Remote sensing estimation of land surface evapotranspiration of typical river basins in China

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Abstract Land surface evapotranspiration (LET) from typical river basins in China in the years 1991, 1995 and 1999, was modelled with a quantitative remote sensing method, which is based on a modified version of the Surface Energy Balance System (SEBS) model. LET simulations were conducted on several river basins, and validations demonstrated good agreement with observational data on all basins, except the Yellow River. In the Yangtze River basin for example, the study analysed the change in LET corresponding to land use and land cover change from 1991 to 1999. Results showed that the average LET decreased when paddy fields, dry land, grassland, and built-up lands were transformed to other land cover types, and increased when forest land was transformed to dry land and grassland.

Key words China; LET; LUCC; remote sensing; river basin; SEBS

INTRODUCTION

Detailed knowledge of land surface evapotranspiration (LET) is important for monitoring regional and global climate through the hydrological cycle, and its estimation has significant applications in agriculture (Kustas & Norman, 1996). Thus, the development of methods to monitor LET efficiently has become an inter-disciplinary research topic. Most conventional techniques that use point measurements to estimate LET are only representative of local areas and usually cannot be extended to large areas because of the dynamic nature and regional variation of LET (Courault *et al*., 2003). Remote sensing has proven to be the only suitable approach for regional estimation of LET because satellite remote sensing is the only technology that can provide spatially representative parameters such as radiometric surface temperature, albedo, and vegetation index in a globally consistent and economically feasible manner (Choudhury, 1989; Kustas & Norman, 1996).

A Surface Energy Balance System (SEBS), for the estimation of surface heat fluxes and evaporation, using satellite data in the visible, near infrared, and thermal infrared spectral range has been designed for composite terrain at a larger spatial scale with heterogeneous surfaces (Su, 2001). SEBS has been applied to many case studies in Europe and Asia, and is regarded as one of the most logical and precise methods in evaporation estimation at present. In view of spatial and temporal scales and the complexity of the land use and surface characteristics of China, the original SEBS has been revised and improved with respect to data input and in the simulation of some land physical parameters and daily net radiation. The revised SEBS, known as SEBS-China, is more suitable for calculating daily LET of composite terrains in China.

This study aims to estimate the LET of typical river basins of China in the years 1991, 1995 and 1999 based on satellite, meteorological, soil, and land cover data sets, then validate the modelling precision by regional LET comparisons, and analyse the LUCC (Land Use and Land Cover Change) influence on regional LET of typical river basins.

MODELS AND METHODS

The SEBS model

Details of the SEBS model are provided in Su & Jacobs (2001) and Su (2001). The model consists of the following main components: (a) a set of land surface physical parameters, such as albedo, emissivity, temperature, vegetation coverage, etc. calculated from spectral reflectance and radiance data (Su *et al*., 1999); (b) an equation for the roughness length for the heat transfer (Su *et al*., 2001); (c) the BAS (Bulk Atmospheric Similarity) theory (Brutsaert, 1999) used to calculate the friction velocity, the sensible heat flux, and the Obukhov stability length; (d) the SEBI (Surface Energy Balance Index) concept (Menenti & Choudhury, 1993) used to determine the evaporative fraction.

The SEBS model requires three sets of data as inputs. The first set consists of the land surface temperature, albedo, fractional vegetation coverage, leaf area index, and roughness length etc.; the second set is the meteorological field at a reference height including air temperature, air pressure, wind speed, humidity; the third set includes land use and the land cover classifications.

Improvement of SEBS for application in China

The SEBS model has been applied successfully throughout Europe and many other global locations. However, it has not performed well in some regions, for instance in the Heihe and Urumqi River basins of China. The reason for this poor performance was the highly varying surface character and climate. Therefore, the original SEBS model required certain modifications for improved application in China. A new sub-module has been developed for daily net radiation simulation, and the retrieval of some land surface physical parameters has been improved as follows. The new model was named SEBS-China.

