Estimation of Growing Season Daily ET in the Middle Stream and Downstream Areas of the Heihe River Basin Using HJ-1 Data

Zhansheng Li, Li Jia, Guangcheng Hu, Jing Lu, Jingxiao Zhang, Qiting Chen, and Kun Wang

***Abstract*—Spatial mapping of evapotranspiration (ET) is specifically critical for the semi-arid inland river basin with great heterogeneity in land-cover types. This letter estimates the spatial distribution of daily ET over the middle stream and downstream areas of the Heihe River Basin during the growing season of 2012 by using the Surface Energy Balance System algorithm with land surface temperature at high spatial resolution (300 m) derived from observations by the Chinese satellite HJ-1. The results demonstrate that ET estimates are consistent with ground-based measurements collected during the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) with acceptable accuracy. The magnitude of daily ET in the downstream area is obviously lower than that in the middle stream area. Further analysis based on classification maps shows that there is significant temporal–spatial heterogeneity of daily ET over different land-cover surfaces and also within the same vegetation type. The temporal variation of ET in the middle stream area has clear seasonality with an obvious peak in July, whereas it is flat in the downstream area due to the dominating arid-region vegetation species and low soil water content in growing season. In addition, because of the abundant irrigation in the maize and irrigated orchard fields, the daily ET values of them are higher than that of wetland and even comparable with that of water surface in the middle stream area of the Heihe River Basin.**

***Index Terms*—Evapotranspiration (ET), Heihe River Basin, Heihe Watershed Allied Telemetry Experimental Research (HiWATER), heterogeneity, Surface Energy Balance System (SEBS).**

I. Introduction

THE Heihe River Basin is the second largest inland river basin in the northwest of China. It is characterized by the distinct cold and arid climate from the upstream to the downstream areas and with complex landscapes, including glaciers, frozen soil, alpine meadow, forest, irrigated crops, riparian ecosystem, and desert [1]. This area faces great pressure to deliver and manage very scarce water resources. The agricultural expansion in the middle stream area of the Heihe River Basin has exacerbated regional conflicts between water demand and water supply. In particular, overuse of water in the middle stream for crop irrigation leads to less water to be allocated to the downstream area and resulted in remarkable degradation of downstream ecosystems in the past few decades. The rational use of the water resources is therefore becoming an urgent and important issue in this area.

Evapotranspiration (ET) is closely related to the ecological processes such as vegetation spatial variation and structural dynamics and plays a crucial role in the local water balance and water cycle, particularly in arid and semi-arid regions. Therefore, quantifying the use of water resources for different land-cover types will improve our understanding of the inherent ecohydrological processes and improve the rational allocation of water resources with more efficiency, equity, and sustainability.

Due to the heterogeneity of land-cover and vegetation types, it is difficult to estimate regional ET by means of conventional point or patch scale measurements done locally for a specific land cover, particularly for the area undergoing dramatic landscape modification. Remote sensing technology has been proved to be a promising method to get land surface variables [2] and regional ET with acceptable accuracy over the Heihe River Basin [3], [4].

In this letter, the widely used Surface Energy Balance System (SEBS) model [5]–[7] is employed to derive regional ET distribution over the middle stream and downstream areas of the Heihe River Basin using the observations from HJ-1 satellite on cloud-free days during the growing season of 2012. A detailed vegetation classification map produced from high-spatial-resolution images was used to identify various vegetation types over middle stream and downstream areas. Moreover, the classification map was also used to improve the parameterization of the aerodynamic roughness length.

II. Study Area and Data

A. Study Area

The Heihe River Basin has an area of 143 000 km^2. Its main stream with a total length of 928 km originates from the Qilian Mountains and flows through the Hexi Corridor in Gansu Province and enters into the western Inner Mongolia [8].

