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# Quantitative estimation of land surface evapotranspiration in Taiwan based on MODIS data

Che-sheng ZHAN*[1], Jie ZHAO[2], Hui-xiao WANG[3], Jian YIN[3]

*1. Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, P. R. China*
*2. Beijing Tsinghua Urban Planning and Design Institute, Beijing 100085, P. R. China*
*3. Key Laboratory of Water and Sediment Sciences, Ministry of Education, College of Water Sciences, Beijing Normal University, Beijing 100875, P. R. China*

**Abstract:** Land surface evapotranspiration (ET) determines the local and regional water-heat balances. Accurate estimation of regional surface ET provides a scientific basis for the formulation and implementation of water conservation programs. This study set up a table of the momentum roughness length and zero-plane displacement related with land cover and an empirical relationship between land surface temperature and air temperature. A revised quantitative remote sensing ET model, the SEBS-Taiwan model, was developed. Based on Moderate Resolution Imaging Spectroradiometer (MODIS) data, SEBS-Taiwan was used to simulate and evaluate the typical actual daily ET values in different seasons of 2002 and 2003 in Taiwan. SEBS-Taiwan generally performed well and could accurately simulate the actual daily ET. The simulated daily ET values matched the observed values satisfactorily. The results indicate that the net regional solar radiation, evaporation ratio, and surface ET values for the whole area of Taiwan are larger in summer than in spring, and larger in autumn than in winter. The results also show that the regional average daily ET values of 2002 are a little higher than those of 2003. Through analysis of the ET values from different types of land cover, we found that forest has the largest ET value, while water areas, bare land, and urban areas have the lowest ET values. Generally, the Northern Taiwan area, including Ilan County, Nantou County, and Hualien County, has higher ET values, while other cities, such as Chiayi, Taichung, and Tainan, have lower ET values.

**Key words:** *evapotranspiration; quantitative remote sensing; MODIS; SEBS model; Taiwan*

## 1 Introduction

Regional land surface evapotranspiration (ET), a key component of the terrestrial hydrologic cycle, has always been the focus of international frontier studies, including the International Geosphere-Biosphere Project (IGBP), the Global Energy and Water Cycle Experiment (GEWEX), the Integrated Global Observing Strategy Partnership (IGOS-P), and Predictions in Ungauged Basins (PUB) of the International Association of Hydrological Sciences (IAHS) (Xia and Zuo 2006). Since the 1970s, remote sensing technology has been

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*Corresponding author (e-mail: *zhancs@igsnrr.ac.cn*)
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developed and used as a new approach to solve this problem. Regional ET estimation using remote sensing is mainly based upon the land surface heat balance, including the use of the remote sensing technique to extract information existing in the energy from the soil-vegetation-atmosphere interface, and the combination of interrelated data from meteorological stations. Superior to conventional methods, this method enables the estimation of land surface ET based on remote sensing data.

Loheide and Gorelick (2005) used a scaled value between air temperature and dry surface temperature to estimate ET. Their study required some auxiliary data and one or two reference objects determined by ground observations. In order to avoid the calculation of aerodynamic resistance, Qiu et al. (1998, 2006) developed a simple site-scale model for ET study using a scaled temperature. The remote sensing retrieval of land surface ET requires non-remote sensing parameters, such as the air temperature and wind speed at reference heights. These parameters, generally obtained from the observed values at meteorological and ecological network stations, have restricted the application of remote sensing in ET estimation. This problem will be solved by an integrated remote sensing information model, but the uncertainty of the model will greatly increase (Zhang 1996). It is becoming more and more important to build a simple and practical remote sensing ET model for models such as S-SEBI (Simplified Surface Energy Balance Index) (Roerink et al. 2000), SEBAL (Surface Energy Balance Algorithms for Land) (Bastiaanssen et al. 1998), and SEBS (Surface Energy Balance System) (Su 2001). SEBS has been widely used in China (Du 2005; Yu 2007; He 2008) because it has a certain physical mechanism with few parameters, and the parametric algorithm of the model reduces the retrieval uncertainty of the heat transmission roughness of heterogeneous surfaces at large scales. This study, based on the land surface and climatic changes in Taiwan, sought to set up a table of the momentum roughness length and zero-plane displacement related with land cover, and an empirical relationship between land surface temperature and air temperature. It also sought to develop a revised quantitative remote sensing ET model, the SEBS-Taiwan model. `

