The Climate Information System of China

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ABSTRACT: The Climate Information System of China (CISC) was built using Visual C++ and Java to perform 4 main functions: (1) to describe the variation in the spatial distribution of particular climatic variables with minimal digital information; (2) to separate the impacts of large-scale factors and local factors on climatic distribution and generate a raster database from the data collected from dispersed stations; (3) to share the climatic data on the Internet; and (4) to evaluate the impact of global change on Chinese water conditions under a number of prescribed climate scenarios. The establishment of CISC is described in detail. A digital elevation model and some meteorological (climatic) equations were used to calculate raster radiation data. Trend surface analysis and the interpolation method were used to analyze the spatial distribution of temperature, precipitation, relative humidity, sunshine fraction, and wind velocity and to generate the raster database. Penman's equation was amended and parameterized to calculate the potential evapotranspiration over China. An aridity index was calculated under present situations and 12 prescribed climate scenarios (raising mean temperature by 1.5, 3.0 and 4.5°C and changing precipitation by 0, +10, +20 and –10%) to assess the sensitivity of Chinese water conditions to global change. Some Java applets were written to make it possible to share Chinese climate information on the Internet.

KEY WORDS: Climate Information System of China (CISC) · Trend surface analysis · Aridity index · Global change

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1. INTRODUCTION

Anthropogenic and biogenic emissions of atmospheric CO₂ and other radiatively active trace gases (e.g. CH₄, N₂O, CFC₃, CF₂Cl₂) are modifying the earth's climate (Rawson 1992). Predictions (Houghton et al. 1990) for the global greenhouse of the mid-21st century include increases in mean temperature of between 1.5 and 4.5°C and altered precipitation. Global changes have attracted the attention of scientists, governments and the entire world.

More and more ecologists are studying the interactions between spatial patterns and ecological processes and are developing ecological models to evaluate the impact of global change. Some issues with regard to climatic variables have become more signifi-

cant: (1) What are the dominant factors that determine the spatial distribution of climatic variables, and how can we find the patterns? (2) All climatic data are collected from dispersed stations, but raster data would be more useful in landscape modelling. How can we generate raster data from the dispersed stations with sound theories? (3) How can we efficiently extract information from the large amount of data? (4) How can we share the climatic data on Internet? (5) How can we evaluate the impact of global change on climatic factors other than the case variables (i.e. temperature, precipitation and CO₂ concentration) for which we have estimated potential changes?

In this article, we have tried to describe the variation in the spatial distribution of climatic variables, separate the functions of large-scale factors and local factors, and describe a method to generate raster data for climatic variables from dispersed stations, with trend surface analysis (TSA) and the interpolation method.

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Case studies were performed on the spatial distribution of temperature, precipitation, relative humidity, sunshine fraction and wind velocity. A Climate Information System of China (CISC) was built with Visual C++ and Java to generate the raster database and share the information on the Internet. Twelve prescribed climatic scenarios were formulated according to the research of the IPCC (Houghton et al. 1990) to describe potential climatic conditions under global climate change (raising mean temperature by 1.5, 3.0 and 4.5°C and changing precipitation by 0, +10, +20, and -10. An aridity index was used as an index to assess the sensitivity of Chinese water conditions to global change under the 12 prescribed climate scenarios.

2. METHODS

Climate variables such as radiation, temperature, precipitation, relative humidity, sunshine fraction, wind velocity, potential evapotranspiration, and aridity index are some of the dominant environmental factors in ecological studies. The interpolation method is a widely used approach for generating raster data from the dispersed data of meteorological observation stations; it is simple and convenient, but it is unable to analyze the spatial variations in scattered data. TSA (Chorley & Haggett 1968, Gittins 1968) is a statistical method that is fully able to describe the variation in the spatial (or spatial-temporal) distribution of certain factors. It uses spatial coordinates as independent variables: abscissa and ordinate in a 2-dimensional TSA or longitude, latitude and elevation in a 3-dimensional TSA. In addition, it can use spatio-temporal coordinates, such as abscissa, ordinate and time, as independent variables in a 3-dimensional TSA. Here, raster data for radiation were calculated with digital elevation models (DEMs) and meteorological (climatic) equations. Three-dimensional TSA was used to evaluate the spatial distribution of temperature, precipitation, sunshine fraction and relative humidity, and the interpolation method was used to interpolate the residuals into each grid cell to obtain all of the information. Potential evapotranspiration was calculated with amended Penman's methods and verified with observed data for pan evaporation.

