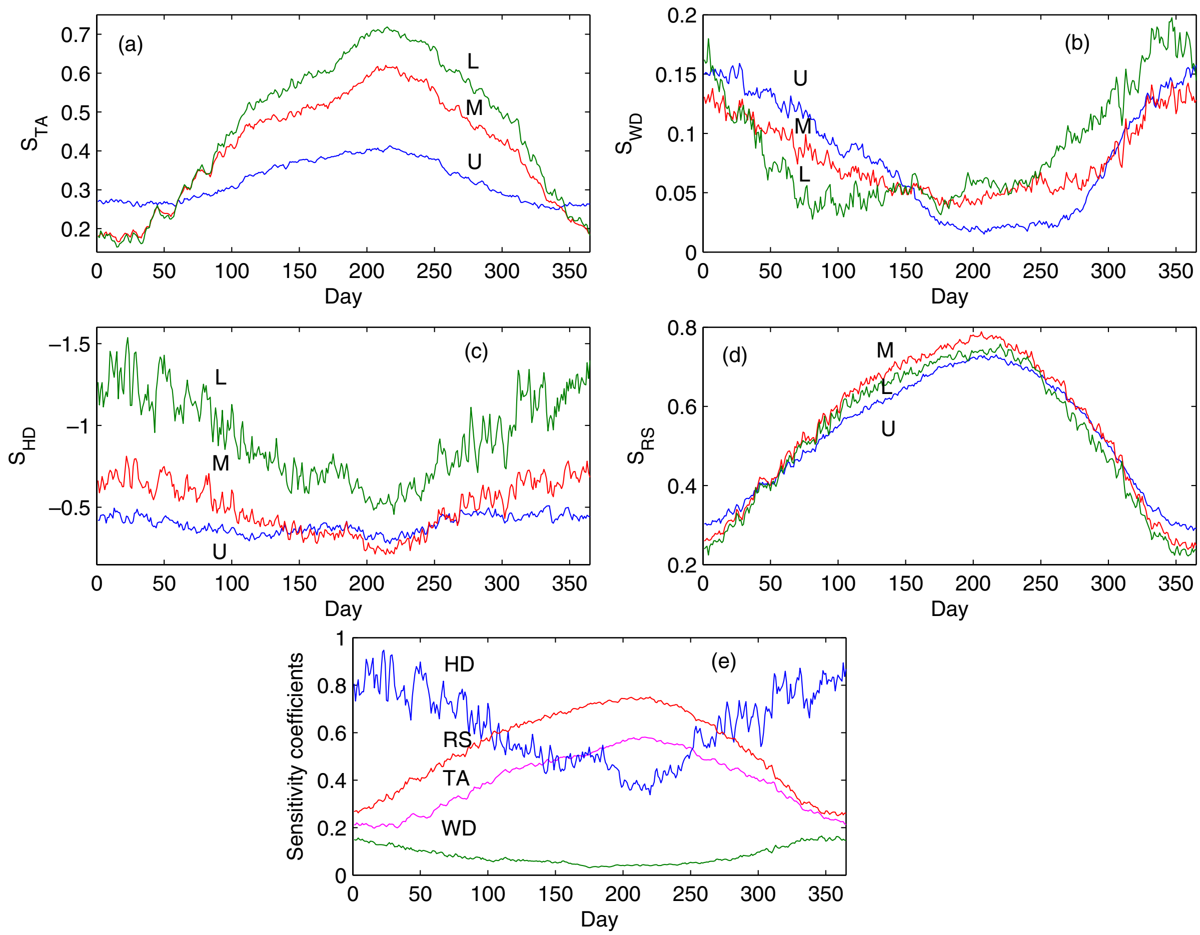

Figure 3 Mean daily sensitivity coefficients for air temperature (S_{TA}) (a), wind speed (S_{WD}) (b), relative humidity (S_{HD}) (c) and shortwave radiation (S_{RS}) (d) in the upper (U), middle (M) and lower (L) regions of Changjiang basin. (e) Comparison of mean daily sensitivity coefficients for major climatic variables in the whole Changjiang basin (S_{HD} is multiplied by -1 to facilitate visual comparison).

the year. Similar findings were reported elsewhere (Saxton, 1975; Beven, 1979; Rana and Katerji, 1998; Hupet and Vanclooster, 2001). S_{TA} and S_{RS} had a similar pattern while opposite patterns were found for S_{HD} and S_{WD}. In general, relative humidity was the most sensitive variable at the daily scale. In winter, a 10% change in HD could cause approximately a 15% change in ET_{ref} in the lower region. Shortwave radiation and air temperature were less influential to ET_{ref}, and their sensitivities were similar to each other. Similarly to other studies (e.g., McKenney and Rosenberg, 1993; Ley et al., 1994), we found wind speed to be the least sensitive variable in all regions throughout the year.

