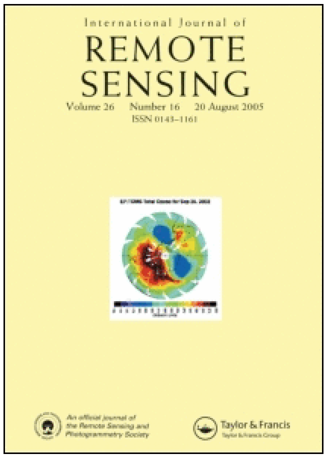

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

Effect of spatial variation on areal evapotranspiration simulation in Haibei, Tibet plateau, China

Zhengquan Li [ab]; Guirui Yu [a]; Qingkang Li [a]; Yuling Fu [ab]; Yingnian Li [c]
[a] Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China
[b] Graduate School of the Chinese Academy of Sciences, Beijing 100039, China
[c] Northwest Institute of Plateau Biology, CAS, Xining 810001, China

Online Publication Date: 01 August 2006
To cite this Article: Li, Zhengquan, Yu, Guirui, Li, Qingkang, Fu, Yuling and Li, Yingnian (2006) 'Effect of spatial variation on areal evapotranspiration simulation in Haibei, Tibet plateau, China', International Journal of Remote Sensing, 27:16, 3487 - 3498
To link to this article: DOI: 10.1080/01431160600647241
URL: http://dx.doi.org/10.1080/01431160600647241

International Journal of Remote Sensing
Vol. 27, No. 16, 20 August 2006, 3487–3498

Effect of spatial variation on areal evapotranspiration simulation in Haibei, Tibet plateau, China

ZHENGQUAN LI†‡, GUIRUI YU*†, QINGKANG LI†, YULING FU†‡ and YINGNIAN LI§

†Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China
‡Graduate School of the Chinese Academy of Sciences, Beijing 100039, China
§Northwest Institute of Plateau Biology, CAS, Xining 810001, China

(*Received 10 October 2005; in final form 17 February 2006*)

Quantification of areal evapotranspiration from remote sensing data requires the determination of surface energy balance components with support of field observations. Much attention should be given to spatial resolution sensitivity to the physics of surface heterogeneity. Using the Priestley–Taylor model, we generated evapotranspiration maps at several spatial resolutions for a heterogeneous area at Haibei, and validated the evapotranspiration maps with the flux tower data. The results suggested that the mean values for all evapotranspiration maps were quite similar but their standard deviations decreased with the coarsening of spatial resolution. When the resolution transcended about 480 m, the standard deviations drastically decreased, indicating a loss of spatial structure information of the original resolution evapotranspiration map. The absolute values of relative errors of the points for evapotranspiration maps showed a fluctuant trend as spatial resolution of input parameter data layers coarsening, and the absolute value of relative errors reached minimum when pixel size of map matched up to measuring scale of eddy covariance system. Finally, based on the analyses of the semi-variogram of the original resolution evapotranspiration map and the shapes of spatial autocorrelation indices of Moran and Geary for evapotranspiration maps at different resolutions, an appropriate resolution was suggested for the areal evapotranspiration simulation in this study area.

1. Introduction

Evapotranspiration is a very important part of the hydrologic cycle and the knowledge of its variation at different spatial and temporal scales is needed in areal estimation. Owing to the spatial variations of land use, land cover, soil physical properties and microclimate condition, the accurate quantification of areal evapotranspiration is a current challenge (Xu *et al.* 2004). Reliable areal evapotranspiration estimating is hindered by a number of feedback mechanisms as well as by a lack of basic hydrometeorological data. In many studies, only very few points evapotranspiration measurement are available, and the few point data cannot detailedly reveal the spatial patterns of evapotranspiration, particularly in the region with complicated land surface (Tenalem 2003).

*Corresponding author. Email: yugr@igsnrr.ac.cn

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160600647241

With the advance in remote sensing technique, increasing number of studies made use of it to improve our understanding of evapotranspiration of the natural system (e.g. Granger 2000, Boegha *et al.* 2002, Pamela *et al.* 2005). However, validating the dependability of the satellite-derived estimation of evapotranspiration is still an issue due to the lack of actual measured data. Eddy covariance was considered to be the most accurate method for measuring the flux of water and carbon at scales of 100 m~1 km (Rana and Katerji 2000). Using eddy covariance measurements to validate the carbon flux, which estimated from remote sensing data, had been reported in many studies (e.g. Reich *et al.* 1999, Walterc *et al.* 2000, Ray *et al.* 2005), but few studies compared the areal evapotranspiration to the flux data. On the other hand, the reliability of the satellite-derived estimation at region scale is often questioned because of the sensitivity of the model outputs to the spatial variations of impact factors (Price 1990, Friedl 1997, Danielle and Geoffrey 1999). Many studies suggested that a change of spatial resolution of parameter maps may introduce significant difference to modeling evapotranspiration. Leenhardt *et al.* (1994) had studied errors in evapotranspiration predictions introduced by coarsening the resolution of soil property maps. Turner *et al.* (1996) demonstrated that the outputs of spatially distributed biogeochemicel model (Forest-BGC) were quite different as spatial resolution of inputs was coarsened. Xu *et al.* (2004) had been assessed the effect of spatially distributed precipitation and soil heterogeneity on modeling daily water flux simulations. However, few studies have been conducted to determine the appropriate resolution in previous research. Atkinson and Curran (1997) recommended analyzing the spatial variation by using geostatistic method to explore the appropriate resolution for certain studying object, but this method has not been applied in study of evapotranspiration. Therefore, it is necessary to develop a method for determining the appropriate resolution for evapotranspiration estimating.

