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# Heat Flux Apportionment to Heterogeneous Surfaces Using Flux Footprint Analysis

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**ABSTRACT**

Heat flux data collected from the Baiyangdian Heterogeneous Field Experiment were analyzed using the footprint method. High resolution (25 m) Landsat-5 satellite imaging was used to determine the land cover as one of four surface types: farmland, lake, wetland, or village. Data from two observation sites in September 2005 were used. One site (Wangjiazhai) was characterized by highly heterogeneous surfaces in the central area of the Baiyangdian: lake/wetland. The other site (Xiongxian) was on land with more uniform surface cover. An improved Eulerian analytical flux footprint model was used to determine "source areas" of the heat fluxes measured at towers located at each site from surrounding landscapes of mixed surface types. In relative terms results show that wetland and lake areas generally contributed most to the observed heat flux at Wangjiazhai, while farmland contributed most at Xiongxian. Given the areal distribution of surface type contributions, calculations were made to obtain the magnitudes of the heat flux from lake, wetland and farmland to the total observed flux and apportioned contributions of each surface type to the sensible and latent heat fluxes. Results show that on average the sensible heat flux from wetland and farmland were comparable over the diurnal cycle, while the latent heat flux from farmland was somewhat larger by about $30-50$ W m$^{-2}$ during daytime. The latent and sensible fluxes from the lake source in daytime were about 50 W m$^{-2}$ and 100 W m$^{-2}$ less, respectively, than from wetland and farmland. The results are judged reasonable and serve to demonstrate the potential for flux apportionment over heterogeneous surfaces.

**Key words**: Eulerian analytical model, flux footprint, heat flux, heterogeneous surface

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## 1. Introduction

There is considerable current interest in monitoring and characterizing the transfer of latent and sensible heat between terrestrial ecosystems and the atmosphere over extended periods of time. The interest on this subject has led to many experiments on land surface processes in different parts of the world. At present the most mature technique to obtain and analyze near-surface turbulent fluxes is measurement of eddy-flux covariances and contributions thereto based on flux footprint models to determine the "source areas" of the flux data. Such an approach contributes to understanding the differences in heat transfer fluxes over complex land cover.

As pioneered by Schuepp et al. (1990), the "footprint" concept is used to specify the relative contribution of each source element of the upwind surface area to the measured concentration or flux. In simpler terms, it is the probability that a scalar coming from a given elemental source reaches the measurement point (Guo and Cai, 2005). The footprint func-

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tion, i.e., source weight function, gives a qualitative and quantitative description of the relationship between the spatial distribution of surface sources and the measured signal.

Since the 1990s, several flux footprint models have been designed and studied by many scientists (Leclerc and Thurtell, 1990; Schuepp et al., 1990, 1992; Horst and Weil, 1992, 1994; Schmid, 1994, 1997, 2002; Leclerc et al., 2003a,b; Sogachev et al., 2006). There are two widely used approaches. The first obtains analytical solutions to the Eulerian advection-diffusion equation. The second obtains Lagrangian Stochastic (LS) descriptions of the trajectories of passive particles in a turbulent flow (Cai and Leclerc, 2007, Cai et al., 2007). Each approach has advantages and disadvantages. The Eulerian analytical flux footprint models are relatively easy to use and less computationally expensive but, since homogeneity is assumed, these models, cannot account for inhomogeneous turbulence. The LS flux footprint models do well with heterogeneous surfaces but require larger computational resources. To mitigate the problem of the analytical approach, an Eulerian footprint model has been improved recently through use of satellite maps for explicit assignment of surface type (Göckede et al., 2004). Rebmann et al. (2005) applied this new model at 18 sites of the programme "An Investigation on Carbon and Energy Exchanges of Terrestrial Ecosystems in Europe" (CARBOEUROFLUX) to assess the satellite based surface typing used in flux measurements over complex surfaces and obtained results considered satisfactory.

At present footprint models are used primarily in three ways in conjunction with turbulent flux measurements. First, they are used to estimate the source areas contributing to the flux observations. Second, they provide a tool for quality control of the flux measurements. Third, footprint models provide guidance in designing experiments. Together these applications indicate the models have considerable potential in microclimatology investigations, especially in studies which include non-homogeneous surfaces.

This study expands the potential application of footprint models to calculating contributions from various surface types to the observed total heat flux and to apportioning the individual sensible and latent heat components over each surface type. Previously measurements over complex surface regions reflected a mix of differing sources, and it was difficult to judge the representatives of any particular surface over some interval of time.

