Regional Hydrological Impacts of Climatic Change—Hydroclimatic Variability
(Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 296, 2005.

Modelling the spatial distribution of actual terrestrial evapotranspiration using a hydrological and meteorological approach

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Abstract Terrestrial evapotranspiration (TET) plays an important role in determining water balance and heat balance in a water cycle between land surface and atmosphere. In this paper a dynamic approach based on the integration of meteorological and hydrological methods was proposed for simulating actual TET distribution across large spatial and temporal extents by reflecting the impacts of climate, complex land cover features, and the movement characteristics of soil moisture upon actual TET. The proposed approach was then used to simulate the actual TET in China. The distribution characteristics of actual TET demonstrate that the TET in eastern China is larger than that in western China, and the actual TET in the region with low latitude is larger than that with high latitude in the context of China. From 1991 to 1995 and 2000, actual monthly and annual TET in most regions show an increasing trend within the 10-year horizon, especially in arid and semiarid regions.

Key words China; hydrology; modelling; spatial distribution; TET

INTRODUCTION

Accurate modelling of terrestrial evapotranspiration (TET) at a large spatial scale is critical for better understanding of the feedback mechanisms of the water cycle between the land surface and atmosphere. In the past decades, a number of methods were proposed for TET simulation. Generally, these methods can be categorized into three groups: improving traditional computing technology, considering the interactive mechanisms of vegetation and the atmosphere, and calculating regional TET by utilizing remote sensing.

However, for TET simulation at a large temporal and spatial scale, due to the complexity of the underlying surface in large study regions, multiple methods should be considered to calculate the TET (Moran *et al.*, 1996; Price, 1990). Therefore, motivated by previous work, the objective of this study is to propose an integrated approach based on meteorological and hydrological methods in dealing with terrestrial evapotranspiration (TET) simulation at a large spatial scale; and to apply the proposed approach to simulate actual TET in China. In order to reflect the impacts of different land cover types and movement characteristics of soil moisture in an actual TET simulation, a soil humidity iterative computation method is applied for TET calculation. The approach developed and this Chinese study will be important contributions to the literature of evapotranspiration simulation. The objectives are as follows: (a) collecting and analysing the meteorological and hydrological data recorded at 661 observation stations, which are evenly distributed across the whole country; (b) simulating potential TET using the Penman equation; (c) applying soil humidity iterative computation method, water balance model, the soil texture–soil moisture relation model, and the mathematical iterative method to simulate actual TET, and (d) analysing the variation of spatial distribution of actual TET in China within a 10-year horizon.

METHODOLOGY

Potential TET modelling

For simulating the potential TET value, the Penman ET equation is used in this study (Penman, 1948). The equation can be described as follows:

$$ET_p = \frac{\Delta(R_n - G) + \gamma E_a}{\Delta + \gamma} \tag{1}$$

where ET_p is the potential TET (mm day^{-1}), Δ is the slope of a saturation vapour pressure curve (kPa °C^{-1}), R_n is the net radiation at land surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), and is ignored for daily calculation in this study because it is insignificant in a short temporal scale, γ is the psychrometric constant (kPa° C^{-1}) and E_a is the dry capacity of air (mm day^{-1}):

$$E_a = 0.26(1 + 0.54U_2)(e_s - e_a) \tag{2}$$

where U_2 is the mean wind speed at the height of 2 m (m s^{-1}), e_s is saturation vapour pressure (kPa), and e_a is actual vapour pressure (kPa).

For the calculation of potential TET, only meteorological and geographical data are needed. The meteorological data in this study include daily average temperature, daily maximum and minimum temperature, daily observed wind speed, actual daily sunshine time and maximum (minimum) relative humidity. The geographical data include altitude, latitude and longitude of the land surface.

Actual TET modelling

To obtain a more accurate actual TET, an integrated hydrological and methodological approach is applied to reflect the impacts of the complicated underlying surface on the determination of actual TET through a soil-humidity-iterative computation.

The integration is carried out in five steps:

(a) By using geographic information system (GIS) software, the location of individual meteorological observation stations is distributed by grid. Each grid contains the point data of meteorological variables including temperature, precipitation, humidity, radiation and wind.

(b) By applying a digital elevation model (DEM) to get the information associated with geographic elevation in the grid with a resolution of 1 km × 1 km, the spatial distribution of the meteorological variables is adjusted based on the geographic information obtained.