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TABLE I
AVAILABLE HJ-1B DATA FROM MAY TO SEPTEMBER OF 2012

Study Area	Clear Sky Days in 2012 (Month/Day)
Middle stream area	5/1, 5/16, 6/19, 6/30, 7/8, 7/27, 8/14, 8/15, 8/22, 8/29, 9/6
Downstream area	5/16, 5/31, 6/15, 6/19, 6/30, 8/7, 8/18, 8/22, 9/6, 9/17, 9/28, 9/29

The middle stream area of the Heihe River Basin is located in a flat plain with annual mean precipitation of approximately 100–250 mm. The landscape is dominated by irrigated croplands and desert. The major crops are maize, spring wheat, and vegetables [9]. In the downstream area, the landscape is composed of sandy and gravelly deserts; a natural oasis dominated by *Populus euphratica*, *Tamarix*, and other arid-region species; and lakes as the Heihe River terminal. The downstream area is a typical arid region with annual mean precipitation of less than 50 mm.

B. Remotely Sensed Data Sets

Remote sensing data used in this letter are mainly from HJ-1A/B satellite and MODIS sensor onboard both Terra and Aqua satellites, including MCD43 Albedo and MCD15 LAI products. HJ-1A/B can provide visible/near-infrared/thermal infrared (VIS/NIR/TIR) images with 30-, 150-, and 300-m spatial resolution values, respectively, with every four days' revisit time covering China and the surrounding areas [10]. The LAI was retrieved using images from VIS/NIR bands of HJ-1A/B. The land surface temperature was calculated from the TIR images of HJ-1B based on single split window method [11].

During the growing season from May 1 to September 30 in 2012, only 11 clear-sky images over the middle stream area and 12 images over the downstream area were available for ET calculation (see Table I).

C. Meteorological Data

The near-surface meteorological variables, including wind speed, air temperature, air specific humidity, air pressure, and downward short-wave and long-wave radiations at 5-km spatial resolution and 1-h temporal interval, were from the Heihe Plan Science Data Center (doi: 10.3972/heihe.019.2013.db), which were provided by Pan *et al.* [12].

D. Ground Data

The land surface energy flux data from four eddy-covariance (EC) sites (i.e., EC-01-Vegetable, EC-07-Maize, EC-17-Orchard, and EC-Wetland) are the products of the Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces 2012 (MUSOEXE-12) [13] and can be found at http://www.heihedata.org/. This experiment was carried out in the Zhangye Oasis in the middle stream area of the Heihe River Basin as part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) project [1]. The data collected at the four sites represent three typical vegetation types in the experimental area, i.e., vegetable (EC-01), maize (EC-07), and irrigated orchard (EC-17), and the wetland (EC-Wetland). More detailed information about the methods of data

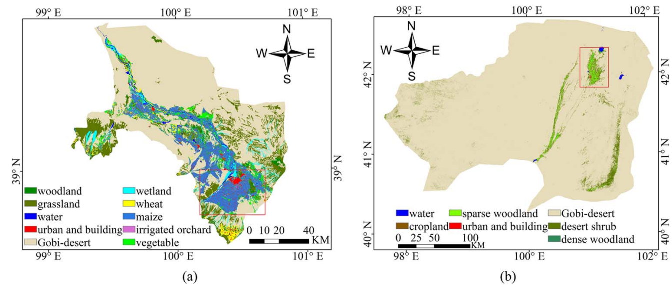

Fig. 1. Land-cover map of (a) middle stream and (b) downstream areas of the Heihe River Basin. The red rectangles in land-cover map (a) and (b) indicate the Zhangye Oasis and Ejin Banner Oasis, respectively.

processing and quality control of EC flux measurements is given in [14].

E. Land-Cover Data

The land-cover maps (see Fig. 1) of the middle stream and downstream areas of the Heihe River Basin were generated based on high-spatial-resolution Landsat TM images. Intensive field survey was also carried out during the HiWATER experiment in the Zhangye Oasis and Ejin Banner Oasis to validate and improve the accuracy of classification of vegetation and land cover.

The complex land-cover types were grouped into six major vegetation classes (i.e., wheat, maize, vegetable, grassland, woodland, and irrigated orchard) and four nonvegetation classes (i.e., urban and building, wetland, water, and Gobi desert) in the middle stream area. For the downstream area, the land cover is classified into seven types, including four vegetation classes and three other classes, i.e., cropland, dense woodland (NDVI $\geqslant 0.25$ in June), sparse woodland (NDVI $\geqslant 0.25$ in June), desert shrub, urban and build-up, Gobi desert, and water.

All the input data sets, including the satellite data, the meteorological data, and the map of vegetation types, are resampled to the same pixel size of HJ-1B TIR band (300 m).

