

# *Evapotranspiration estimation considering anthropogenic heat based on remote sensing in urban area*

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1 **Evapotranspiration estimation considering anthropogenic heat based**  
2 **on remote sensing in urban area**

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20

21 **Abstract**

22 Urbanization influences hydrologic cycle significantly on local, regional even global  
23 scale. With urbanization the water resources demand for dense population sharpened,  
24 thus it is a great challenge to ensure water supply for some metropolises such as Beijing.  
25 Urban area is traditionally considered as the area with lower evapotranspiration (ET)  
26 on account of the impervious surface and the lower wind speed. For most remote  
27 sensing models, the ET, defined as latent heat in energy budget, is estimated as the  
28 difference between net radiation and sensible heat. The sensible heat is generally higher  
29 in urban area due to the high surface temperature caused by heat island, therefore the  
30 latent heat (i.e. the ET) in urban area is lower than that in other region. We estimated  
31 water consumption from 2003 to 2012 in Beijing based on water balance method and  
32 found that the annual mean ET in urban area was about 654 mm. However, using  
33 Surface Energy Balance System (SEBS) model, the annual mean ET in urban area was  
34 only 348 mm. We attributed this inconsistency to the impact of anthropogenic heat and  
35 quantified this impact on the basis of the night-light maps. Therefore, a new model  
36 SEBS-Urban, coupling SEBS model and anthropogenic heat was developed to estimate  
37 the ET in urban area. The ET in urban area of Beijing estimated by SEBS-Urban showed  
38 a good agreement with the ET from water balance method. The findings from this study  
39 highlighted that anthropogenic heat should be included in the surface energy budget for  
40 a highly urbanized area.

41 **Keywords:**

42 Urban; Evapotranspiration; SEBS; Remote sensing; Anthropogenic heat

## 43 1. Introduction

44 Urbanization is progressing at a rapid rate on a global scale. Over half of  
45 population now lives in urban area, and by 2050 that fraction is expected to exceed 70%  
46 (Bratman et al., 2015; Heilig, 2012). Natural terrains are continuously converted to  
47 urban landscapes to meet the ever-increasing demand of the expanding urban  
48 population (Yang et al., 2015). The surface and atmospheric conditions in urban areas  
49 are modified, resulting in large variation of regional hydroclimate and energy balance  
50 (Oke, 2002; Tam et al., 2015; Yang et al., 2016; Zhang et al., 2009; Zhong et al., 2015).  
51 In addition, human activities make cities more vulnerable to a number of water resource  
52 problems (Bai and Imura, 2001; Iglesias et al., 2007; Jiang, 2009; Paul and Meyer,  
53 2008). Therefore, further understanding of water cycle and energy balance in urban  
54 areas is necessary for future water resources planning.

55 Evapotranspiration (ET) is a combination of two processes: evaporation of liquid  
56 water from various surfaces and transpiration from the plants through stomata (Allen et  
57 al., 1998). It is a major component of water cycle and plays a vital role in surface energy  
58 balance system. In urban areas, ET research is central to green spaces irrigation, water  
59 consumption monitoring as well as the mechanism by which rainfall retention capacity  
60 is recovered between storm events. Common ET estimation procedures were developed  
61 for agricultural applications, however, researches on ET remained limited in urban areas  
62 (DiGiovanni et al., 2012; Grimmond and Oke, 1991; Zheng, 2012). In that regard,  
63 reliable estimation of urban ET is of particular importance for development of urban  
64 hydrology and water resource management.

65 A number of methods have been developed to estimate ET, including water  
66 balance method (Alley, 1984; Granier et al., 1999; Long and Singh, 2010; Palmroth et  
67 al., 2010; Senay et al., 2011; Xu and Singh, 2005), meteorological method (Alexandris  
68 et al., 2008; McMahon et al., 2013; Penman, 1948; Priestley and Taylor, 1972; Sumner  
69 and Jacobs, 2005) and remotely-sensed energy balance model (Allen et al., 2007;  
70 Bastiaanssen et al., 1998; Roerink et al., 2000; Su, 2002). For the acquisition of free  
71 information at all scales, remote sensing data has been extensively applied in numerous  
72 fields. The most popular remotely-sensed models include the Surface Energy Balance  
73 System (SEBS) (Su, 2002), the Surface Energy Balance Algorithm for Land (SEBAL)  
74 (Bastiaanssen et al., 1998), and the Mapping Evapotranspiration at High Resolution  
75 with Internalized Calibration (METRIC) (Allen et al., 2007), which have been widely  
76 used in ET estimation from regional to continental scales.

77 In ET estimation, remote sensing based methods provide a feasible alternative to  
78 the spatiotemporal characteristics of ET at different scales, which have advantages over  
79 the other approaches. In traditional remotely sensed models, the anthropogenic heat and  
80 net advection are negligible in energy balance equation. However, in cities  
81 anthropogenic heat from human metabolism, vehicles and building heat emissions is a  
82 significant contribution to the surface energy budget (Allen et al., 2011; McCarthy et  
83 al., 2010; Sailor, 2011). Anthropogenic heat is  $0.028 \text{ W m}^{-2}$  on global average, while  
84 localized estimation ranges from tens to hundreds of  $\text{W m}^{-2}$  and even as high as  $1590$   
85  $\text{W m}^{-2}$  for the extreme business district of Tokyo (Flanner, 2009; Ichinose et al., 1999;  
86 Kłysik, 1996; Pigeon et al., 2007; Sailor and Lu, 2004). Therefore, the impacts of  
87 anthropogenic heat are usually considerable and should be included in the surface  
88 energy budget for a highly urbanized area.

89 In this study, we hypothesize that ET was equal to the water consumption in the  
90 study area. The objectives of this study were (1) to estimate annual ET in Beijing based  
91 on water balance model and the original SEBS model; (2) to consider the influence of

123 anthropogenic heat on ET in Beijing by a modified SEBS model (will be called as  
 124 SEBS-Urban in the following); (3) to discuss the results and uncertainties in ET  
 125 estimation.

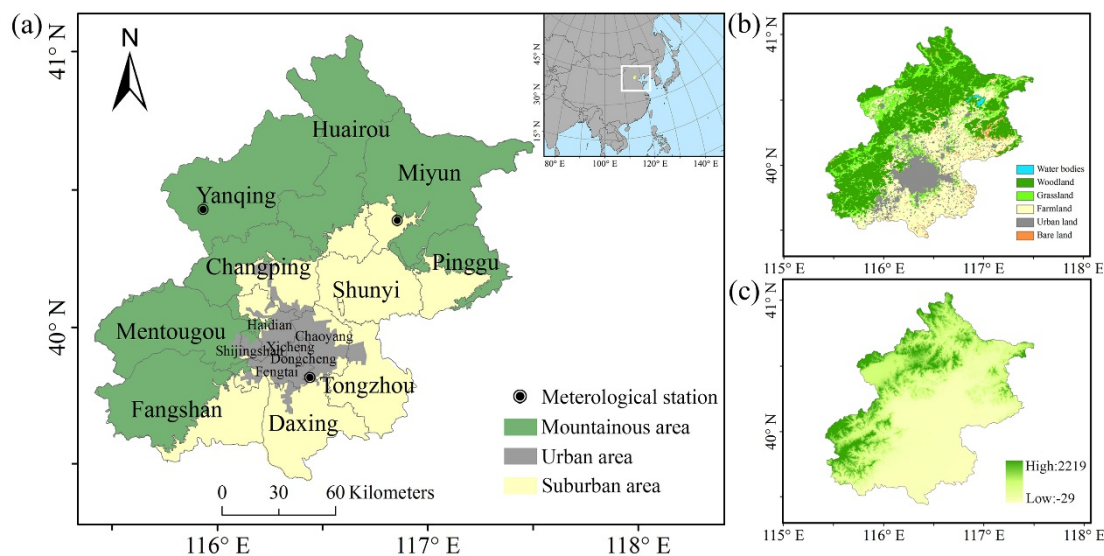
126 This paper is organized as follows. The study area and data are given in the Section  
 127 2; Section 3 is the description of methods used (water balance method, SEBS model  
 128 and SEBS-Urban model); the results and discussions are shown in Section 4; the  
 129 conclusions are presented in Section 5.