(c) The daily spatial distribution of potential TET will be simulated by calculating the obtained data of meteorological variables in each grid with the Penman equation.

(d) According to soil texture, the distribution of terrestrial soil water content can be estimated. Then, the distribution of critical point of saturated water content (field capacity) for a specific soil will be simulated based on the estimation.

(e) Integrating information of daily precipitation, potential TET and field capacity into a water balance model by each grid, the daily, monthly and yearly actual TET value in the grid could be simulated through soil humidity iterative computation.

The evaporation ratio β is a climate index reflecting the dry or wet degree of land surface, and can be determined by the ratio of actual TET to potential TET:

$$\beta = \frac{ET_a}{ET_p} \tag{3}$$

where ET_a is actual TET, ET_p is potential TET. When the data for calculating ET_a are not available, the evaporation ratio β can be determined by the following empirical formula:

$$\beta = \min\left(\frac{w}{w_k}, 1\right) \tag{4}$$

where w is water content in soil, and w_k denotes soil water content at the point when the TET value is determined by water content in the soil rather than from the initial atmospheric condition. The value of w_k is about 70–80% of field capacity.

The water content in soil is calculated based on a water balance equation expressed as follows:

$$\frac{\mathrm{d}w}{\mathrm{d}t} = PT - ET_\alpha - F \tag{5}$$

where, $\mathrm{d}w/\mathrm{d}t$ is the change of soil moisture with time, PT is precipitation, ET_a is actual TET, and F is runoff volume. Carrying out discretization of the water balance equation, with a month as the time step, and assuming that when water content in the soil exceeds field capacity the excess part is considered as the runoff loss item, equation (5) could be reduced to the following form:

$$w_i = \min(w_{i-1} + PT_i - ET_{ai}, w_{FC}) \tag{6}$$

where, w_i, and w_{i-1} denote soil moisture content (mm) in month i and month i–1, PT_i denotes precipitation in month i (mm), ET_{ai} denotes actual TET in month i (mm), and w_{FC} denotes field capacity (mm). w_{FC} can be calculated according to the empirical relation between soil moisture content and soil texture (Cosby, 1984; Saxton *et al.*, 1986).

We transform equation (4) and then substitute equation (4) and (5) together with equation (6); the result obtained is:

$$w_i = \min[w_{i-1} + PT_i - \beta_i \times ET_{pi}, w_{FC}] \quad (7)$$

The initial value of monthly soil moisture is input, and then the iterative computation of monthly soil moisture is carried out by using equation (7). Finally, the initial value is determined by assuming the precipitation in a given time, for example, the soil moisture of December 1990 is the initial value. Then a loop computation from January to December every year is conducted until the soil moisture content is relatively stable.

The integrated hydrological and meteorological approach is effective for simulating actual TET over large spatial and temporal extents. The approach developed is advantageous over the existing evapotranspiration–simulation techniques. For example, most of the existing methods are based on individual meteorological, hydrological, experimental or remote sensing methods, while the approach developed is based on an integrated hydrological and meteorological framework; moreover, the approach developed allows dynamic simulation of actual TET where the effects of surface soil moisture are reflected.

APPLICATION

Background

China is located between the largest ocean and the largest continent in the world. It has a vast territory and the terrain in the country reaches peak height in the Qinghai-Tibet Plateau, and then descends from the west to the east. The mainland of China and the oceanic basin of the Pacific are linked by the broad continental shelf. There is an obvious climatic difference by zonal spatial patterns due to its huge south–north and east–west span. Such climatic difference includes unevenly spatial and temporal distribution of annual rainfall (with an average of about 648 mm), and the rainfall and air temperature are synchronous by season. These climatic differences have a significant influence on the distribution of terrestrial evapotranspiration (TET) and lead to the amount of water resource unevenly distributed by spatial area and temporal period in the country, hence increase the frequency of floods and droughts.

The major data of this study include: 1-km DEM of China; 1-km grid distribution maps of land use in 1990/1991, 1995/1996 and 1999/2000, respectively, and 10-km grid distribution map of soil texture; national administrative map; and daily meteorological data from the year 1991 to 2000 recorded at 621 observation stations. The geographical distribution of the meteorological stations is shown in Fig. 1.