2.1. Method for obtaining raster radiation data

Radiation (Gao & Lu 1988) can be determined by local topographical situation, i.e. latitude, elevation, slope gradient, slope aspect, and shading limit. Dozier (Dozier & Outcalt 1979, Dozier & Frew 1990) evaluated the radiation with a DEM. Fu & Weng (Fu 1983,

Fu & Weng 1994, Weng & Luo 1990) studied the radiation in a mountain region and developed a new method with analytical equations to calculate the radiation in any topographical situation. Here, we used a DEM (Ke et al. 1992) to calculate the elevation, slope gradient, slope aspect, and shading limit, and used Fu's methods (Fu 1983, Fu & Weng 1994) to calculate the radiation data, including (1) possible duration of sunshine, (2) exoatmospheric solar radiation, and (3) total solar radiation. Detailed mathematical equations are given in Appendix 1.

2.2. Trend surface analysis

On a large scale, the spatial distribution of climate variables is impacted by large-scale environmental factors (Gao & Lu 1988), including latitude, distance from the sea, the influence of great mountains, plateaus or basins, and background atmospheric circulation, and local environmental factors, such as slope gradient, slope aspect, hypsography, degree of shading, vegetative canopy and microclimatic factors. Here longitude, latitude and elevation were selected as large-scale environmental factors, and slope gradient, slope aspect, and vegetation canopy were selected as local environmental factors. However, the distribution of climatic variables is somewhat non-determinant, because of the random fluctuation in the environment. To decrease the function of random events, we integrated the spatial function by time to obtain the average spatial distribution of climatic variables in a certain period:

$$Y_p = q_p\{\phi, \lambda, H, \alpha, \beta, V, \dots\} + \sigma_p \quad (1)$$

where Y_p is the average spatial distribution of climatic variables, λ is the latitude, ϕ is the longitude, H is the elevation, α is the slope gradient, β is the slope aspect, V is the vegetative factor, and σ_p is the function of random events. It was found that in a certain area, with the extension of the period, the functions of random events decrease sharply, and the accuracy of the simulation increases greatly. It was hypothesized that for some climatic variables, i.e. temperature, precipitation, relative humidity and sunshine fraction, the functions of large-scale environmental factors and local environmental factors could be separated from each other, and hence we obtained:

$$Y_p = f_p\{\phi, \lambda, H\} + g_p\{\alpha, \beta, V, \dots\} + \sigma_p \quad (2)$$

where f_p is the function for large-scale environmental factors and g_p is the function for local environmental factors.

TSA is a special method for multivariate statistical analysis; it is specialized for spatial (or spatial-tempo-

ral) analysis and is capable of separating the functions of large topographical factors from local environmental factors and random events. A detailed description of TSA is given in Appendix 2.

With TSA, we can obtain the function of large-scale topography factors easily; we use latitude, longitude and elevation as the 3 independent variables and use climate variables (i.e. temperature, precipitation, relative humidity, and sunshine fraction) as the dependent variables. All these data come from scattered meteorological observations. After obtaining the TSM and the residual matrix, we can calculate raster data of certain climatic variables:

$$\hat{Y}_{ij} = D_{ij} \bar{A}_T \quad (3)$$

where $\hat{Y}_{ij}$ is the simulated result of climate variables, D is the row vector of spatial coordinates, and $\bar{A}_T$ is the coefficient vector.