Firstly, the land cover classification system of China was incorporated into the SEBS model, and monthly vegetation data for the different land covers were added, based on mapped monthly vegetation data from the Global Land Data Assimilation System, GLDAS). Secondly, this study established a satellite data-based regional air temperature estimation model (Bastiaanssen *et al*., 1998). A simple air temperature-land surface temperature model suitable to China is expressed as:

$$T_a = 28.5 + 0.1T_s - (f_c + a) \cdot \xi \quad (1)$$

where T_s and T_a are the land surface temperature and air temperature at a reference height of 2 m, respectively (K), f_c is the fractional vegetation coverage, a is an adjustive constant and changes with T_s, and ξ is average thermal inertia for different land cover types and reflects the magnitude of thermal inertia of land surface.

Thirdly, we efficiently established the meteorological field in reference height and developed the daily net radiation module. The large-scale meteorological field in the atmospheric boundary layer is usually simulated with regional climate models. It is too time-consuming to use climate model simulations in this study, since the input data have very high temporal and spatial resolution and a long time series. Therefore we changed the inputs of SEBS-China to ten-daily continuous meteorological field by interpolating meteorological data from weather stations of China. The daily net radiation module was embedded in SEBS, and mainly depended on meteorological parameters.

MODELLING RESULTS AND VALIDATION OF SEBS-CHINA

Data preparation

The input data consist of satellite data, ground observations, and background and historical data. These data have been gridded to a uniform coordinate system with the same spatial and temporal resolutions. The daily meteorological data are provided by 400 weather stations with a relatively uniform spatial distribution in China. The satellite data consist of 10-day 8-km AVHRR composite images for the years 1991, 1995 and 1999. Another relevant auxiliary data set includes Land Use Land Cover Change (LUCC) data for China for the years 1991, 1995 and 1999. LUCC data adopts a three-level classification system, where the first level includes six basic classes; cultivated land (paddy field and dry land), forest, grassland, open water, urban built-up land, and barren land.

Modelling results

The LET distribution for China for the years 1991, 1995 and 1999 was modelled, based on SEBS-China, and analysed for several river basins, including the Yellow River, Yangtze River, Pearl River, Haihe River, and Liaohe River. Analysis indicated that areas of low LET (<200 mm/year^{-1}) are mainly located in bare to sparsely vegetated regions to the east of the Taklamakan Desert of the Xinjiang Autonomous Region. Areas of relatively low LET (200–400 mm/year^{-1}) are mainly grassland and shrub regions of northeastern and northern China. Medium LET regions (400–600 mm/year^{-1}) are mainly located in northern forests, some shrub and croplands, and agriculture–forest mixed lands. The high LET regions (>600 mm/year^{-1}) are mainly located in the south of Qinghai-Tibet Plateau, forests of Southern China, croplands, mixed agriculture-forest lands, and some shrub lands.

Based on the LET distribution for China, We obtained the average annual LET of each river basin for the years 1991, 1995, and 1999, as shown in Table 3. The Yangtze

River and Pearl River basins are located in high LET regions, with an average annual LET of 657 mm for the Yangtze basin and 640 mm for the Pearl River basin. The Liaohe River basin is mainly located in regions of medium LET, with an average LET of about 414 mm. The Yellow River and Haihe River basins are located in both medium to low LET regions. However, modelled LET was found to be somewhat overestimated in some locations within these two basins. On average, LET is higher in the south than in the north, and higher in the east than in the west.

Validation of results

Two other analysis methods were also performed; one is an ecological system validation of representative experimental areas, and the other is a regional average validation using those river basins that have long term meteorological observations.

Experimental regional validation Experimental and modeling data from the Changbai Mountain region of China was provided by Feng (2004), and mainly included the validation and comparison of MODIS-BEPS data with TM-BEPS data (BEPS: Boreal Ecosystem Productivity Simulator) in the Changbai Mountains.

We first calculated the average LET using TM-BEPS data and MODIS-BEPS data, then compared their total LET, average LET, and average LET of various ecological systems. The LET spatial distribution in the Changbai Mountain region was modelled with TM-BEPS data for the year 2001 and shows a distinct elevational zonality. The simulated LET with MODIS-BEPS data shows a good agreement with the LET distribution with TM-BEPS data. There is approximately the same average LET for the same land cover using the two kinds of data sources without regard to the influence of LUCC, mixed pixel, and the temporal difference among remote sensing images. The detailed average LET comparison is shown in Table 1 as follows.

Table 1 Comparison of average LET over different land cover based on TM-BEPS and MODIS-BEPS data (Feng, 2004).