The primary objective of this study was to estimate evapotranspiration at different spatial resolutions for a heterogeneous area at alpine grassland on Tibet by using the Priestley–Taylor model, to find a method to validating the dependability of the evapotranspiration map by comparing eddy covariance measurement data, and to determine the appropriate resolution for evapotranspiration simulation in this study area.

2. Materials and methods

2.1 *Study sites description*

The study sites lie in the alpine grassland on the northeast of the Qinghai-Tibetan plateau in northwestern China (figure 1(*a*)). The terrain is shown as large-area flat plains with mild hills around and elevation ranging from 3100~3400 m. It has a highland continental climate due to its hinterland location and high elevation. The annual mean temperature was only -1.7°C, and annual precipitation was about 580 mm, with most occurring from May to September. The annual global solar radiation was up to 6000~7000 MJ m^{-2}. The study area encompasses a 65 km^2 area including three ecosystems (meadow, swamp and shrub). The area of swamp ecosystem was smallest, and the area of shrub ecosystem was largest. Eddy covariance flux towers have been established to measure CO_2 and H_2O fluxes in the three ecosystems, namely the meadow site (BT), the swamp site (SD), and the shrub site (GCT). The information of three sites is shown in table 1.

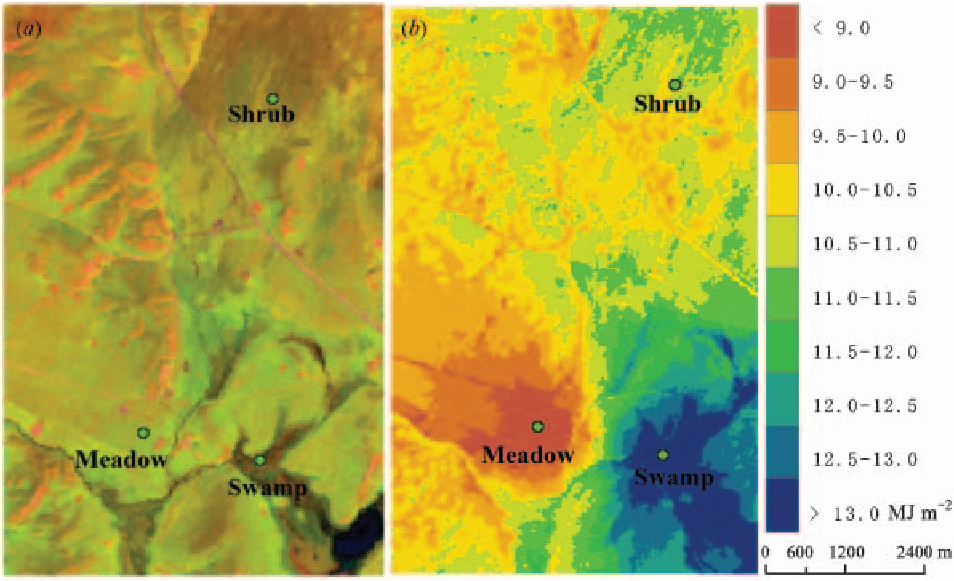

Figure 1(*a*) Location of the flux towers in the study area shown against the 30 m Landsat image; (*b*) The spatial distribution of daytime areal evapotraspiration at 30 m resolution.

2.2 *Data sources*

A Landsat TM image recorded on 5 July 2004 was collected, from which a subscene of 332 by 212 pixels was identified. It was radiometrically and geometrically corrected using 102 ground control points (GCP) to ensure minimum root mean square error (with a residues of one pixel). The image data was georeferenced to the Transverse Mercator (TM). Afterwards, TM3 and TM4 bands were used to derive the normalized difference vegetation index (NDVI). To derive the surface albedo, the TM bands were firstly topographically correted by using digital elevation models, then the surface reflectances were derived from the TM2, TM4 and TM7 bands, finally the surface albedo was calculated by integrating the surface reflectances of TM2, TM4 and TM7 bands (Liu *et al.* 2003).