The residuals can be regarded as the synthetic functions of local environmental factors and random events that cannot be explained by large-scale topography factors. Residuals are interpolated into each raster to obtain all of the information about the spatial distribution of the climatic variables. The distances from neighboring meteorological stations are used for the impact coefficient, and the interpolation method is expressed as:

$$V_p = \frac{\sum_{i=1}^t (V_i / d_i)}{\sum_{i=1}^t (1 / d_i)} \quad (4)$$

where V_p is the interpolated result of climatic variable, d_i is the distance from the neighboring station, V_i is the residual of neighboring station, and t is the number of neighboring stations. By searching in 4 directions (north, south, east and west), 6 stations are selected, with at least 1 station in each direction, and the residuals of these 6 stations are used for the interpolation. By adding the TSM results and the interpolation results, we can obtain the raster data for each climate variable.

2.3. Methods for calculating the potential evapotranspiration and the aridity index

Penman's methods (Penman 1948, 1950, 1956, McCulloch 1965) are commonly used to calculate the potential evapotranspiration, due to their reliable physical basis. Many scientists have tried to modify Penman's method to increase the accuracy and some excellent methods have been developed, such as the Penman-Monteith method (Monteith 1965) and the FAO methods (Frere & Pruitt 1979). Some Chinese sci-

entists (Xie et al. 1991, Yu & Shi 1998) developed amended Penman's methods for China. Here we use one of the amended Penman's methods (Xie et al. 1991):

$$ET_p = \zeta \cdot \left\{ \frac{P_0}{P} \cdot \frac{\Delta}{\gamma} \cdot [Q_A(a + b \cdot s) - \sigma T_K^4 (0.56 - 0.079 \sqrt{e_a}) (0.1 + 0.9 \cdot s)] + 0.26(e_a + e_d)(1 + c \cdot U_2) \right\} \left[\frac{P_0}{P} \cdot \frac{\Delta}{\gamma} + 1 \right] \quad (5)$$

where ET_p is the potential evapotranspiration (cm d^{-1}); P_0 and P are the air pressures at sea level and at the observation point (hPa); Δ is the curve slope gradient that describes the change in saturated vapor pressure with temperature ($\text{hPa } ^\circ\text{C}^{-1}$); γ is the psychrometric constant ($\text{hPa } ^\circ\text{C}^{-1}$); Q_A is exoatmospheric solar radiation ($\text{J cm}^{-2} \text{ d}^{-1}$), which can be calculated with Fu's methods (Fu 1983, Fu & Weng 1994); s is the sunshine fraction; T_K is the air temperature (K); e_a is the saturated vapor pressure (hPa); e_d is the water vapor pressure (hPa); U_2 is the wind velocity at a height of 2 m (m s^{-1}); σ is the Stefan-Boltzmann constant ($\text{W cm}^{-2} \text{ K}^{-4}$); ζ is the amending constant; and a , b and c are constants.

Many scientists (e.g. Gao & Lu 1988) have studied the index of aridity (or index of humidity) for climatic divisions. Here we used the aridity index as an index of arid-humidity climate analysis, which is expressed as:

$$A_I = \log_{10} \left(\frac{ET_p}{R} \right) \quad (6)$$

where A_I is aridity index, ET_p is potential evapotranspiration, and R is mean annual precipitation.

2.4. Methods for smoothing the raster data

As the raster data calculated by TSA and the interpolation method are not smooth enough, it is necessary to 'smooth' them. The smoothing method was expressed as:

$$Y_S = \frac{\sum_{i=1}^8 (Y_i / d_i)}{\sum_{i=1}^8 (1 / d_i)} \quad (7)$$

where Y_S is the smoothed result of raster data, Y_i are the 8 raster data surrounding the smoothing grid cell, and d_i is the distance between the neighboring raster and the smoothed raster. This method was verified to be a useful approach by omitting the singular data. To avoid losing information, the raster data can be smoothed only 1 or 2 times.

2.5. Methods for establishing a climate information inquiry system

Some Java applets were developed with the free software JDK1.2, downloaded from the homepage of Sun Microsystems (<http://java.sun.com>) to share the climatic information for China and graphically display the maps on the Internet. Please contact the first author (shangzb@sohu.com) for climatic information for the whole of China, i.e. temperature, precipitation, relative humidity, sunshine fraction, wind velocity, potential evapotranspiration, and aridity index.