III. METHOD AND VALIDATION

A. Method for Daily ET Estimation

The method used to estimate instantaneous latent heat flux (LE) is based on the SEBS algorithm; more information about this model can be found in the work in [5]–[7]. In addition, aerodynamic roughness length of the land surface for momentum transfer (z_{0m}) is estimated using the algorithms by Raupach [15] and Jasinski *et al.* [16] with the information of canopy height and density derived from LAI.

The SEBS model provides only instantaneous ET value at HJ-1B overpass time. For the application of water resources management, the daily ET is more meaningful. In this letter, sinusoidal function is used to extrapolate the instantaneous ET to daily ET value [17].

B. Validation

The turbulent heat flux data from four sites in the middle reach of Heihe River Basin (i.e., EC-01-Vegetable, EC-07-Maize, EC-17-Orchard, and EC-Wetland) on nine clear-sky days were selected for validation of the estimated daily ET.

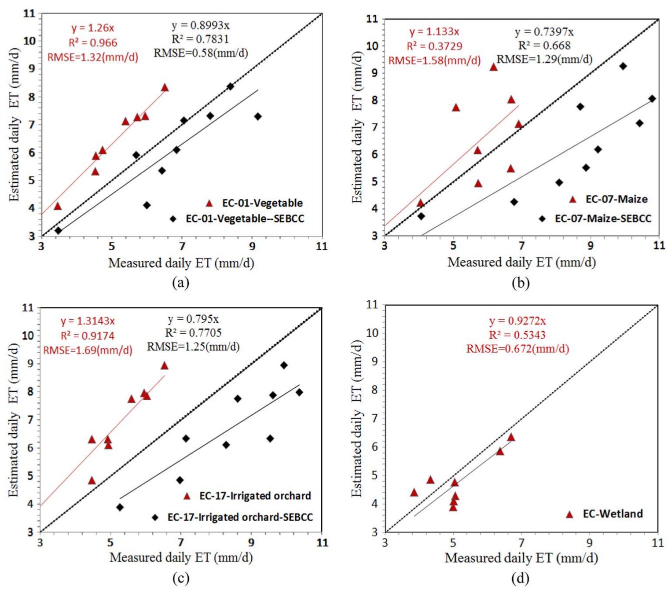

Fig. 2. Comparison between estimated daily ET and the ground measurements (black rhombus) with SEBCC and (red triangle) without SEBCC on nine cloud-free days in 2012 at four sites in the middle reach of the Heihe River Basin. (a) EC-01-Vegetable. (b) EC-07-Maize. (c) EC-17-Orchard. (d) EC-Wetland.

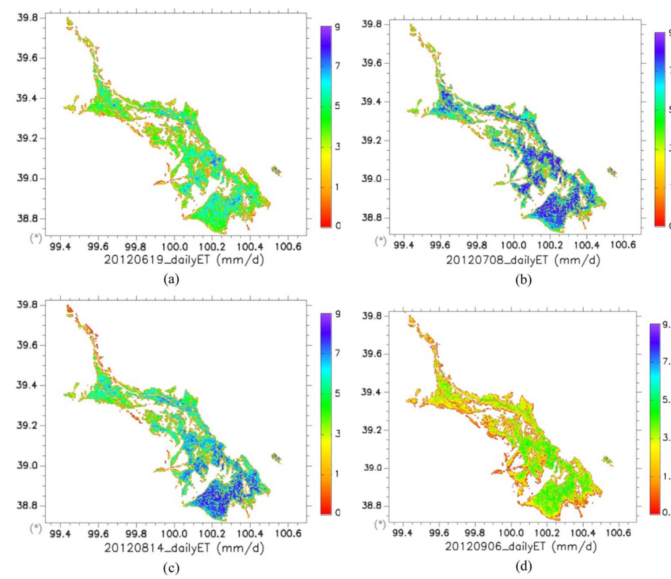

Fig. 3. Spatial distribution of daily ET in the middle reach of the Heihe River Basin on (a) June 19, (b) July 08, (c) August 14, and (d) September 06, in 2012.