## 130 2. Study area and data

### 131 2.1 Study area

132 Beijing (115°25'~117°30'E, 39°26'~41°04'N), the capital of China, is located at  
 133 North China Plain with a coverage of about 16410 km<sup>2</sup> (see **Figure 1a**). The region has  
 134 a typical temperate and monsoonal climate, with an annual mean rainfall of 576 mm  
 135 and an annual mean temperature of about 12.5 °C from 1961 to 2010 (Li and Yang,  
 136 2015; You et al., 2012). Beijing is the political and cultural center of China, with a  
 137 history of over 3000 years and a permanent population of more than 20 million (Beijing  
 138 Municipal Bureau of Statistics, 2012, website: [http://www.bjstats.gov.cn/English/MR/Population/201603/t20160303\\_337912.html](http://www.bjstats.gov.cn/English/MR/Population/201603/t20160303_337912.html)). However, it is one of the most water-  
 140 deficient metropolises in the world. The per capita water resources available is about  
 141 150 m<sup>3</sup> in Beijing in 2012, which is far below the international minimum standard of  
 142 1000 m<sup>3</sup> per capita defined by the United Nations (Wang and Wang, 2005). There are  
 143 many water regulation projects in the city and the Miyun reservoir is the primary project  
 144 to ensure potable water for Beijing.

145 Woodland, farmland and urban land are the major land use types in Beijing (see  
 146 **Figure 1b**) and the geography of the city is characterized by alluvial plains in the  
 147 southeast and mountains in the north and west (see **Figure 1c**). In this study, Beijing  
 148 was divided into a mountain area of 10174 km<sup>2</sup> and a plain area of 6236 km<sup>2</sup> in  
 149 accordance with elevation and surface heterogeneity. Based on the land use data, the  
 150 plain area was further subdivided into urban area and suburban area, which are changing  
 151 over time with average of 1154 km<sup>2</sup> and 5082 km<sup>2</sup>, respectively (see **Figure 1a**).



152 Figure 1. Information of the study area: (a) the location and the subareas of  
 153 Beijing; (b) the land use map; (c) the elevation map.

## 154 2.2 Data

### 155 2.2.1 Data for water balance method

156 The data used in water balance method were mainly collected from the Beijing  
157 Water Resources Bulletin (Beijing Water Authority, website:  
158 [http://www.bjwater.gov.cn/pub/bjwater/zfgk/tjxx/index\\_1.html](http://www.bjwater.gov.cn/pub/bjwater/zfgk/tjxx/index_1.html)) and Beijing Statistical  
159 Yearbook (Beijing Municipal Bureau of Statistics, website: <http://www.bjstats.gov.cn/tjsj/>). Due to the limited resources, the study concentrated on the period from  
160 2003 to 2012. In addition, the divisional precipitation was estimated based on the  
161 combination of meteorological stations and local precipitation contour maps.  
162

### 163 2.2.2 Data for remote sensing models

164 Remote sensing products are the key inputs to SEBS model. The information of  
165 the input data are listed in **Table 1**. In this study, emissivity, LAI, NDVI, LST and land  
166 use data were derived from MODIS standard products (website:  
167 <http://reverb.echo.nasa.gov/>). Land surface albedo was retrieved using the algorithm  
168 proposed by Liang (2001). NDVI values were scaled to fractional vegetation cover as  
169 follow (Gillies and Carlson, 1995):

$$170 \quad f_c = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (1)$$

171 where  $f_c$  is fractional vegetation cover,  $NDVI_{\min}$  is the minimum  $NDVI$ , which  
172 can be estimated as the averaged  $NDVI$  for bare soil,  $NDVI_{\max}$  is the maximum  
173  $NDVI$ , which can be estimated as the averaged  $NDVI$  for forest.

174 Meteorological elements including air temperature, pressure, specific humidity,  
175 wind speed, downward shortwave radiation and downward longwave radiation were  
176 collected from China Meteorological Forcing Dataset (He and Yang, 2011). The  
177 evaluation of anthropogenic heat was based on the remote sensing nighttime lights data,  
178 a product of DMSP/OLS (website: <http://ngdc.noaa.gov/eog/>). All the information was  
179 interpolated into daily maps at 500 m resolution, using the linear interpolation method.

180 The quality of remote sensing image is affected by weather condition. In this study,  
181 only the cloud-free days with high-quality images of MODIS were selected for the  
182 analysis. The number of selected days in the study period are listed in **Table 2**.

183

184 **Table 1.** Information of the remote sensing data used in SEBS model.

Data	Source	Spatial resolution	Temporal resolution	Time period
Emissivity	MOD11A1	1km	Daily	2003-2012
LAI	MOD15A2	1km	8 days	2003-2012
NDVI	MOD13A2	1km	16 days	2003-2012
LST	MOD11A1	1km	Daily	2003-2012
Land use	MCD12Q1	500m	yearly	2003-2012
Albedo	MOD09GA	500m	Daily	2003-2012
Air temperature	China Meteorological Forcing Dataset	$0.1^\circ \times 0.1^\circ$	3 hr	2003-2012
Pressure	China Meteorological Forcing Dataset	$0.1^\circ \times 0.1^\circ$	3 hr	2003-2012

Specific humidity	China Meteorological Forcing Dataset	0.1° × 0.1°	3 hr	2003-2012
Wind speed	China Meteorological Forcing Dataset	0.1° × 0.1°	3 hr	2003-2012
Downward shortwave radiation	China Meteorological Forcing Dataset	0.1° × 0.1°	3 hr	2003-2012
Downward longwave radiation	China Meteorological Forcing Dataset	0.1° × 0.1°	3 hr	2003-2012
Nighttime lights data	DMSP/OLS	1km	yearly	2003-2012

185  
186

**Table 2.** The number of selected days in the study period (2003-2012).

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Number of days	60	64	91	57	82	72	90	77	64	80

