Applicable algorithm to map daily evapotranspiration using MODIS images for the Laohahe River basin, northeastern China

XIUQIN FANG[1], LILIANG REN[1], QIONGFANG LI[1], QIUAN ZHU[2], XIAOFAN LIU[1] & YONGHUA ZHU[1]

1 *State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University, No.1 Xikang Road, Nanjing City, 210098, China*
kinkinfang@hhu.edu.cn

2 *International Institute for Earth System Science, Nanjing University,No.22, Hankou Road, Nanjing City, 210093, China*

Abstract An algorithm for mapping daily spatial actual evapotranspiration (ET) from remotely sensed MODIS data is presented. It is based on the surface energy balance scheme and the modified Priestley-Taylor equation, and has been applied to the MODIS data acquired during growing seasons over the Laohahe River basin, northeastern China. Regional daily ET values computed by the modified Xinanjiang hydrological model were used to validate ET values derived from MODIS data. The results were in good agreement, with a root mean square error of 0.3843 mm and correlation coefficient of 0.9029. It is suggested that the algorithm is applicable and operational for mapping daily actual ET over the study area.

Key words daily actual evapotranspiration; MODIS; Priestley-Taylor equation; Laohahe River basin, China

INTRODUCTION

Evapotranspiration (ET) is an important variable for water and energy balances on the Earth's surface (Rivas & Caselles, 2004; Sobrino *et al.*, 2007). Satellite remote sensing provides an unprecedented global coverage of critical hydrological data which are logistically and economically impossible to obtain through ground-based observation networks (Jiang & Islam, 2001).

It is well known that the residual method is the most commonly used scheme to calculate surface latent heat flux based on the surface energy balance:

$$\lambda E + H = R_n - G \tag{1}$$

where R_n is the net radiation (including long-wave and short-wave), G is the soil heat flux, H is the sensible heat flux, and λE is the latent heat flux. It is possible to obtain spatial information of net radiation and soil heat flux satisfactorily from satellite remote sensing images and derive information from them. But significant uncertainty exists in the estimation of sensible heat flux using remotely sensed data, because the aerodynamic resistance and surface roughness length that are required are difficult to estimate accurately (Stewart *et al.*, 1994; Chehbouni *et al.*, 1996). Therefore, the ratio of latent heat flux and available radiant energy was introduced to estimate ET from remote sensing images in many publications (Priestley & Taylor, 1972; Jiang & Islam, 2001; Wang *et al.*, 2006, 2007; Venturini *et al.*, 2008).

Parlange *et al.* (1995) provided a general form of various formulations describing ET:

$$\lambda E = \psi \left[A \frac{\Delta}{\Delta + \gamma}(R_n - G) + B \frac{\gamma}{\Delta + \gamma} f(u)(e_a^* - e_a) \right] \tag{2}$$

where e_a is the air vapour pressure at a reference height (often 2 m); e_a^* is the air saturation vapour pressure; Δ is the gradient of the saturated vapour pressure to the air temperature; ($\Delta = \mathrm{d}e_a^*/\mathrm{d}T$), and γ is the psychrometric constant. The $f(u)$ term represents some function of the wind velocity; A and B are model-dependent parameters; and ψ is generally taken to be unity.

Equation (2) gives daily estimates of latent heat flux with high reliability when applied locally, but has been less successful when applied over large areas (Parlange *et al.*, 1995). One of the major stumbling blocks is that we are unable to obtain effective regional values for the free parameters in these equations (Jiang & Islam, 2001).

Priestley & Taylor (1972) simplified equation (2) to:

$$\lambda E = \alpha\left[\left(R_n - G\right)\frac{\Delta}{\Delta + \gamma}\right] \tag{3}$$

where α = 1.26 is the so-called Priestley-Taylor parameter. Equation (3) can form the basis for estimating evaporation over large areas using primarily remote sensing observations. However, it is only applicable for water bodies and wet vegetation surfaces.

Based on the above study, Jiang & Islam (2001) adapted equation (2) to:

$$\lambda E = \varphi\left[\left(R_n - G\right)\frac{\Delta}{\Delta + \gamma}\right] \tag{4}$$

where φ is a modified form of the parameter α ranging from 0 to 1.26. Equation (4) can be treated as an extension of the Priestley-Taylor equation, since the parameter φ takes a wider range of values than the Priestley-Taylor parameter α. More importantly, the Priestley-Taylor evaporation is primarily applicable for wet conditions, while the use of contextual information allows the application of equation (4) over large heterogeneous areas (Jiang & Islam, 2001).