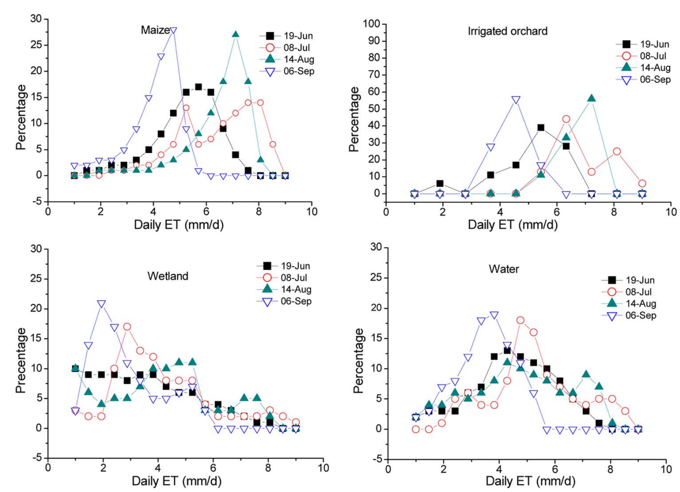

Fig. 4. Statistical histogram of the estimated daily ET on June 19, July 08, August 14, and September 06, 2012 for (a) maize, (b) irrigated orchard, (c) wetland, and (d) water.

The surface energy balance (SEB) closure correction (SEBCC) using Bowen ratio (BR) method was applied to the EC measurements of turbulent heat fluxes [18]. Due to the lack of soil heat flux measurements at the EC-Wetland site, the comparisons between the estimated and corrected daily ET values only for three vegetation sites are plotted in Fig. 2(a)–(c) using the diamond symbols.

The modeled daily ET in general is underestimated when compared with ground measurements with SEBCC at the three sites EC-01-Vegetable, EC-07-Maize, and EC-17-Orchard with the correlation coefficients as 0.79, 0.81, and 0.86 and RMSE = 0.58, 1.29, and 1.25 mm/day, respectively. At the instantaneous scale, the average correlation coefficient between the SEBS-estimated LE and the measurements corrected by BR method at the three sites is 0.88 with an RMSE = 37 W/m^2. Compared with the estimated LE across the Heihe River Basin from other works [2], [3], our work has shown better accuracy for the instantaneous LE estimation. When compared with the observed daily ET without SEBCC, the SEBS model tends to overestimate the daily ET at the three vegetation sites. It should be noticed that the observed daily ET from wetland showed relatively smaller values compared with those from the other three land surface types.

Although the EC measurements are widely used to validate the pixel-scale ET estimates, one should keep in mind that such comparison might only be taken as a relative reference for evaluation of the model performance at the spatial resolution of 300 m considering the limited spatial representative of EC measurements, particularly for heterogeneous land surface [19].

IV. Results

A. Daily ET Over the Middle Reach of the Heihe River Basin

The spatial patterns of daily ET over the middle reach of the Heihe River Basin on four clear-sky days in different months of the growing season (June, July, August, and September) are presented in Fig. 3. Regional ET distribution shows strong spatial and temporal variations during the growing season. In general, the daily ET in the whole region began to increase from June and reached the peak values in July, then started to decline in August, and reached the lowest values in September. The largest values were observed in July 8, 2012, attributed to the fact that all crops, particularly the major crop maize, were under peak development period. The largest spatial variation appeared in August 14 for the whole region with the larger daily ET values in the maize-growing region in the Zhangye Oasis. This could be explained by the fact that the Zhangye Oasis with better water infrastructure are undergoing high-intensity irrigation compared with other maize areas in August.

Corresponding to the results in Fig. 3, the statistical histograms of daily ET of four land-cover types (maize, irrigated orchard, wetland, and water) are presented in Fig. 4.

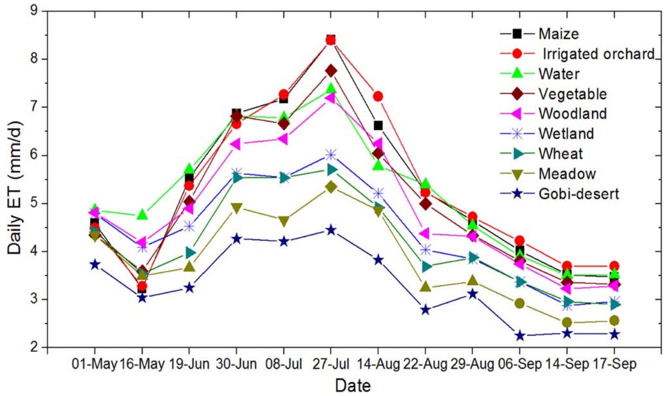

Fig. 5. Seasonal variation of daily ET of different land-cover types in the middle reach of the Heihe River Basin on 11 clear-sky days in 2012.