Latent heat flux data and routine meteorological data on 5 July 2004 was collected for the three ecosystems. Latent heat flux was directly measured by eddy covariance system (CSAT-3, Campbell Scientific Inc and IRGA, Li7500, LICOR

Table 1. Location and characteristics of the three flux tower sites in this study.[a]

Site	Lon (°E)	Lat (°N)	Elevation (m)	Ecosystem type	Canopy height (m)	Soil type	LAI	EC height (m)
BT	101.3050	37.6135	3148	Meadow	0.2	Alpine meadow soil	3.4	2.2~2.5
SD	101.3271	37.6088	3160	Swamp	0.4	Alpine swamp soil	3.5	2.2
GCT	101.3312	37.6654	3293	Shrub	0.5	Alpine scrubby Meadow soil	2.8	2.2

[a]Note: EC is Eddy covariance system.

Inc), and radiation data was measured directly by radiometers (CNR-1, Kipp & Zonnen). Considering the uncertainty of measurement of latent heat flux during nocturnal periods, only the latent heat data during daytime (global radiation $>1\ \mathrm{W m^{-2}}$) was chosen for analysis in this study (Li *et al.* 2005).

2.3 *Generation of multiresolution data sets*

In order to investigate the effect of the spatial resolution of input parameter data layers on the evapotranspiration estimated from the Priestley–Taylor approach, the original resolution (30 m) images for each input parameter data layers were spatially averaged using windows with dimensions of $2^n \times 2^n$ pixels, $n=\{1, 2, \ldots, 6\}$(Patricia and David 1997). The input parameter data layers at 60 m, 120 m, 240 m, 480 m, 960 m, and 1920 m resolutions were generated. Moreover, the 420 m resolution data layers, whose pixel sizes were nearly equal to measuring scale of eddy covariance systems, were also generated using windows with dimensions of 14×14 pixels. In the operation, the coarse resolution output pixels were assigned the arithmetic mean of the values of all the original pixels within the averaging windows. NDVI and surface albedo were calculated after the original TM bands maps were aggregated.

2.4 *The Priestley–Taylor approach*

The Priestley–Taylor equation, a simplification that does not require the measurement of wind speed and humidity, can be used across a region (Priestley and Taylor 1972, Castellv *et al.* 2001), and is described as follows:

$$\mathrm{LE}=\alpha[\Delta(R\mathrm{n}-G)]/(\Delta+\gamma) \quad (1)$$

where *LE* is the latent heat flux (the energy equivalent of evapotranspiration); Rn is net radiation; G is soil heat flux at land surface; Δ is slope of the saturation vapor pressure curve; γ is the psychometric constant; α is usually described as a synthetical environmental variable, and is an empirically determined dimensionless correction.

In equation (1), net radiation (Rn) is estimated from incoming solar radiation, incoming and outgoing long waves radiation fluxes which measured at three ground stations and the surface albedo which derived from remote sensing data:

$$R\mathrm{n}=(1-r)Q-\left(L_{\mathrm{down}}-L_{\mathrm{up}}\right) \quad (2)$$

where r is the surface albedo; Q is the incoming solar radiation; L_{down} is the downwelling long wave radiation and L_{up} is the upwelling long wave radiation.

As Rn can be mapped aerially on the basis of space borne r (surface albedo), Q, L_{down} and L_{up} data, the G/Rn fraction is an attractive tool to describe the areal soil heat flux (G) patterns. Based former studies (Kustas and Daughtry 1990, Oevelen 1993), the G/Rn fraction was described as the follow equation:

$$G/R\mathrm{n}=0.30\times\left[1-0.98(\mathrm{NDVI})^4\right] \quad (3)$$

And the Δ/γ fraction can be described as a function of air pressure and air temperature (Cheng and Chen, 2003).

$$\Delta/\gamma=(P_{\mathrm{o}}/P_{\mathrm{a}})\times 0.67\times 10^{0.0235T_a} \quad (4)$$

where P_{o} is the normal air pressure; P_{a} is the actual observated air pressure and T_{a} is the air temperature.