Land cover type	Average LET (mm/year^{-1})	
	TM-BEPS data	MODIS-BEPS data
Needle and broad-leaf mixed forest	519	475
Tundra	226	230
Needle-leaf forest	345	346
Erman's birch forest and Broad-leaf forest	568	532
Crops	446	440
Total area	450.2	515.4

Table 2 Annual average LET of Changbai mountain.

Year	LET (mm/year^{-1})
1991	415
1995	485
1999	412
Average	437

We only compared average LETs of experiment area. Table 2 shows the simulated annual average LET of the Changbai Mountains with the SEBS-China model.

As shown in Tables 1 and 2, based on the SEBS-China model, the annual average LET for three modelled years is 437 mm for the Changbai Mountain region, which is very close to the modelled values (450.2 mm) for the year 2001 with TM-BEPS data, and just a little lower than that (515.4 mm) with MODIS-BEPS data. The modelled results from the SEBS-China model appear, then, to be reasonably consistent.

River basin validation Regional LET validations were performed on the five closed river basins described previously. It has been shown that, over a multi-year average, these basins closely follow the basic water balance relationship, P = RO + LET. Thus, we calculated their annual average LET for the period 1991–1999, and then compared the calculated LET with the simulated LET by the SEBS-China model, as shown in Table 3.

Table 3 Comparison of annual average LET in representative river basins.

River basin	Area (10^4 m^2)	Observed water balance parameters Precipitation (mm)	Runoff (mm)	LET (mm)	Simulated LET (mm) 1991	1995	1999
Yangtze River	180.7	1100	525	575	642	727	601
Yellow River	75.2	456	77	379	619	633	547
Pearl River	44.4	1469	752	717	640	695	584
Haihe River	26.4	499	103	396	570	577	476
Liaohe River	22.9	473	65	408	397	461	384

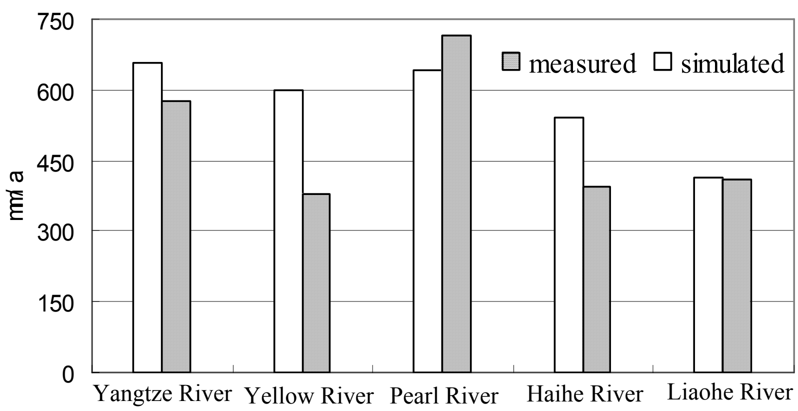

Fig. 1 Comparison of the measured and simulated annual average LET of representative river basins.

Comparison of modelled LET to observed average LET (P – RO) shows that the model simulations for the Yellow and Haihe rivers are considerably higher than the observations. These relatively large errors appear to be the result of improper parameterizations within the model itself, and also the possibility of losses to groundwater recharge. The simulated average LET for all basins change with an increasing trend from 1991 to 1995 and a decreasing trend from 1995 to 1999, which are consistent with long-term changing trend of the regional climate of China. As shown in Fig. 1, the Yellow River has the maximum error between the simulated and measured average annual LET in the last 10 years, the maximum error reaches 221 mm, and the relative error is about 58%, although the relative error for the Haiha River is also quite high at 36%. The errors of the remaining three basins are significantly less: 82 mm and 14% for the Yangtze, 77 mm and 11% for the Pearl, and 6 mm and 1.5% for the Liaohe River. The error comparisons show that the simulated results in wetter regions are somewhat better than those in drier regions, although the Liaohe River appears to be an exception to this generalization, as it has the second lowest average annual precipitation.

LUCC impacts on LET changes of typical river basins

We also calculated the average annual LET of different land covers of the five river basins for the years 1991, 1995 and 1999. Combining with land cover distribution of the three years, we can analyse the LUCC impacts on LET changes of the river basins during this period. In this study, we take the Yangtze River basin as an example to quantify the LUCC impact on LET change from 1991 to 1999.

