Using Large Aperture Scintillometer to Validate Pixel Heat Flux Based on Remote Sensing Models

Zhilin Zhu, Xiaomin Sun, Jinping Xu, weimin Wang & Renhua Zhang
Institute of Geographical Sciences and Natural Resources Research,
Chinese Academy of Sciences, Beijing 100101, P. R. China.
E-mail: zhuzl@igsnrr.ac.cn

Abstract—To validate the accuracy of remote sensing flux model and to test the sensitivities of parameters, one Large Aperture Scintillometer (LAS), one Eddy Covariance (EC) system and other supporting observations were used to estimate sensible heat flux of a typical natural surface. The remote sensing model is Surface Temperature — Resistance (STR) model. The results obtained from different spatial scales were inter-compared. It shows that (1) there are better changing trend of sensible heat fluxes obtained by LAS and EC and STR methods; (2) the remote sensing assessed sensible heat flux was a good agreement with measurements by using LAS and EC, $H_{STR}$ is rough 8% larger than $H_{LAS}$; (3) LAS is reliable to validate the pixel sensible heat flux derived by remote sensing model.

Key words: LAS, Pixel Flux, Validation, Remote Sensing model

I. INTRODUCTION

With the increase of the interest to regional or global scales fluxes, such as sensible heat flux, latent heat flux and CO2 flux, remote sensing data were used to estimate heat flux [1]. One important problem is how to valid or calibrate the modeled fluxes based on the remote sensing data. In general, the remote sensing modeled results were compared with the micrometeorological measurements. However, routine micrometeorological measurements are taken in a single point, and remote sensing modeled results are based on the pixel-averaged results [2]. The ground measurements cannot be considered as the pixel-averaged result, unless it was taken over a very wide and homogeneous field. In recent years, near-infrared scintillometer are becoming increasingly popular as a means of determining the sensible heat flux [3, 4]. Scintillometer can determine path-averaged surface fluxes and have the potential to bridge the gap between local and regional scales. The path-averaged of kilometer distances ground-truth data can be used to test global or regional remote sensing models. Their spatial resolution is comparable with the pixel sizes of remote sensing satellite images. This path-averaging ability may be an advantage over conventional measurement methods, particularly in applications characterizing fluxes over patchwork surfaces [5,12].

In this paper, the authors will first briefly introduce the theories, methods and instruments of LAS, Eddy Covariance (EC) and Surface Temperature-Resistance (STR) model; then compare the results obtained by different methods and analyze and discuss the reasons of differences; finally we will give some preliminary conclusions.

II. THEORIES AND METHODS

A. Scintillometer

The scintillometer measurements are based on the scattering of the light beam caused by the atmospheric turbulence. A beam of light is transmitted over a horizontal path and the fluctuations of the light intensity resulting from the refractive index inhomogeneity of the air are analysed at the receiver. The structure parameter of refractive index ($C_n^2$) can be expressed as

$$C_n^2 = 1.12 \sigma_{\ln I}^2 D_{7/3} L^3$$

Where $D$ is the aperture diameter of LAS, $L$ is the distance between the transmitter and receiver (i.e. the path length), $\sigma_{\ln I}^2$ is the measured variance of the natural logarithm of intensity fluctuations. In the moist atmosphere, $C_n^2$ can be decomposed into the structure parameter of temperature $C_T^2$, $C_Q^2$ and the covariant term $C_{TQ}$.

$$C_n^2 = \frac{A_T}{T} C_T^2 + \frac{2 A_T A_Q}{T Q} C_{TQ} + \frac{A_Q}{Q} C_Q^2$$

Where $A_T$ and $A_Q$ are functions of the wavelength and mean values of temperature ($T$), humidity ($Q$) and atmospheric pressure ($P$). As $A_T$ is much more than $A_Q$, Eq. (2) can be simplified into

$$C_n^2 \approx \left( \frac{28 \times 10^{-6} P}{T} \right)^2 C_T^2 \left( 1 + \frac{0.03}{\beta} \right)^2$$

Where $\beta$ is Bowen ratio, the unit of $P$ and $T$ are Pa and K, respectively.