187

### 188 3. Methodology

#### 189 3.1 Water balance method

190 It was assumed that ET was equal to the water consumption in the study area.  
191 Based on the water balance equation, the annual ET can be estimated as follow:

$$192 ET = P + 10^5 (S_i - S_o + G_i - G_o - \Delta S - \Delta G) / A \quad (2)$$

$$193 ET_m = P_m + 10^5 (S_{mi} - S_{mo} + G_{mi} - G_{mo} - \Delta S_m - \Delta G_m) / A_m \quad (3)$$

$$194 ET_p = P_p + 10^5 (S_{pi} - S_{po} + G_{pi} - G_{po} - \Delta S_p - \Delta G_p) / A_p \quad (4)$$

$$195 ET_u = P_u + 10^5 (S_{ui} - S_{uo} + G_{ui} - G_{uo} - \Delta S_u - \Delta G_u) / A_u \quad (5)$$

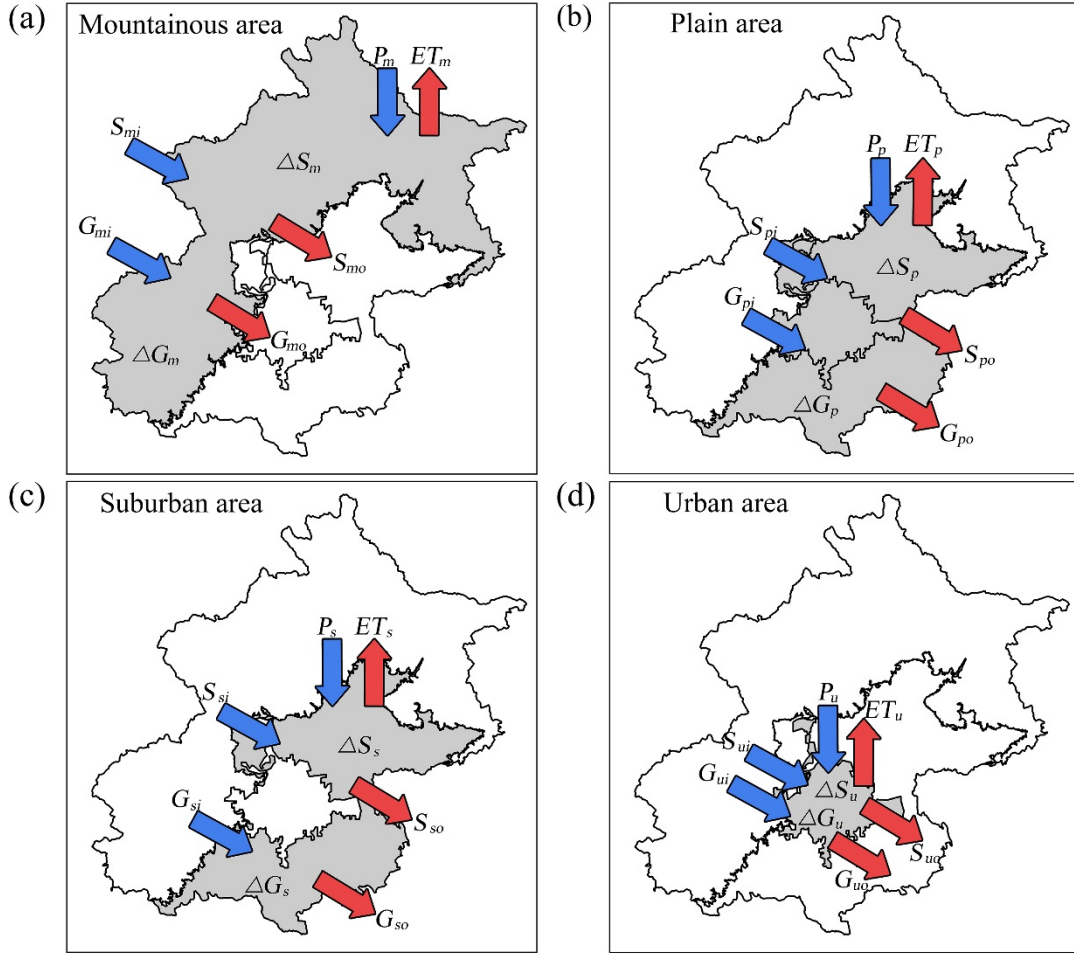
$$196 ET_s = P_s + 10^5 (S_{si} - S_{so} + G_{si} - G_{so} - \Delta S_s - \Delta G_s) / A_s \quad (6)$$

197 Eq. (2) to Eq. (6) are for the entire area, mountainous area, plain area, urban area  
198 and suburb area, respectively, where  $ET$  is the annual evapotranspiration, mm;  $P$  is the  
199 annual precipitation, mm;  $S_i$  is the annual surface inflow, i.e. the supply from runoff and  
200 South-North Water Transfer Project,  $10^8 \text{ m}^3$ ;  $S_o$  is the annual surface outflow,  $10^8 \text{ m}^3$ ;  $G_i$   
201 is the annual groundwater input,  $10^8 \text{ m}^3$ ;  $G_o$  is the annual groundwater outflow,  $10^8 \text{ m}^3$ ,  
202 and it was assumed that  $G_o$  equaled  $G_i$  in this study;  $\Delta S$  is the variation in surface water  
203 storage,  $10^8 \text{ m}^3$ , estimating from change in reservoir storage;  $\Delta G$  is the variation in  
204 groundwater storage,  $10^8 \text{ m}^3$ ;  $A$  is the corresponding area,  $\text{km}^2$ .

205 **Figure 2** shows the water balance of subareas in Beijing. Note that in mountainous  
206 area,  $S_{mi}$  was estimated as the annual runoff supply;  $S_{mo}$  was calculated as surface water  
207 resources in mountainous area;  $G_{mi}$  was equal to  $G_i$ ;  $G_{mo}$  was regarded as water supply  
208 from mountainous area to plain area;  $\Delta G_m$  was generally neglected due to few extraction  
209 of groundwater and the self-adjustment of ecosystem; and  $\Delta S_m$  was equal to  $\Delta S$ . When  
210 it comes to plain area,  $S_{pi}$  was considered as the sum of  $S_{mo}$  and annual supply from  
211 South–North Water Transfer Project;  $S_{po}$ ,  $G_{pi}$ ,  $G_{po}$  and  $\Delta G_p$  were equal to  $S_o$ ,  $G_{mo}$ ,  $G_o$ ,  
212 and  $\Delta G$ , respectively; and  $\Delta S_p$  was neglected considering that there were few large scale  
213 reservoirs in plain area. As for urban area,  $S_{ui}$  was estimated as the difference between  
214 water supply (includes industrial, domestic and ecological water use) and underground  
215 water exploited in urban area;  $S_{uo}$  was considered as urban drainage;  $G_{ui}$  was estimated  
216 according to the underground supply from mountainous area;  $G_{uo}$  was neglected due to  
217 the intensive extraction of underground water in urban area;  $\Delta G_u$  was calculated as  
218  $\Delta G_u = \Delta G \times A_u / A_p$ ; and  $\Delta S_u$  was neglected. With regard to suburb area,  $S_{si}$ ,  $S_{so}$ ,  $G_{si}$ ,  $G_{so}$   
219  $\Delta G_s$  and  $\Delta S_s$  were calculated as the differences between the corresponding items in plain



220 area and urban area.