3. Results

3.1 *Estimating evapotranspiration by the Priestley–Taylor approach*

Figure 1(*b*) shows the spatial distribution of the daytime areal evapotranspiration, which was estimated using Priestley–Taylor approach. The result indicated that evapotranspiration from the land surface varied significantly from place to place. The evapotranspiration in the swamp ecosysytem was highest, and the meadow ecosystem was the lowest. The mean value obtained for the evapotranspiration map at orignal resolution was 10.73 MJ/m^2 d with a standard deviation of 1.16 MJ m^{-2} d. Comparison between the simulated values and the actual observation values was shown in table 2. The surface albedo estimated using remote sensing data was higher than the actual observation values at the BT and GCT sites, but was nearly equal to the actual observation value at the SD site. The net radiation (Rn) calculated by equation (2) matched well with the values measured directly by radiometers at three sites, with the relative errors less than 6.6%. Comparing the evapotranspiration (latent heat flux) measured by eddy covariance system to the simulated evapotranspiration based on equation (1), we found only a little difference between them. The absolute value of relative errors of the original resolution evapotranspiration map at three sits were less than 5.5%, and less than 1.8% for evapotranspiration map at 420 m resolution. The implies that the evapotranspiration of this study area could be modeled quite well by the Priestley–Taylor approach.

3.2 *Validation of evapotranspiration maps by using eddy covariance flux data*

Integrated remote sensing data with models was widely used to simulate the spatial distribution of the areal evapotranspiration. However, owing to the lack of actual observation data, validating the dependability of evapotranspiration map is difficulty. Rana and Katerji (2000) reported that eddy covariance was the most accurate method for measuring the flux of water and carbon at scales of 100 m$\sim$1 km. In this study, measuring scale of eddy covariance system is approximately 400 m$\sim$450 m, depending on rule-of-thumb and the installed height of eddy covariance system (Garratt 1990). Figure 2 shows the variations of relative errors of the points for simulated evapotranspiration maps depended on the resolution coarsening. At shrub ecosystem (GCT), the relative errors decreased firstly and then hold almost a constant as the resolution coarsening. The absolute value of relative error always increased with the resolution coarsening at swamp ecosystem (SD). At meadow ecosystem (BT), there was a slight variation initially, followed by a drastic increase. A common phenomenon of the three ecosystems was that the mean of absolute value of relative errors of three ecosystems nearly reached minimum when pixel size (420 m) of map matched up to measuring scale of eddy covariance system. But we cannot conclude that the dependability of evapotranspiration map at 420 m resolution is higher than the evapotranspiration map at 30 m. The reason being that maybe scale mismatch between the pixel size of the map and the measuring scale of eddy covariance system induced the errors of evapotranspiration map (more discussion in section 4.2). Figure 2 demonstrates that validating the dependability of map should use measured data with the representative area equivalent to a single map resolution cell. Otherwise, we may educe misjudgement depending on false information.

Table 2. Comparison between the simulated and the actual observation values.[a]

Site	Surface albedo		Rn (MJ m^{-2} d^{-1})		Evapotranspiration (MJ m^{-2} d^{-1})		
	Observation	Simulation	Observation	Simulation	Observation	Simulation(30m)	Simulation(420m)
BT (Meadow)	0.17	0.21 (AE=0.04)	14.40	13.44 (ARE=6.6%)	8.87	8.74 (ARE=1.5%)	8.75 (ARE=1.4%)
SD (Swamp)	0.12	0.12 (AE=0.00)	22.81	23.11 (ARE=1.3%)	14.52	14.61 (ARE=0.6%)	14.38 (ARE=1.0%)
GCT (Shrub)	0.11	0.15 (AE=0.04)	18.06	17.04 (ARE=5.6%)	10.37	10.94 (ARE=5.5%)	10.56 (ARE=1.8%)

[a]Note: AE is the absolute error and ARE is the absolute value of relative error; Simulation (30 m) and Simulation (420 m) are simulation values of points for evapotranspiration maps at 30 m (original resolution) and 420 m resolutions; AE=Simulation – Observation, ARE=|[(Simulation – Observation)/Observation] × 100%|.

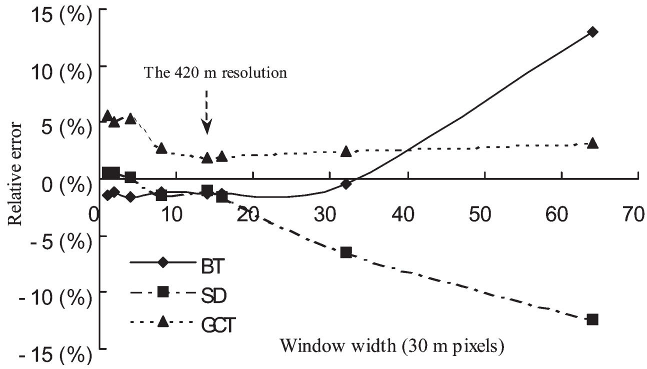

Figure 2. Different response of evapotranspiration simulation with resolution coarsening at three ecosystems. BT: Meadow ecosystem, SD: Swamp ecosystem and GCT: Shrub ecosystem.