This work is a part of the "Field Experiment for Surface Flux Parameterization and Atmospheric Boundary Layer Process", a project jointly conducted by Peking University and Institute of Atmospheric Physics, Chinese Academy of Sciences, with emphasis on land processes over heterogeneous surfaces (Hu et al., 2006). Measurements from two sites of this experiment were used, Wangjiazhai and Xiongxian. A 5×5 $km^2$ domain around the respective sites was used for land cover analysis. An Eulerian analytical footprint model based on the theory suggested by Kormann and Meixner (2001), along with the method of Göckede et al. (2004), was developed by Peking University in order to analyze the observed heat flux data. The focus is to explore the potential capability of applying the model to characterizing heat fluxes over the heterogeneous surfaces such as the over the experiment domains.

## 2. Site and data

### 2.1 *Site description and instruments*

This experiment was carried out at two sites, Wangjiazhai and Xiongxian, both located in Baiyangdian to the south of Beijing. Baiyangdian is the largest wetland ecosystem in Hebei province, which is part of the north China plain and is composed of 143 small lakes with dozens of fishing villages scattered on many islands.

Wangjiazhai is located on an island (38.917°N, 115.976°E), surrounded by shallow water. The surface around the site is complex and inhomogeneous and, thereby, ideal for the objectives of this project. A 12-meter tower was set up on the island. A large region of wetland about 25 $km^2$ in area is located to the north of the tower. The eastern side of the tower is adjacent to a small lake. To the south the land cover is a combination of wetland and lake, while there are scattered villages and farm fields to the northwest. The top of the tower was instrumented with three-dimensional ultrasonic anemometers and $CO_2$-humidity probes (LICOR7500). The measurements at this site were made from 9–26 September 2005.

Xiongxian is located 16 km to the northeast of the Wangjiazhai site (38.948°N, 116.03°E). The town of Xiongxian is located about 2 km to the south. A large farm field surrounds the site and can be regarded as nearly homogeneous. This site served as a reference point for comparison with the analysis of the turbulence fluxes over the more heterogeneous surfaces at Wangjiazhai. A corresponding set of instruments to those used at Wangjiazhai was mounted on a 3.4-meter stand at Xiongxian. Measurements at this site were taken from 10–26 September 2005.

At both sites, the turbulence data were collected at 10 Hz, and the fluxes of momentum, sensible heat,

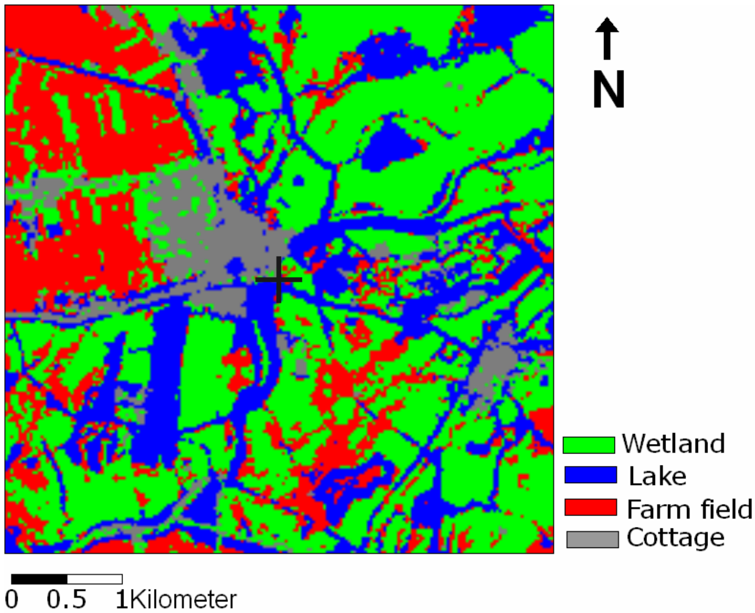


**Fig. 1.** Classification of land use in the domain (5 × 5 km$^2$) of the Wangjiazhai footprint analyses. The cross (+) at the center is the location of the instrument tower.

and latent heat were calculated using the eddy covariance method. More details about this field experiment are found in the paper of Hu et al. (2006).

### 2.2 *Satellite data*

A Landsat-5 Thematic Mapper (TM) Satellite Image on 11 September 2005 was selected for classifying the land cover because of the clear conditions and the availability of high-resolution (25 m) imagery on that day. This remote sensing capability provides more detailed information around the measurement site than available topographical maps and, therefore, more compatible with the resolution of micrometeorological models (Hasager et al., 2003). A 5×5 km$^2$ domain around the Wangjiazhai tower was used in the footprint analyses. Figure 1 shows the land cover classification in the domain based on the satellite image. The measurement site located at the center of Fig. 1.