221

Figure 2. Water balance of subareas in Beijing. Blue arrows and red arrows represent water input and output, respectively.

222

### 223 3.2 Surface Energy Balance System (SEBS) model

224 The Surface Energy Balance System (SEBS) was developed by Su (2002) for the  
 225 estimation of turbulent heat fluxes and the daily evapotranspiration using remote  
 226 sensing data. Only the main SEBS equations and concepts are presented in this paper,  
 227 further details were given by Su et al. (2001) and Su (2002). The SEBS algorithm is  
 228 based on the energy balance equation expressed as:

$$229 R_n = G_0 + H + \lambda ET \quad (7)$$

230 where  $R_n$  is net radiation,  $W m^{-2}$ ;  $G_0$  is soil heat flux,  $W m^{-2}$ ;  $H$  is sensible heat  
 231 flux,  $W m^{-2}$  and  $\lambda ET$  is the latent heat flux,  $W m^{-2}$  ( $\lambda$  is the latent heat of  
 232 vapourization and  $ET$  is evapotranspiration).  $R_n$  is calculated by:

$$233 R_n = (1 - \alpha) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4 \quad (8)$$

234 where  $\alpha$  is albedo,  $R_{swd}$  is downward shortwave radiation,  $W m^{-2}$ ;  $R_{lwd}$  is  
 235 downward longwave radiation,  $W m^{-2}$ ;  $\varepsilon$  is emissivity;  $\sigma$  is the Stefan-Boltzmann  
 236 constant,  $W m^{-2} K^{-4}$ ; and  $T_0$  is surface temperature, K.

237 The soil heat flux is calculated taking into account fractional vegetation cover:

$$238 G_0 = R_n \cdot [\Gamma_c + (1 - f_c) \cdot (\Gamma_s - \Gamma_c)] \quad (9)$$

239 where  $f_c$  is fractional vegetation cover;  $\Gamma_c = 0.05$  (dimensionless) for full  
 240 vegetation cover and  $\Gamma_s = 0.315$  (dimensionless) for bare soil. An interpolation is  
 241 then performed between the two limiting cases based on  $f_c$ .

242 For deriving the sensible and latent heat flux, the similarity theory was used. In  
 243 SEBS model, distinction were made between the Atmospheric Boundary Layer (ABL)  
 244 and the Atmospheric Surface Layer (ASL). Since the field measurements were  
 245 performed in ASL, the Monin-Obukhov Similarity (MOS) functions by Brutsaert (1999)  
 246 were used. For stable conditions in ASL, the equations proposed by Beljaars and  
 247 Holtslag (1991) and Van den Hurk and Holtslag (1997) were used, while in ABL the  
 248 functions proposed by Brutsaert (1982) were used. The MOS expressions are not  
 249 presented in this paper.

250 The roughness height for momentum transfer and roughness height for heat  
 251 transfer were calculated taking into account the canopy height  $h$  and reference height  
 252  $z_{ref}$ . The equations were given by Su (2001; 2002) based on surface layer similarity  
 253 theory (Brutsaert, 1982):

$$254 \quad z_{0m} = h \cdot (1 - d_0 / h) \cdot e^{-ku(h)/u_*} \quad (10)$$

$$255 \quad d_0 / h = 1 - (1 - e^{-2n_{ec}}) / 2n_{ec} \quad (11)$$

$$256 \quad n_{ec} = C_d \cdot LAI / (2u_*^2 / u(h)^2) \quad (12)$$

$$257 \quad u(h) = u_{ref} \frac{\ln(h - d / z_{0m})}{\ln(z_{ref} - d / z_{0m})} \quad (13)$$

$$258 \quad z_{0h} = z_{0m} / e^{kB^{-1}} \quad (14)$$

259 where  $z_{0m}$  is the roughness height for momentum transfer;  $h$  is the canopy  
 260 height;  $d_0$  is the displacement height;  $k$  is the von Karman constant with a numeric value  
 261 of 0.4;  $u(h)$  is the horizontal wind speed at the canopy top;  $u_*$  is the friction velocity;  
 262  $n_{ec}$  is the within-canopy wind speed profile extinction;  $C_d$  is the drag coefficient taken  
 263 as 0.2;  $LAI$  is the leaf area index;  $u_{ref}$  is the reference wind speed;  $z_{ref}$  is the reference  
 264 height; and  $B^{-1}$  is the inverse Stanton number. See Su (2002) for more details.

265 In this study, the essential parameter  $h$  was estimated in accordance with different  
 266 land use types from MODIS. The land use types were reclassified into 10 types based  
 267 on the definition given by International Geosphere-Biosphere Programme (IGBP) and  
 268 the corresponding values of canopy height were obtained from relative researches in  
 269 Beijing (see **Table 3**).

270  
 271

**Table 3.** The values of the parameter  $h$  in this study.

Code in MODIS	Class name	Recode	Rename	$h$	Reference
0	Water Bodies	0	Water Bodies	0.0001	---
1	Evergreen Needleleaf Forest	1	Evergreen Forest	10~12	(Che, 2008; Zhang et al., 2014; Zhang, 2011)
3	Deciduous Needleleaf Forest	2	Deciduous Forest	10~12	(Che, 2008; Zhang et al., 2014; Zhang, 2011)
4	Deciduous Broadleaf Forest	2	Deciduous Forest	10~12	(Che, 2008; Zhang et al., 2014; Zhang, 2011)
5	Mixed Forest	3	Mixed Forest	10~12	(Che, 2008; Zhang et al., 2014; Zhang, 2011)

6	Closed Shrublands	4	Shrublands	1.2~2.5	(Che, 2008; Du and Xing, 2009)
7	Open Shrublands	4	Shrublands	1.2~2.5	(Che, 2008; Du and Xing, 2009)
8	Woody Savannas	5	Grasslands	0.005~0.03	(Xu et al., 2009)
9	Savannas	5	Grasslands	0.005~0.03	(Xu et al., 2009)
10	Grasslands	5	Grasslands	0.005~0.03	(Xu et al., 2009)
11	Permanent Wetlands	6	Wetlands	0.0001	---
12	Croplands	7	Croplands	0.003~1	(Song et al., 2009)
13	Urban and Built-Up	8	Urban	20	(He et al., 2001; Shi et al., 2015)
14	Cropland/Natural Vegetation Mosaic	9	Bare land	0.0005	---
15	Snow and Ice	9	Bare land	0.0005	---
16	Barren or Sparsely Vegetated	9	Bare land	0.0005	---

272

273 The value of  $H$  was then determined by considering the dry-limit and wet-limit  
274 conditions. Under dry-limit condition (soil moisture at limiting cases), the latent heat  
275 becomes zero while the sensible heat flux is at its maximum value. By definition, from  
276 Eq. (7), it follows that:

$$277 \quad \lambda ET_{dry} = R_n - G_0 - H_{dry} \equiv 0 \quad \text{or} \quad H_{dry} = R_n - G_0 \quad (15)$$

278 Under wet-limit condition (energy at limiting cases), ET occurs at the potential  
279 rate, while sensible heat flux takes its minimum value, which therefore follows:

$$280 \quad \lambda ET_{wet} = R_n - G_0 - H_{wet} \quad \text{or} \quad H_{wet} = R_n - G_0 - \lambda ET_{wet} \quad (16)$$

281 Then the evaporative fraction,  $\Lambda$  was expressed as:

$$282 \quad \Lambda = \frac{\lambda ET}{R_n - G_0} \quad (17)$$

283 By inverting Eq. (12), the latent heat can be calculated as:

$$284 \quad \lambda E = \Lambda \cdot (R_n - G_0) \quad (18)$$

285 Actual ET converted to water depth in mm per time unit was then calculated by  
286  $ET = \lambda ET / (\lambda \cdot \rho_w)$ , where  $\rho_w$  is the density of water  $\text{kg m}^{-3}$  (Jia et al., 2009).