It has been found that the modified Priestley-Taylor parameter φ can be estimated from the trapezoid feature space of land surface temperature and Normalized Difference Vegetation Index (NDVI) (Jiang & Islam, 2001; Wan *et al.*, 2004; Wang *et al.*, 2006).

In this paper, an algorithm based on equation (4) was applied to MODIS data to estimate the spatial distribution of the daily ET over the Laohahe River basin, northeastern China.

METHODOLOGY

Study area and data

The Laohahe River (catchment area: 18 599 km^2) is located in a semi-arid region and is a tributary of the West Liaohe River. It is situated in northeast China between 41°–43°18′N and 117°–120°30′E (Fig. 1). Topographically, the Laohahe River basin shows well-pronounced variations, with the elevation ranging from about 400 m at the channel outlet to around 2000 m at the mountain ridges in the area.

The MODIS products were downloaded from the Level1 and Atmosphere Archive and Distribution System (LAADS) provided by NASA. A total of 28 MODIS images acquired under

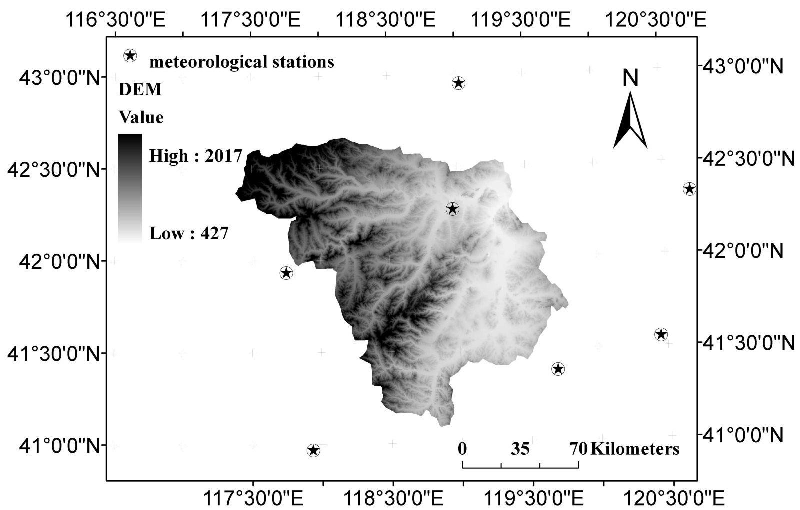

Fig. 1 Topography of the Laohahe River basin and the location of nearby meteorological stations.

clear-sky conditions over the basin were used. The image acquisition period ranged from June to September 2000, covering the growing season. The 1–7, 19 and 31–32 bands of MODIS data were used to retrieve land surface temperature, albedo, atmospheric water content and NDVI respectively.

Daily maximum and minimum air temperature data, collected from standard meteorological stations shown in Fig. 1, were utilized to produce instantaneous air temperature on the days when MODIS images were acquired. Furthermore, 30″ DEM data from SRTM were also used in this study to calculate relative parameters.

ESTIMATION OF RELATIVE PARAMETERS

The modified Priestley-Taylor parameter, φ

The modified Priestley-Taylor parameter, φ of each pixel of the MODIS images was calculated as follows (Jiang & Islam, 2001; Wang *et al.*, 2006):

$$\varphi_i = \frac{LST_{\max} - LST_i}{LST_{\max} - LST_{\min}}\left(\varphi_{\max} - \varphi_{\min}\right) + \varphi_{\min} \tag{5}$$

where $LST_{\max}$, $LST_{\min}$ and LST_i are, respectively, the maximum, minimum and estimated pixel land surface temperature value in the image; $\varphi_{\max}$ = 1.26 and $\varphi_{\min}$ = 0. The maximum value of φ (= 1.26) corresponds to pixels with maximum ET under equilibrium surface moisture conditions, while a value of 0 for φ corresponds to pixels with no ET. The applicable split-window algorithm for retrieving land surface temperature from MODIS data was used herein (Mao *et al.*, 2005).