3.3 *Effect of spatial resolution on evapotranspiration simulation*

In order to investigate the effect of the spatial resolution of the input parameter data layers on the quantification of areal evapotranspiration, the input parameter data layers were generated at different spatial resolution using the aggregation procedure as described in section 2.3. The areal evapotranspiration maps were estimated using equation (1) at spatial resolutions of 30, 60, 120, 240, 420, 480, 960, and 1920 m, respectively. The mean values and the standard deviations for all evapotranspiration maps were shown in figure 3. The mean values for all evapotranspiration maps were similar to each other. This indicates that the mean of evapotranspiration map was invariable with the spatial resolution coarsening. Their standard deviations showed different shape in comparison to their mean values. At the beginning (the resolution was less than 480 m), the standard deviation decreased slightly with the spatial resolution coarsening. However, the resolution transcended about 480 m, it

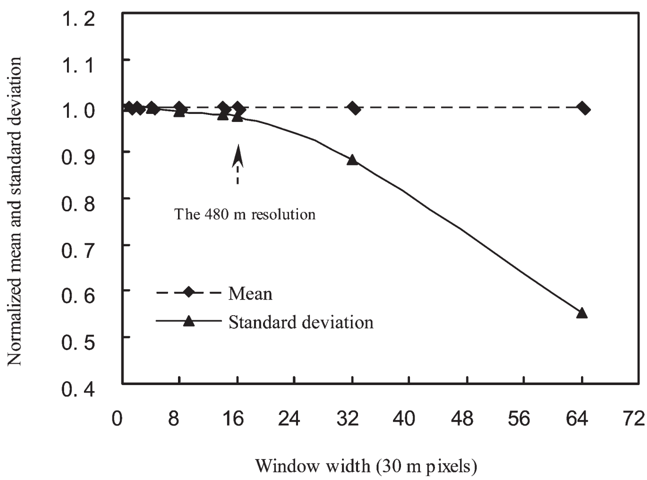

Figure 3. The variation of the mean and the standard deviation for evapotranspiration map depended on spatial resolution of the input parameter data layers coarsening. Map means and standard deviations were nomalized by the mean and standard deviations of the original resolution evapotranspiration map, respectively.

decreased drastically, implying that spatial structure information of the original map was badly lost. The result suggested that the coarse resolution (>480 m) evapotranspiration maps were incapable to capture the actual spatial distribution of areal evapotranspiration in the area of this study.

3.4 *Determining appropriate resolution of evapotranspiration simulation*

The existence of spatial heterogeneity in natural vegetation and its impact on modeling are necessitating to specify the appropriate spatial scale and pixel size for studying different aspects of ecosystems. Estimated using remotely sensed data or ground data, the semi-variogram provides a basic tool for examining the spatial structure and its function gives an idea of the spatial dependence of each point on its neighbor (Curran 2001). At a distance referred to as the range, the semi-variance levels off to a relatively constant value referred to as the sill. This implies that within the range, the pixels value variation is smaller when the pairs of sample points are closer together, and beyond this range distance, the variation in pixels values is no longer spatially correlated.

The lag size of semi-variogram can affect the analysis of map spatial variability, using the pixel of the original map as the lag size of simulated semi-variogram, can avoid masking the small-scale spatial structure of the original map due to larger lag size (Bai and Wang 2002). In this study, the spatial variation of the original resolution evapotranspiration map was quantified by the semi-variogram with lag size of one pixel. The spherical model with a nugget (nugget=0.0025) effect was applied to the image and could simulate the data well when compared to the sample variograms. The range and sill of the spherical model was 485.56 m and 0.1523, respectively. The variation of evapotranspiration map can be partly explained by the variations of surface albedo and NDVI maps (figure 4). The range was the object size of the original map, that is, the pixels within the range belong to the same object, and the pixels outside the range belong to different objects. From the parameters of the spherical mode, it can be found that the resolution at 485.56 m (approximately was 480 m) was the appropriate spatial resolution for the areal evapotranspiration simulated at this study area.

Another index to study spatial heterogeneity within an area is spatial autocorrelation index. Two of the most widely accepted spatial autocorrelation indices are the Geary and Moran indices. When the Moran indices are higher than 0.5 or Geary indices are less than 0.5 which means the image has evidently autocorrelation (Bai and Wang 2002). As another method of examining the optimal spatial resolution, the Geary and Moran indices for all evapotranspiration maps at different resolutions were calculated by using the geostatistical analyst. Figure 5 shows that the Moran indices decreased with the coarsening of map resolution, whereas the Geary indices increased with the resolution coarsening. In the resolution from 30 m to 480 m, the Geary and Moran indices have only slight variation, suggesting a reasonable aggregation of the map pixels. However, if the resolution coarsed more than 480 m, the Geary and Moran indices change rapidly, indicating a loss of aggregation of the map pixels.