In this study, terrestrial evapotranspiration (TET) is simulated and presented based on the grid resolution of 1 km. The value of meteorological variables are interpolated into each grid by the interpolation method of Distance Direction Weighted Mean (DDWM) (Lin *et al.*, 2002), and a continuous distribution of meteorological variable is then generated based on interpolated grids. In addition, the cross-validation method is used to verify the interpolated results at a given station. The cross-validation of potential TET can be conducted by comparing the observed pan value with the simulated one. According to the climatic zoning in China, to verify the simulated

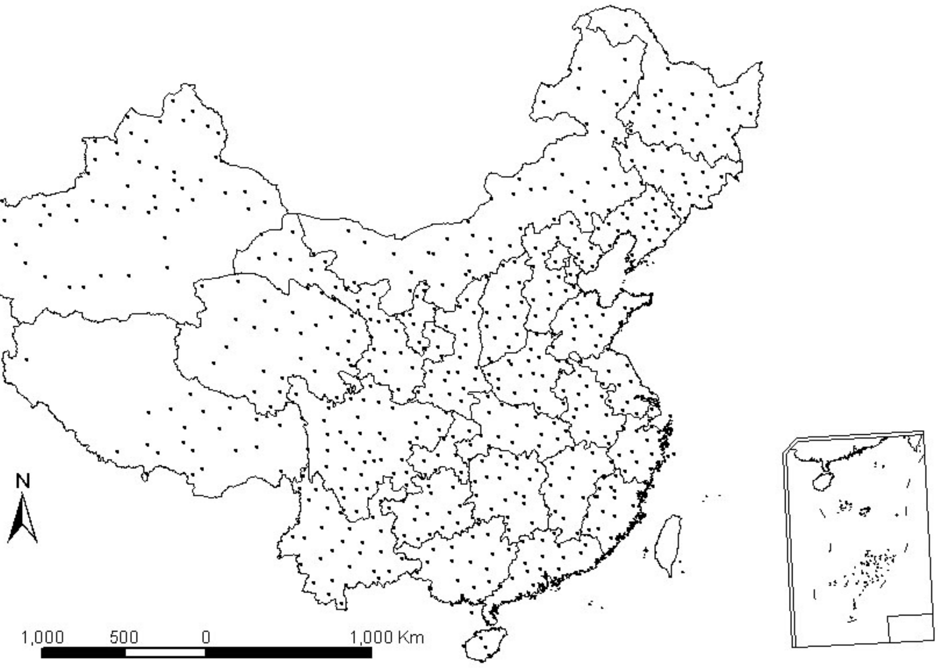

Fig. 1 Distributed map of meteorological stations of China.

results four typical climatic regions were chosen as the experimental areas, with northeastern, western, centre and southern China representing the semihumid zone, arid zone, northern subtropical humid zone, and southern subtropical humid zone, respectively. The observed monthly TET and daily TET data are provided by meteorological stations located in the four regions. The results show that the observed values are a little higher than the corresponding simulated values. By comparing the converted potential TET with the simulated one, the errors are calculated; all were lower than 18%. Therefore, it can be concluded that the Penman equation can be effectively used for simulating the potential TET in China.

Actual TET simulation

There are multiple factors that could affect actual TET value in a given region. Among them, the climatic factor is the primary one since the TET is partially determined by a combined process of the heating action of solar radiation and the drying action of atmospheric dry force. Such a combined process will show a significant difference in responding to different climate regions. This is especially true in the China context due to the significant difference of climate existing among different zones in the country. Hence, the effects of different climate regions on actual TET should be considered in this study for actual TET simulation within a large temporal and spatial scale. In addition, geographical factsor and land use also have significant impacts directly on the determination of TET value. Such effects are desired to be integrated with climatic impacts for the actual TET simulation in this study to provide a more reliable spatial and temporal distribution of TET for supporting decision making in China.

