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Simplified SEBAL method for estimating vast areal evapotranspiration with MODIS data

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Abstract: The SEBAL (surface energy balance algorithm for land) model provides an efficient tool for estimating the spatial distribution of evapotranspiration, and performs a simple adjustment procedure to calculate sensible heat flux using the wind speed data set from only one weather station. This paper proposes a simplified method to modify the traditional SEBAL model for calculating the 24-hour evapotranspiration (ET_{daily}) in the Haihe Basin with data from 34 weather stations. We interpolated the wind speeds using the inverse distance weighting method to establish a wind field and then used it to calculate the friction velocity directly. This process also simplifies the iterative computation process of sensible heat flux. To validate the feasibility of this simplified method, we compared the results with those obtained with an appropriate but more complex method proposed by Tasumi, which separates a vast area into several sub-areas based on the weather conditions, and runs the SEBAL model separately in each sub-area. The results show good agreement between the evapotranspiration generated by the two methods, with a coefficient of determination (r^2) of 0.966, which indicates the feasibility of estimating evapotranspiration over a large region with the simplified method.

Key words: *evapotranspiration; SEBAL model; MODIS; remote sensing; sensible heat flux; Haihe Basin*

1 Introduction

Evapotranspiration is of great importance to water resources management. Over most of the global land area, evapotranspiration is the second largest element of the water cycle (after precipitation), and accurate estimation of it at a regional scale is therefore necessary for designing appropriate management strategies.

Experimentally, there are a lot of methods for accurately estimating point evapotranspiration, including weighing lysimeters, the Bowen ratio technique, and the eddy correlation techniques. Unfortunately, these methods only provide evapotranspiration for a specific location and fail to

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provide regional evapotranspiration estimation at an affordable cost. In recent years, remote sensing techniques have been extensively developed due to their ability to provide periodic data and reliable regional estimates. They are recognized as the only viable means to map regional- and meso-scale patterns of evapotranspiration on the earth's surface in a globally consistent and economically feasible manner (McCabe and Wood 2006). Many researchers (Vidal and Perrier 1989; Bastiaanssen 1995; Granger 1997; Allen et al. 2007) have worked on developing models with a combination of satellite images and weather data for vast areas.

SEBAL (surface energy balance algorithm for land) is one of the most widely used models around the world (Ahmad et al. 2006; Bastiaanssen et al. 1998a, 1998b, 2005, 2010; Bastiaanssen and Bos 1999; Hemakumara et al. 2003; Morse et al. 2000; Singh et al. 2008; Zhang et al. 2010). It calculates evapotranspiration through 25 computational sub-models that generate net surface radiation, soil heat flux, and sensible heat flux to the air. By subtracting the soil heat flux and sensible heat flux from the net radiation at the surface, we are left with a residual energy flux that is used for evapotranspiration. The most difficult and complex procedure of SEBAL is the calculation of sensible heat flux, which is closely related to the surface type and weather conditions. Sensible heat flux is estimated from wind speed and surface temperature using a unique internal calibration of the near surface-to-air temperature difference as described by Bastiaanssen et al. (1998a). The traditional SEBAL model of Bastiaanssen et al. uses the wind speed data set from only one weather station to calculate the wind speed at a height of 200 m, which is assumed to be constant over all pixels of the vast area. This assumption is practical and does not result in obvious error when applied to a small region.

However, water resources managers are often concerned with the evapotranspiration over vast areas where weather conditions and surface features cannot be seen as uniform. To estimate evapotranspiration in such areas using the SEBAL model, one solution is to separate a vast area into several sub-areas based on the weather conditions, and then run the SEBAL model separately in each sub-area, using different coldest and hottest pixels and weather data (Tasumi 2003). However, the large time requirement for this method is not acceptable when processing time-series images with more than ten weather stations.

We propose a simplified SEBAL method for computing the 24-hour evapotranspiration (ET_{daily}) over a vast area and validate it by comparing the results with those from Tasumi (2003). As an example, we selected the high-quality MODIS (moderate-resolution imaging spectroradiometer) scenes from August 13, 2007, which cover the Haihe Basin, with 34 weather stations inside.