In terms of accuracy, the best quantification of areal evapotranspiration would be obtained with the highest spatial resolution. However, the need to match scales between models, or the need for computational efficiency, often requires aggregating variables. The appropriate resolution of aggregation should be fine enough to capture significant spatial variability but coarse enough to minimize redundancy

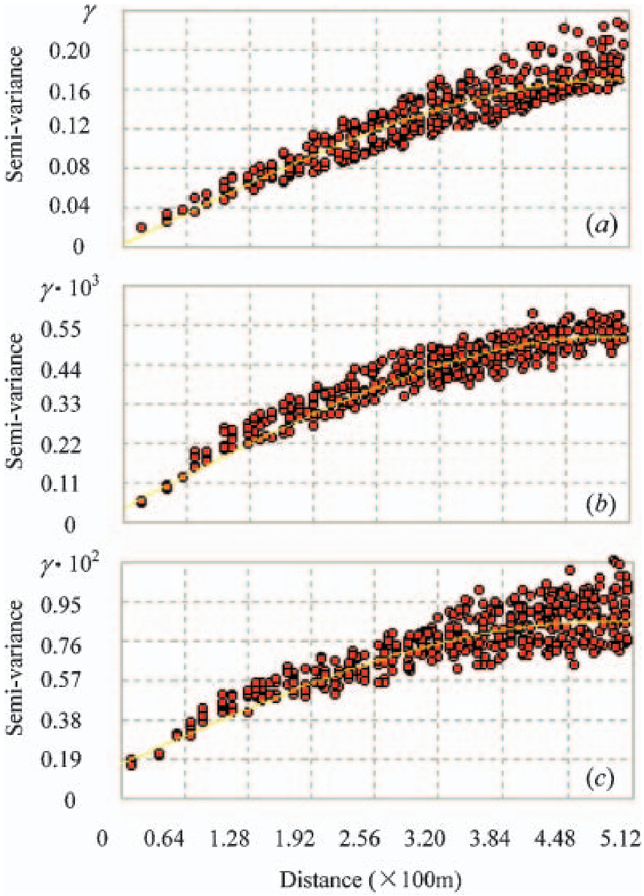

Figure 4. The semi-variogram of maps at original resolution with lag size of one pixel. (*a*) evapotranspiration: semi-variance=0.1523 × spherical (485.56) + 0.0025; (*b*) surface albedo: semi-variance=0.00048 × spherical (480.37) + 0.00004; (*c*) NDVI: semi-variance=0.0071 × spherical (475.12) + 0.0164.

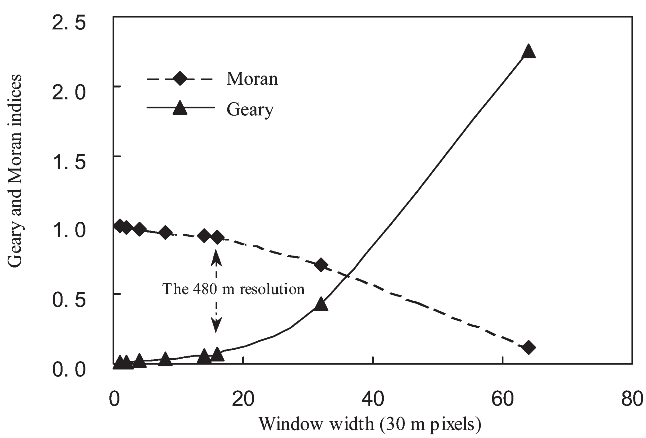

Figure 5. The variations of Geary and Moran indices depended on resolution coarsening.

(Patricia 1997). The analysis of the semi-variogram and the variations of the Geary and Moran indices indicate that the spatial structure information of the original evapotranspiration map was hold well at 480 m resolution and badly lost at resolution coarser than 480 m. This study suggests that 480 m resolution could be a good compromise in terms of volume of data, processing time and accuracy. It is a reasonable spatial resolution to appropriately aggregate original map pixels for studying the spatial distribution of evapotranspiration at this study area.

4. Discussion

4.1 *Determination of α in the Priestley–Taylor approach*

In the Priestley–Taylor approach (equation (1)), partitioning of available energy ($Rn-G$) into latent and sensible heat fluxes is governed by the synthetical environmental variable α, air temperature, and air pressure (through the dependence of $\Delta/(\Delta+\gamma)$ on air temperature and air press). The synthetical environmental variable α was controlled by air temperature, wind speed, vapor-pressure deficit, LAI, incoming solar radiation, and soil moisture in the upper 30 cm layer. Due to the specific environmental characteristics in this study area, the synthetical environmental variable α was assumed to be 1.37. This value was larger than that ($\alpha=1.26$) reported in the previous study (Priestley and Taylor 1972). Another reason for assuming α a little higher in this study was due to overestimation of soil heat flux (G) by the equation (3). The soil heat flux (G) estimated using the normalized difference vegetation index (NDVI) and Rn turned to be 45~60% higher than the observation by soil heat flux plates. Increase of α value can counteract the effect of overestimation of soil heat flux (G) on simulation of the evapotranspiration.