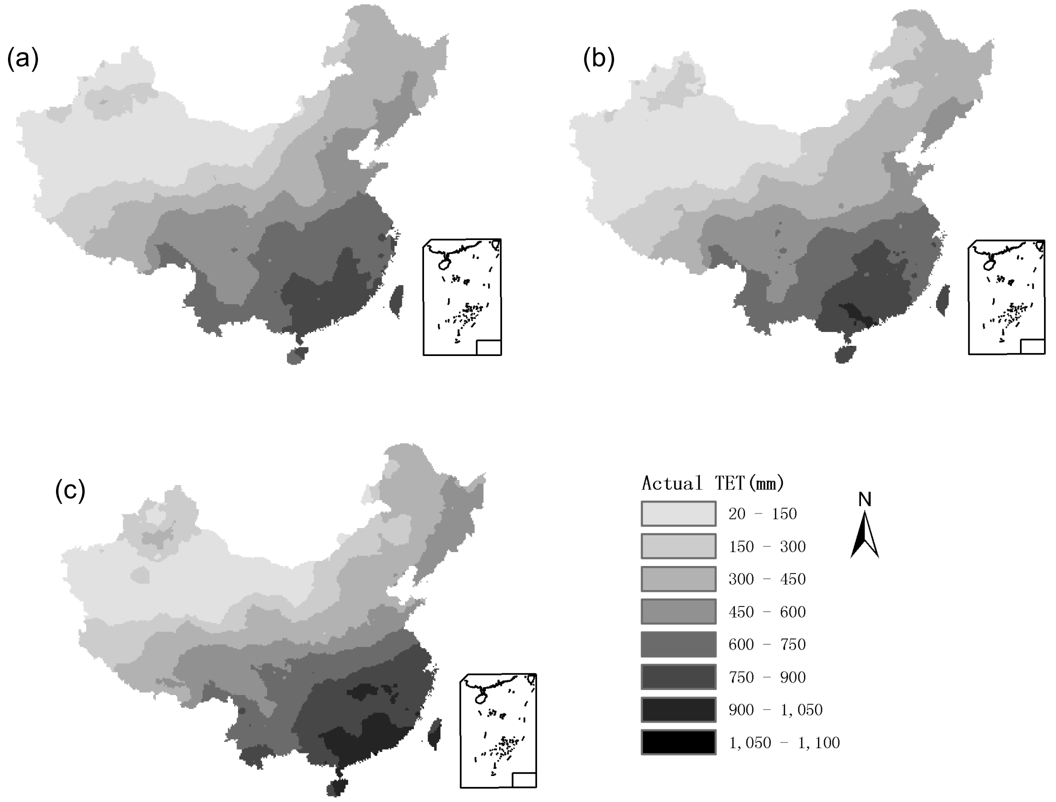

Fig. 2 Actual annual TET distribution map in China for the years (a) 1991, (b) 1995 and (c) 2000.

The spatial and temporal distribution of actual TET by 1991, 1995, and 2000 are simulated as shown in Fig. 2. Spatially, the simulated actual TET value in the east region is generally larger than that in the west and that in the low latitude region is larger than that in the high latitude one. This leads to the largest TET value in southeastern China. The amount in this region is around 580 to 880 mm, being much higher than that in northwestern China, which is below 250 mm. Comparing the TET at the same latitude, the TET increases along longitude from west to east and reach high values at the eastern coastline. With respect to the TET in the identical longitude, the TET would decrease along with the increase of latitude and reach the highest level in the southern coastline. However, although the latitude in the province of Heilongjiang, the most north of China, is higher than that in the Xinjiang Uygur Autonomous Region, its simulated TET is much higher than that in Xinjiang. This bias could be accounted for by the different type of land cover and influence of human activities, where the land cover in Heilongjiang is dominated by vast forest and crop land, while that in Xinjiang is dominated by vast dessert. This explanation could also be supported by the bias of TET between the western Xinjiang and eastern Xinjiang, where the former has more grassland and cropland than the latter, leading to the higher TET in the west than in the east in the same region.

With respect to the yearly TET amount, it can be concluded from Fig. 3 that from 1991 to 1995 and 2000, yearly TET in the northwestern and the southern region would increase. The increased rate of the TET in the northwestern region would be 25.6%