287 Note that satellite images provide for the instantaneous observation in time,  
288 therefore, daily ET was derived by assuming that the evaporative fraction remain  
289 constant throughout the day (Jia et al., 2009; Sugita and Brutsaert, 1991). The daily ET  
290 was then given by:

$$291 \quad \begin{aligned} ET_{daily} &= \sum_{i=0}^{24} \left[ \Lambda \cdot \frac{R_n - G}{\lambda \rho_w} \right] \\ &= 24(\text{h}) \cdot 3600(\text{s}) \cdot \left[ \Lambda \cdot \frac{R_{ndaily} - G_{daily}}{\lambda \rho_w} \right] \\ &= 8.67 \times 10^7 \cdot \left[ \Lambda \cdot \frac{R_{ndaily} - G_{daily}}{\lambda \rho_w} \right] \end{aligned} \quad (19)$$

292 where  $ET_{daily}$  is the daily evapotranspiration, mm;  $R_{ndaily}$  is the daily mean net

293 radiation,  $W m^{-2}$ ;  $G_{daily}$  is the daily mean soil surface heat flux,  $W m^{-2}$ ;  $\rho_w$  is the density  
 294 of water,  $kg m^{-3}$ ;  $\lambda$  is the latent heat of vapourization taken as  $2.45 \times 10^6 J kg^{-1}$ .

295 Since the ET was estimated from discrete remote sensing images, to produce time  
 296 series of ET, the crop coefficient method proposed by Allen (2000) was used for  
 297 reference in this study. Researches indicate that crop coefficient method is generally  
 298 sufficient to estimate time series of ET, also on a monthly basis (Morse et al., 2000;  
 299 Allen et al., 2001; Allen et al., 2007). Thus this method is considered valid for extending  
 300 ET series in Beijing, where the image intervals are no more than two weeks.

301 The crop coefficient is basically the ratio of actual ET to the reference  
 302 evapotranspiration ( $ET_0$ ). The crop coefficient method interpolated the crop coefficients  
 303 derived from remotely sensed actual ET and corresponding  $ET_0$  for the days of image  
 304 available. Then combining the interpolated crop coefficient with  $ET_0$ , actual ET for  
 305 days without good quality images could be inferred, which was formulated as:

$$306 \quad ET_{period} = \sum_{i=b}^f \left[ \frac{1}{2} \left( \frac{ET_b}{ET_{0b}} + \frac{ET_f}{ET_{0f}} \right) (ET_{0i}) \right] \quad (20)$$

307 where  $ET_{period}$  represents the accumulated actual ET for a period with beginning  
 308 day  $b$  and ending day  $f$ , which are cloud-free days;  $ET_b$  and  $ET_f$  are the actual ET derived  
 309 from the beginning day and ending day, respectively;  $ET_{0b}$  and  $ET_{0f}$  are the  
 310 corresponding reference ET for the beginning day and ending day, respectively; and  
 311  $ET_{0i}$  is the reference ET for day  $i$ . In this study, the reference ET was calculated using  
 312 FAO-Penman-Monteith equation (Allen et al., 1998).

### 313 3.3 SEBS-Urban model

314 In traditional remote sensing-based models, the anthropogenic heat and net  
 315 advection are neglected in energy balance equation. However, in metropolis with  
 316 intensive human activities, anthropogenic heat would contribute significantly to the  
 317 surface energy budget (Allen et al., 2011; McCarthy et al., 2010; Sailor, 2011). High  
 318 anthropogenic heat is generally observed in Beijing and in the densely built-up areas  
 319 the hourly maximum value even as high as  $474.3 W m^{-2}$ . (Nie et al., 2014; Tong et al.,  
 320 2004). In this section, anthropogenic heat was quantified to estimate ET in Beijing by  
 321 a modified SEBS model. Therefore, the energy balance equation was given as:

$$322 \quad R_n + Q_f = G_0 + H + \lambda ET \quad (21)$$

323 where  $R_n$  is net radiation,  $W m^{-2}$ ;  $Q_f$  is anthropogenic heat,  $W m^{-2}$ ;  $G_0$  is soil  
 324 heat flux,  $W m^{-2}$ ;  $H$  is sensible heat flux,  $W m^{-2}$  and  $\lambda ET$  is the latent heat flux,  $W$   
 325  $m^{-2}$ .

326 The evaluation of anthropogenic heat was based on the remote sensing product of  
 327 DMSP/OLS, which provide annual averaged nighttime lights maps with numeric values  
 328 range from 0 to 63. In this study, the threshold value was defined as 52 for separating  
 329 the anthropogenic heat-impacted areas from the anthropogenic heat-free areas (Shu et  
 330 al., 2011). The values of anthropogenic heat were set as a range from  $50 W m^{-2}$  to  $75$   
 331  $W m^{-2}$  for summer and winter, and  $30 W m^{-2}$  to  $50 W m^{-2}$  for spring and autumn, on  
 332 the basis of researches conducted by Nie et al. (2014) and Tong et al. (2004). Then the  
 333 corresponding light intensity limits were 52 and 63 and the internal values were  
 334 produced by linear interpolation. Therefore, the value of anthropogenic heat was given  
 335 as:

$$336 \quad Q_{f1} = Q_{f1} + (I - I_{min}) \cdot \frac{Q_{f1} - Q_{f1}}{I_{max} - I_{min}} \quad (22)$$

337

$$Q_{f2} = Q_{fl2} + (I - I_{min}) \cdot \frac{Q_{fu2} - Q_{fl2}}{I_{max} - I_{min}} \quad (23)$$

338

Eq. (22) is for summer and winter, where  $Q_{fl}$  is the anthropogenic heat,  $W m^{-2}$ ;  $Q_{fl1}$  ( $50 W m^{-2}$ ) and  $Q_{fu1}$  ( $75 W m^{-2}$ ) are the lower limit and upper limit of anthropogenic heat, respectively;  $I$  is the numeric value of light intensity;  $I_{max}$  is the maximum light intensity with a value of 63;  $I_{min}$  is the minimum light intensity set as 52, i.e. the threshold value for identifying the anthropogenic heat-impacted areas.

343

Eq. (23) is for spring and autumn, where  $Q_{fl2}$  ( $30 W m^{-2}$ ) and  $Q_{fu2}$  ( $50 W m^{-2}$ ) are the lower limit and upper limit of anthropogenic heat, respectively; and the other items are set ibid.