3. DATA SET AND PREPROCESSING

The following data sets were used in this research: (1) monthly data of 954 meteorological observation stations in China, from 1951 to 1980, including mean temperature, precipitation, wind velocity, relative humidity, sunshine fraction, and pan evaporation; (2) a 1:500 000 relief map; (3) raster elevation data of China, at the scale of $1/48$ latitude and $1/32$ longitude for each element.

Some computer programs were developed with Visual C++ 5.0 to calculate the mean monthly and annual meteorological data for 30 yr; to build the DEM and calculate the slope gradient, slope aspect and shading limit of each grid cell; to calculate the TSA and get TSM; to

interpolate the residuals; to calculate the potential evapotranspiration; to calculate the aridity index under the present situation and 12 climate scenarios; and to form the climatic database. All the raster data of each climatic variable were smoothed twice. These raster data of climate variables were partitioned into portions and saved in 212 files. Each file held 96×96 raster data, which cover a region of $3^\circ \times 2^\circ$ (longitude $\times$ latitude). Some applets were written with Java to display the graphs and share the climatic information on the Internet.

4. RESULTS AND DISCUSSION

4.1. Radiation

With the 1:500 000 relief map and the raster elevation data for China, DEMs of China were built, and some topographical variables, such as average elevation, slope, slope aspect, and shading limit of each grid, were calculated. Fig. 1 shows the topography of China. With Fu's methods (Fu 1983, Fu & Weng 1994), the possible duration of sunshine, exoatmospheric solar radiation, and total solar radiation were calculated for each grid cell. As the largest slope angle at such a spatial scale is no larger than 12.5° , the influence of topography factors is minor compared with that of latitude, and the spatial distribution of exoatmospheric solar radiation decreases gradually with increasing latitude.

Fig. 1. Topography of China (heights in m)

Table 1. Comparison between trend surface analysis simulated results and observed data

Climatic variable	Monthly		Annual	
	N	R ²	N	R ²
Mean temperature	25524	0.9898	2126	0.9847
Precipitation	25236	0.8765	2103	0.8997
Mean relative humidity	25236	0.8826	2103	0.8780
Mean sunshine fraction	24852	0.9008	2071	0.9006
Mean wind velocity	25236	0.5536	2103	0.5296

4.2. Temperature, precipitation, relative humidity, sunshine fraction and wind velocity

As TSA is fit for spatial analysis of some ecological factors at a regional scale, China was divided into 8 subareas: (1) Northeast China, (2) North China, (3) Middle China, (4) South China, (5) Southeast China, (6) Inner Mongolia, (7) Northwest China, and (8) Tibetan Plateau. Subareas were overlapped to avoid 'gaps'. With monthly

data from 954 meteorological observation stations in China, from 1951 to 1980, 3 factorial TSA (the maximum power of the TSA is 3) were built to analyze the spatial distribution regulation of 5 climatic variables (i.e. mean temperature, precipitation, relative humidity, sunshine fraction and wind velocity) at 2 temporal scales: mean monthly data and mean annual data over 30 yr. Table 1 and Fig. 2 show the comparison between simulated results and observed data from 520 trend surface models. It was found that TSA is suitable for spatial analysis of 4 climatic variables (temperature, precipitation, relative humidity and sunshine fraction) but not for that of wind velocity. TSA was used to calculate the function of large-scale environmental factors, and the residual data were interpolated into each raster element to obtain the full spatial distribution information for the 4 applicable climate variables. The interpolation method was used to calculate the raster data for wind velocity. The spatial distributions of all 5 climatic variables are given in Figs 3–7.

Fig. 2. Comparison between observed data (from meteorological observation stations) and simulated (by trend surface analysis) data of 5 climatic variables: (A,B) temperature, (C,D) precipitation, (E,F) relative humidity, (G,H) sunshine fractions, and (I,J) wind velocity, at 2 temporal scales: left panels (A,C,E,G,I), mean monthly data of 30 yr; right panels (B,D,F,H,J), mean annual data of 30 yr. (Figure continued on next page)

Fig. 2 (continued)

TSA is a very nice and efficient approach to express the variation in the spatial distribution of climatic variables. Just as shown in Table 1, we can use 160 parameters to express the 98.47% of the information for annual temperature in China with TSA. We can generate the raster database for the climatic variables at any spatial scale, but only if we have the raster elevation data at the same scale.