2 Study area and data collection

2.1 Description of study area

The Haihe Basin is located between about 111.5°E and 120.0°E, and 35.0°N and 43.0°N, and has an area of 318 200 km^2. To the north are the Yanshan Mountains, to the west are the

Taihang Mountains, and to the east is the vast North China Plain. The area has water shortages because it must provide for 195 million people, 15% of China's population, with only 1.5% of the country's water resources. Hills and plateaus occupy nearly 60% of the total area, and the remaining 40% is plains. A land use map from the MODIS Land Cover Type product (MCD12Q1) is shown in Fig. 1.

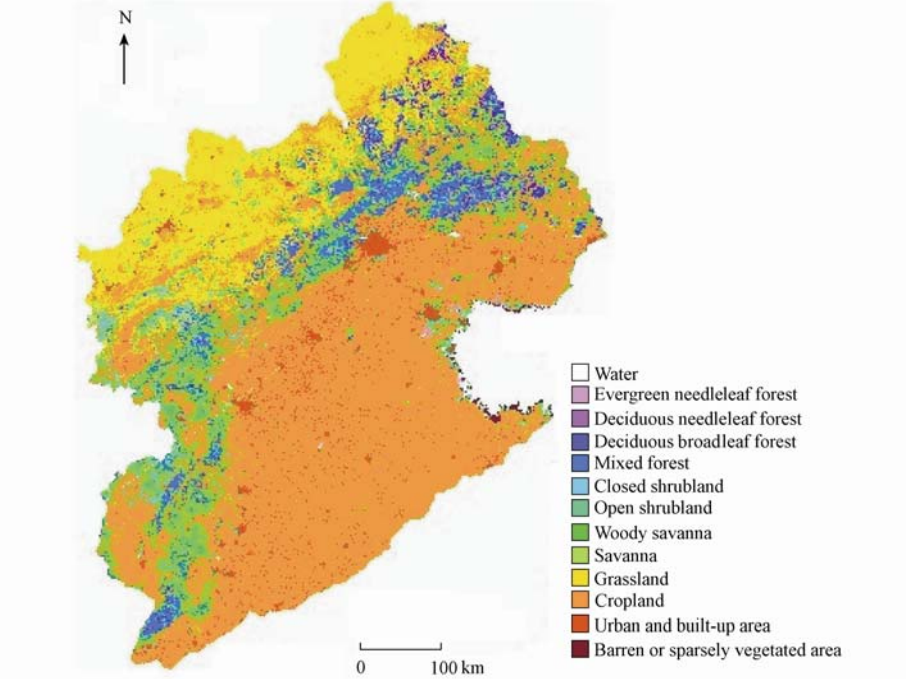

Fig. 1 Land use map of Haihe Basin

2.2 Data collection

The key input data based on SEBAL include digital image data collected by MODIS, digital elevation data, and weather data.

2.2.1 MODIS data

In this study we used high-level gridded MODIS products (see details in Table 1), which were obtained from the National Aeronautics and Space Administration (NASA) of China website using the FtpPull protocol. In order to get full coverage of the Haihe Basin, four sets of images, "h26v04", "h26v05", "h27v04," and "h27v05," were selected.

Table 1 MODIS data used in this study

MODIS data	Description	Spatial resolution (m)	Image acquisition date
MOD09GA	Surface reflectance bands 1-7, daily	500	August 13, 2007
MOD11A1	Land surface temperature (LST)/emissivity, daily	1 000	August 13, 2007
MOD13Q1	Normalized difference vegetation index (NDVI), 16-day	250	August 1 to 16, 2007
MCD12Q1	Land cover type, yearly	500	2007

2.2.2 Data from digital elevation model

To account for differences in slope, aspect, and elevation, a digital elevation model (DEM) was used for the SEBAL mountain model. The original DEM data from SRTM (Shuttle Radar Topography Mission) in 2007 was downloaded from the website of the International Center for Tropical Agriculture (CIAT). The slope and aspect were calculated from the DEM using models provided in the ERDAS IMAGINE software.