346

#### 4. Results and discussions

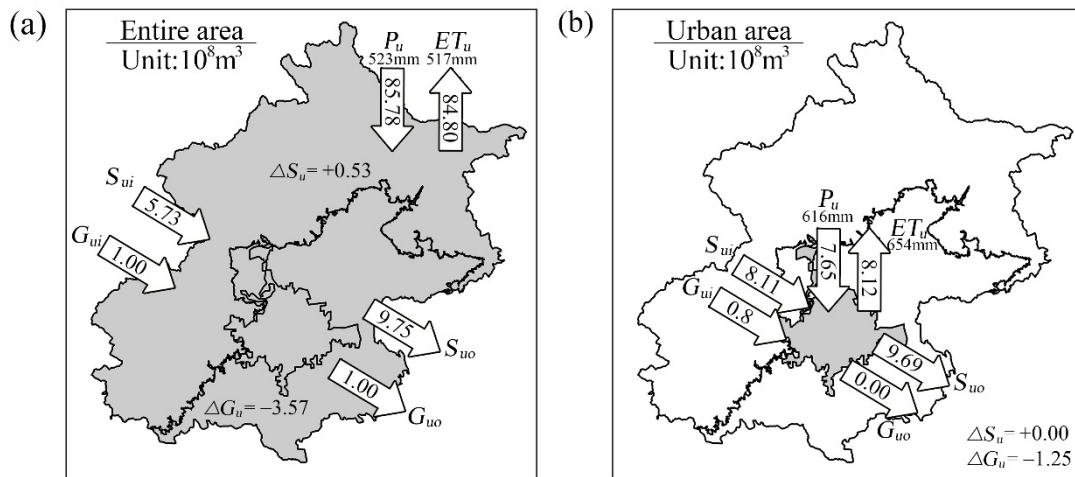
347

##### 4.1 ET estimated by water balance method

348

ET estimation of each subarea based on water balance method from 2003 to 2012 are listed in **Table 4**. It can be seen that the average ET in Beijing from 2003 to 2012 was 517 mm, which was roughly equivalent to average precipitation of 523 mm. This indicates that Beijing made little contribution to the water resources of Hai River Basin. It should be noted that averaged annual ET in urban area was the highest among all subareas (654 mm), while the lowest in mountainous area (472 mm). **Figure 3a** and **Figure 3b** shows the averaged ET and water input/output over the decade in entire Beijing and urban area, respectively. According to **Figure 3**, precipitation made up most of ET in entire Beijing at a long-term scale, however, as for urban area surface inflow and precipitation both contributed greatly to ET. **Figure 4** illustrates the time series of ET estimated by water balance method in subareas of Beijing from 2003 to 2012. It can also be observed that ET in urban area was generally higher than other areas. Additionally, relative smooth changes in ET were observed in plain area and suburban area, while a dramatic variation was shown in mountainous area. This may be attributed to the significant fluctuation of rainfall received in mountain region.

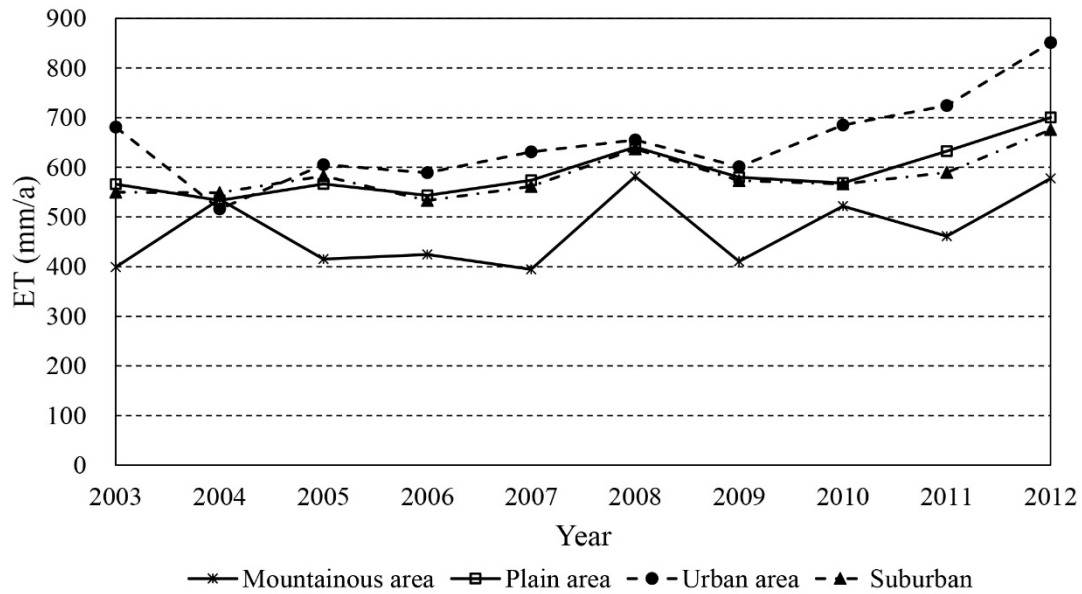
363



364

Figure 3. Averaged annual precipitation and ET in entire Beijing and urban area over 2003 to 2012.

364



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Figure 4. Time series of ET estimation from water balance method in subareas of Beijing during 2003-2012.

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**Table 4** Annual precipitation and ET estimation using SEBS, SEBS-Urban and water balance method (mm).