Spatial distribution of monthly and yearly sensitivity coefficients

A large spatial variability was found for the monthly sensitivity coefficients for all climatic variables. As an example, opposite spatial patterns for S_{WD} in March and September are shown in Fig. 4. After mapping the spatial distributions of average yearly sensitivity coefficients for TA, WD, HD and RS (Fig. 5a—d) we found (1) increasing trends exist from upper to lower region for S_{TA} and S_{HD}; (2) opposite spatial patterns are for S_{WD} and S_{RS}. The magnitude of spatial variations of S_{WD} and S_{RS} were relatively small compared to the other two variables; (3) the rank of the average yearly sensitivity coefficient throughout the basin was the same as the daily are.

Air temperature and relative humidity were expected to be more influential in the lower region than in the rest of the basin (Figs. 2 and 3). Since all climatic variables except wind speed in the middle and lower regions did not have any significant regional variations (Fig. 2), the spatial variability of sensitivity coefficients there could be explained by the large variability of wind speed (Fig. 2). In fact, strong positive spatial correlation between WD and S_{HD} (0.80 and 0.88) and negative correlation between WD and S_{RS} (-0.62 and -0.67) were found in the middle and lower regions, respectively.

Predictive power for a one-at-a-time perturbation of variables

Results for January and July are presented in Fig. 6 for illustrative purpose. A large slope of the transmitting curve indicates a limited predictive power of sensitivity coefficient. For example, for the lower region in July, a transmitting factor of 0.65, rather than the sensitivity coefficient of

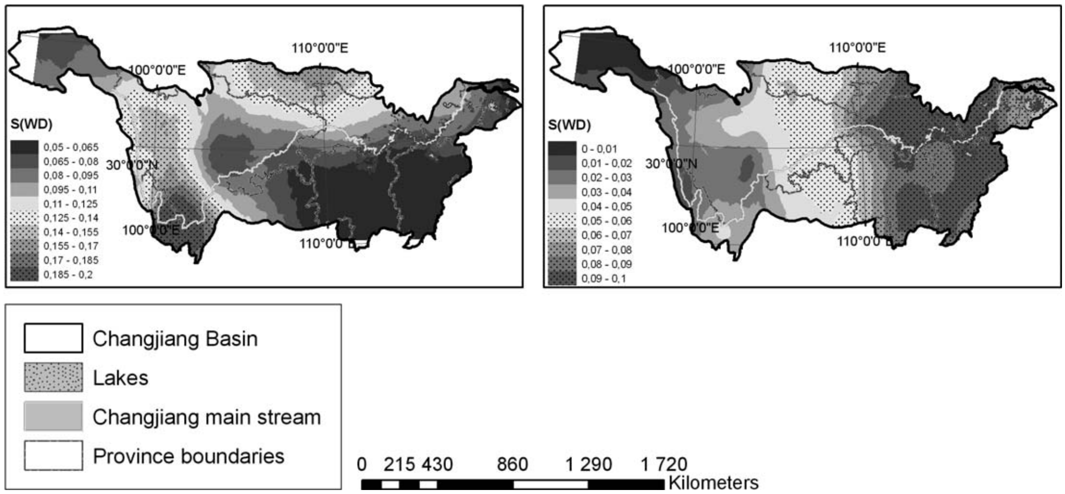

Figure 4 Spatial distributions of sensitivity coefficients for wind speed in March (left) and September (right).