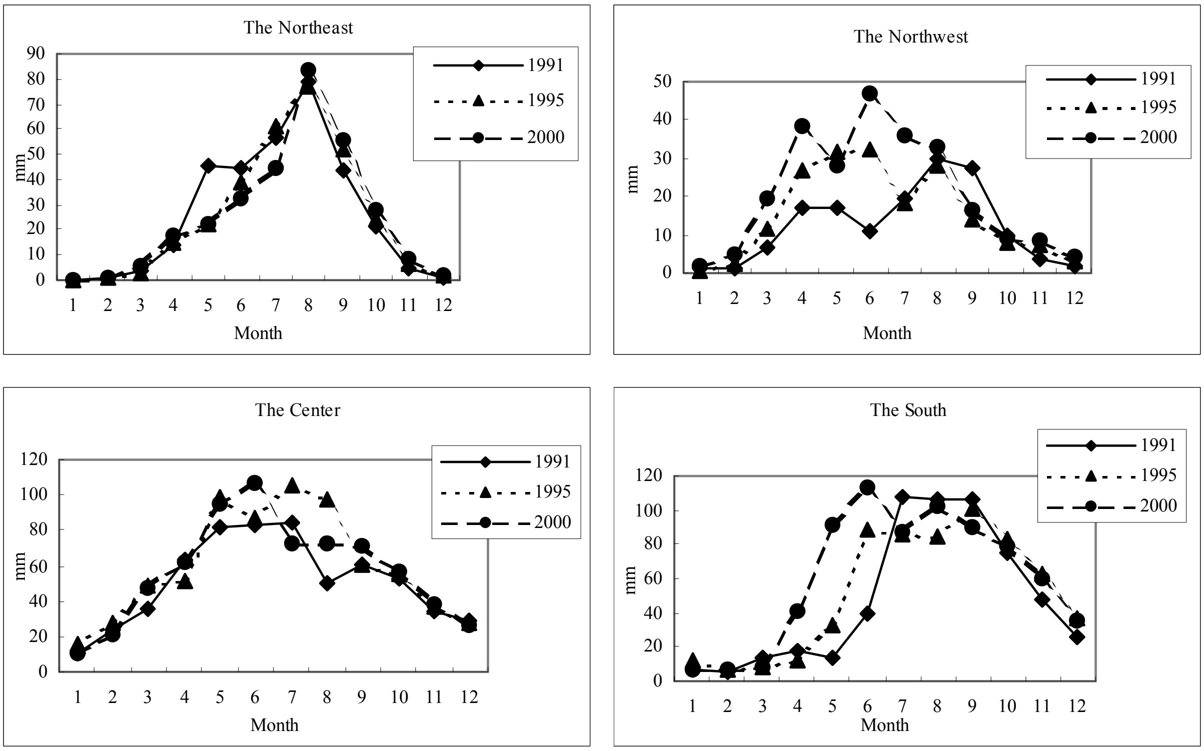

Fig. 3 Changing trends of monthly TET in different representative regions.

from 1991 and 34.7% for 1995, being higher than in the southern region, which is 8.7% and 17.4% for 1995 and 2000, respectively. However, in the northeast, the TET would decrease from 315 mm in 1991 to 300 mm in 1995 and 300 mm in 2000 and the TET in the south would increase from 610 mm in 1991 to 740 mm in 1995, then decline to 680 mm in 2000. Generally, annual TET would increase in response to the monthly actual TET increasing more or less, especially in the northwestern region which is the most arid area in China. The reason could be attributed to climatic change and land-use change associated with human activities within the 10-year horizon.

CONCLUSIONS

In this study, an integrated dynamic approach based on meteorological and hydrological methods was developed in dealing with terrestrial evapotranspiration (TET) simulation at large temporal and spatial extents, by reflecting the impacts of climate, complex land cover features and movement characteristics of soil moisture on the actual TET. A soil-humidity-iterative-computation method is also applied for the actual TET calculation. Also, the integrated hydrological and meteorological approach is effective for simulating the actual TET within large spatial and temporal extents.

The results of the study demonstrated that actual TET in northeastern China is greater than that in northwestern China, and that in the low latitude region it is greater than in the high latitude region. In arid regions it shows a significant seasonal trend, increasing from the minimum level in winter to the maximum one in summer. The climate characteristics, types of underlying surface, precipitation distribution and human activities are other major factors influencing actual TET in China.

The proposed approach can be used for simulating the actual TET when information on climatic change and land cover conditions (e.g. soil moisture) is available. The forecast actual TET can be used as a basis for supporting decisions on agricultural development planning, environmental management, and flood control.

Acknowledgements This research is supported by the Outstanding Overseas Chinese Scholars Fund of Chinese Academy of Sciences, and the Opening Study Foundation of State Key Laboratory of Water Resources and Hydropower Engineering Science (2003B007), and the Natural Sciences Foundation of China (NSFC no. 50279049).

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