Four land-cover types have a similar frequency distribution but with significant different peak values in different months. For example, when the daily ET reached the lowest values in September, the range of frequency distribution is minimum and the peak values appear around 4.2, 4.1, 2.6, and 1.9 mm/day for maize, irrigated orchard, water, and wetland, respectively. Compared with that for water and wetland, the range of daily ET for maize and irrigated orchard is relatively narrow and the frequency distribution is more concentrated. The results in Fig. 4 also prove that there is significant spatial variation even for the same land-cover type.

The areal statistical means of daily ET of each land-cover type in the middle stream area of the Heihe River Basin on the 11 clear-sky days are presented in Fig. 5. The SEBS algorithm is developed mainly for soil and vegetation areas and may be inapplicable over city area. Therefore, the results of ET over the urban and building area of the Heihe River Basin are eliminated.

The daily ET of different land-cover types showed similar seasonality from May to September in 2012. Peak values of daily ET of all land-cover types appeared in the peak growing season (July).

Among the vegetation classes, the ET values of maize fields and irrigated orchards are found always higher than those of the other land-cover types, followed by those of the vegetable, woodland, wheat, and meadow. Although the land-cover classification map with 300-m resolution would bring some errors into the spatial statistical results due to mixing classes in a pixel, the magnitude of daily ET from maize fields is still dramatically large compared with the water surface and the wetland. This can be attributed to abundant water supply to the maize field from frequent flooding irrigation to ensure the growth of seed maize under no-stress condition for better seed product. This apparently has resulted in soil water content reaching its field capacity and, in turn, large daily ET. In the peak growing season (mid-June to August), the daily ET from maize was even larger than that from water surface when maize plants have strong transpiration due to sufficient water supply.

In the orchard in the Zhangye Oasis, other types of crops (soybean, spring wheat, and maize) were intercropped in the orchard field in different seasons. Frequent irrigation to these crops led to relatively higher daily ET from the orchard during the growing season.

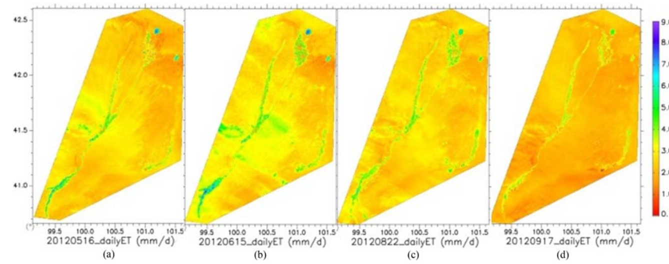

Fig. 6. Spatial distribution of estimated daily ET in the downstream area of the Heihe River Basin on: (a) May 16, (b) June 15, (c) August 22, and (d) September 17, in 2012.

The spring wheat was in maturity period in summer; hence, the ET of wheat fields was obviously lower than that of the other vegetation types.

For the wetland, the ET value is obviously lower than that of irrigated orchard and maize, which is consistent with the ground measurements (see Fig. 2). Part of the Zhangye wetland is seasonal wetland; the area of surface water significantly changes with season and year depending on water supply to the wetlands, which, in turn, has influence on soil moisture and vegetation development, particularly in dry years. In fact, the area of water surface in the wetland region was relatively small in 2012 in comparison with other years.

The water surface in the middle stream areas is mainly the river canal surrounded by river beds characterized by sandy soil surface and sparsely covered vegetation (bushes and trees). Part of the pixels classed as “water surface” at 300-m resolution are not pure water surface but mixed pixels with relative lower ET values, as shown in Fig. 4(d). As a consequence, the areal statistical means of daily ET are not the highest among all the land-cover types.

In addition, as expected, the Gobi desert has the lowest daily ET.