# 2 Methods

## 2.1 Land surface temperature

The day/night land surface temperature (LST) algorithm (Wan and Dozier 1996) used in this study is formulated as:

$$T_{\mathrm{s}} = \left( A_1 + A_2 \frac{1-\varepsilon}{\varepsilon} + A_3 \frac{\Delta\varepsilon}{\varepsilon^2} \right) \frac{T_{31} + T_{32}}{2} + \left( B_1 + B_2 \frac{1-\varepsilon}{\varepsilon} + B_3 \frac{\Delta\varepsilon}{\varepsilon^2} \right) \left( T_{31} - T_{32} \right) + C \qquad (1)$$

where $T_{\mathrm{s}}$ is the land surface temperature; $\varepsilon$ is the average emissivity, and $\varepsilon = 0.5\left(\varepsilon_{31} + \varepsilon_{32}\right)$; $\Delta\varepsilon$ is the emissivity difference between MODIS channels 31 and 32, and $\Delta\varepsilon = \varepsilon_{31} - \varepsilon_{32}$; $\varepsilon_{31}$ and $\varepsilon_{32}$ are the average emissivities in channels 31 and 32, respectively; $T_{31}$ and $T_{32}$ are the brightness temperatures in MODIS channels 31 and 32, respectively; and

$A_1$, $A_2$, $A_3$, $B_1$, $B_2$, $B_3$, and $C$ are unknown coefficients derived from the MODIS data.

## 2.2 Evaporative fraction

The evaporative fraction $\Lambda$ is defined as the ratio of actual evaporation to available energy:

$$\Lambda = \frac{\lambda E}{R_{\mathrm{n}} - G} \tag{2}$$

where $R_{\mathrm{n}}$ is the net radiation flux, $G$ is the soil heat flux, $\lambda E$ is the turbulent latent heat flux, $E$ is the evaporation rate, and $\lambda$ is the latent heat of evaporation.

In the SEBI (Surface Energy Balance Index) model (Menenti and Choudhury 1993), the dependence of the external resistance on the atmospheric stability is considered. Additionally, the surface energy balance index $I_{\mathrm{SEB}}$ is formulated as a pixel-wise parameter. The general idea is that with a given net radiation and within an area where the atmospheric conditions may be assumed to be constant, the surface temperature normalized by the external resistance is directly related to the ratio of actual to maximum land evaporation values:

$$I_{\mathrm{SEB}} = \frac{\dfrac{\theta_0 - \theta_{\mathrm{a}}}{r_{\mathrm{e}}} - \dfrac{\left(\theta_0 - \theta_{\mathrm{a}}\right)_{\mathrm{w}}}{\left(r_{\mathrm{e}}\right)_{\mathrm{w}}}}{\dfrac{\left(\theta_0 - \theta_{\mathrm{a}}\right)_{\mathrm{d}}}{\left(r_{\mathrm{e}}\right)_{\mathrm{d}}} - \dfrac{\left(\theta_0 - \theta_{\mathrm{a}}\right)_{\mathrm{w}}}{\left(r_{\mathrm{e}}\right)_{\mathrm{w}}}} \tag{3}$$

where $\theta_0$ is the potential temperature at the surface, $\theta_{\mathrm{a}}$ is the potential air temperature at the reference height, $r_{\mathrm{e}}$ is the external resistance, the subscript w refers to the completely wet surface, and the subscript d refers to the completely dry surface.