Once $C_T^2$ is known, the sensible heat flux ($H$) can be derived from the Monin-Obukhov Similarity Theory (MOST).

$$C_T^2 \approx \frac{(Z - d)^{2/3}}{T_s^2} = f(z-d/L_MO)$$

Where $d$ is the zero plane displacement, $Z$ is the height of the scintillometer beam, $T_s$ is a temperature scale defined as

$$T_s = \frac{-H}{\beta c_p u}$$

$L_MO$ is the Obukhov length

This research was supported by the Knowledge Innovation Project of Institute of Sciences and Natural Resources Research, CAS (Grant No. CXIOG-E01-04-02 and CXIOG-E01-01-02), the Key Project of the NSFC (Grant No.40371089) and the National Basic Research Project (Grant No. 2000077900)

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\[ L_{\text{MO}} = \frac{u_*^2}{\rho T_s} \]  

(6)

Where \( \rho \) is the air density (kg m\(^{-3}\)), \( c_p \) is the specific heat of air at constant pressure (1005 J kg\(^{-1}\) K\(^{-1}\)), \( k \) is the Von Kármán constant (≈0.4), \( g \) the gravitational acceleration (≈9.8 m s\(^{-2}\)), \( u_* \) the friction velocity. The universal function \( f \) is defined as follows for unstable (daytime)

\[ f \left( \frac{Z-d}{L_{\text{MO}}} \right) = 4.9 \left( 1 \right) \left( \frac{Z-d}{L_{\text{MO}}} \right)^{-2/3} \]  

(7)

and for stable (night time) conditions

\[ f \left( \frac{Z-d}{L_{\text{MO}}} \right) = 4.9 \left( 1 + \frac{2.2 \left( Z-d \right)^{2/3}}{L_{\text{MO}}} \right) \]  

(8)

In order to derive \( H \) from equations above, \( u_* \) is needed, which can be obtained by wind speed profiles and the estimation of surface roughness length \( (z_0) \), also by Eddy Covariance (EC) method. In the study, \( u_* \) was calculated by

\[ u_* = k_u \left[ \ln \left( \frac{z-d}{z_0} \right) - \psi_M \left( \frac{z-d}{L_{\text{MO}}} \right)^{-1} \right] \]  

(9)

Where \( z_0 \) is roughness length, \( \psi_M \) is the classical stability function estimated by Panofsky and Dutton [6]. The determination of \( H \) should follow an iterative procedure [7]. An initial computation is made assuming neutrality \((z/L = 0)\). The value of \( H \) obtained allows a better estimation of \( T_a \) and \( u_* \) through Eqs. (4)–(9), which provides a new approximation of \( H \), and then new \( T_a \) and \( u_* \), \( z/L \), etc. The procedure is repeated until the convergence on \( z/L \) is obtained.

As the simplification of procedure, \( H \) can be empirically expressed as

\[ H_{\text{EC}} = \rho c_p h (z-d) (g/T) (z/L)^{2/3} \]  

(10)

Where \( b \) is empirical constant (≈0.48).

B. Micrometeorological Methods

Nowadays, in micrometeorological field, Eddy Covariance (EC) is one of the best techniques to measure vertical fluxes and is applied widely. It is regarded as the criterion of fluxes between land and atmosphere. The expression of calculating \( H \) is

\[ H_{\text{EC}} = \rho c_p \overline{w'T'} \]  

(11)

Where \( w' \) and \( t' \) are the fluctuation of vertical wind speed and temperature, respectively. In the study, EC will be considered as the relate standard.

C. Remote Sensing Model Method

As a preliminary product of thermal infrared remote sensing, surface temperature \((T_s)\) is an important factor for estimating regional heat flux. The most common method using \( T_s \) to estimate sensible heat flux is [8, 9]:

\[ H_{\text{EC}} = \rho c_p \left( T_a - T_s \right) / r_a \]  

(12)

Where \( T_a \) is the air temperature at a height, and \( r_a \) the aerodynamic resistance, which may be measured [10] or calculated by [11]

\[ r_a = u / u_*^2 \]  

(13)

Where \( u_* \) can be calculated using Eq. (9).