Parameters Δ and γ

Richards (1971) suggested a simple algorithm to calculate Δ:

$$\Delta = \frac{373.15e^*}{T_a^2}(13.3185 - 3.952T_r - 1.9335T_r^2 - 0.5196T_r^3) \tag{6}$$

$$e^* = P_0 \exp(13.3185T_r - 1.976T_r^2 - 0.6445T_r^3 - 0.1299T_r^4) \tag{7}$$

$$T_r = 1 - 373.15 / T_a \tag{8}$$

where T_a is instantaneous air temperature (K), which was calculated from daily maximum and minimum air temperature (Parton & Jogan, 1981).

The psychrometric constant γ was calculated according to the research of FAO (Allen *et al.*, 1998):

$$\gamma = 0.665 \times 10^{-3} P \tag{9}$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{10}$$

where P is atmospheric pressure (kPa), and z is elevation above sea level (m).

Net radiation, R_n

Net radiation R_n is calculated as:

$$R_n = R_s(1-\alpha) + R_l\downarrow - R_l\uparrow \tag{11}$$

where R_s is the incoming short-wave solar radiation (Wm^{-2}); α is the surface albedo; $R_l\downarrow$ is the long-wave downward radiation (Wm^{-2}) from the atmosphere; and $R_l\uparrow$ is the long-wave upward radiation from land surface (Wm^{-2}).

The parameter R_s is calculated as:

$$R_s = K_0 \cdot dr \cdot \tau_{sw} \cos\theta \tag{12}$$

where K_0 is the solar constant at the atmosphere top (=1370 Wm^{-2}); dr is the sun–earth distance calculated from the Julian day of year; τ_{sw} is the atmospheric clear-sky short-wave transmission factor; and θ is the solar zenith angle. The factor τ_{sw} is obtained by (Tasumi *et al.*, 2000):

$$\tau_{sw} = 0.75 + 2 \times 10^{-5} Z \tag{13}$$

where Z is pixel elevation obtained from DEM data.

The parameter α is calculated from linear combination bands following the Liang's model (Liang, 2001):

$$\alpha = 0.16R(1) + 0.29R(2) + 0.24R(3) + 0.116R(4) + 0.112R(5) + 0.081R(7) - 0.0015 \tag{14}$$

where $R(i)$ is the ith band's reflectance of MODIS images.

Given a certain atmospheric condition, the atmospheric long-wave downward radiation ($R_i\downarrow$) is expected to be very homogeneous over a large synoptic area (Jiang & Islam, 2001). Thus the measurements of $R_i\downarrow$ from Chifeng ground station within the study area were applied to the whole study region.

The parameter $R_i\uparrow$ is calculated as:

$$R_i \uparrow = \varepsilon_s \sigma T_s^4 \tag{15}$$

where ε_s is the land surface emissivity; σ is the Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2} K^{-4}$); and T_s is the land surface temperature (K). According to Sobrino *et al.* (2001), ε_s can be calculated from an empirical relationship with NDVI, which is obtained using the reflectance of the second and first bands ($R(2)$ and $R(1)$) of MODIS images:

$$NDVI = \frac{R(2) - R(1)}{R(2) + R(1)} \tag{16}$$

Soil heat flux, *G*

Although soil heat flux often changes with time, the magnitude is small compared to net radiation over dense vegetation. Soil heat flux generally can be estimated according to relationships between the above parameters R_n, T_s, α and NDVI (Bastiaanssen *et al.*, 1998). In this study we use the following method to estimate G:

$$G = (T_s - 273.15)[0.0036 + 0.0077\alpha](1 - 0.978 NDVI^4) R_n \tag{17}$$

Daily ET

The ET estimated from MODIS data was instantaneous for the time of the satellite sensor overpass. According to the model by Jackson *et al.* (1983), the instantaneous ET can be converted to daily actual total ET under the assumption that the diurnal change of ET is similar to that of solar irradiance on a clear day. The method is:

$$\frac{E_d}{E_i} = \frac{2N}{\pi \sin(\pi \cdot t / N} \tag{18}$$

$$N = 0.945\left[a + b \sin^2\left(\pi(D + 10)/365\right)\right] \tag{19}$$

$$a = 12.0 - 5.96 \times 10^{-2} L - 2.02 \times 10^{-4} L^2 + 8.25 \times 10^{-4} L^3 - 3.15 \times 10^{-7} L^4 \tag{20}$$

$$b = 0.123L - 3.10 \times 10^{-4} L^2 + 8.00 \times 10^{-7} L^3 + 4.99 \times 10^{-7} L^4 \tag{21}$$

where E_d is the daily ET, E_i is the instantaneous ET, t is the time (beginning at sunrise) when a

MODIS image is acquired, N is the time period between sunrise and sunset in units of t, D is the Julian day of year, and L is the pixel's latitude.