Following Menenti and Choudhury (1993), the evaporative fraction has a complementarity relationship with $I_{\mathrm{SEB}}$:

$$\Lambda = 1 - I_{\mathrm{SEB}} \tag{4}$$

## 2.3 Daily net radiation

The solar radiation penetrates the atmospheric layer to generate the surface net radiation flux $R_{\mathrm{n}}$ after the atmospheric absorption, scattering, and reflection, and, according to the Stefan-Boltzmann law, it can be expressed as

$$R_{\mathrm{n}} = \left(1 - \alpha\right) R_{\mathrm{swd}} + \varepsilon \delta_0 \left(\varepsilon_{\mathrm{a}} T_{\mathrm{a}}{}^4 - T_{\mathrm{s}}{}^4\right) \tag{5}$$

where $\alpha$ is the albedo (obtained from the MODIS Terra BRDF product MOD43C); $\delta_0$ is the Stefan-Boltzmann constant; $\varepsilon_{\mathrm{a}}$ is the atmospheric effective emissivity; $T_{\mathrm{a}}$ is the air temperature; and $R_{\mathrm{swd}}$ is the downward solar radiation:

$$R_{\mathrm{swd}} = \left(a_{\mathrm{s}} + b_{\mathrm{s}} \frac{n}{N}\right) W_{\mathrm{d}} \tag{6}$$

where $n$ and $N$ are the actual sunshine duration and maximum sunshine duration, respectively; $n/N$ is the relative sunshine duration, and $n/N \in \left[0,1\right]$; $a_{\mathrm{s}}$ and $b_{\mathrm{s}}$ are empirical regression coefficients, whose recommended values without the correction of the data from measured solar radiation are 0.25 and 0.5, respectively (Allen et al. 1998); and $W_{\mathrm{d}}$ is the daily astronomical radiation:

$$W_{\mathrm{d}}=\frac{t}{2\pi}\left(\frac{1}{R}\right)^{2} I_{0}\left(\omega_{0}\sin\phi\sin\delta+\cos\phi\cos\delta\sin\omega_{0}\right) \tag{7}$$

where $t$ is the time length of the whole day, $\left(1/R\right)^{2}$ is the sun-earth distance correction coefficient (or the earth's orbit eccentricity correction factor), $I_0$ is the solar constant, $\omega_0$ is the sunset hour angle, $\phi$ is the geographic latitude, and $\delta$ is the solar declination.

The land surface emissivity is represented as

$$\varepsilon=\varepsilon_{\mathrm{v}} f_{\mathrm{v}}+\varepsilon_{\mathrm{g}}\left(1-f_{\mathrm{v}}\right)+4\Delta\varepsilon\left(1-f_{\mathrm{v}}\right) \tag{8}$$

where $f_{\mathrm{v}}$ is the fractional vegetation coverage; $\Delta\varepsilon$ is a regional representative value, and $\Delta\varepsilon\in(0, 0.02)$ ; and $\varepsilon_{\mathrm{v}}$ and $\varepsilon_{\mathrm{g}}$ are the emissivities for full vegetation and bare land surfaces, respectively, whose respective values within the 10.5 μm to 12.5 μm spectral region are $\varepsilon_{\mathrm{v}}=0.985\pm0.007$ and $\varepsilon_{\mathrm{g}}=0.960\pm0.010$ .

## 2.4 Improvement of SEBS model

The momentum roughness model adopted by the SEBS model is adaptive to uniform dense grassland. In order to minimize the uncertainty caused by the retrieval of various vegetation parameters, as a reference we used the field experiment database (http://ldas.gsfc.nasa.gov/LDAS8th/MAPPED.VEG/web.veg.monthly.table.html), which has been widely used around the world. This study use the categorical data of land resources in Taiwan and built Taiwan's regional database for its monthly vegetation parameters in terms of various types of land cover, which enables the SEBS model to directly use parameters such as the monthly average roughness, zero-plane displacement, and vegetation height from the vegetation parameter database to reduce the simulation errors of the original model.

Research on the relationships between the measured air temperature, surface temperature, and vegetation fractional coverage for various types of land cover shows that the air temperature at the reference height is closely related to some elements such as surface temperature, vegetation fractional coverage, and average apparent thermal inertia at the upper land surface (Zhan et al. 2007). Based on statistical analysis of field data for different land cover types in different months, a simple air temperature-land surface temperature model suitable for Taiwan was established (Zhan et al. 2007):

$$T_{\mathrm{a}}=28.5+0.1T_{\mathrm{s}}-\left(f_{\mathrm{c}}+a\right)\xi \tag{9}$$

where $f_{\mathrm{c}}$ is the vegetation coverage; $a$ is a constant varying with $T_{\mathrm{s}}$ ; and $\xi$ is the average thermal inertia for different land cover types, which is determined by local vegetations and soil.