In fact, \( T_s \) in Eq. (12) is aerodynamic surface temperature, it is different from that observed by infrared thermometer \((T_r)\) over a partly vegetation-covered field [1]. The difference is related to the Leaf Area Index \((LAI)\). In this study, experiment was executed over a bare soil. So we regard \( T_r \) as the same as the \( T_s \).

III. SITE, INSTRUMENTS AND EXPERIMENT

During April to July 2002, we carried out field experiment over a farmland with about 1200m in length and 800m in width. The site is located near Xiaotangshan town, Beijing suburb (116°26'E, 40°11'N, 35 m) in China. The selected site was a more homogeneous and open, which was fallow (bare soil) in April and May, and was corn in June and July.

The scintillometer was made by Kipp & Zonen Co.(LAS 150), the Netherlands. The heights of transmitter and receiver is 4.2 m, path length is about 970m. The path direction of LAS is N-S. Other supporting observations, such as Eddy Covariance (sonic anemometer is model DA6000, KAIJO, Japan; \( \text{H}_2\text{O}/\text{CO}_2 \) analyzer is Licor 7500, Licor, Inc., USA), infrared temperature \( T_s \) (BS-32T, 7–20 µm, OPTEX Co. Ltd., Japan), air temperature (Pt100 precision platinum resistance thermometer), Wind speed (3-cup anemometer, model VF-1, Meteorological Instruments Co., Changchun, China), net radiation (Q7-L, Compbell Sci. Co. USA), etc., were taken at the middle of the field. The main instruments heights are 2m. The sampling rates of LAS and EC were 0.5Hz and 20Hz respectively, and output averages every 10 minutes. In order to get correct conclusion, some distinctly incorrect data were removed.

IV. RESULTS AND DISCUSSION

A. Comparison of the Diurnal Changes of \( H \) Calculated by 3 Methods

Presented in Fig. 1 are the time series of net radiation \((R_{\text{n}})\), eddy covariance \((H_{\text{EC}})\), Surface temperature-Resistance \((H_{\text{STR}})\) and scintillometer derived sensible heat Flux \((H_{\text{LAS}})\) during daytime (6:00-18:00, and hereafter) on 10 April. Temporal resolution of all the quantities plotted are 10 min. Good changing trends can be seen among the measurements in most of the time, with the scintillometer sensible heat Flux \((H_{\text{LAS}})\) displaying smoother variations than that by the surface temperature - resistance method \((H_{\text{STR}})\). Especially, in the morning, \( H_{\text{LAS}} \) is almost equal to \( H_{\text{EC}} \). In addition, during 6:00-7:00, in despite of the positive net radiation, sensible heat flux \((H_{\text{STR}})\) is still downward. However, \( H_{\text{LAS}} \) shows positive or upward flux. In fact, \( H_{\text{LAS}} \) is a wrong here, as we don’t give correct atmospheric stability, which cannot be determined only depend upon LAS data. Meanwhile, the preliminary results are always positive, \( H_{\text{LAS}} \) cannot determine heat flux direction (upward or downward). So, necessary supporting observation should be executed.
B. Comparison of $H_{\text{STR}}$ and $H_{\text{EC}}$

To check the sensible heat flux by STR method, 10-min averaged calculations of $H_{\text{STR}}$ were compared to eddy covariance values (Fig. 2). The selected data are in daytime and spikes were removed. Although the EC and STR measurements are taken at the same location, it is found that, as shown in Fig. 2, difference and scatter are still exist, but there is not obvious difference between them in overall. The slope and $R^2$ are 0.977 and 0.8921 respectively. It means that heat flux calculated by STR method is reliable in a point measurements.

$$y = 0.977x + 14.888$$
$$R^2 = 0.8921$$

Fig. 2 The comparison of sensible heat flux estimated using Eddy Covariance method and Surface Temperature – Resistance method, 6:00-18:00, 29/3-20/4, 2002.