4.3. Potential evapotranspiration

The monthly climate data of 905 meteorological observation stations during the period 1951–1980 were used to calculate the potential evapotranspiration. Fig. 8 shows the comparison between simulated results of monthly potential evapotranspiration and 10 860 effectively monthly observed pan evaporation data at 905

Fig. 3. Spatial distribution of annual mean temperature (°C) in China

Fig. 4. Spatial distribution of annual precipitation (mm) in China

Fig. 5. Spatial distribution of annual mean relative humidity (%) in China

Fig. 6. Spatial distribution of annual mean sunshine fraction (%) in China

Fig. 7. Spatial distribution of annual mean wind velocity (m s^{-1}) in China

stations. The correlation relation was very good ($R^2 = 0.9288$). With monthly raster data for 5 climatic variables, i.e. temperature, precipitation, relative humidity, sunshine fraction and wind velocity, we calculated the potential evapotranspiration for each raster element. Fig. 9 shows the spatial distribution of potential evapotranspiration in China.

4.4. Aridity index

The aridity index is an excellent climatic index to describe moisture conditions. Graphical analysis of the spatial distribution of aridity index in China is shown in Fig. 10. Potential aridity index was calculated under 12 prescribed climate scenarios, including raising the mean temperature by 1.5, 3.0 and 4.5°C, and changing precipitation by 0, +10, +20 and -10%, to assess the sensitivity of China water conditions to global change (Fig. 11).

By exploring the impacts of global change on the aridity index in different regions, we can determine which are most sensitive: (1) The wide area in South China—This region is the most important agricultural area of China, so the changes in water conditions will influence crop yields greatly. (2) The great ecotone from northeastern to southwestern China, covering the

Greater Xingan Mountains, Yinshan Mountains, Erdos Plateau, Qilian Mountains, and the southeastern part of the Tibetan Plateau—Both the climate and vegetation will change remarkably across this ecotone. It is still well known as a transition zone from farmland to pastoral area. The changes in water conditions will cause large changes in vegetation in this sensitive region. (3) West China—This is an arid region covered with desert vegetation. The density of vegetation is

Fig. 8. Comparison between observed evaporation data (from meteorological observation stations) and simulated (using amended Penman's formula) potential evapotranspiration data

low and sparse, because of the adverse environment, and great importance should be attached to the vital impact of changes in water conditions on the vegetation canopy.

To show the difference clearly, we calculated the average potential evapotranspiration and aridity index for China under the present situation and the 12 prescribed climate scenarios (Table 2). It is very clear that potential evapotranspiration will increase sharply with an increase in temperature. An increase in temperature of 1.5°C will lead to an increase in the average potential evapotranspiration of about 100 mm, 5% of the previous value. Present potential evapotranspiration (1933 mm) is much larger than average precipitation (565 mm), but the actual evapotranspiration will be low, as there is not sufficient water supply in the soil.

Changes in aridity index are more complex. Two trends can be surmised distinctly as follows: (1) the average aridity index will increase sharply with an increase in temperature; (2) average aridity index will decrease greatly with an increase in precipitation. However, the situation becomes very complicated when the compound changes in temperature and precipitation are considered. The aridity index under the climatic scenario in which temperature is increased by 3.0°C and precipitation by 10% is somewhat alike to

that of the present situation. Therefore, we can draw another conclusion: the change caused by an increase in temperature of 3.0°C will be counteracted by an increase in precipitation of 10%. This principle can be verified by comparing the changes in the aridity index under the 12 prescribed climate scenarios.