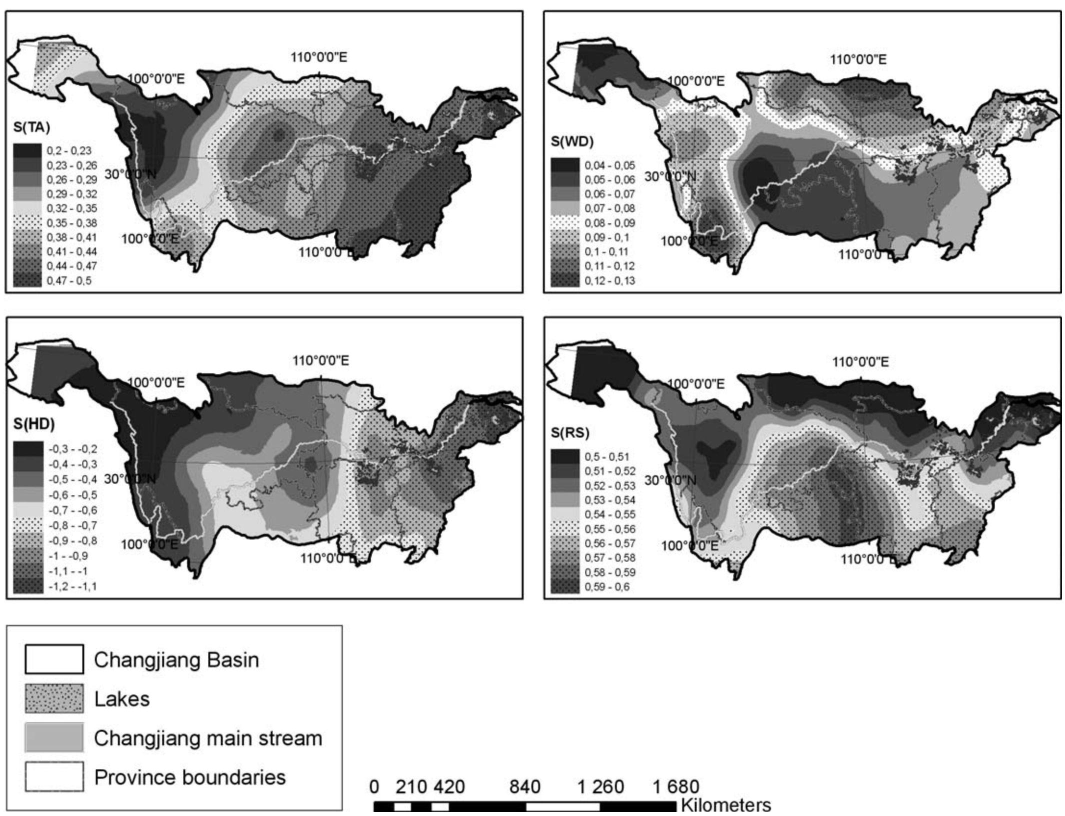

Figure 5 Spatial distribution of mean yearly sensitivity coefficients for air temperature (S_{TA}), wind speed (S_{ND}), relative humidity (S_{HD}) and shortwave radiation (S_{RS}) in Changjiang basin.

0.62, should be used to transform the 20% relative change of climatic variables to the relative change of ET_{ref} (Fig. 6b). The predictive power of the sensitivity coefficient of wind speed in January was also somewhat limited. The predictive power of the sensitivity coefficient of shortwave radiation was not influenced by the magnitude of the relative change. In general, sensitivity coefficients work as well as transmitting factors within a reasonable range of perturbation. The errors brought by the non-linearity of the sensitivity curve, as showed in Fig. 6, were much smaller compared to seasonal and regional variations of the sensitivity coefficients. However, for some specific region/season and for certain variables such as air temperature in the summer in the lower region, inappropriate use of sensitivity coefficients might cause a significant underestimation of ET_{ref} under a large temperature perturbation.

Predictive power for co-perturbation of variables

Results showed that the predictive power of the sensitivity coefficient for co-perturbation of variables increased from the lower to the upper region (Fig. 7). This might be due