### 2.3 *Data processing*

The measurements were made for nearly 3 weeks at both sites. During this period, it was mostly clear and free of precipitation, except on two days (15 and 20 September). The prevailing wind directions at Wangjiazhai were northeast and southwest while east and west at Xiongxian. The raw data collected by the ultrasonic anemometer at 10 Hz was used to calculate hourly the Obukhov length, friction velocity, mean wind speed, mean wind direction, heat and momentum fluxes using the eddy covariance method. Data judged erroneous was removed before input to the footprint model described in section 3.

## 3. Footprint model and method

The flux footprint model used in this study is an Eulerian analytical system described by Kormann and Meixner (2001). The approach uses standard power laws to obtain vertical profiles of the eddy diffusivity, $K(z)$, and the horizontal wind velocity, $u(z)$. These values together with Monin-Obukhov similarity theory establish relationships between the flux footprint, $f$, the upwind distance, $x$ and the diffusion height, $z$.

In order to apply this model over complex surfaces, Göckede et al. (2004) introduced improvements through the use of high-resolution satellite maps for assigning surface types and a new procedure to obtain solutions for heterogeneous surfaces. This improved model was also compared with a LS footprint model in a field experiment using natural tracer measurements (Göckede et al., 2005) to demonstrate the validity and value of the new model when applied to complex surfaces.

The first step in the procedure used here is to determineland use type from the satellite image. Surfaces were identified as belonging to one of four types, wetland, lake, village, or farmland. Each grid point (25 m resolution) of the 5×5 km$^2$ domains was assigned a roughness length according to roughness length classifications in Stull (1988). Table 1 lists the roughness

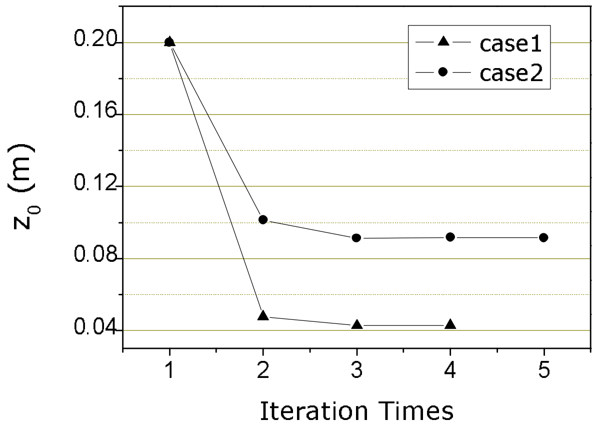


**Fig. 2.** Examples of the iteration of the average surface roughness length ($z_0$) calculated by footprint model.

**Table 1.** Roughness length and fraction of each land cover for Wangjiazhai.

| Land Type | Roughness length (m) | Fraction (%) |
|---|---|---|
| Wetland | 0.1 | 45.6 |
| Lake | 0.01 | 23.58 |
| Village | 0.2 | 8.21 |
| Farm field | 0.15 | 22.61 |

length and the fraction of each land cover type in the domain of the Wangjiazhai site.

The second step is to run model for hourly data sample to estimate the characteristic size of the flux footprint under corresponding stability conditions. An iteration method is used to determine the average surface roughness length, $z_0$, of the area covered by each footprint. The initial value of $z_0$ is a prescribed model parameter. The flux footprint at each grid point within a domain is then calculated. If this value exceeds 10% of the domain maximum, the roughness length is multiplied by the percentage. This leads to a new footprint weighted average, $z_0$, of the domain. The iteration for $z_0$ continues until the difference between the new, $z_0$, and the one from the previous step is less than a preset threshold. The resultant flux footprint is considered more representative of regions with heterogeneous surfaces. Details of this method are included in the paper of Göckede et al. (2004). Figure 2 shows the iteration of roughness length calculated by the footprint model for two hypothetical cases. In case 1, the frictional velocity $u_*, z/L$, wind direction, and the mean wind speed are 0.13 m s$^{-1}$, 0.612, 49°, and 1.23 m s$^{-1}$, respectively. In case 2, $u_*, z/L$, wind direction, and the mean wind speed are 0.05 m s$^{-1}$, $-0.287$, 272°, 0.36 m s$^{-1}$, respectively. The initial $z_0$ for both cases is set to be 0.2 m. As seen in Fig. 2, the iterations are completed after 3 or 4 steps.