5. CONCLUSION

The Climate Information System of China (CISC) is a theoretical approach (software has also been generated) to define the variation in the spatial distribution of climatic variables in order to generate a raster database with the data from dispersed stations and to evaluate the impact of global change on Chinese water conditions under some prescribed climate scenarios. Digital elevation models and meteorological equations were used to calculate the radiation with respect to different locations and various topographical situations. Trend surface analysis (TSA) was used to express the impact of large-scale environmental factors on the spatial distribution of climatic elements and to succinctly describe the real data with very few parameters. TSA and the interpolation method were applied to calculate the raster data. The aridity index was calculated under

Fig. 9. Spatial distribution of annual potential evapotranspiration (mm) in China

Fig. 10. Spatial distribution of the aridity index in China

the present situation and 12 prescribed climate scenarios. The simulated results show that the water conditions will change remarkably in southern China, in the transitional regions from northeastern to southwestern

China, and in western China. Regarding the impact of global change on the aridity index, the effect of raising temperature by 3.0°C was shown to be balanced approximately by that of raising precipitation by 10%.

Table 2. Average potential evapotranspiration and aridity index for China under the present situation and the 12 climate scenarios

Temperature	Precipitation	Average potential evapotranspiration (mm)	Average aridity index
Present temperature	Present precipitation	1932.98	0.7402
Raising mean temperature by 1.5°C	Decreasing precipitation by 10 %	2035.97	0.8072
	Present precipitation	2035.97	0.7616
	Raising precipitation by 10 %	2035.97	0.7205
	Raising precipitation by 20 %	2035.97	0.683
Raising mean temperature by 3.0°C	Decreasing precipitation by 10 %	2140.83	0.8293
	Present precipitation	2140.83	0.7836
	Raising precipitation by 10 %	2140.83	0.7424
	Raising precipitation by 20 %	2140.83	0.7049
Raising mean temperature by 4.5°C	Decreasing precipitation by 10 %	2247.48	0.8506
	Present precipitation	2247.48	0.8049
	Raising precipitation by 10 %	2247.48	0.7636
	Raising precipitation by 20 %	2247.48	0.7261

Fig. 11 (this and next 5 pages). Spatial distribution of the aridity index in China under 12 prescribed climate scenarios: raising temperature by (A–D) 1.5, (E–H) 3.0 and (I–L) 4.5°C and (A,E,I) decreasing precipitation by 10 %, (B,F,J) present precipitation, (C,G,K) raising precipitation by 10 % and (D,H,L) raising precipitation by 20 %

Fig. 11 (continued)

Fig. 11 (continued)

Fig. 11 (continued)

Fig. 11 (continued)

Appendix 1. Equations for the possible duration of sunshine, the exoatmospheric solar radiation, the total solar radiation

Possible duration of sunshine

Solar altitude can be expressed as

$$\sin h_F = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega \quad (A1)$$

$$\sin h_{\alpha\beta} = u \sin \delta + v \cos \delta \cos \omega + \sin \beta \sin \alpha \cos \delta \sin \omega \quad (A2)$$

$$u = \sin \varphi \cos \alpha - \cos \varphi \sin \alpha \cos \beta \quad (A3)$$

$$v = \cos \varphi \cos \alpha + \sin \varphi \sin \alpha \cos \beta \quad (A4)$$

where h_F is the solar altitude on flat ground, $h_{\alpha\beta}$ is the solar altitude on a sloping field, α is the slope gradient, β is the slope aspect, δ is the declination, and ω is the hour angle.

We can obtain the possible duration of sunshine on flat ground as follows

$$\omega_S = \arccos(-\tan \varphi \cdot \tan \delta) \quad (A5)$$

$$\omega_t = -\omega_S \quad (A6)$$

where ω_S is the hour angle at sunset and ω_t is the hour angle at sunrise.

The influence of elevation on sunrise (sunset) hour angle can be described by

$$\omega_{SH} = \arccos(-\tan \varphi \cdot \tan \delta - 0.0177 \cdot \sqrt{H} \cdot \sec \varphi \cdot \sec \delta) \quad (A7)$$

where ω_{SH} is the sunrise (sunset) hour angle at a different height and H is the elevation (10^3 m).