## 2.5 Actual daily ET

The real-time surface information is acquired by remote sensing, including the retrieved surface parameters, estimated surface radiation, and related heat flux, which only represent the status of the surface at that moment. It is crucial to calculate accumulation values over 24 hours from the real-time values. One common method in the surface ET temporal scaling regards the evaporative fraction as invariable, assuming that the relative proportion of energy flux components remains stable during the daytime based on the energy balance. The relationship is given by

$$\frac{\lambda E_{\mathrm{d}}}{F_{\mathrm{d}}} = \frac{\lambda E}{F} = E_{\mathrm{R}} \tag{10}$$

where $F_{\mathrm{d}}$ is the daily effective energy, and $\lambda E_{\mathrm{d}}$ is the daily turbulent latent heat. If $F$ is the instantaneous effective energy $(R_{\mathrm{n}} - G)$, $E_{\mathrm{R}}$ is the evaporative fraction. On the basis of the evaporative fraction $\Lambda$ and the surface daily net radiation $R_{\mathrm{n}}$ and neglecting the soil heat flux $G$, the daily ET $E_{\mathrm{d}}$ is obtained from numerical integration of Eq. (10) in the diurnal period as follows:

$$E_{\mathrm{d}} = \frac{\Lambda R_{\mathrm{n}}}{\lambda} \tag{11}$$

## 3 Results and analysis

The improved SEBS model was named SEBS-Taiwan, and its input data were requested with the uniform coordinate projection and the same spatial resolution. The ordinary kriging method was used to interpolate the daily meteorological data from 24 meteorological stations evenly distributed around Taiwan (Fig. 1). Data included atmospheric pressure, wind speed,

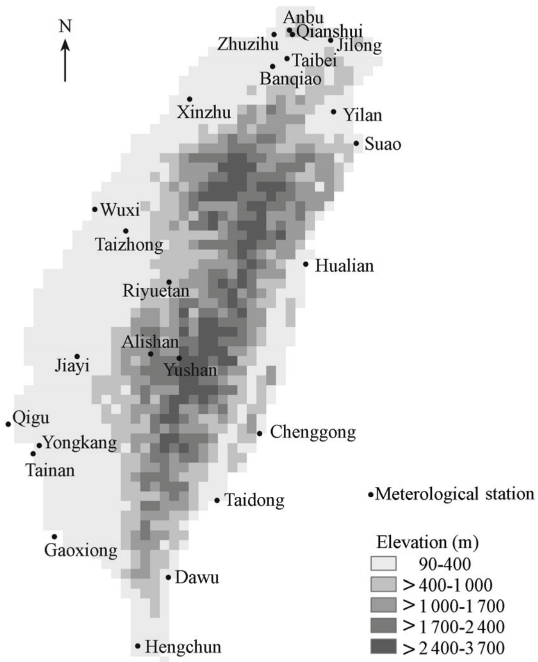


**Fig. 1** Distribution of 24 meteorological stations

and relative humidity with a 1-km spatial resolution and the Albers equal-area conic projection. The remote sensing product included the normalized difference vegetation index (NDVI), surface albedo came mainly from MODIS data with a 1-km spatial resolution, and MRT (the MODIS Reprojection Tool) was employed in the projection transformation from integerized sinusoidal (ISIN) to Albers. The land use and land cover data from the MODIS data were classified as forest, grassland, farmland, water body, urban area, and unutilized area, representing the average land use/land cover conditions for the years of 2002 and 2003. The values of the corresponding land surface physical characteristic parameters came from the land use and land cover data. The SEBS-Taiwan model in this study output eight regional representative daily ET values for 2002 and 2003 in Taiwan (Table 1), and Fig. 2 shows the spatial distribution of daily ET values on two typical days in summers of the two years. The results indicate that the surface ET value in Taiwan is larger in summer than in spring, and larger in autumn than in winter, and the simulation values of four typical days in 2002 are generally higher than the ones in 2003.

