Comparison of Surface Layer Scintillometer and Eddy Covariance Footprint and Sensible Heat Flux Estimates for Different Wind Directions

George O. Odhiambo
Department of Geography & Urban Planning, CHSS, UAE University, P. O. Box 17771, Al Ain, UAE
godhiambo@uaeu.ac.ae

Abstract-The results reported in this paper are based on a study carried out to investigate sensible heat flux estimated by the SLS method compared with measurements obtained by the EC method for wind direction approximately perpendicular to the SLS beam path and measurements obtained when the wind direction is approximately parallel to the beam path. Comparison of footprints for the two systems is also reported.

Keywords- Surface layer scintillometer, Eddy covariance, Sensible heat flux, footprint, wind direction. Introduction

I. INTRODUCTION

Most of the studies carried out using the scintillometer method for measurement of sensible heat flux have used the LAS method with only few involving use of the SLS method. These studies indicate that scintillometer measurements, mostly using the LAS method, can be adopted for reliable routine momentum and sensible heat flux measurements (Kohsiek, 1985; Hill, 1992; Hill et al., 1992; de Bruin et al., 1995). Turbulent fluxes play important roles in governing the transfer processes in the lower layers of the atmosphere and in fact are the basic parameters which are directly related to thermal and mechanical turbulence in the atmosphere and characterise the turbulence condition of the atmosphere in terms of ‘atmospheric stability’ (Daoo et al., 2004). The main objective of this paper was to investigate and compare sensible heat flux estimated by the SLS and the EC method for wind direction approximately perpendicular to the SLS beam path and sensible heat measurements obtained when the wind direction is approximately parallel to the beam path, and as well compare footprints for the two systems.

II. FIELD MEASUREMENTS

Field measurements were carried out from January to December 2004 over an open, mixed community grassland site in Ashburton (30° 27' E, 29° 40' S) close to Pietemaritzburg in KwaZulu-Natal, South Africa, at an altitude of 671.3 m. The surface above which the SLS was installed was nearly flat over a distance of 135 m along the prevailing S-E wind direction, with a downward slope of 1° 15' to the S-E (Savage et al., 2004, 2005). To the north of the study site is a residential area with tall trees. KwaZulu-Natal, on the eastern seaboard of South Africa is bordered by the warm Indian Ocean to the east and the high escarpment of the Drakensberg Mountains to the west. The climate is subtropical and humid with summer rainfall. Occasional frosts occur in winter.

A dual-beam surface layer scintillometer (SLS40-A, Scintec Atmosphärenmessetechnik, Tübingen, Germany) was set up at a height of about 1.68 metres (m) above the ground surface and the path length between the transmitter and receiver units was 101 metres. Input values of air temperature (°C), atmospheric pressure (hPa), beam path length (m) and effective height (which is the beam height above the ground level minus \( d + z_g \)) were entered into the SLSRUN program before commencement of measurements. For each site visit, the following were checked: Error Free Data (EFD) (should be greater than 25 %); the inner scale length \( l_o \) (should be greater than 2 mm for the beam path distance used in this study since if \( l_o \) falls out of this range, the instrument is susceptible to measurement errors); beam distance, which should be greater than 80 % and the signal strength, which should range between 700 and 1400 digits for both beams and both channel detectors. The SLS data that did not meet certain specifications were rejected using a filtering procedure so that only data that falls within the defined limits were used for analysis. For instance, SLS data were rejected if the percentage of error free data (EFD) was less than or equal to 25 % and inner scale length was less than or equal to 2 mm.

Daytime (06h00 to 18h00) wind speed values were calculated from 2-min values of the horizontal wind speed (\( U \)) and wind direction (\( \theta \)) referenced to North and anticlockwise from North using vector algebra for which the number of data points \( n \) in the 2-min period is 1200:

\[
\begin{align*}
\vec{u}_x &= u = \left( \sum U \cos\theta \right) / n \\
\vec{u}_y &= v = \left( \sum U \sin\theta \right) / n \\
U &= \sqrt{u_x^2 + v^2} \\
\theta &= \arctan \left( \frac{\vec{u}_y}{\vec{u}_x} \right)
\end{align*}
\] (1)

