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Evaluation of MOST functions and roughness length parameterization on sensible heat flux measured by large aperture scintillometer over a corn field

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ABSTRACT

As part of a comprehensive study investigating how subsurface drainage systems affect the energy and water balances on land surfaces, a large aperture scintillometer (LAS) was used to determine the sensible heat and momentum fluxes over a corn (*Zea mays*) field. To keep the flux footprint of the observation within the 22 ha field boundary, the LAS had to be placed at a height no greater than 1.8 m above displacement height. As a result, the surface layer was mostly near-neutral at the LAS path height. Sensible heat fluxes were derived from the LAS measurements (H_{LAS}) using four different Monin–Obukhov Similarity Theory (MOST) functions for temperature (f_T). While correlating well with the sensible heat fluxes measured by the Eddy covariance system (H_{EC}), the values of H_{LAS} were systematically higher if the rule of thumb formula for estimating the roughness length (z_0) was used. The use of this rule of thumb formula led to higher estimates than the EC measurements of the frictional velocity u_*, to which H_{LAS} is particularly sensitive under near-neutral conditions. With a modified formula for z_0, a better agreement between H_{LAS} and H_{EC} is achieved for all the f_T functions tested. Using the f_T function (W71) proposed by Wyngaard et al. (1971) and the improved estimate of z_0, H_{LAS} agreed with H_{EC} within 32 W m^{-2} and with a regression slope of 1.0 ± 0.05.

1. Introduction

A wet weather cycle since 1993 has brought the groundwater level closer to the soil surface in many areas in the Red River of the North Basin. Subsurface drainage can be an effective way to maintain crop production in the areas with shallow groundwater or high soil salinity. Eddy covariance and scintillometry, among other instruments, were used to study the water balance over a test field in North Dakota where subsurface drainage was installed.

Eddy covariance (EC) measures the sensible heat flux through statistical covariance between the air temperature and vertical wind speeds using rapid response sensors at frequencies typically equal to or greater than 10 Hz. Despite its inherent uncertainty in terms of energy closure (~20%) (Wilson et al., 2002), which can be approximately corrected (e.g., Twine et al., 2000), the EC technique has been generally accepted as the most accurate means of providing flux estimates.

An alternative method to estimate the sensible heat flux is the scintillometry method, in which a receiver measures the intensity fluctuation in the radiation (scintillation) emitted by a transmitter caused by refractive scattering of turbulent eddies along a path length of the order of 10 m to 10 km (De Bruin, 2002; Hill, 1997). The scintillations measured by a large aperture scintillometer (LAS) are only a measure of the structure parameter of the refractive index of air (C_n^2)(Wang et al., 1978), which primarily depends on the fluctuations in air temperature and humidity. At the visible and near infrared wavelengths, the effect of temperature on C_n^2 dominates (Wesely, 1976a) and the corresponding structure parameter of temperature (C_T^2) can be used to estimate sensible heat flux following the semi-empirical Monin–Obukhov similarity theory (MOST) (e.g., De Bruin et al., 1993; De Bruin et al., 1995; Hill, 1997).

The estimates of sensible heat flux by the scintillometry method represent a spatial average over a path, and the system is relatively affordable and easy to maintain as compared to EC. A disadvantage is that, contrary to the EC technique, which uses direct turbulent measurements, it relies on the validity of MOST for the calculation of surface fluxes. Therefore, for MOST-based estimates of fluxes to be reliable, a final test should be a comparison of heat fluxes derived from the scintillometry method with those measured independently, such as by an EC (De Bruin et al., 1993).

Comparisons of LAS and EC measurements have shown that the LAS works well not only over uniform landscape (e.g., McAneney et al., 1995) but also over heterogeneous surfaces (Chehbouni et al., 2000; Lagouarde et al., 2002b; Meijninger et al., 2002b) and terrain of changing elevation (Hartogensis et al., 2003). LAS-derived surface heat fluxes have also been evaluated against other methods,

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such as Bowen-ratio energy balance, satellite, or hydrologic models (e.g., Marx et al., 2008; Pauwels et al., 2008).

Some studies have reported the overestimates of the sensible heat flux by LAS over EC. De Bruin et al. (1995) found that the sensible heat fluxes measured by both EC and LAS over a vineyard in a dry area in Spain agreed well with each other if a reasonable estimate of frictional velocity was available. They also found an overestimate by LAS under neutral conditions. Chehbouni et al. (2000) found that their LAS-based sensible heat flux overestimated EC-based values by an average of 30 W m^{-2} over grass and 40 W m^{-2} over mesquite, respectively. They attributed this bias to the overestimation of momentum transfer by the LAS. Lagouarde et al. (2002a) found a systematic overestimation of ~10% in LAS-measured sensible heat flux over a two-surface composite landscape as compared with reference values obtained by the EC, and they attributed this bias to the non-linearity in the integration weighting function for C_n^2 along the LAS path length. In a comparison study of sensible heat flux over a semi-arid grassland in Mongolia, Asanuma and Iemoto (2007) found that their LAS estimates were greater than the EC measurements for sensible heat flux >50 W m^{-2} and path length <1500 m. Hoedjes et al. (2007) also found a systematic overestimation of sensible heat flux by LAS over EC over an irrigated olive orchard in Morocco and concluded that it was largely due to the advection of dry, warm air from the area surrounding the orchard. Von Randow et al. (2008) compared measurements of sensible heat flux by a LAS with an EC over an area of Amazonian rain forest and found the flux estimates by the EC are often lower than those by the LAS. The differences between the two measurements would decrease if the averaging periods for EC calculation increase. They attributed the overestimation to the spatial averaging effect of the LAS. Kleissl et al. (2008) reported that sensible heat flux by their three LAS instruments over the same path were 2–17% higher than those by the EC, and the inter-comparison studies (Hartogensis et al., 2008; Kleissl et al., 2008; Kleissl et al., 2009) showed that this systematic overestimation was due to electronic or optical problems in the Kipp & Zonen (the Netherlands) LAS instruments that they used. This performance problem, which also caused significant inter-LAS differences of up to 21%, however, was not found in the LAS instruments either by Scintec, Germany (Kleissl et al., 2009) or by Wageningen University, the Netherlands (Hartogensis et al., 2008), which were used in the other studies mentioned above.