2.2.3 Weather data

In this study, we collected weather data in August 13, 2007 from 34 weather stations unevenly distributed in the Haihe Basin (Fig. 2). They include daily average temperature, daily average atmospheric pressure, wind speed, and actual vapor pressure. The time when the wind speed was observed was quite close to that of the satellite image acquisition.

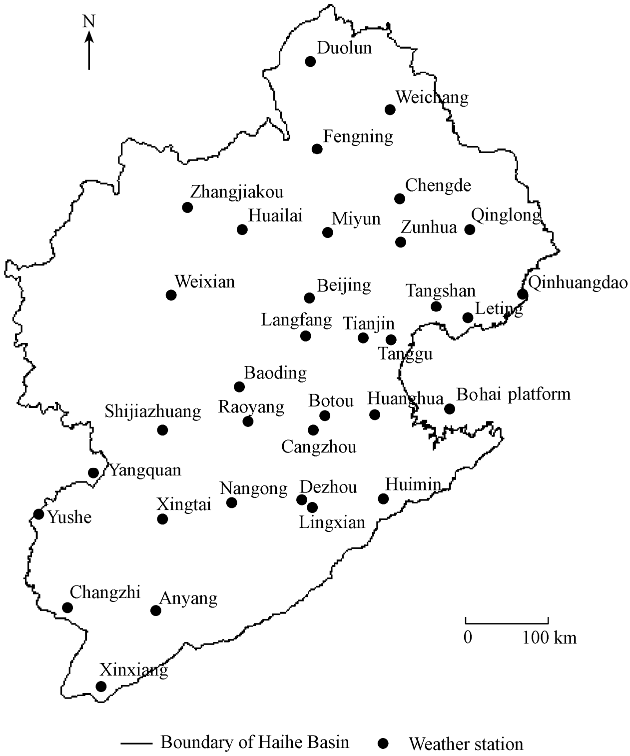

Fig. 2 Weather stations in Haihe Basin

3 Two methods based on SEBAL

In SEBAL, evapotranspiration is estimated as the residual of an energy balance applied to the land surface for each pixel of the satellite image (e.g., for each 1 000 m × 1 000 m square for MODIS images):

$$L_{\mathrm{E}} = R_{\mathrm{n}} - H - G \tag{1}$$

where L_{E} is the latent heat flux (W/m^2), which is readily converted to evapotranspiration (mm);

R_n is the net radiation (W/m^2); H is the sensible heat flux (W/m^2); and G is the soil heat flux (W/m^2). This is accomplished in a series of steps using the ERDAS Model Maker tool to compute the terms in Eq. (1).

In this study, we used two methods to estimate evapotranspiration for the Haihe Basin. One was the simplified SEBAL model, proposed by the authors, and the other was the method proposed by Tasumi (2003). A brief introduction of the similar parts (R_n and G) of the two methods and a detailed elaboration on the differences in the computation of H is given below.

3.1 Similar parts of two methods

3.1.1 Net radiation

Net radiation is the net radiant energy that the land surface actually receives from or loses to the atmosphere. It is computed from the land surface radiation balance equation:

$$R_n = (1-\alpha)S_{in} + L_{in} - L_{out} - (1-\varepsilon_0)L_{in} \tag{2}$$

where α is the surface albedo (dimensionless), S_{in} is the incoming short-wave radiation (W/m^2), ε_0 is the land surface emissivity (dimensionless), and L_{in} and L_{out} are incoming and outgoing long-wave radiations, respectively (W/m^2). Potential values for S_{in} are determined for each sloping pixel using theoretical clear sky curves (Allen 1996). L_{in} and L_{out} are computed as functions of surface temperature derived from the MOD11A1 product. The value of ε_0 is estimated by averaging the emissivity values of Band 31 and Band 32 contained within the MOD11A1 product. The value of α is calculated by integrating band reflectance within the short-wave spectrum using a weighting function (Starks et al. 1991):

$$\alpha = \sum_{i=1}^{n} \rho_i w_i \tag{3}$$

where w_i is a weighting coefficient with values of 0.215, 0.215, 0.242, 0.129, 0.101, 0.062, and 0.036 (Tasumi et al. 2008); n is the number of satellite bands integrated (n = 7); and ρ_i is the reflectance of seven MODIS bands from the MOD09GA product.