4.2 *Variation of relative errors with resolution coarsening at three ecosystems*

Figure 2 shows that the variations of relative errors had different response to the resolution coarsening at three ecosystems when the resolution is coarser than 480 m. According to the actual observation by eddy covariance system, the evapotranspiration was 14.52 MJ m^{-2} d^{-1}, 10.37 MJ m^{-2} d^{-1} and 8.87 MJ m^{-2} d^{-1} at the swamp, shrub and meadow ecosystem respectively. As the resolution farther coarsened (pixel size >480 m), the pixels may be comprised of multi-ecosystem vegetations. Based on the relationship between the NDVI spatial distribution and pixels size of evapotranspiration maps, we can see that the simulated value of the pixel at the swamp ecosystem kept decreasing, due to appearance of more and more vegetations of the meadow and/or shrub ecosystem coming in the pixel area with the resolution coarsening (shown in figure 6). On the contrary, the pixel value increased with coarsening of resolution at the meadow ecosystem, due to vegetations of the shrub and/or swamp ecosystem gradually mixed into the pixel area. The shrub ecosystem was a considerable uniform in vegetation composition, so the pixel was composed of only shrubs, regardless of the coarsening of the resolution. This resulted in the stability of the simulated value of the pixel.

5. Conclusion

Using the Priestley–Taylor approach, the spatial distribution of the areal evapotranspiration at different resolutions in Haibei was estimated by integrated remote sensing data and *in situ* measurements. The simulated evapotranspiration values

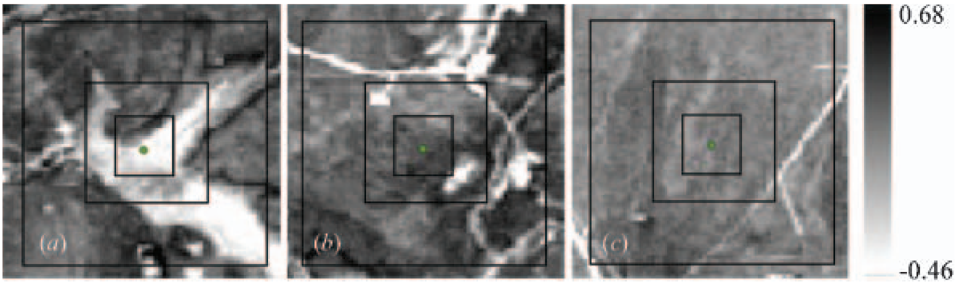

Figure 6. The NDVI spatial distribution of three ecosystems with the pixels size of 480, 960 and 1920 m resolution maps from inner to outer respectively. (*a*) swamp, (*b*) meadow, (*c*) shrub. The point is the flux tower position.

matched well with the latent heat flux that was directly measured by eddy covariance system. The relative errors of the 420 m resolution (approximately equal to measuring scale of eddy covariance system) evapotranspiration map were less than 1.8%. Based on the investigation of the relationship between pixel size of simulation map and measuring scale of eddy covariance system, the right way to validation for the dependability of the evapotranspiration map was found. When the representative area of actual observation is approximately equal to pixel size, the result of validation of the evapotranspiration map was much justifiable. The analysis of spatial variation of evapotranspiration maps indicate that the spatial structure information of the original map was hold well at 480 m resolution and badly lost at resolution coarser than 480 m, and suggested that the resolution was appropriate to simulate the spatial distribution of evapotranspiration at the study area.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Grant No. 30225012), the National Key Research and Development Program (Grant No. 2002CB412501), and the Global Environment Research Fund of the Ministry of the Environment, Japan (S-1: Integrated study for terrestrial carbon management of Asia in the 21st century based on scientific advancements). The authors would like to thank Dr Zhuang Jie and Dr Wang Shaoqiang for their constructive comments and suggestions on this paper.

References

ATKINSON, P.M. and CURRAN, P.J., 1997, Choosing an appropriate spatial resolution for remote sensing. *Photogrammetric Engineering and Remote Sensing*, **63**, pp. 1345–1351.

BAI, Y.C. and WANG, J.F., 2002, *Uncertainty in Remote Sensing: Classification and Scale Effect Modeling* (Beijing: Geological Publishing House).

BOEGHA, E., SOEGAARDA, H. and THOMSEN, A., 2002, Evaluating evapotranspiration rates and surface conditions using Landsat TM to estimate atmospheric resistance and surface resistance. *Remote Sensing of Environment*, **79**, pp. 329–343.