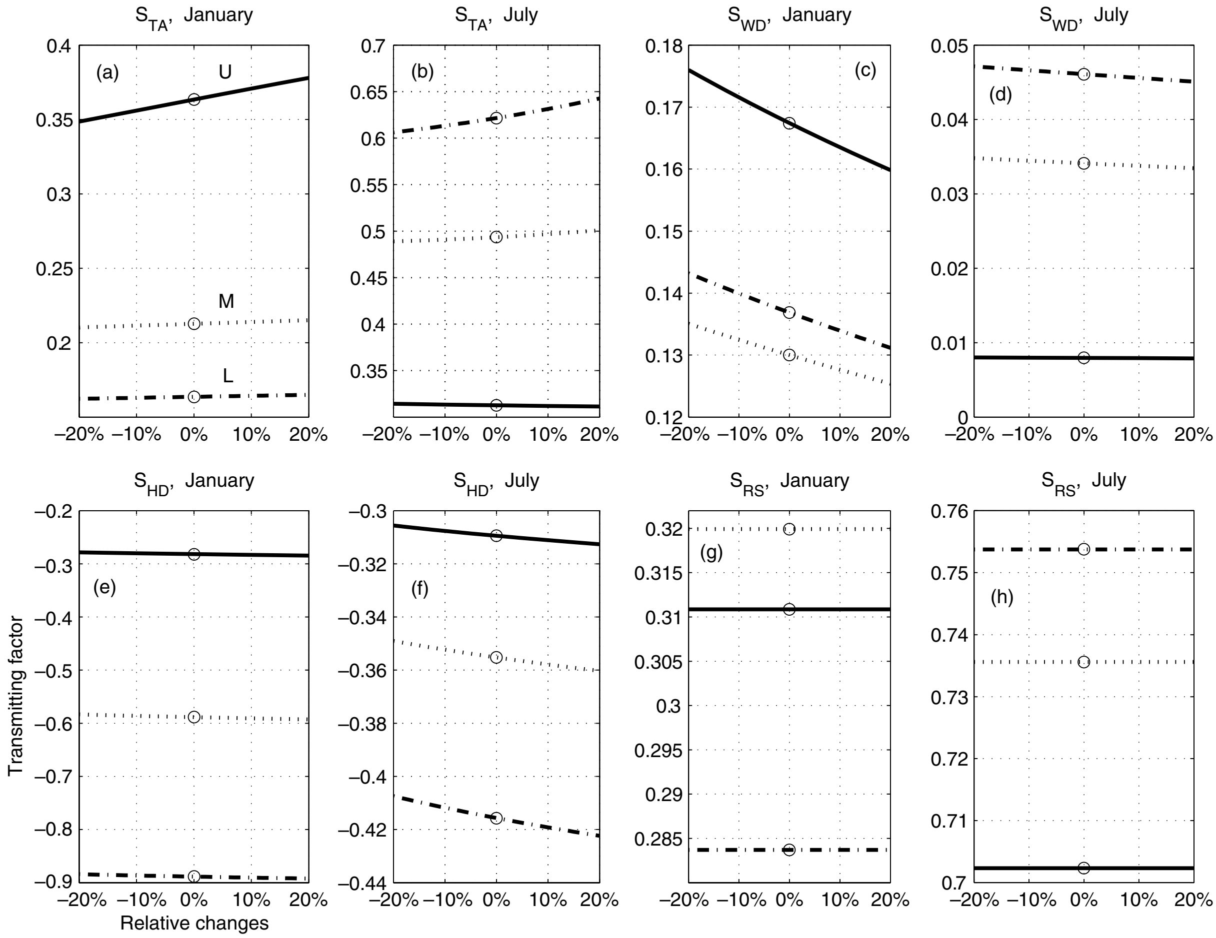

Figure 6 Transmitting curves of January and July for each climatic variable and each region of the basin. Solid, dashed and dash-dotted lines stand for upper, middle and lower regions, respectively.

to the fact that inter-dependence among the climatic variables in the upper region is limited by the relatively low temperature and humidity. Although the plots get more scatter in the middle and lower regions, R^2 values were still quite satisfactory, and the plots showing the average regional results (Fig. 7f, i) indicated that no significant systematic deviation was found from the actual perturbation for the estimated perturbation of ET_{ref} by sensitivity coefficient.

It appears that the non-dimensional relative sensitivity coefficient (S_{V_i}) could give satisfactory prediction of the ET_{ref} response of the perturbation of one or more climatic variables in the Changjiang basin, although the prediction accuracy may vary with variable, region and season. The method had an advantage over the sensitivity-curve method by its explicitly defined mathematical formulation, and also by its convenience in spatial graphic presentation.

Summary and conclusions

Sensitivities of reference evapotranspiration to four major climatic variables were studied in the Changjiang (Yangtze River) basin using a 41-year dataset. The basin was divided into three sub-regions with distinct geographic and climatic conditions, which gave rise to large spatial and temporal variations of sensitivity. Long-term average sensitivities were mapped regionally. The study showed that relative humidity was the most sensitive variable in general for the basin, followed by shortwave radiation and air temperature, which had similar sensitivities. Wind speed has the least impact. In the middle and lower regions, the spatial variations of sensitivities to air temperature, relative humidity and shortwave radiation were determined to a large extent by the large spatial variability of the wind speed.

The results of this work can be used as a theoretical basis for future research on the response of reference evapotranspiration to climatic change. The large spatial-temporal variability of the sensitivity coefficients indicated that the ET_{ref} response to climate change will differ with region and season. Generally, the non-dimensional relative sensitivity coefficient (S_{V_i}) gave satisfactory prediction of the ET_{ref} response to a perturbation of one or more climatic variables.