3.1.2 Soil heat flux

Soil heat flux G is empirically estimated using a function from Bastiaanssen (2000) based on the surface albedo, surface temperature, and NDVI:

$$G = (T_s - 273.16)(0.0038 + 0.0074\alpha)(1 - 0.98N^4) \tag{4}$$

where T_s is the surface temperature (K), and N is the NDVI from the MOD13Q1 product.

3.2 Differences between two methods

The major difference between the method proposed by Tasumi (2003) and the simplified method lies in the computation of H. The Tasumi approach is to split the vast area into sub-areas and then compute H for each sub-area individually by selecting respective weather data, the coldest and hottest pixels. The simplified approach is to interpolate the wind speed of the weather station with inverse distance weighting, using ArcGIS software, to establish a wind field, and then to select only one coldest pixel and one hottest pixel.

3.2.1 Calculation of *H*

In SEBAL, *H* is predicted from an aerodynamic function:

$$H = \rho_{\mathrm{air}} C_{\mathrm{P}} \frac{T_{\mathrm{d}}}{r_{\mathrm{ah}}} \tag{5}$$

where ρ_{air} is the air density as a function of atmospheric pressure, C_{P} is the heat capacity of air (1 004 J/(kg·K)), r_{ah} is the aerodynamic resistance to heat transport (s/m), and T_{d} (K) is the temperature difference between z_1 and z_2, which are heights above the ground surface, generally 0.1 m and 2 m, respectively.

r_{ah} is calculated as

$$r_{\mathrm{ah}} = \frac{\ln\left(\dfrac{z_2}{z_1}\right)}{uk} \tag{6}$$

where u is the friction velocity for each pixel, and k is von Karman's constant (k = 0.41).

To estimate the value of u in Eq. (6), the traditional SEBAL model uses only one wind speed observation data point at the moment when the image is acquired. The calculation process is shown in Fig. 3 and briefly explained below.

The relationship between the wind speed u_x (m/s) at height z_x (m) and the friction velocity is

$$\frac{u_x}{u} = \frac{\ln\left(\dfrac{z_x}{z_{\mathrm{om}}}\right)}{k} \tag{7}$$

where z_{om} is the momentum roughness length (m).

The friction velocity at the weather station (u') is calculated when u_x, z_x, and z_{om} are available from a weather station. Once u' is identified, wind speed at a height of 200 m (u_{200}) is determined using Eq. (7). In this process, 200 m is selected as the height where wind speed is no longer affected by surface roughness, so u_{200} is fixed in the vast area and assumed to float above mountains and other changes in terrain (Morse et al. 2000). Based on the computed u_{200}, SEBAL uses Eq. (7) once again to calculate u for each pixel. Then, r_{ah} can be calculated by Eq. (6) using u for each pixel.

T_{d} can be approximated as a relatively simple linear function of T_0, as pioneered by Bastiaanssen (1995):

$$T_{\mathrm{d}} = a + bT_0 \tag{8}$$

where a and b are constants determined using the T_0 and T_{d} values of the coldest and hottest pixels, and T_0 is the DEM-corrected surface temperature.

After T_{d} is determined, a preliminary estimate of *H* is calculated with Eq. (5), and an internal repeat of the calculation of *H* should be performed at least five times. The iterative process to compute *H* follows the procedure shown in Fig. 3.

