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A comparison of optical and microwave scintillometers with eddy covariance derived surface heat fluxes

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ABSTRACT

Accurate measurements of energy fluxes between land and atmosphere are important for understanding and modeling climatic patterns. Several methods are available to measure heat fluxes, and scintillometers are becoming increasingly popular because of their ability to measure sensible (H) and latent (L_vE) heat fluxes over large spatial scales. The main motivation of this study was to test the use of different methods and technologies to derive surface heat fluxes.

Measurements of H and L_vE were carried out with an eddy covariance (EC) system, two different makes of optical large aperture scintillometers (LAS) and two microwave scintillometers (MWS) with different frequencies at a pasture site in a semi-arid environment of New South Wales, Australia. We used the EC measurements as a benchmark. Fluxes derived from the EC system and LAS systems agreed ($R^2 > 0.94$), whereas the MWS systems measured lower H (bias ~60 W m^{-2}) and larger L_vE (bias ~65 W m^{-2}) than EC. When the scintillometers were compared against each other, the two LASs showed good agreement of H ($R^2 = 0.98$), while MWS with different frequencies and polarizations led to different results. Combination of LAS and MWS measurements (i.e., two wavelength method) resulted in performance that fell in between those estimated using either LAS or MWS alone when compared with the EC system. The cause for discrepancies between surface heat fluxes derived from the EC system and those from the MWS systems and the two-wavelength method are possibly related to inaccurate assignment of the structure parameter of temperature and humidity. Additionally, measurements from MWSs can be associated with two values of the Bowen ratio, thereby leading to uncertainties in the estimation of the fluxes. While only one solution has been considered in this study, when L_vE was approximately less than 200 W m^{-2}, the alternate solution may be more accurate. Therefore, for measurements of surface heat fluxes in a semi-arid or dry environment, the optical scintillometer is recommended, whereas further work will be required to improve the estimation of surface heat fluxes from microwave systems.

1. Introduction

The ability to quantify the energy and mass exchange between the land surface and the atmosphere is important for improving models used in water resource management. Field measurements of sensible heat (H) and latent heat (L_vE) are also crucial for the validation of remote sensing surface heat flux products (Brunsell et al., 2011; Fritschen et al., 1992; Jung et al., 2009; Kite and Droogers, 2000).

The most popular approach adopted to measure surface heat fluxes is based on the eddy-covariance (EC) method (Kaimal and Finnigan, 1994), with EC systems deployed globally through the FLUXNET network (Baldocchi et al., 2001; Maayar et al., 2008). However, as the footprint of EC systems changes with meteorological conditions, its representativeness of model grids and satellite pixels, particularly in a heterogeneous landscape, is debatable (Ward et al., 2014). Scintillometry presents an alternative method, as meteorological changes have little impact on its footprint and it is able to measure path integrated fluxes ranging from a few hundred meters to 10 km (Baghdadi et al., 2007; Beyrich et al., 2002; Meijninger and De Bruin, 2000; Samain et al., 2011), thereby making it more suitable for long-term validation of model simulations

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and remotely sensed surface heat flux products (Hemakumara et al., 2003; Hendrickx et al., 2007).

A scintillometer consists of a transmitter that emits electromagnetic wave signals to a receiver, which records the intensity of this signal from a distance. As the signal propagates through the atmosphere toward the receiver, it is scattered by turbulent eddies in the atmosphere. This scattering is detected as fluctuations in the intensities of the signal recorded by the scintillometer's receiver (i.e., scintillations). These eddies are driven by surface forcing, such as wind shear from frictional drag of winds flowing over the ground, heat fluxes from the ground caused by solar incident radiation, and turbulent wakes from obstacles like trees (Stull, 1988). Consequently, by combining theoretical principles of atmospheric turbulence with the physics of electromagnetic wave propagation, surface heat fluxes can be derived (e.g., Van Kesteren, 2012).

The turbulence causing scintillations in the atmosphere can be quantified by the structural parameter of the refractive index, C_n^2, and are mainly affected by the structural parameters of temperature, C_T^2, humidity, C_Q^2, and the cross structural parameter of temperature and humidity, C_{TQ} (Kohsiek, 1982). C_T^2 is directly related to H whereas C_Q^2 is directly related to L_vE. Temperature fluctuations given by C_T^2 are the dominant cause of scintillation in the optical wavelengths, and therefore optical scintillometers can be applied to measure H without making measurements of, or assumptions on, humidity fluctuations. Commercially available optical scintillometers have been widely used and have shown to perform similarly to Bowen ratio energy balance (BREB) techniques, hydrological models, and satellite and EC measurements over different types of landscapes (e.g., Brunsell et al., 2011; Chehbouni et al., 2000; Ezzahar et al., 2009; Lagouarde et al., 2002; Liu et al., 2013; McJannet et al., 2011; Meijninger et al., 2002, 2002; Pauwels et al., 2008; Savage, 2009; Samain et al., 2011, 2011, 2012; Zeweldi et al., 2010), including open water and urban areas (Samain et al., 2011; McJannet et al., 2013; Lagouarde et al., 2006; Ward et al., 2013).