C. Comparison of $H_{\text{LAS}}$ and $H_{\text{EC}}$

The sensible heat flux obtained from the LAS and the EC are compared in Fig. 3. $H_{\text{LAS}}$ was calculated by iterative procedure. There is a good agreement between $H_{\text{LAS}}$ and $H_{\text{EC}}$, but in overall, the heat flux estimated by LAS is little smaller than that by EC method, the slope and $R^2$ of them are 0.892 and 0.8696 respectively. This indicates that the iterative procedure used in processing the LAS data is adequate and that the site is relatively homogeneous. The difference is acceptable. The reason of error will be given in the next section.

$$y = 0.892x + 18.004$$
$$R^2 = 0.8696$$

Fig. 3 The comparison between sensible heat flux by LAS ($H_{\text{LAS}}$) and by Eddy Covariance method ($H_{\text{EC}}$), 6:00-18:00, 29/3-20/4, 2002.

D. Comparison of H by LAS and STR

Fig. 4 plots the comparison of $H_{\text{LAS}}$ and $H_{\text{STR}}$ in the same days mentioned above. It shows that $H_{\text{STR}}$ is rough 8% larger than $H_{\text{LAS}}$. The main reason is: although the field is relatively homogeneous, difference between the LAS path and EC observation location exists. In addition, the uncertainties of micrometeorological methods and LAS are more than 10%, so it is impossible that two results are completely equal to each other. The slope and $R^2$ are 1.083 and 0.864, respectively. The agreement of them is acceptable.

$$y = 1.083x + 4.8665$$
$$R^2 = 0.864$$

Fig. 4 The comparison between sensible heat flux by LAS ($H_{\text{LAS}}$) and by Surface Temperature -Resistance method ($H_{\text{STR}}$), 6:00-18:00, 29/3-20/4, 2002.


E. Error analysis

In fact, any methods have their error sources or uncertainties. W.J. Massman and X. Lee [11] concluded the uncertainties of EC method. It concerns that the instrument sensors and installations, sampling rate and averaging periods, power spectra or co-spectra characteristic of wind velocities and other scalar, high frequency and low frequency attenuation, advective correction and coordinate system transformation resulting from underlying surface conditions, such as homogeneous and/or sloping etc. and nighttime fluxes and gravity wave, etc.

The error sources of LAS may include: (1) the departure of beam between transmitter and receiver, it means that receiver cannot receive the maximum of beam; (2) the inadequate choices of other parameters, such as zero-plane displacement, roughness length, equation of stability correction; in the study, we assumed that $Z_0 = 0.01 m$ and $d = 0$, inadequate $Z_0$ will result in more errors; (3) the neglect of the effect of water vapor on the $C_{T^2}$. In order to simplify calculation, we assume that Bowen ratio was infinite, which is not correct.

The error sources of remote sensing model (e.g. STR method) may include (1) the observation error surface temperature, as infrared thermometer’s precision is about 0.5°C, and the result is affected by azimuth and zenith angles, weather conditions, etc. (2) the determination of aerodynamic resistance is more difficult, it is also affected by roughness length and atmospheric stability; inadequate parameter values will result in errors;

As for the application in the regional flux estimation, more difficulties still exist. The most difficult is the acquirement of accurate surface temperature, especially, how to eliminate the effect of clouds, how to determine the emissivity of pixel, etc. The brightness temperature derived from various remote sensing images have relatively large error, now. It is difficult that the error of retrieved temperature is less than 1K in complicate surface. More, due to the effect of cloud, the everyday acquirement of temperature from remote sensing images is impossible. In most days, we cannot directly get temperature from AVHRR, MODIS or TM images. Another difficulty is how to calculate aerodynamic resistance of a pixel area. It concerns that how to determine roughness length and wind speed, etc.

V. CONCLUSION

Based on the analysis and inter-comparisons above, the sensible heat fluxes acquired from LAS are agreement with those derived from the Surface Temperatures- Resistance and EC methods over a homogeneous field. It means that the LAS is a practically alternative method to estimate sensible heat flux. More ever, compared with traditional micrometeorological techniques, LAS can determine wider area flux. In despite of better relationship among the heat fluxes from 3 methods, differences is still existed, e.g. $H_{ST}^T$ is rough 8% larger than $H_{LAS}$. The error sources mainly concern to instrument’s precision, the determination of accessorial parameters, such as zero-plane displacement, roughness length, etc. In addition, because of the difficulty of retrieving surface temperature from remote sensing images and determining regional distribution of non remote sensing parameters, continuous monitor of regional sensible heat flux distribution using remotely sensing data is still unpractical.

REFERENCES