CASTELLV, F., STOCKLE, C.O., PEREZ, P.J. and IBANEZ, M., 2001, Comparison of methods for applying the Priestley-Taylor equation at a regional scale. *Hydrological Processes*, **15**, pp. 1609–1620.

CURRAN, P.J., 2001, Remote sensing: Using the spatial domain. *Environmental and Ecological Statistics*, **8**, pp. 311–344.

DANIELLE, J.M. and GEOFFREY, J.H., 1999, Remote sensing contributions to the scale issue. *Canadian Journal of Remote Sensing*, **25**, pp. 357–366.

FRIEDL, M.A., 1997, Examining the effects of sensor resolution and sub-pixel hetegeneity on spectral vegetation indices: implications for biophysical modeling. In *Scale in Remote Sensing and GIS*, A.Q. Dale and F.G. Michael (Eds) (Boca Raton, FL: CRC Lewis), pp. 113–139.

GARRATT, J.R., 1990, The internal boundary layer. *Boundary-Layer Meteorology*, **50**, pp. 171–203.

GRANGER, R.J., 2000, Satellite-derived estimates of evapotranspiration in the Gediz basin. *Journal of Hydrology*, **229**, pp. 70–76.

KUSTAS, W.P. and DAUGHTRY, C.S.T., 1990, Estimation of the soil heat flux/net radiation ratio from spectral data. *Agricultural and Forest Meteorology*, **49**, pp. 205–223.

LEENHARDT, D., VOLTZ, M. and BORNAND, M., 1994, Propagation of the error of spatial prediction of soil properties in simulating crop evapotranspiration. *European Journal of Soil Science*, **45**, pp. 303–310.

LI, Z.Q., YU, G.R., WEN, X.F., ZHANG, L.M., REN, C.Y. and FU, Y.L., 2005, Energy balance closure at ChinaFLUX sites. *Science in China Series. D*, Supplement I, pp. 54–72.

LIU, S.C., ZHANG, W.C., JIANG, J.J. and ZHAO, D.Z., 2003, Derivation of ground reflectance and albedo by integration of landsat thematic mapper and DEM in Heihe river basin, northwestern China. *Scientia Geographica Sinica*, **23**, pp. 585–591.

OEVELEN, P.J., 1993, Determination of the available energy for evapotranspiration with remote sensing *MSc Thesis*, Agricultural University of Wageningen, 68.

PAMELA, L.N., JAMES, C., EDWARD, G., DERRICK, L., ALFREDO, H. and WAN, Z.M., 2005, Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. *Remote Sensing Environment*, **94**, pp. 17–30.

PATRICIA, A.B. and DAVID, R.M., 1997, Choice of data scale: predicting resolution error in a regional evapotranspiration model. *Agricultural and Forest Meteorology*, **84**, pp. 97–113.

PRICE, J.C., 1990, Using spatial context in satellite data to infer regional scale evapotranspiration. *IEEE Transactions on Geoscience and Remote Sensing*, **28**, pp. 940–948.

PRIESTLEY, C.H.B. and TAYLOR, R.J., 1972, On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, **100**, pp. 81–92.

RANA, G. and KATERJI, N., 2000, Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of Agronomy*, **13**, pp. 125–153.

RAY, L., HELEN, A.C., STEVEN, J.Z. and DALE, H., 2005, Carbon and water fluxes over a temperate Eucalyptus forest and a tropical wet/dry savanna in Australia: measurements and comparison with MODIS remote sensing estimates. *Agricultural and Forest Meteorology*, **129**, pp. 151–173.

REICH, P.B., TURNER, D.P. and BOLSTAD, P., 1999, Approach to spatially distributed modeling of net primary production (NPP) at the landscape scale and its application in validation of EOS NPP products. *Remote Sensing Environment*, **70**, pp. 69–81.

TENALEM, A., 2003, Evapotranspiration estimation using thematic mapper spectral satellite data in the Ethiopian rift and adjacent highlands. *Journal of Hydrology*, **279**, pp. 83–93.

TURNER, D.P., DODSON, R. and MARKS, D., 1996, Comparison of alternative spatial resolutions in the application of a spatially distributed biogeochemical model over complex terrain. *Ecological Modelling*, **90**, pp. 53–67.

WALTERC, O., GEORGEL, V., JOSEPH, V., TIM, C., STEVE, B., EDWARD, D., ALLEN, H., DOUGLAS, S., BILL, B., VIKTOR, N. and ROMMEL, Z., 2000, A scaling approach for quantifying the net CO_2 flux of the Kuparuk River Basin, Alaska. *Global Change Biology*, **6**(Suppl. 1), pp. 160–173.

XU, L., GUO, J.Z. and LEUNG, L.R., 2004, Assessment of the effects of spatial resolutions on daily water flux simulations. *Journal of Hydrology*, **298**, pp. 287–310.