Conversely, no wavelengths have been identified in which C_Q^2 is most dominant. Therefore, to derive C_Q^2, the microwave (or millimeter wave) scintillometer (MWS), which is sensitive to both humidity and temperature fluctuations, can be used in combination with an LAS by making assumptions on the value of r_{TQ} (e.g., Evans, 2009; Meijninger et al., 2002) or measuring r_{TQ} based on the bichromatic correlation method (Beyrich et al., 2005; Lüdi et al., 2005; Ward et al., 2015, 2015). The combined use of MWS and LAS is commonly referred to as the two-wavelength method. As for MWS systems, they were not used independently until Kohsiek and Herben (1983) derived surface heat fluxes using a standalone MWS (frequency, f = 30 GHz) by making assumptions regarding r_{TQ} and the Bowen ratio (β). Leijnse et al. (2007) showed that by introducing the energy budget constraint to derive the surface heat fluxes, the standalone MWS (f = 27 GHz) can be used to measure H and L_vE in relatively moist environments. Given the success of LAS in measuring area-averaged H, the possibility of using a standalone MWS in the same way to measure area-averaged L_vE is undeniably attractive. However, to this date, no studies using the two-wavelength method or a standalone MWS have been carried out in a semi-arid environment. Due to differences in the frequencies used in different studies, it is also of value to understand the effect this might have on the measurements.

Consequently, the aim of this study is to test the application of scintillometers to measure H and L_vE in a semi-arid environment. Here, the results from comparing an EC system with two different LAS manufacturers, Kipp and Zonen (LAS) and Scintec (BLS 900) (herein referred to as Kipp and Scintec, respectively), two MWSs with f of 26 GHz and 38 GHz (herein referred to as MW26 and MW38, respectively) and two polarizations (horizontal, h and vertical, v), and different combinations of LAS and MWS in the two-wavelength method, are presented.

2. Methods

2.1. Site description

The site of this intercomparison is located in the Yanco Study Area (contained between 34.56° S and 35.17° S, and 145.83° E and 146.4° E) (Fig. 1), which is situated within the western plains of the Murrumbidgee River catchment, in New South Wales, Australia (Smith et al., 2012). According to data from 1981 to 2010 (Bureau of Meteorology station ID. 074037), the daily mean temperatures vary significantly from 34.0 °C in January to 14.2 °C in July. Mean annual rainfall is 418.5 mm and is distributed relatively evenly across all months. The dominant wind directions are from the south-west and north-east. The site consists of a homogeneous flat grassland that is used for the grazing of cattle; the grassland is dominated by perennial tussock grasses, such as kangaroo and wallaby grasses (Natural Resources Advisory Council, 2010). The soil type is sand over clay (loamy sand) and typical porosity of this soil type is about 0.30 $m^3\,m^{-3}$ (Hornbuckle and Christen, 1999; Smith et al., 2012).

2.2. Measurement description

The EC system was mounted on a 20 m tower (located at 34.99° S and 146.30° E) at 6 m above the ground, and has been in operation since May 2012. The EC system consists of a CSAT3 3-D sonic anemometer (Campbell Scientific, Inc.) and a LI-7500 open path infrared gas analyzer (IRGA) (LI-COR Inc., U.S.) with a sampling frequency of 10 Hz following the general approach of Beringer et al. (2007) and Hutley et al. (2005).

In November 2012, the two LAS systems, Kipp and Scintec, were deployed along a 1 km path (L) (Fig. 1). The receivers were situated about 1 km west of the EC tower and the transmitters were installed approximately 10 m from the foot of the EC tower (Fig. 1). Due to complexity of setting up multiple towers within a flat and remote open area, both LAS systems were set up with an effective beam height, z_s, of 2.50 m. Despite the seemingly low height, due to the success of other studies in using scintillometers below blending height (e.g., Ezzahar et al., 2007; Meijninger et al., 2002), and the homogeneity and low vegetation height (<0.30 m) at the site, this is deemed to be acceptable. To avoid interference, the two LAS transmitters were installed approximately 250 m apart. The 1-min values of C_n^2, computed internally by the LAS systems provided by the manufacturers, were used to derive H and L_vE.

The two MWS systems, MW26 and MW38, were deployed in November 2013 between the two LAS systems. Both MWS systems also have an effective beam height of 2.50 m. The MWS transmitters transmit signals rotated from the horizontal plane by 45° to allow splitting by an ortho-mode transducer on the receiver antenna into identical h and v polarization receiver channels. The raw voltages measured at 10 Hz frequency by the MWS receivers were converted to intensities, I, as provided by the manufacturer of the MWS system. To avoid absorption effects, the lower cut-off frequency for the MWS was 0.03 Hz respectively (Green et al., 2001). Values of C_n^2 every minute were calculated from the intensities as

$$C_n^2 = \frac{2^{14/3}\Gamma(7/3)\cos(\pi/12)}{\pi\sqrt{3\pi}\,\Gamma(8/3)}k^{-7/6}L^{-11/6}\sigma^2_{\ln(I)}, \quad (1)$$

where $\Gamma(\cdot)$ is the gamma function and $k = 2\pi/\lambda$ is the wave number of the electromagnetic wave and its wavelength, λ (Leijnse et al., 2007).

Net radiation (R_n) was derived from incoming and outgoing short- and long-wave radiation measured using two CMP-21