Table 4 is the conversion matrix of land uses of the Yangtze River basin from 1991 to 1999, and indicates the conversion direction and the sources for different land use types. The cultivated land (paddy field and dry land) has been transformed to built-up land on a large-scale, and the conversion area reaches up to 56 grids (8 km × 8 km per grid). It is also obvious for Mutual transformation between forestland and grassland, but there is little influence on their respective totality in 1999. Therefore, the urban built-up land shows rapid and irreversible expansion, as the sources are mainly cultivated lands. However, built-up lands are seldom transformed to other types.

Table 5 illustrates the statistic results of average LET changes from 1991 to 1999 corresponding to land-use change as shown in Table 4. As shown in Table 5, the average LET in conversion areas always decreases when paddy field areas remain static or are transformed to other types, and especially when transformed to urban built-up land. The average LET in 1999 decreased by 309 mm in the conversion area compared with 1991. The dry land, cultivated land, and grassland also have the same trend as the paddy field. However, the average LET of forestland shows a different trend, where the average LET in conversion areas in 1999 increases when forest land is

Table 4 Conversion matrix of land uses of the Yangtze River basin in 1991 and 1999 (Unit: 64 km^2).

1999 1991	Paddy field	Dry land	Forestland	Grassland	Built-up land	Barren land
Paddy field	3836	22	16	6	41	–
Dry land	21	3533	18	14	15	–
Forestland	9	24	11921	72	3	–
Grassland	–	22	68	6458	–	–
Build–up land	–	–	–	–	108	–
Barren land	–	–	–	–	–	870

NB "–" represents the land use area change less than 0.05%.

Table 5 Average LET changing matrix corresponding to LUCC of Yangtze River basin from 1991 to 1999 (Unit: mm).

1999 / 1991	Paddy field	Dry land	Forestland	Grassland	Build–up land	Barren land
Paddy field	–72.9	–58.7	–185.9	–113.0	–309.0	–
Dry land	–2.3	–54.9	–84.3	–42.1	–274.2	–
Forestland	56.3	45.1	–33.1	48.5	–263.4	–
Grassland	–	–27.1	–86.5	–28.6	–	–
Build–up land	–	–	–	–	–79.6	–
Barren land	–	–	–	–	–	–25.1

"–" represents the null value of LET change.

transformed to paddy field, dry land and grassland, and increases by 56.3 mm when transformed to paddy field. The average LET of statis forestland has decreased by 1999. In general, the LET in 1991 is higher than that in 1999, and the LET decreasing trend is more obvious for the conversion to urban built-up land compared with the conversion to other types.

CONCLUSIONS

In this paper we have modified the original SEBS model according to actual regional characteristics of China, and proposed a new SEBS-China model suitable to simulate long-term LET on a large spatial scale.

The simulated LET results show that the Yangtze and Pearl rivers locate in high LET regions, the Liaohe River mainly locates in the medium LET regions, the Yellow and Haihe rivers cross the medium and low LET regions, but their simulated LET in some places is significantly higher. We adopted two kinds of method for regional validation, and found only the simulated average annual LET of the Yellow River is much larger than the observation result compared with the other four basins. The simulated LET regional distribution generally has a good agreement with actual regional LET.

Taking the Yangtze River basin as an example, the paper also analysed its LET change corresponding to LUCC from 1991 to 1999. The results indicate the common relations between LET change and LUCC for all river basins. The LET will decrease when paddy fields, dry land, grassland, and built-up land are transformed to other land cover types. However, the LET of forestland has different trend, its LET increases in 1999 when forest land was transformed to dry land and grassland.

There are still some urgent problems to be solved in model structure, modelling processes and mechanisms. The atmosphere boundary layer meteorological data should be provided by multi-dimensional data assimilation technology. Some sub-models need to be improved, such as leaf area index model, fractional vegetation coverage model, and net radiation model. Furthermore, the time scaling-up model to LET using fractional evaporation also need further improvement. The simulation over arid and semi-arid areas with SEBS-China is still deficient, and it is necessary to extend SEBS-China to be a multi-layer mechanisms.

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