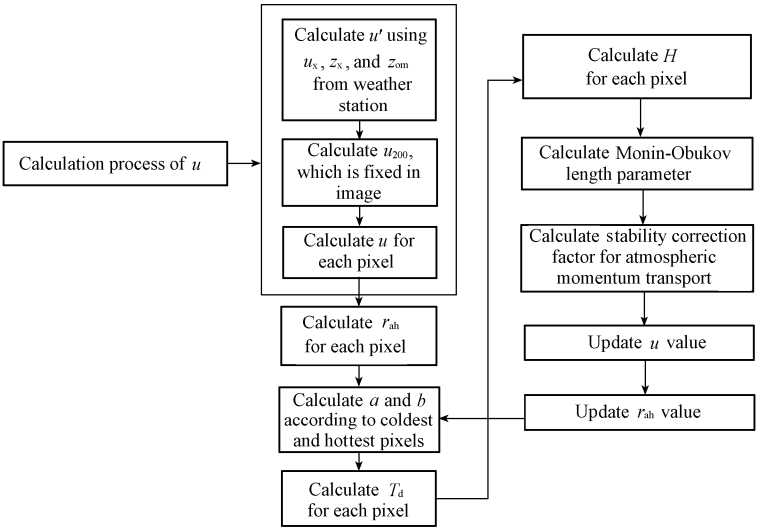

Fig. 3 Fundamental steps of computing *H* based on one wind speed

3.2.2 Tasumi method

The method used in Tasumi (2003) is fundamentally the same as the method described above. The difference is that this method divides the image of the Haihe Basin into 34 sub-areas based on the weather conditions, selects 34 coldest and hottest pixels, and runs the fundamental model 34 times, using different coldest and hottest pixels and weather data. The iterative process to compute *H* follows the course described in Fig. 4.

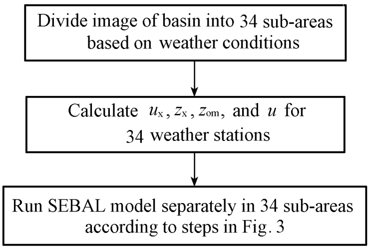

Fig. 4 Iterative process of computing *H* in Tasumi method

3.2.3 Simplified method

The primary difference between the simplified method and the traditional SEBAL model is in the calculation of *u*. The latter method uses the same value of u_{200} to calculate *u* for the whole area, while the former method uses pixel-based values, since there may be significant spatial variation over a vast basin. From Fig. 3 and Fig. 4, we can see that the Tasumi method splits the vast area into several sub-areas, thus requiring an unacceptable amount of time to process time-series images with more than ten weather stations. However, with the simplified method we regard the vast area as a whole, so the wind speed at the height of 200 m is different in every pixel in such a vast basin. Therefore, the simplified method calculates *u* directly with Eq. (7), rather than with u_{200} as in the Tasumi method. A detailed elaboration is provided below.

To obtain the value of wind speed for each pixel, we interpolated 34 wind speeds in the Haihe Basin with the inverse distance weighting (IDW) method in the ArcGIS software, and established the wind field (Fig. 5) at the height where the weather station measures the wind speed. Using the ArcGIS spatial analyst tool, the interpolated wind field was stored in the TIF format and transformed into the IMG format with the ERDAS software.

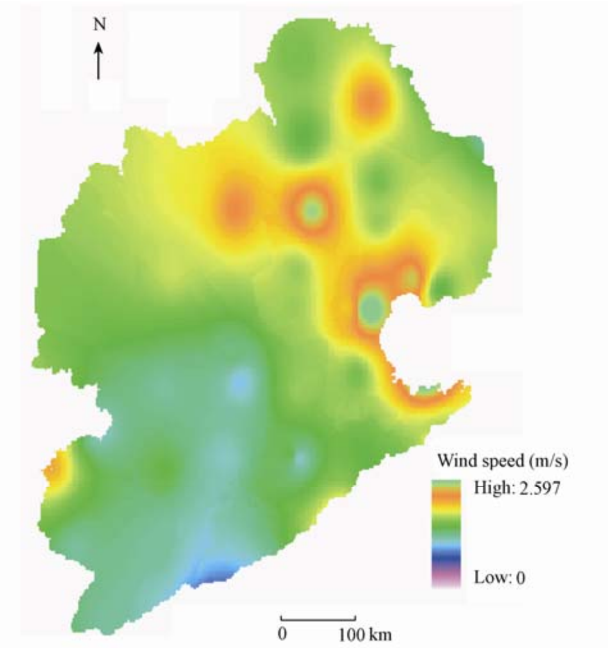

Fig. 5 Interpolated wind field

Subsequently, we used the wind field in the IMG format to calculate u, shown in Fig. 6, using the following equation:

$$u = \frac{k u_{x\mathrm{IMG}}}{\ln\left(\dfrac{11}{z_{\mathrm{omIMG}}}\right)} \tag{9}$$

where $u_{x\mathrm{IMG}}$ is the interpolated wind field in the IMG format, Z_{omIMG} is the momentum roughness length in the IMG format from NASA's Land Data Assimilation Schemes (LDAS), and 11 m is the height where the weather station measures the wind speed in the Haihe Basin.

The remaining steps in calculating H with this simplified method are the same as in the traditional SEBAL model except for the updated u. As shown in Fig. 6, u is updated by interpolating wind speed from 34 weather stations with the simplified method. Moreover, we regard the Haihe Basin as a region, and only select one coldest pixel and one hottest pixel to simplify the process. The iterative process of computing H follows the steps shown in Fig. 6.

Iterations continue until the estimated r_{ah} (and therefore T_{d}) values numerically converge. The recommended number of iterations varies from 5 to 10, depending on weather conditions

(Morse et al. 2000). Generally, calmer days require more iterations. In this study there were six iterations according to the weather conditions of the Haihe Basin.

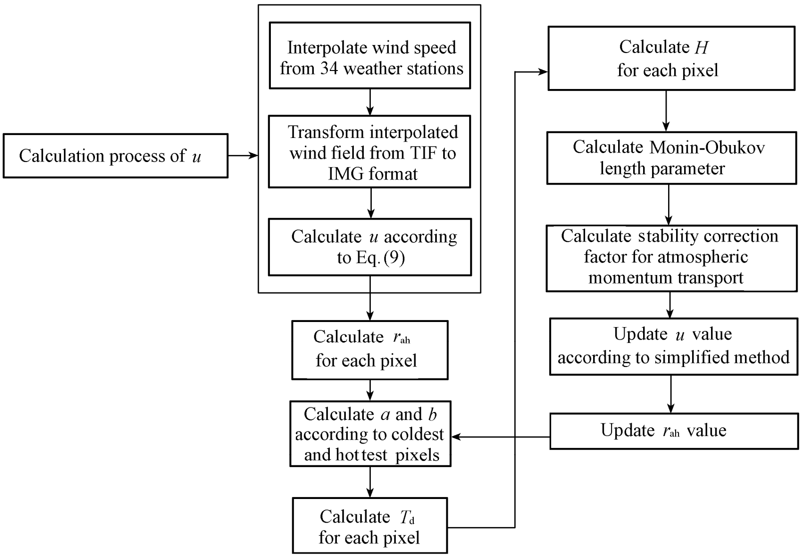

Fig. 6 Iterative process of computing *H* in simplified method

Finally, we estimated ET_{daily} using the evaporative fraction (Λ) from *H*, *G*, L_{E}, and R_{n}, explained in detail in the SEBAL model (Bastiaanssen et al. 1998a; Bastiaanssen 2000; Morse et al. 2000). The formula is

$$ET_{\text{daily}} = \frac{86\,400\Lambda\left(R_{\mathrm{n}24} - G_{24}\right)}{\lambda} \tag{10}$$

where $R_{\mathrm{n}24}$ is daily net radiation (W/m^2), G_{24} is daily soil heat flux (W/m^2), and λ is the latent heat of vaporization (J/kg).