Next, two-dimensional footprint distributions of heat flux about the observation site, obtained from model output, are used to assess contributions of each surface type to the observed flux by calculating the total footprint values over the specific land cover under different wind directions. Results are obtained for stable ($\zeta > 0.012, \zeta = z/L$), neutral ($-0.012 < \zeta < 0.012$), and unstable ($\zeta < -0.012$) conditions. Input parameters to the model are roughness length, the Obukhov length, mean wind direction and speed, and the height of the sensor.

The procedure for the apportioning mentioned above is described in section 4.3.

## 4. Results

### 4.1 *Measured turbulent fluxes*

Figure 3 shows the total (sensible and latent) heat flux measured at each site during the experiment. The temporal variability in the observations is consistent with the diurnal evolution of the atmospheric boundary layer (ABL). The average peak of the sensible heat flux is about 150 W m$^{-2}$ at both sites, while the latent heat flux is about 250 W m$^{-2}$ at the Wangjiazhai site and 300 W m$^{-2}$ at Xiongxian.

### 4.2 *Footprint analysis*

The domain for footprint modeling is a 5×5 km$^2$ square with the location of measurement tower located at the center. The domain is divided into a 200×200 grid matrix with the same resolution (25 m) of the satellite image used to establish land cover type required for the roughness length iteration described in section 3.

Figure 4 shows the two dimensional distribution over the Wangjiazhai domain of the cumulative contributions of footprint flux values to the cumulative flux of individual measurements over the length of the experiment. The results are expressed in terms of the relative, i.e., percentage, contributions to the total observed flux from surfaces surrounding the measurement site. They apply to a mean footprint and include stable ($\zeta > 0.012$), neutral, and unstable ($\zeta < -0.012$) conditions. It can be seen that two portions of the domain dominate the contributions, one lies to the northeast of the measurement tower and the other to the southwest. These regions coincide with the prevailing wind directions over the experimental period (Table 2). Peak values appear to be about 100 m from the observation tower. Figure 5 shows the results of the flux footprint calculation for the Xiongxian site. The footprint covers a smaller area than at Wangjiazhai with the peak values about 20 meters west of the