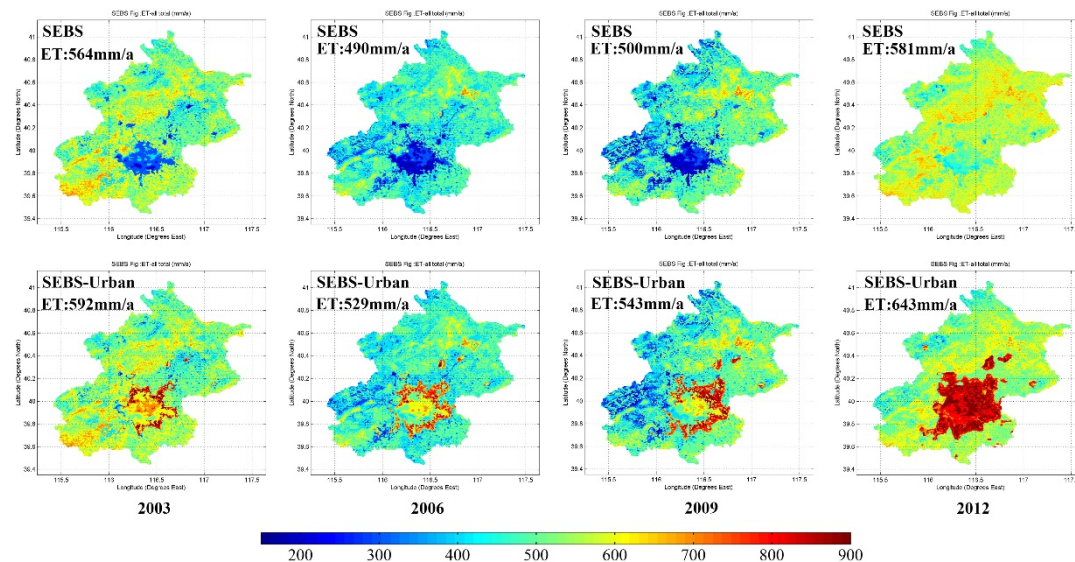
Year		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average
Entire area	Water balance	453	534	474	471	472	603	476	538	521	625	517
	SEBS	564	510	541	490	461	549	500	523	551	581	527
	SEBS-Urban	592	546	574	529	506	595	543	586	607	643	572
	P	453	539	468	448	449	638	448	524	552	708	523
Mountainous area	Water balance	399	536	415	424	395	582	410	522	461	578	472
	SEBS	581	540	561	513	478	566	509	545	578	587	546
	SEBS-Urban	582	542	563	516	481	568	511	550	581	593	549
	P <sub>m</sub>	425	558	442	434	407	648	419	542	492	652	502
Plain area	Water balance	566	533	567	544	574	641	580	568	632	700	591
	SEBS	538	462	508	452	433	523	485	488	507	571	497
	SEBS-Urban	607	553	590	550	547	637	596	644	650	725	610
	P <sub>p</sub>	525	510	510	470	495	625	494	501	665	796	559
Urban area	Water balance	681	516	605	589	631	655	601	685	724	851	654
	SEBS	395	270	328	305	297	372	301	329	361	518	348
	SEBS-Urban	665	537	591	607	613	679	594	658	698	882	652
	P <sub>u</sub>	634	602	450	505	558	680	496	622	743	911	620
Suburban area	Water balance	550	549	582	533	561	637	573	566	589	676	582
	SEBS	569	504	547	484	463	555	524	523	538	582	529
	SEBS-Urban	593	556	589	536	532	627	595	640	638	691	600
	P <sub>s</sub>	510	501	548	462	481	611	493	498	634	780	552

## 369 4.2 ET estimated by original SEBS

370 The annual ET values estimated from original SEBS are listed in **Table 4**. It  
371 represents a contrary results from water balance method that mountainous area has the  
372 highest average ET of 546 mm, while urban area has the lowest average ET of 348 mm.  
373 In this study, 2003, 2006, 2009 and 2012 had been selected as the typical years for  
374 comparison. The spatial variability of annual ET was significant large over the entire  
375 Beijing and the lowest ET was found in urban area (see **Figure 5**).

## 376 4.3 ET estimated by SEBS-Urban

377 The annual ET calculated using SEBS-Urban are listed in **Table 4**. It can be seen  
378 that annual ET in urban area was the highest among all subareas (652 mm), while the  
379 lowest in mountainous area (549 mm), which was coincident with the result from water  
380 balance method. ET spatial patterns vary dramatically over the entire Beijing as  
381 illustrated by **Figure 5**. It can be observed that higher ET values across the study region  
382 were yielded in urban area, and an increasingly trend was also observed from 2003 to  
383 2012.



384

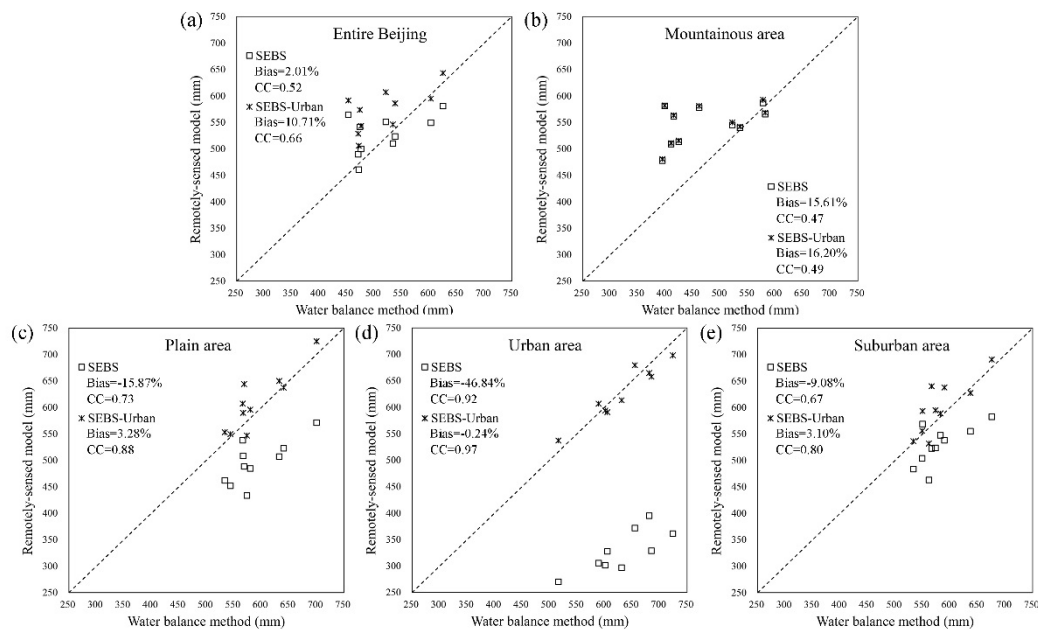
Figure 5. Annual values and spatial distribution of ET estimation using SEBS and SEBS-Urban in the typical years.

385

## 386 4.4 Comparison of ET estimated by different methods

387 The relationships between ET estimation from water balance method and  
388 remotely-sensed models in subareas of Beijing from 2003 to 2012 are demonstrated in  
389 **Figure 6**, and the corresponding ET values are given in **Table 4**. It should be noted that  
390 averaged annual ET in urban area was the highest among all subareas using water  
391 balance method (654 mm) and SEBE-Urban (652 mm). The anthropogenic heat-  
392 impacted areas were extracted from the night-light maps with a numeric value greater  
393 than 52, and the variation is demonstrated in **Figure 7** and **Figure 8**. From **Figure 7**, it  
394 can be seen that in 2003, the extreme values of anthropogenic heat were mainly  
395 concentrated in Xicheng District, Dongcheng District, while partially occurred in Haidian  
396 District and Chaoyang District. The impact of anthropogenic heat gradually intensified  
397 from 2003 to 2012 (see **Figure 8**). By 2012, the concentrations of anthropogenic heat  
398 extended to the entire urban area as well as some surrounding suburban regions,  
399 showing a great expansion in the past decade (see **Figure 7**). In urban area, the existence