In this study, the use of LAS was evaluated by comparing with the EC measurements over a corn field with subsurface drainage installed in southeast North Dakota, USA. Even though the field is relatively uniform with a single crop, this study differs from earlier experiments in two aspects. Environmentally, the recent wet weather cycle has caused significant rise in the water table, and many fields have subsurface drainage systems installed to mitigate flooding impact. However, the effect of these drainage systems on the surface heat and water fluxes is still unknown (Smits et al., 2010). Operationally, the small area of the field (~22 ha) where subsurface drainage was installed has restricted the size of the footprints of the EC and the LAS, which in turn limits the maximum heights of both instruments to ~1.8 m (relative to the zero-plane displacement). This posed a challenge: the dramatic increases in the height of corn during the growing season might change the surface condition that the LAS saw from within the surface layer initially to the roughness sublayer later. It was of interest to examine whether the change in surface conditions affected the estimate of sensible flux, because, theoretically, MOST only applies in the surface layer. Given these characteristics of our experiment, the objectives of this study include: (1) examine whether changing surface conditions affect the application of LAS in measuring sensible heat fluxes; and (2) test different MOST similarity functions to determine the one that is applicable for the experiment.

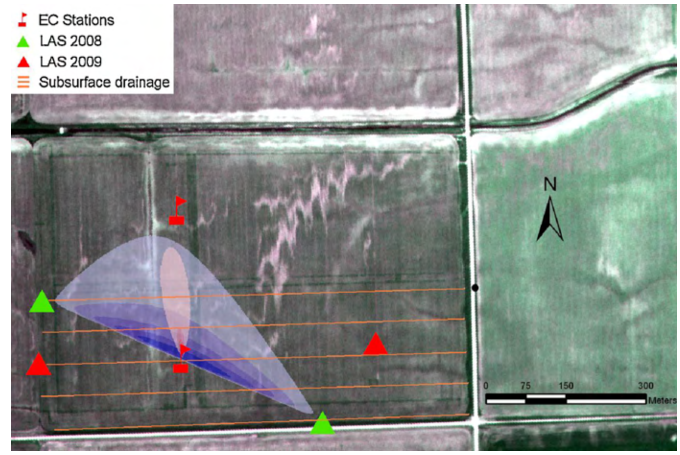

Fig. 1. The subsurface drainage map and locations of the LAS and the EC for 2008 and 2009 are overlaid on a false color image acquired by AeroCam on June 25, 2009. The shaded areas in blue and pink are the footprints estimated with $L_{MO} = -100$ m, $z_0 = 0.04$ m and $z - d_0 = 1.8$ m for the LAS and the EC respectively. Each footprint has 5 levels of shade, each represents an increase of weighting of 20%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2. Experiment and theory

2.1. Descriptions of the site and the instruments

The test site (Fig. 1) is located near the border of North Dakota, South Dakota and Minnesota at Fairmount, North Dakota, USA (46.00895°N, 96.60368°W), with an elevation of 296 m above sea level. The climate is typical continental, with an annual mean temperature of 6 °C, mean precipitation of 330–717 mm and mean potential evapotranspiration of 1030–1307 mm (NDAWN, 2009). The average frost-free days are 137. The prevailing winds during the growing season are either northerly or southerly. The field has an area of 44 ha, of which 22 ha had subsurface drainage system (orange lines in Fig. 1) installed in August 2002 at a mean depth of 1.1 m. In 2008, corn (*Zea mays*) was planted on April 19 but did not germinate until June 1 because snow storms occurred during late April and early May. In 2009, corn was not planted until May 17 because of early-spring flooding in the area and germinated around May 27.

One EC system was installed in the drained field in both years, and a second EC system was installed in the undrained field in 2009. The EC systems operated from June 10 to October 19, 2008 and from June 2 to October 20, 2009. The configurations for the two EC systems were the same, and each consisted of the following instruments: CSI CSAT3 3D sonic anemometer, CSI KH20 krypton hygrometer, Li-Cor 7500 gas analyzer, Texas Electronics TE525WS tipping bucket, Kipp & Zonen CNR1 net radiometer in 2008 and REBS Q7.1 net radiometer in 2009, Vaisala HMP45C temperature/relative humidity sensor, Hukseflux HFP01SC self-calibrating soil heat flux plate, TCAV averaging soil thermocouple probe, and CS616 water content reflectometer. In this study, only the measurements by the EC in the drained field were used. The EC data were recorded every 30 min. In deriving sensible and latent heat fluxes from the EC several standard procedures were followed (Jia et al., 2009), including coordinate rotation correction to force average vertical velocity to zero (Sumner, 2001), sonic temperature to air temperature correction (Paw et al., 2000; Schotanus et al., 1983), the Webb correction to adjust for temperature-induced fluctuations in air density (Webb et al., 1980), oxygen correction accounting for the hygrometer sensitivity to oxygen (Tanner and Greene, 1989), and the Horst correction accounting for the separation between sonic and krypton hygrometer (Horst, 2003). The