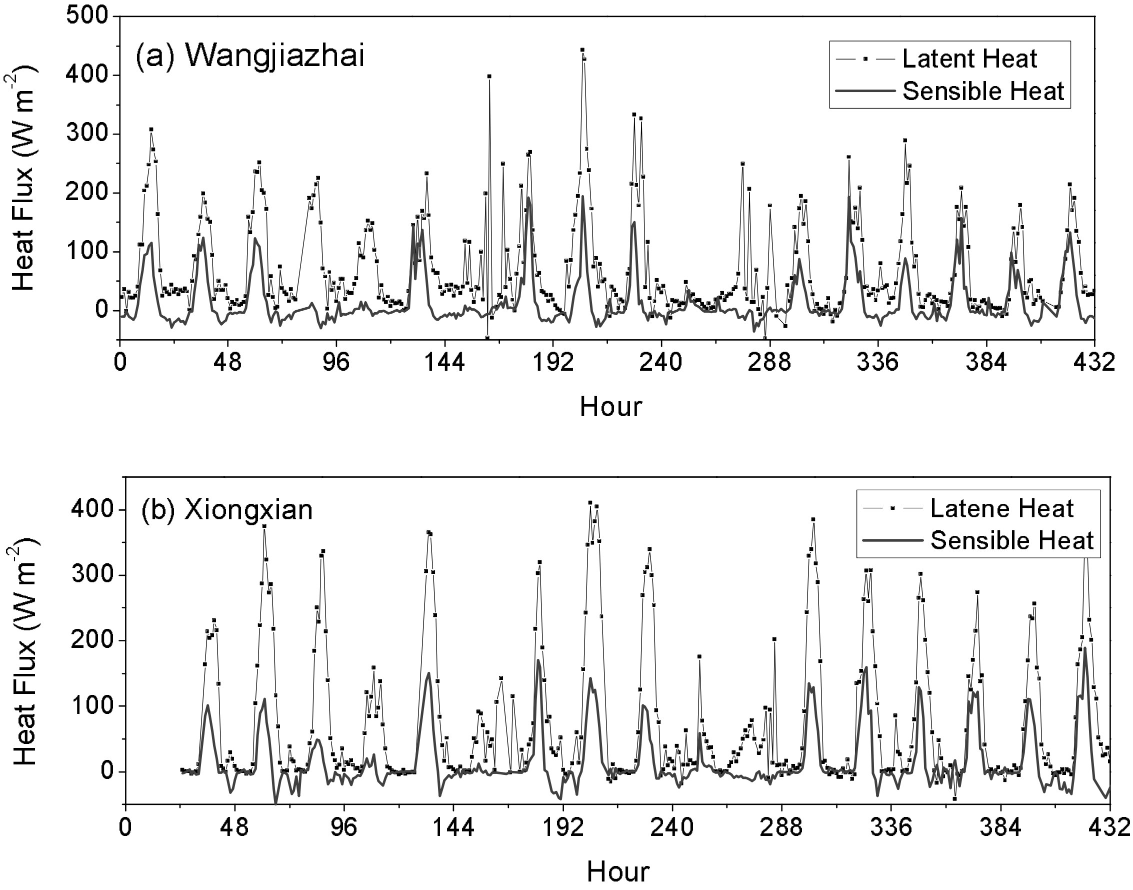


**Fig. 3.** Observed total heat flux during the experiment at (a) Wangjiazhai (9–26 September 2005); (b) Xiongxian (10–26 September 2005). The horizontal axis is the number of hours after 0000 LST 9 September 2005.

measurement site.

Over heterogeneous surfaces, the different roughness and composition of land cover affect the footprint results. To understand this effect the flux footprint model was run individually for the four most observed wind direction sectors at Wangjiazhai, NE, E, SW, and S (see Table 2). Figure 6 compares flux contributions of different land types for each wind direction sector. The total contribution (sum over all sectors) from each land cover is also presented. The results show that the wetland and lake play an important role in heat flux transfer. To the northeast and east of the measurement site wetland and lake are the main land cover, so both have the largest contribution to the flux in these two sectors. In the southwest more than 60% of the flux contribution comes from lake, as it comprises an increased proportion of surface types in this sector. In the west the flux contribution from a village is comparable to that from lake and together they provide nearly 80% to the total flux. The farm field in this sector is only about 1 km from the site, and as a result its contribution is small except in the stable or near neutral conditions.

### 4.3 *Contributions sensible and latent heat fluxes from different land types*

As seen described above, wetland and lake are the dominant contributions to the total, heat flux over the heterogeneous surface at Wangjiazhai, while farmland dominates the nearly homogeneous land cover at Xiongxian. In this section we assess contributions of the differing land surface types to the observed sensible and latent heat flux.

Similar individual footprint calculations were made for Xiongxian for the four most frequent wind direction sectors (W, E, NW, NE), as well as for the total over all wind directions. The results are shown in Table 3. Unlike Wangjiazhai, surface properties are relatively homogeneous, such that farm field plays a dominant role in flux contributions—above 60% with W and NW winds and 97% when E and NE.

Aggregation methods (Gottschalk et al., 1999) have been used to obtain area-averaged flux contributions over heterogeneous land cover. However it is

**Table 2.** Distribution of observations as percent of total for wind direction sectors. [N(0°–22.5°, 337.5° − 360°), NE(22.5°–67.5°), E(67.5°–112.5°), SE(112.5°–157.5°), S(157.5°–202.5°), SW(202.5°–247.5°), W(247.5°–292.5°) and NW(292.5°–337.5°)]

| Site | N | NE | E | SE | S | SW | W | NW |
|---|---|---|---|---|---|---|---|---|
| Wangjiazhai | 10.24 | 30.33 | 17.03 | 6.27 | 5.12 | 16.32 | 10.48 | 4.21 |
| Xiongxian | 5.8 | 11.45 | 14.15 | 9.5 | 4.7 | 9.75 | 32.7 | 11.95 |

**Table 3.** Domain individual land contributions (%) to the heat flux observed at Xiongxian for wind independent direction data (Total) and four most frequent wind directions.

| Land Type | Total | W | E | NW | NE |
|---|---|---|---|---|---|
| Wetland | 9.28 | 16.57 | 1.18 | 20.10 | 1.01 |
| Water | 0.45 | 0.84 | 0.0 | 0.02 | 0.01 |
| Village | 12.0 | 15.18 | 1.28 | 18.48 | 1.71 |
| Farm field | 78.28 | 67.41 | 97.53 | 61.40 | 97.26 |

critical to know the representative flux for each surface type of heterogeneous domains. A frequent approach is to employ multiple towers with each tower measuring one type of surface (Mahrt and Vickers, 2002; Beyrich et al., 2002). Here, an attempt is made to apportion the measured flux from a single tower to different surface types in a region. This work should benefit not only interpretation of measurements, but also to upscaling the measurements representative of a larger areas. For the Wangjiazhai site, contributions to the observed total sensible and total latent heat fluxes (CTF) from different land types were calculated with the footprint model for hourly data sample. Data apportioned