**Table 1** Eight daily ET values in Taiwan

| Date | Daily ET (mm) | Date | Daily ET (mm) |
|---|---|---|---|
| 2002-01-11 | 2.76 | 2003-01-25 | 2.80 |
| 2002-04-08 | 4.51 | 2003-04-29 | 3.77 |
| 2002-07-22 | 5.34 | 2003-06-30 | 4.23 |
| 2002-10-15 | 3.63 | 2003-09-30 | 3.34 |
| Average | 4.06 | Average | 3.53 |

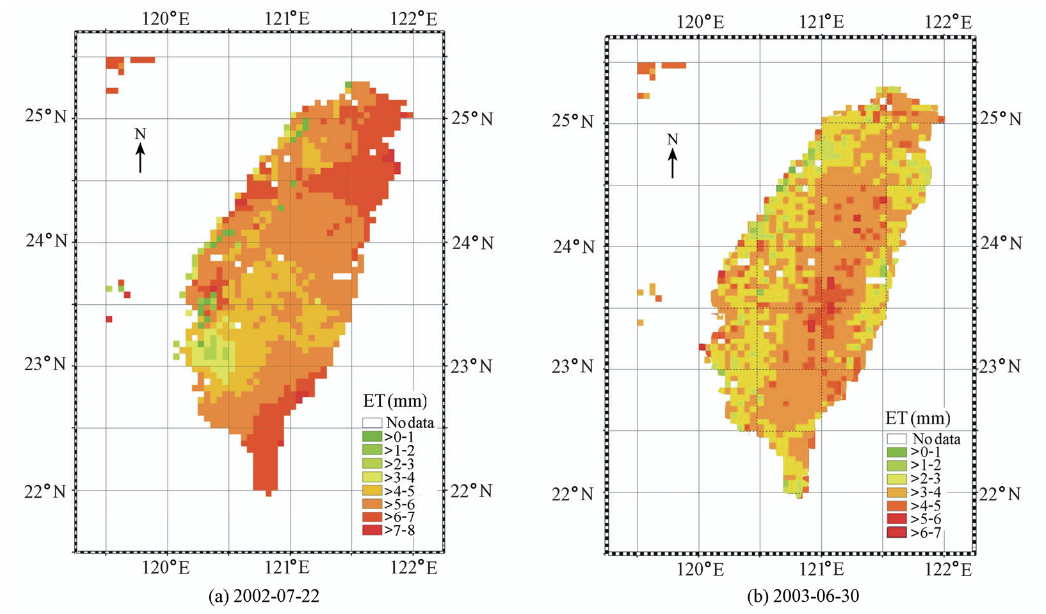


**Fig. 2** Distribution of typical daily ET values in summers of 2002 and 2003

According to land use and land cover variations in 2002-2003 in Taiwan (Zhan et al. 2011), the main types of land cover include forest, grassland, urban areas, water areas, and unutilized areas. Taking the year of 2002 for example, the average daily ET values from different types of land cover were calculated (Table 2). Through analysis, it was found that the forest has the largest ET value, and the water areas, bare land, and urban areas have the lowest ET values. There is an obvious spatial distribution variation in Taiwan: the ET values of urban areas are significantly lower than those of forest and grassland. Generally, areas in the Northern Taiwan area, including Ilan County, Nantou County, and Hualien County, have higher ET values, while other cities, such as Chiayi, Taichung, and Tainan, have lower ET values.