The influence of shading limit on sunrise (sunset) hour angle on flat ground is expressed as

$$\omega_{SS} = \arccos\left(\frac{\sin \gamma_A - \sin \varphi \cdot \sin \delta}{\cos \varphi \cdot \cos \delta}\right) \quad (A8)$$

where ω_{SS} is the sunrise (sunset) hour angle with shade, and γ_A is the shading angle.

The sunrise (ω_{SR}) and sunset (ω_{ST}) hour angles on a sloping field can be calculated from

$$\begin{cases} \cos h_{\alpha\beta} \cos \theta = -\sin \delta \cos \varphi + \cos \delta \sin \varphi \cos \omega \\ \cos h_{\alpha\beta} \sin \theta = \cos \delta \sin \varphi \\ \sin h_{\alpha\beta} \geq \sin \gamma_A \\ \sin h_{\alpha\beta} \geq 0 \end{cases} \quad (A9)$$

Exoatmospheric solar radiation

Daily exoatmospheric solar radiation can be calculated by integration for 1 d from

$$Q_{i,j} = \int_{\omega_S}^{\omega_t} \rho^2 \cdot S_0 \cdot \sin h \cdot \frac{T}{2\pi} d\omega \quad (A10)$$

where $Q_{i,j}$ is the daily exoatmospheric solar radiation, ω_S is the sunrise hour angle, ω_t is the sunset hour angle, ρ is the radius vector, S_0 is the solar constant, and T is 86 400 s. Analytical equations can be generated from Eq. (A10) to calculate the daily exoatmospheric solar radiation for different topography.

Daily exoatmospheric solar radiation on flat ground Q_F is expressed as

$$Q_F = \frac{T}{\pi \rho^2} S_0 (\omega_S \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_S) \quad (A11)$$

Daily exoatmospheric solar radiation on sloping fields $Q_{\alpha\beta}$ can be described by

$$Q_{\alpha\beta} = \frac{T}{2\pi \rho^2} [u \sin \delta (\omega_S - \omega_t) + v \cos \delta (\sin \omega_S - \sin \omega_t) - \sin \beta \sin \alpha \cos \delta (\cos \omega_S - \cos \omega_t)] \quad (A12)$$

Total solar radiation

Total solar radiation is expressed as

$$Q_S = Q_{i,j} (a + b \cdot S) \quad (A13)$$

where Q_S is the total solar radiation, S is the sunshine fraction, and a and b are coefficients.

Appendix 2. Detailed description of trend surface analysis

Assume a point in 3-dimensional space has coordinates (x_t, y_t, z_t) , and observational data w_t . We used Trend Surface Models (TSMs) to simulate the spatial distribution of many such points as follows:

$$W = GA + \varepsilon \quad (A14)$$

where W is the matrix of observational data, and ε is the residual matrix; both are vector matrices of the form $(N \times 1)$, where N is the number of observational data. G is a vector matrix of the form $N \times q$; A is a matrix of coefficients $q \times 1$, and q is determined by s , the rank of the TSM

$$q = (s+1)(s+2)(s+3)/6 \quad (A15)$$

Here we give D , one row vector of G , from which the sub-

scripts for the code of the observation point have been omitted:

$$D = \{1, z, z^2, \dots, z^s, y, yz, yz^2, \dots, yz^{s-1}, \dots, y^{s-1}, y^{s-1}z, y^s, x, xz, xz^2, \dots, xy, xyz, \dots, xyz^{s-2}, \dots, xy^{s-1}, x^2, x^s z, \dots, x^2 z^{s-2}, x^2 y, x^2 yz, \dots, x^2 yz^{s-3}, \dots, x^{s-1} y, x^s\} \quad (A16)$$

TSA can be performed with the method of least squares or the method utilizing a generalized inverse matrix. As the second method has greater accuracy, and is convenient for higher-order TSM, it was used here.

With Gram-Schmidt's method of orthogonalization (Pan & Zhou 1984), we calculated the Moore-Penrose's generalized inverse matrix G^+ of real matrix G and obtained the shortest least squares solution $\hat{A}$ of A :

$$\hat{A} = G^+ Z \quad (A17)$$

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