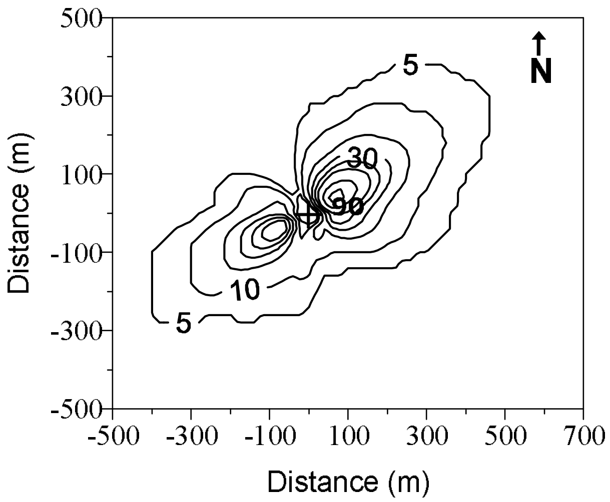


**Fig. 4.** Areal distribution of the relative contribution to the observed total heat flux at the Wangjiazhai instrument tower (+) obtained with the footprint model for the period 9–26 September 2005. Grid resolution within the domain is 25 m. Values are percent relative to the domain maximum (100% in this case).

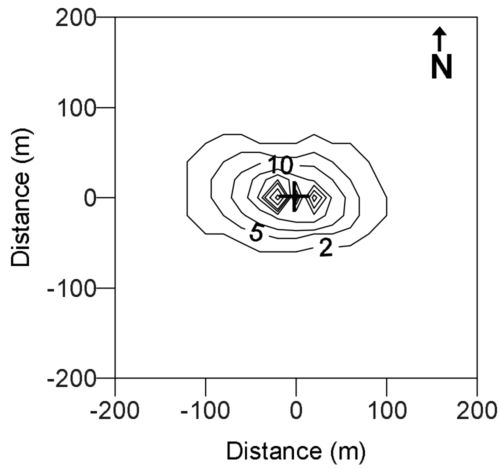


**Fig. 5.** Same as Fig. 4, except for Xiongxian over the period 10–26 September 2005.

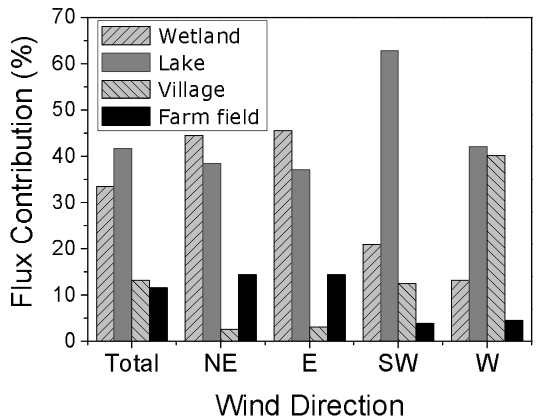


**Fig. 6.** The flux contribution of land types for the four most frequently observed wind direction sectors at Wangjiazhai. Vertical scale is the percentage contribution to the measured total flux.

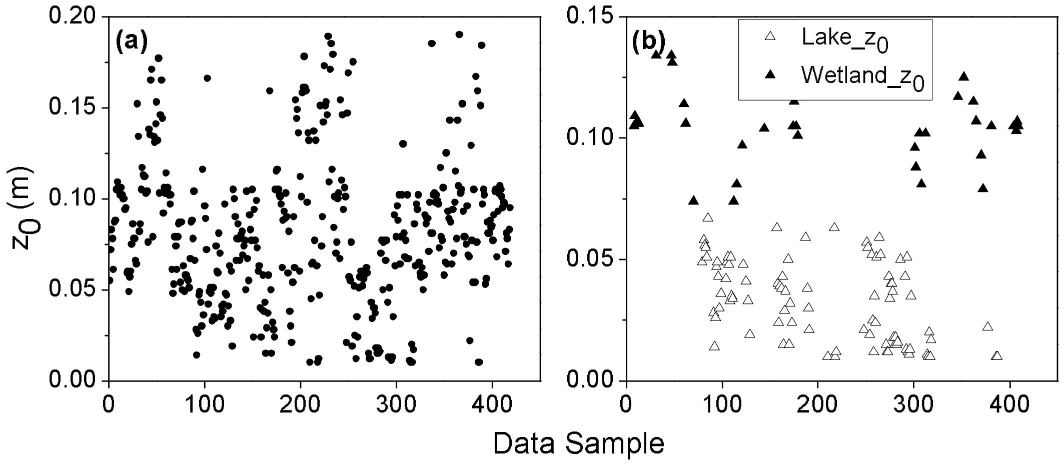


**Fig. 7.** Scatter diagram of the Wangjiazhai domain average surface roughness length ($z_0$) calculated by the footprint model versus size of data sample for (a) all data during the experiment period; (b) data selected on basis of two dominant land types (lake and wetland).