B. *Daily ET Over the Downstream of the Heihe River Basin*

The spatial patterns of daily ET over downstream area of the Heihe River Basin on four clear-sky days in different months of the growing season (May, June, August, and September) are presented in Fig. 6. It is observed that the spatial patterns of daily ET during the growing season are highly heterogeneous in the downstream area, particularly in the Ejin Banner Oasis.

Fig. 7 shows the temporal variation of daily ET for six major land-cover types of the downstream area from May to September. In general, the daily ET of the water body in the downstream area is the highest among all land-cover types, with the ET of the woodland being the second, followed by the cropland and desert shrubs. The different land-cover types showed similar temporal variations of daily ET along the growing season. Meanwhile, the results in Fig. 7 show that the temporal variability was very flat in comparison with that in the middle reach of the Heihe River Basin for all the land-cover types (see Fig. 5). This is mainly attributed to scarce water resource and rare precipitation in downstream area, leading to the changeless soil evaporation and plant transpiration because of invariable soil water content both at the surface and in the root zone. Dominating arid-region vegetation species in the downstream area, i.e., *Populus euphratica* and *Tamarix*, which

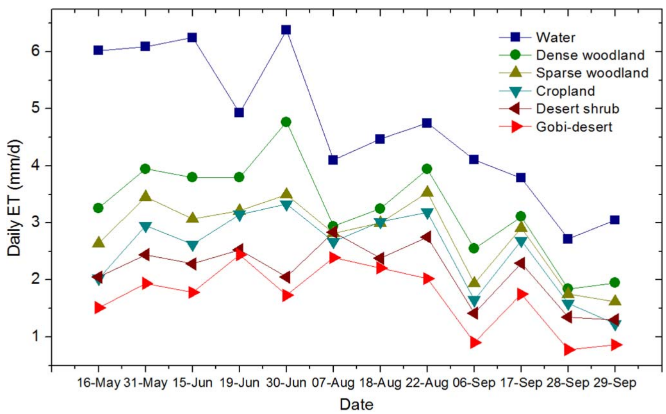

Fig. 7. Temporal variations of the daily ET for different land-cover types in the downstream of the Heihe River Basin during 12 clear-sky days in 2012.

have relative lower plant transpiration, could also lead to the flat temporal variability and small magnitude of daily ET for the vegetation types in a certain degree.

Compared with the estimated daily ET in the middle stream area of the Heihe River Basin, the magnitude of daily ET in the downstream area is obviously lower, particularly for the vegetation types. It could be also explained by the joint lower soil evaporation and lower plant transpiration due to lower water content and the arid-region vegetation species in the downstream areas.

V. Conclusion

In this letter, the spatial distribution of daily ET in the middle stream and downstream areas of the Heihe River Basin has been estimated using HJ-1 satellite observations at high spatial resolution during the growing season of 2012. Estimated daily ET showed consistent trend with the EC measurements, and the comparisons of instantaneous LE between the measured and estimated LE values show that the SEBS can estimate ET with reasonable accuracy.

In the middle stream and downstream areas of the Heihe River Basin, the regional daily ET distribution shows significant spatial and temporal heterogeneity. Further analysis based on a classification map shows that the difference of daily ET over different land-cover/vegetation types is one of the important reasons leading to the heterogeneity of regional ET distribution. Even for the same types, spatial statistics (histograms) significantly change in different months. Compared to the flat temporal variability with small range in downstream, the temporal variation of ET changes with clear seasonality with obvious peak value in July for the vegetative land surface in the middle stream area along the growing season.

The magnitude of daily ET in the downstream area is obviously lower than that in the middle stream area, particularly for the vegetation types, which is caused by lower plant transpiration and lower soil evaporation due to the low soil water content and dominating arid-region vegetation species. In the middle stream area, the daily ET of croplands (i.e., maize and irrigated orchard) is even higher than that of water surface and wetlands due to the abundant irrigation in this region. It implies that there is a great potential for water saving in this area.

Further study should be focused on producing high spatial yet high temporal continuous-time series of daily ET. Such information should be useful for decision makers to fulfill an optimal allocation of limited water resources in this region.

References

[1] X. Li *et al.*, “Heihe Watershed Allied Telemetry Experimental Research (HiWATER): Scientific Objectives and Experimental Design,” *Bull. Amer. Meteorol. Soc.*, vol. 94, pp. 1145–1160, Aug. 2013.