4 Results and validation

To simplify the process of evapotranspiration prediction in the Haihe Basin, the MODIS image for August 13, 2007 was reprocessed using a simplified method and the Tasumi method. The same computer system and version of the ERDAS IMAGINE software were used. A total of 856 pixels were randomly selected from the image of ET_{daily} obtained by the two methods, out of 13 million pixels in total. Locations of pixels were chosen so that the sampled pixels represented a wide range of land use types. Two ET_{daily} images from two different methods are shown in Fig. 7 and Fig. 8.

The agreement in evapotranspiration predicted by the two methods is considered to be good, having an r^2 of 0.966 (Fig. 9). Predictions follow a 1:1 line closely, with a deviation of about 1.5% from the line on average. Some differences in estimates exist at some locations. However, these differences appear to be random and would average out over a wide range. Therefore, the simplified method can be used for estimating the evapotranspiration in the Haihe Basin with high efficiency, but for other vast areas, further verification is needed.

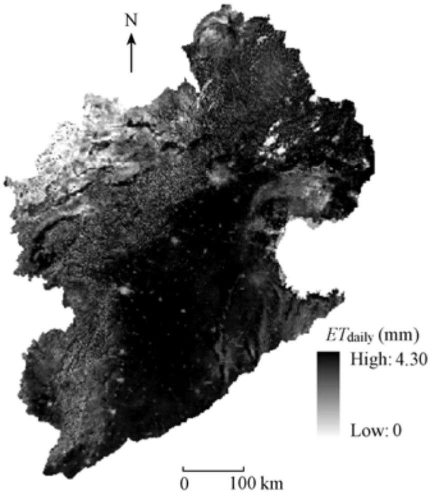

Fig. 7 ET_{daily} estimated by simplified method

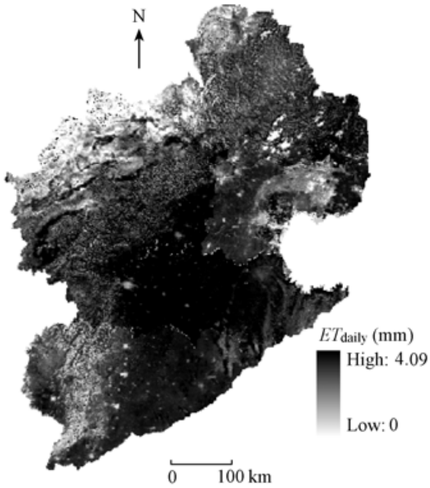

Fig. 8 ET_{daily} estimated by Tasumi method

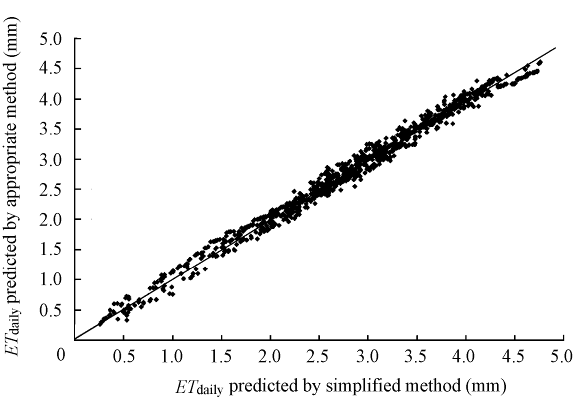

Fig. 9 Comparison of ET_{daily} predicted for August 13, 2007 in Haihe Basin by two different methods

5 Conclusions

A simplified method based on the SEBAL model was developed for estimating ET_{daily} from a MODIS image of a large area of the Haihe Basin. The method proposed by Tasumi (2003) was also used for comparison. The main conclusions are as follows:

(1) The simplified method enables the traditional SEBAL model to be applied to vast areas with many weather stations. By interpolating the wind speed and establishing the wind field, we can use this wind field in the IMG format to calculate the friction velocity directly and consequently to simplify the iterative computation process of sensible heat flux.

(2) The validation shows that the simplified method has a simple structure and an excellent agreement with the traditional SEBAL model. It can be used to estimate the evapotranspiration in the Haihe Basin with high efficiency.

(3) The simplified method is validated only by the Tasumi method; for further large area validation, more measurements are needed.

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