RESULTS AND VALIDATION

In this study we obtained spatial distributed mapping of daily ET for 28 clear-sky days between days 157 and 274 in 2000 over the Laohahe River basin, northeastern China.

Because of the missing of the direct measurement of observed actual ET, we use actual ET calculated from water balance equation to evaluate the performance of ET estimation from MODIS images. The modified Xinanjiang model (denoted XAJ model) was utilized to calculate actual ET during the selected 28 days. The core of the model is the storage capacity distribution curves of tension water and free water, which describe their spatial heterogeneity within a basin (Zhao, 1992). The evapotranspiration component is estimated with a model using three soil layers. The XAJ model was successfully used in the Laohahe catchment for daily runoff simulation and flood forecasting (Ren *et al.*, 2006; Yuan & Ren, 2008).

Daily precipitation and pan evaporation data from 1964 to 1980 were used for the calibration of model parameters and the recorded data at the hydrological control station of the basin from 1981 to 2000 were used for the verification. The model gave daily ET values in the selected 28 days. The relationship between actual daily ET estimated from MODIS images and calculated from the hydrological model is shown in Fig. 2.

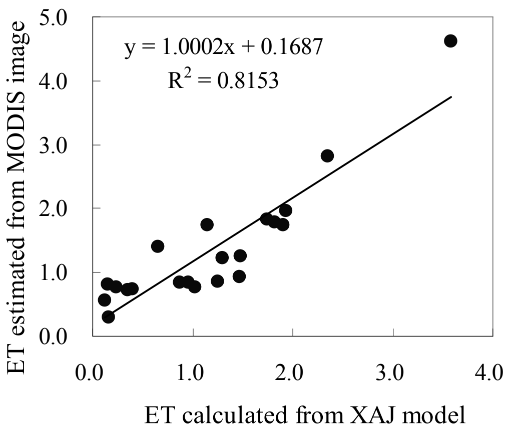

Fig. 2 Relationship between actual daily ET estimated from MODIS images and calculated from the XAJ model.

It can be seen in Fig. 2 that there was a good agreement between both ET, with R^2 and slope coefficient of 0.8153 and 1.0002, respectively. The root mean square error of estimated ET is 0.3843 mm. The results demonstrate that the method used for estimating ET with MODIS images is applicable.

DISCUSSION

An applicable algorithm was developed based on surface energy balance equation and the modified Priestley-Taylor model for the mapping of the distributed daily actual ET using MODIS images. The algorithm was used to estimate actual daily ET from MODIS images during the growing seasons over the Laohahe River basin, northeastern China. Regional daily ET computed by the modified Xinanjiang (XAJ) hydrological model were used to validate the estimated ET values derived from remotely sensed data. The results showed that ET computed from the XAJ model and ET estimated from MODIS images are in good agreement. It is suggested that the algorithm is applicable and operational for mapping daily actual ET over the study area.

In order to use the algorithm proposed by this paper for water recourses management and agricultural decision making, the algorithm should be validated using more data and be tested under different environments and different land use scenario conditions in future work.

Acknowledgements This study was supported by the National Key Basic Research Programme of China under Project no. 2006CB400502. Also this research is the result of the 111 Project under Grant B08048, Ministry of Education and State Administration of Foreign Experts Affairs, China. It is a partial product of National High-Tech Research and Development Program under Grant 2008AA12Z202. And many thanks to Dr Dengzhong Zhao for his kind help with literature collection for this paper.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998) *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy.

Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A. & Holtslag, A. A. M. (1998) A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. *J. Hydrol.* **212-213**, 198–212.

Chehbouni, A., Seen, D. L., Njoku, E. G. & Monteny, B. M. (1996) Examination of the difference between radiative and aerodynamic surface temperature over sparsely vegetated surfaces. *Remote Sens. Environ.* **58**, 177–186.