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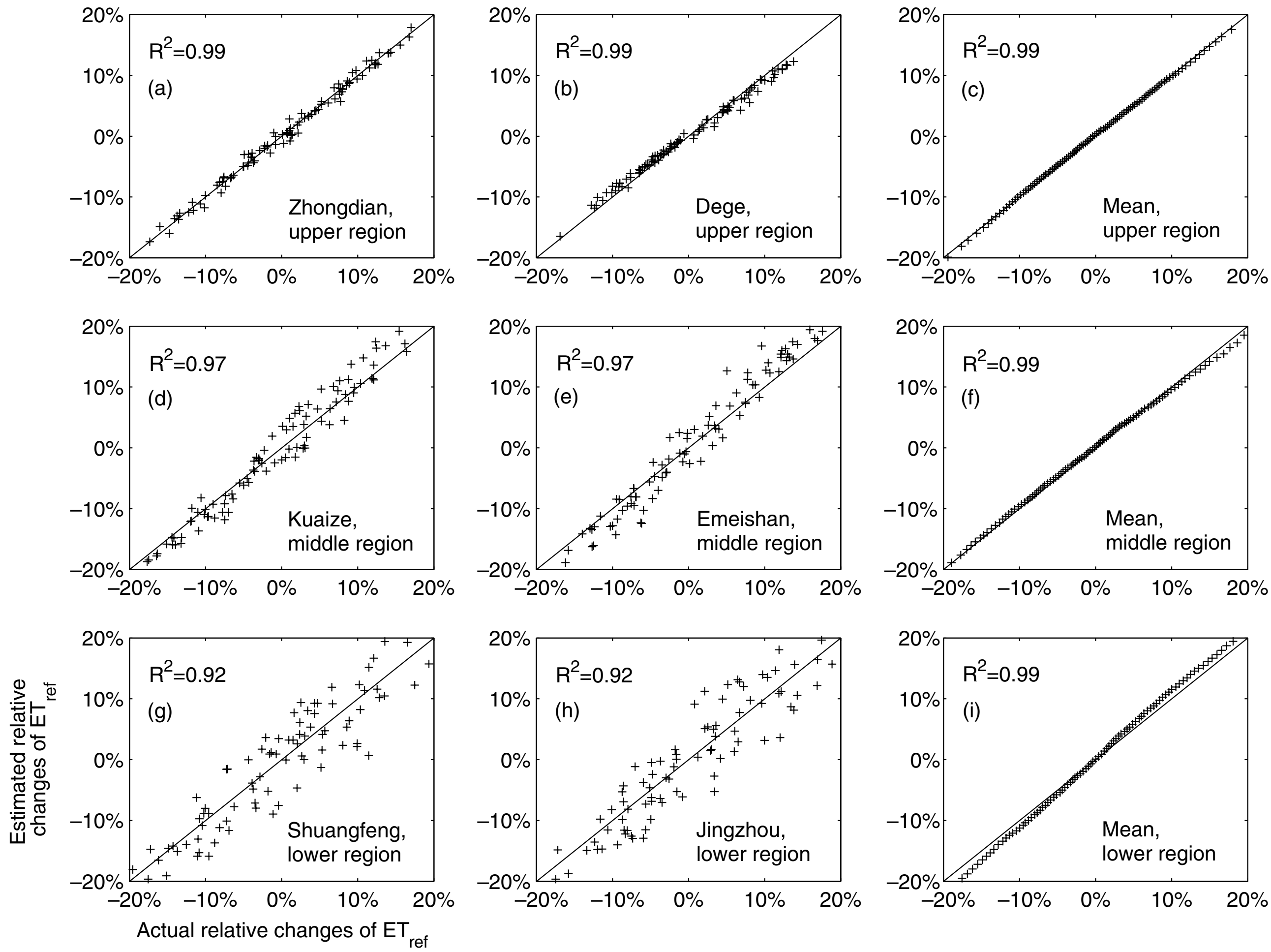

Figure 7 Predictive power of the sensitivity coefficients under simultaneous co-perturbation of variables. a, b, d, e, g, h: show the plot of actual vs. estimated perturbation of ET_{ref} of two randomly selected stations from upper, middle and lower parts of the basin, respectively. c, f, i: show the mean condition for the three regions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhydrol.2006.03.027.

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