[2] W. Ma *et al.*, “Estimating surface fluxes over middle and upper streams of the Heihe River Basin with ASTER imagery,” *Hydrol. Earth Syst. Sci.*, vol. 15, pp. 1403–1413, May 2011.

[3] X. Li, L. Lu, W. Yang, and G. Cheng, “Estimation of evapotranspiration in an arid region by remote sensing—A case study in the middle reaches of the Heihe River Basin,” *Int. J. Appl. Earth Obs. Geoinf.*, vol. 17, pp. 85–93, Jul. 2012.

[4] J. Colin, R. Faivre, and M. Menenti, “Aerodynamic roughness length estimation from very high-resolution imaging LIDAR observations over the Heihe basin in China,” *Hydrol. Earth Syst. Sci.*, vol. 14, pp. 2661–2669, Dec. 2010.

[5] Z. Su, “The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes,” *Hydrol. Earth Syst. Sci.*, vol. 6, pp. 85–99, Feb. 2002.

[6] L. Jia *et al.*, “Estimation of sensible heat flux using the surface energy balance system (SEBS) and ATSR measurements,” *Phys. Chem. Earth*, vol. 28, pp. 75–88, 2003.

[7] L. Jia *et al.*, “Regional estimation of daily to annual regional evapotranspiration with MODIS data in the Yellow River Delta wetland,” *Hydrol. Earth Syst. Sci.*, vol. 13, pp. 1775–1787, Oct. 2009.

[8] L. Jia, H. Shang, G. Hu, and M. Menenti, “Phenological response of vegetation to upstream river flow in the Heihe River basin by time series analysis of MODIS data,” *Hydrol. Earth Syst. Sci.*, vol. 15, pp. 1047–1064, Mar. 2011.

[9] Y. Chen *et al.*, “Water demand management: A case study of the Heihe River Basin in China,” *Phys. Chem. Earth*, vol. 30, pp. 408–419, 2005.

[10] Q. Wang, C. Wu, Q. Li, and J. Li, “Chinese HJ-1A/B satellites and data characteristics,” *Sci. China Earth Sci.*, vol. 53, pp. 51–57, Dec. 2010.

[11] H. Li *et al.*, “A single-channel algorithm for land surface temperature retrieval from HJ-1B/IRS data based on a parametric model,” in *Proc. IEEE Int. Geosci. Remote Sensing Symp. (IGARSS)*, pp. 2448–2451, Jun. 2010.

[12] X. Pan *et al.*, “Dynamic downscaling of near-surface air temperature at the basin scale using WRF—A case study in the Heihe River Basin, China,” *Front. Earth Sci.*, vol. 6, pp. 314–323, Sep. 2012.

[13] Z. Xu *et al.*, “Intercomparison of surface energy flux measurement systems used during the HiWATER-MUSOEXE,” *J. Geophys. Res.*, vol. 118, pp. 13140–13157, Dec. 2013.

[14] S. Liu *et al.*, “A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem,” *Hydrol. Earth Syst. Sci.*, vol. 15, pp. 1291–1306, Apr. 2011.

[15] M. R. Raupach, “Drag and drag partition on rough surfaces,” *Bound-lay. Meteorol.*, vol. 60, pp. 375–395, Sep. 1992.

[16] M. F. Jasinski, J. Borak, and R. Crago, “Bulk surface momentum parameters for satellite-derived vegetation fields,” *Agr. Forest Meteorol.*, vol. 133, pp. 55–68, Jul. 2005.

[17] R. Jackson, J. Hatfield, R. Reginato, S. Idso, and P. Pinter, Jr., “Estimation of daily evapotranspiration from one time-of-day measurements,” *Agr. Water Manage.*, vol. 7, pp. 351–362, Sep. 1983.

[18] T. E. Twine *et al.*, “Correcting eddy-covariance flux underestimates over a grassland,” *Agr. Forest Meteorol.*, vol. 103, pp. 279–300, Jun. 2000.

[19] Z. Jia, S. Liu, Z. Xu, Y. Chen, and M. Zhu, “Validation of remotely sensed evapotranspiration over the Hai River Basin, China,” *J. Geophys. Res.*, vol. 117, p. D13113, Jul. 2012.