**Table 2** Average daily ET values from different types of land cover

| Date | Average daily ET (mm) | | | | |
|---|---|---|---|---|---|
| | Forest | Grassland | Urban areas | Water areas | Unutilized areas |
| 2002-01-11 | 3.31 | 2.57 | 0.26 | 2.23 | 1.48 |
| 2002-04-08 | 5.42 | 4.42 | 1.10 | 3.34 | 2.06 |
| 2002-07-22 | 5.46 | 4.79 | 1.86 | 3.67 | 2.12 |
| 2002-10-15 | 4.62 | 3.74 | 1.19 | 3.14 | 1.96 |
| Average | 4.70 | 3.88 | 1.10 | 3.10 | 1.91 |

In order to test the accuracy of the simulated results, this study collected the daily observed data from A-type evaporation pans at 24 meteorological stations in 2002 and 2003, and validated the simulated ET values with a correction factor of 0.74 from those evaporation pans. The observed ET values can show regional representation of Taiwan because of the uniformly distributed meteorological stations in Taiwan. Through calculation of the arithmetic mean values of 24 A-type evaporation pan ET values on eight simulated days, we compared the mean pan ET values with the corresponding simulated mean ET values, as shown in Fig. 3. It was found that the actual ET values simulated by the SEBS-Taiwan model are lower than the observed values, but the variation trend with different seasons is the same, which indicates that the simulated ET values are regionally reasonable and reliable.

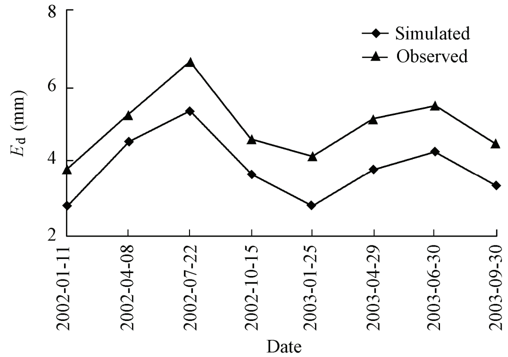


**Fig. 3** Comparison between simulated and observed daily ET values

## 4 Discussion

The data quality directly influences the accuracy of the simulated results. In this study, the land cover data were based on the annual land conditions, which cannot reflect the monthly or daily change. The used land cover data could influence daily simulated results. Furthermore, some meteorological data cannot fully reflect the real-time weather conditions at the time the MODIS satellite passes over the site, and there were always some errors in the temporal interpolation of meteorological data. Therefore, it is necessary to further process the existing climate, land cover, remote sensing, and biophysical data to improve the model input database and simulation accuracy. Meanwhile, it is important to collect the existing measured data from more densely clustered observation stations to set up a detailed ground database, which will strengthen the validation of the SEBS-Taiwan model and make the simulated results more accurate.

Taiwan is strongly influenced by the monsoon climate. However, the SEBS-Taiwan model did not consider the influence of the advection effects upon ET. The influence of advection effect can be included in the SEBS model to improve its theoretical basis in the future. In addition, we can try to transform the one-layer model into a two-layer or multi-layer model to improve the SEBS model.

The ET value from the remote sensing data is the mean flux value of each pixel, and the traditional flux observation is based on point measurement. Thus, there are scale differences between the simulated and observed ET values, especially for the ET validation in the complex and heterogeneous underlying surfaces. Now, LAS (Large Aperture Scintillometer) can be used to improve the validation of the simulation, because it has different regional observed values. The results of ground-based validation using a spatial scale match between the LAS measurement and MODIS data can be reasonable.

## 5 Conclusions

This study developed a revised quantitative remote sensing ET model, the SEBS-Taiwan model. Based on the MODIS data, SEBS-Taiwan was used to simulate and evaluate the typical actual daily ET values in the different seasons of 2002 and 2003. The SEBS-Taiwan model generally verified the reliability of simulated results with observed data from evaporation pans from 24 meteorological stations with spatial representation. The results indicate that the surface ET values for the whole area of Taiwan are lower in January than in July. The results also show that the simulated values of four typical days in 2002 are generally higher than those in 2003. Through analysis of the ET distribution for different types of land cover, we found that the forest has the largest ET value, and water areas, bare land, and urban areas have the lowest ET values. The simulated values are lower than the ET values from evaporation pans, which is reasonable. The ET spatial distribution is similar to some historic research results (Du 2005; Yu 2007). This study shows that the optimized SEBS-Taiwan model is convincing and reliable.

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