Jiang, L. & Islam, S. (2001) Estimation of surface evaporation map over southern Great Plains using remote sensing data. *Water Resour. Res.* **37**(2), 329–340.

Liang, S. (2001) Narrowband to broadband conversion of land surface albedo, I. Algorithms. *Remote Sens. Environ.* **76**(2), 213–238.

Mao, K., Qin, Z., Shi, J. & Gong, P. (2005) A practical split-window algorithm for retrieving land-surface temperature from MODIS data. *Int. J. Remote Sens.* **26**(15), 3181–3204.

Parlange, M. B., Eichinger, W. E. & Albertson, J. D. (1995). Regional scale evaporation and the atmospheric boundary layer. *Rev. Geophys.* **33** (1), 99–124.

Parton, W. J. & Jogan, J. A. (1981) A model for diurnal variation in soil and air temperature. *Agric. Met.* **23**, 205–216.

Priestley, C. H. B. & Taylor, R. J. (1972) On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Rev.* **100**, 81–92.

Ren, L., Huang, Q., Yuan, F., Wang, J., Xu, J., Yu, Z. & Liu, X. (2006) Evaluation of the Xinanjiang model structure by observed discharge and gauged soil moisture data in the HUBEX/GAME Project. In: *Calibration and Reliability in Groundwater Modelling: Coping with Uncertainty*, 153–163**.** IAHS Publ. 265, IAHS Press, Wallingford, UK.

Richards, J. M. (1971) Simple expression for the saturation vapor pressure of water in the range –50° to 140°. *British J. Appl. Physics* **4**, 115–118.

Rivas, R. & Caselles, V. (2004) A simplified equation to estimate spatial reference evaporation from remote sesing-based surface temperature and local meterological data. *Remote Sens. Environ.* **93**, 68–76.

Sobrino, J. A., Gómez, M., Jiménez-Muñoz, J.C. & Olioso, A. (2007) Application of a simple algorithm to estimate daily evapotranspiration from NOAA–AVHRR images for the Iberian Peninsula. *Remote Sens. Environ.* **110**, 139–148.

Sobrino, J. A., Raissouni, N. & Li, Z. L. (2001) A comparative study of land surface emissivity retrieval from NOAA data. *Remote Sens. Environ.* **75**, 256–266.

Stewart, J. B., Kustas, W. P., Humes, K. S., Nichols, W. D., Moran, M. S. & de Bruin, H. A. R. (1994) Sensible heat flux—radiometric surface temperature relationship for eight semiarid areas. *J. Appl. Met.* **33**, 1110–1117.

Tasumi, M., Bastiaanssen, W. G. M. & Allen, R. G. (2000) Application of the SEBAL methodology for estimating consumptive use of water and stream flow depletion in the Bear River Basin of Ldaho through remote sensing. In: Earth Observation System Data and Information System Project. Raytheon Systems Company and the University of Idaho, USA.

Venturini, V., Islam, S. & Rodriguez, L. (2008) Estimation of evaporative fraction and evapotranspiration from MODIS products using a complementary based model. *Remote Sens. Environ.* **112**, 132–141.

Wan, Z., Wang, P. & Li, X. (2004) Using MODIS land surface temperature and normalized difference vegetation index products for monitoring drought in the Southern Great Plains, USA. *Int. J. Remote Sens.* **25** (1), 61–72.

Wang, K., Li, Z. & Cribb, M. (2006) Estimation of evaporative fraction from a combination of day and night land surface temperatures and NDVI: A new method to determine the Priestley-Taylor parameter. *Remote Sens. Environ.* **102** (3-4), 293–305

Wang, K., Wang, P., Li, H., *et al.* (2007) A simple method to estimate actual evapotranspiration from a combination of net radiation, vegetation index, and temperature. *J. Geophys. Res.* **112** (D15107), doi:10.1029/2006JD008351.

Yuan, F. & Ren, L. (2008) Evaluating the influence of land-cover change on catchment hydrology through the modified Xinanjiang model. In: *Hydrological Sciences for Managing Water Resources in the Asian Developing World,* 167–174. IAHS Publ. 319, IAHS Press, Wallingford, UK.

Zhao, R. J. (1992) The Xianjiang model applied in China. *J. Hydrol.* **135**(3), 371–381.