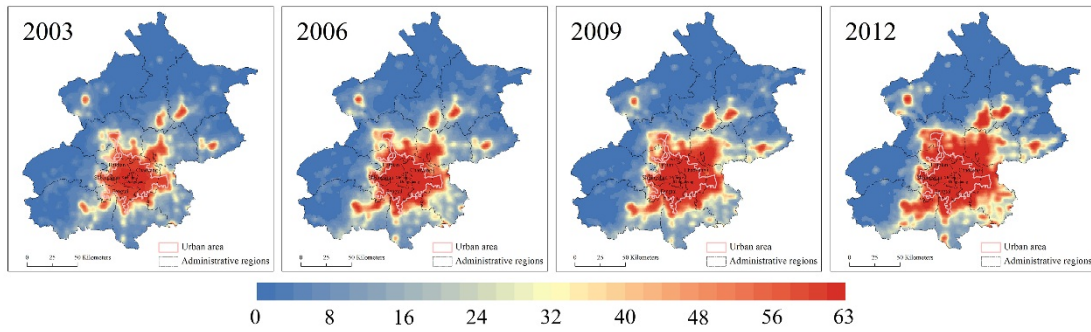
400 of water bodies (e.g. artificial lakes and moats) and constant irrigation for gardens,  
 401 lawns and other greenbelts provide sufficient water for ET purposes. On the other hand,  
 402 anthropogenic heat emission from human metabolism, industrial sector, vehicles and  
 403 buildings contribute greatly to the surface energy budget (Allen et al., 2011; McCarthy  
 404 et al., 2010; Sailor, 2011). These two reasons above can result in a wet-limit condition  
 405 (energy at limiting cases), which could be a main ET additional part compared to  
 406 suburban area. Moreover, domestic water use in the buildings could also be a main  
 407 additional part of ET. The teeming industrial hubs, vehicle exhaust, and densely  
 408 populated make the heart of Beijing city particularly concentrated with anthropogenic  
 409 heat. Therefore, the regions with high value of anthropogenic heat could be the main  
 410 ET additional parts compared to suburban area. It can also be observed that ET values  
 411 estimated by SEBS-Urban showed an agreement with water balance-based estimates in  
 412 urban area, suburban area and plain area, where ET values were underestimated by  
 413 SEBS (see **Figure 6c, 6d, 6e**). Specifically, compared to water balance method, a very  
 414 high correlation coefficient (0.97) as well as small Bias (-0.24%) were showed in urban  
 415 area by SEBS-Urban, while a sharp underestimation in ET values from SEBS was  
 416 observed in urban area (-46.84%). In addition, the results from SEBS and SEBS-Urban  
 417 were approximately equal in mountainous area (see **Figure 6b**), which were in accord  
 418 with the fact that the anthropogenic heat-free areas distribute mostly in mountainous  
 419 area. This provides an insight on how greatly anthropogenic heat impact on ET.  
 420 Therefore, this heat should be included in the urban surface energy budget for an  
 421 accurate estimation of ET in the highly urbanized areas.



422 **Figure 6. Relationships between ET estimation based on water balance method**  
 423 **and remotely-sensed models in subareas of Beijing during 2003-2012.**

422  
 423  
 424



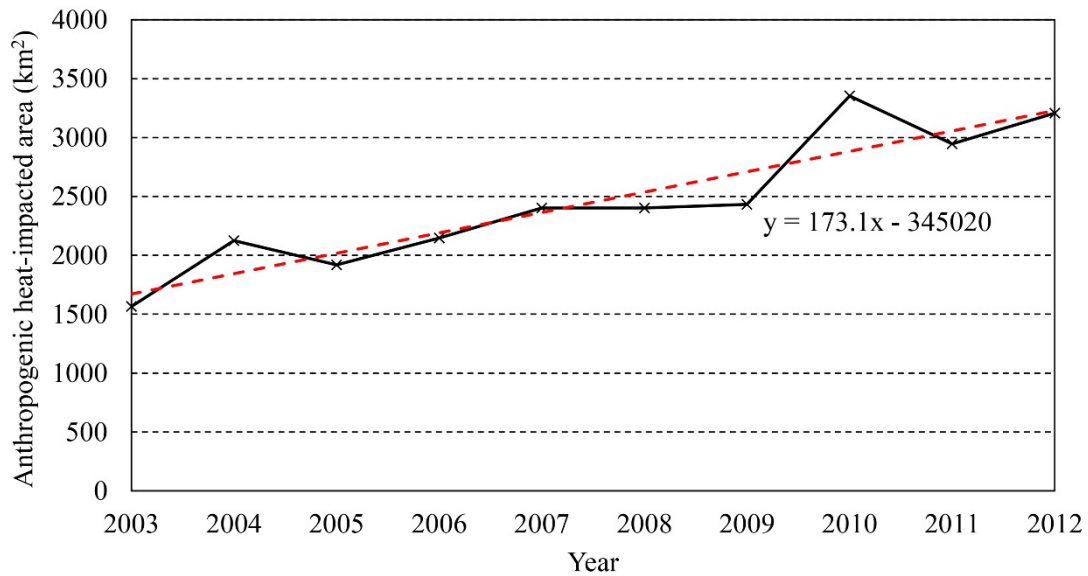


425

Figure 7. The distribution of anthropogenic heat-impacted areas in Beijing in the typical years.

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Figure 8. The evolution of anthropogenic heat-impacted areas in Beijing from 2003 to 2012.

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#### 430 4.5 Uncertainty analysis

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It should be noted that there were some uncertainties existed in ET estimation. As for water balance model, the groundwater inflow was assumed to be equal to groundwater outflow in Beijing city due to the lack of measured data, which would produce uncertainty in ET estimation. Besides, uncertainties could also come from the annual precipitation in subareas, which were estimated according to meteorological stations and local precipitation contour map. In remote sensing-based methods, a major concern is the quality of satellite image which are greatly influenced by weather condition in the study region. The uncertainties were somehow generated from the subjective selection of the cloud-free days in the year.

Actually aerosol can contribute to additional large-scale decrease in radiation budget in the metropolises like Beijing (Charlson and Schwartz, 1992; Hansen et al., 1997; Haywood and Shine, 1995; Kushta et al., 1995; Papayannis et al., 1998). In this study, the long time scale extension was based on the ratio of estimated  $ET_0$  and the corresponding  $ET_0$  for the days of image available, then the actual ET for days without good quality images could be inferred. Note that aerosol played an essential role in sunshine duration, which has a great influence on net radiation, and then the  $ET_0$ . Therefore, aerosol effect was not considered in the estimation of cloud-free days ET,

448 but was implicitly considered in the crop coefficient method which was used to extend  
449 time series of ET. However, the extension of long-time series of ET would lead to some  
450 uncertainties if the intervals between images available were not accordance with the  
451 actual case.

## 452 **5. Conclusions**

453 In this study, water balance method, energy balance model SEBS and SEBS-Urban  
454 were used to estimate ET of Beijing from 2003 to 2012. Our results have shown that:

455 (1) Based on water balance method, the average ET over 2003 to 2012 was 517  
456 mm in entire Beijing. The urban area had the highest ET value (654 mm), while the  
457 mountainous area had the lowest value (472 mm).

458 (2) Using SEBS model, the annual average ET in urban area was sharply  
459 underestimated with a value of 348 mm. By the modified model SEBS-Urban, annual  
460 average ET in urban area was the highest among all subareas (652 mm), while the  
461 lowest in mountainous area (549 mm), which was coincident with the result from water  
462 balance method.

463 (3) Time series of ET estimated by SEBS-Urban showed a good agreement with  
464 water balance method in urban area.

465 The results indicate that anthropogenic heat should be included in the surface  
466 energy budget for a highly urbanized area. Further study should focus on detailed  
467 analysis on the evaluation of anthropogenic heat as well as the impact of net advection.

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