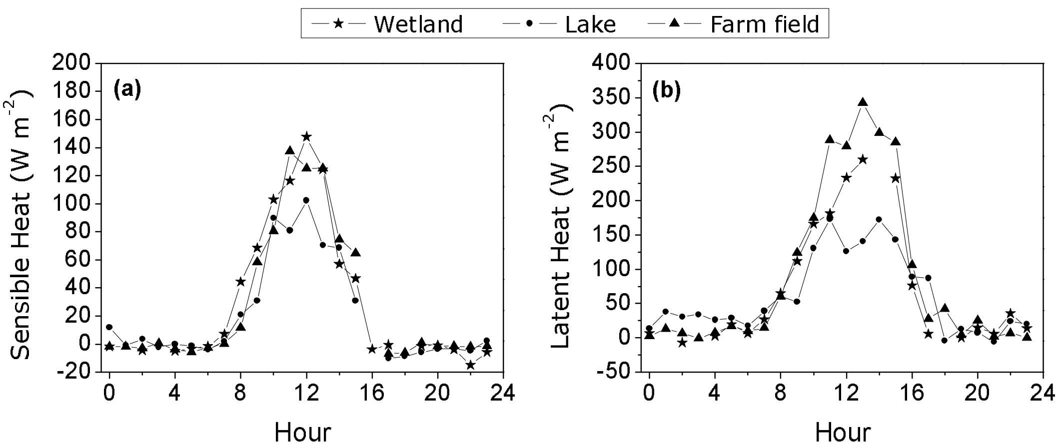


**Fig. 8.** Diurnal cycle of experiment mean apportioned flux calculated by the footprint model for different land types. (a) sensible heat; (b) latent heat. Data for wetland and lake were selected from the measurements at Wangjiazhai while data for farm field were selected from measurements at Xiongxian.

for wetland and lake is selected according to the following criteria:

– cumulative CTF from wetland and lake exceeds 0.6;

– absolute difference between the CTF from village and farm field not larger than 0.25;

– data assumed to represent wetland if CTF from wetland two times larger than from lake; data assumed to represents lake if CTF from wetland two times smaller than from lake.

The first two criteria guaranty wetland and lake are the primary contributors to the flux sample, while the third determines which surface type the flux sample represents.

Figure 7 shows the scatter plot of roughness length ($z_0$), where $z_0$ is a weighted average calculated by iteration of the flux footprint model over the source area and obtained both with and without invoking the above data selection criteria. Figure 7a shows $z_0$ calculated for all data samples, i.e., without data selection. Figure 7b shows $z_0$ for wetland and lake surface types with data selection. Unlike what is seen in Fig. 7a, there are two distinctively different groups of $z_0$ in Fig. 7b. The group with larger $z_0$ (0.08 m to 0.135 m) is from the data representing wetland, and the group with smaller $z_0$ (0.01 m to 0.06 m) is from the lake category. It is clear from the values of $z_0$ that the data selection criteria are effective in discriminating wetland and lake where they dominate the flux footprint. Accordingly, the procedure permits apportioning the

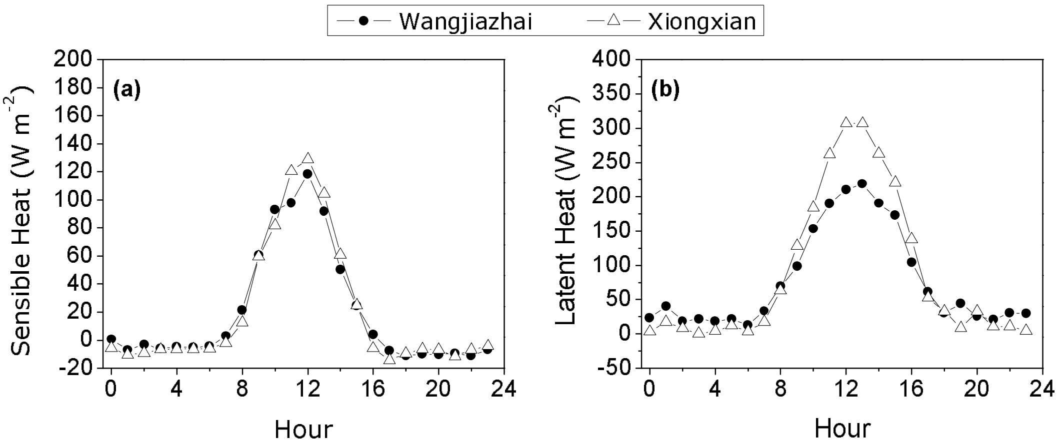


**Fig. 9.** Diurnal cycle of individual site experiment mean heat flux for (a) sensible heat; (b) latent heat.

flux footprint contributing to the measured heat flux to one or the other single surface type.

Similarly, the turbulent flux data from farm field, which dominates the flux at Xiongxian, can be selected from the raw data collection. Because there is less variation of surface type surrounding the instrument site, a stricter threshold for data selection is applied. Specifically, the farm field contribution to the measured flux must be greater than 0.8. Given the above criteria, the footprint model was used to apportion the measured heat fluxes among wetland, lake and farm field. Hourly mean heat fluxes during the experiment for these three land types are shown in Fig. 8. There were some missing data for some hours of a diurnal cycle for all three land types due to insufficient data meeting the data selection criteria. For reference the mean diurnal cycle of fluxes at Wangjiazhai site and Xiongxian site are shown in Fig. 9.

The sensible heat flux (Fig. 8a) from the three land types shows an ordinary diurnal variation, which is characterized by values increasing gradually until noon and then decreasing sharply in the afternoon. The sensible heat flux from the wetland has the same magnitude as that from the farm field, with a peak about 150 W $m^{-2}$, while the flux maximum from the lake is only around 80 W $m^{-2}$. This can be explained by the relatively larger thermal inertia of the water body of the lake. A lower warming rate over lake in the daytime leads to the smaller sensible heat flux. From comparison with Fig. 9a it can be seen that the mean diurnal cycle of sensible heat flux is similar for the two sites. A conclusion from this is that the sensible heat fluxes from wetland and farm field are similar, even though the wetland was water saturated.

It is more interesting to find that, as shown in Fig. 8b, the latent heat flux of farmland is highest during daytime, while that from wetland is lower and lake lower even still. The peaks of latent heat flux for these three types of surface are about 350, 260 and 170 W $m^{-2}$, respectively. This order of latent heat flux is in contrast to the wetness of the three surface types; however, this should not be unexpected. The highest latent heat flux must come from the well irrigated and high density vegetation surrounding the Xiongxian site. It is known that well irrigated plants can have high transpiration rates (Douglas et al., 2006), and increasing the wetness or water content of the wetland and the lake also increases the heat inertia. Although there is a larger potential for evaporation, the turbulent intensity is weaker, so that the accompanying sensible heat flux is smaller (Fig. 8a). As a result, the latent heat flux is also smaller. However, at night (0200 to 0800 LST), the latent heat flux from lake appears higher than the other two land types. Higher storage of heat in daytime may have supported extra evaporation at night.

On average the results during the experiment at Wangjiazhai and Xiongxian (Fig. 9b) show the same wetness trend on the diurnal variation of latent heat flux. The drier Xiongxian site has larger flux of latent heat in daytime, while the more humid Wangjiazhai has a higher latent heat flux at night. This result provides further support of the previous apportionment of heat fluxes as being reasonable.

## 5. Summary and conclusion

This study applies an easy-to-use Eulerian footprint model to analyze measured heat fluxes at two experiment sites, Wangjiazhai (heterogeneous surface) and Xionxian site (nearly homogenous surface). Classification of land cover types (lake, wetland, farm field, or village) was derived from Landsat-5 satellite imagery. The footprint model was used to select the data representative of different surface types and to analyze the characteristics of heat fluxes of each. The principal conclusions are:

At Wangjiazhai, the main source areas of measured heat fluxes were located in the northeast and southwest regions of the domain. The largest contributors to those heat fluxes were wetland (33.5%) and lake (41.7%). At Xiongxian, the source regions of fluxes were much smaller and located to the east and west of the measurement site. Farm field was the main land cover and contributed almost 80% to the heat flux measurements.

Apportionment of heat fluxes showed that on average the sensible heat flux from farmland and wetland were similar in magnitude and the diurnal variation. During daytime the farm field flux of latent heat was larger by about 30–50 W m$^{-2}$. The heat fluxes from lake were about 50 and 150 W m$^{-2}$ lower than farm field in the sensible and latent part, respectively, in daytime but higher at night by about 30 W m$^{-2}$. These results are reasonable and show the potential value of apportioning fluxes over heterogeneous surfaces.

The results in this study are still preliminary. The relatively loose criteria of data selection were based on the limited available observational data in the experiment. The level of uncertainty in the flux apportionment from this is not yet known. Additional efforts in this regard then are clearly in order.

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