III. RESULTS: COMPARISON OF EC- AND SLS-MEASURED SENSIBLE HEAT FLUX MEASUREMENTS FOR DIFFERENT WIND DIRECTIONS

Two-min wind direction and horizontal wind speed data obtained by the EC method were analysed and results for selected days when the prevailing wind direction was either approximately perpendicular, parallel to the SLS beam path, or irregular, are presented in Figs 2 to 3. In these figures, for example, 12h30 wind vector occurs at \( y = 12h \) and \( x = 30 \).
min. The wind direction data obtained from the EC system were converted to radians and plotted using Origin software (OriginLab, 2000). Only daytime data (from 06h00 to 18h00) were plotted. Wind direction is shown by the direction of the arrows whereas horizontal wind speed is indicated by arrow length so that a longer arrow indicates greater wind speed than a shorter one. The orientation of the SLS beam path is also shown on the plots as well as the compass direction.

For most days, the prevailing wind direction was more or less perpendicular to the beam path, although there were days when the wind direction was irregular. Even for the days when the wind direction was mainly perpendicular to the SLS beam path, for some hours during the day there was irregularity in the direction (e.g. DoY 287, 2004). In Figs 2(a) and 3(a) (DoY 275, and 131, respectively) the wind direction was mainly perpendicular to the SLS beam path nearly throughout the day whereas in Fig. 2(b) (DoY 287), the wind direction was perpendicular to the beam except between 11h00 and 14h00, when the wind direction is irregular. Figure 3(b) (DoY 107) on the other hand is an example of when the wind pattern was irregular throughout the daytime period considered in the analysis. For those days when the wind direction was approximately perpendicular to the SLS beam path, the sensible heat flux ($F_h$) values obtained by the EC and SLS methods seemed to be in better agreement than for those days when the wind direction was irregular. For instance, for DoY 275, slope = 1.046 (Fig. 4(a)). The diurnal plots for the respective days also show good agreement in the $F_h$ values obtained by the two methods for the days when the wind direction is mainly perpendicular to the SLS beam path. This is well demonstrated in Fig. 3(b).

An example of one of the days when the wind direction was random for part of the day and perpendicular to the beam for the rest of the day is DoY 287 when the wind direction was irregular between 11h00 and 14h00 but perpendicular for the rest of the day (Fig. 5 b). On this particular day, the diurnal plot of $F_h$ (Fig 5 a and for emphasis b) shows the effect the wind direction or pattern has on the agreement in $F_h$ values estimated by the EC and SLS methods. It can be seen from this plot that in the interval when the wind pattern was highly irregular, there seem to be a disagreement in the $F_h$ values.

In Fig. 5 h, the distinction between SLS estimates of sensible heat flux for times when the wind direction was approximately perpendicular to the beam and when the wind direction was random makes this clearer as can be seen from the diurnal plot. In the early hours of the day (mainly before midday) the sensible heat flux measurements obtained by the two methods do not agree well - this coincides with times when the wind direction was irregular - as compared to the time after midday when the agreement in sensible heat flux measurement by the two methods, as indicated by the coincidence in the plots, is improved.

In Fig. 5.16, the diurnal plot of 2-min SLS- and EC-measured sensible heat flux for DoY 131 with wind direction was nearly perpendicular to the SLS beam path is shown but when the wind speed was low. Wind speed appears to influence the $F_h$ measurements by the EC and SLS methods. The influence of wind speed is noticeable, for example, on DoY 107 (Fig. 5.18) when even though the wind direction appears random, the agreement between the EC and SLS measurements of $F_h$ is better compared to the agreement for DoY 131 (Fig. 6) when wind is more or less perpendicular to the beam path. One of the days (DoY = 107) for which the wind direction was random is shown (Fig. 4). The statistical analysis of the $F_h$ estimates by EC and SLS results in a slope of 0.992 (Fig. 5.18), which is less than for days when the wind direction is nearly perpendicular to the beam. The diurnal plot of $F_h$ values (Fig. 5.19) for this day (DoY 107) exhibits more scatter for most of the day especially from around 10h00 to 14h00 when the $F_h$ values are large.

In Fig. 3 (DoY 131), the wind direction is similar to that of Fig. 2 - nearly perpendicular to the SLS beam path, but the wind speed is less on DoY 131 compared to that for 275 DoY. It can be assumed that the lower wind speeds on DoY 131 resulted in the poorer agreement (slope of 0.931) as shown in Fig. 6, since the wind direction is similar for both days. The influence of wind speed is also noticeable on DoY 107 when even though the wind direction appears random, the agreement between the EC and SLS measurements of $F_h$ is better compared to the relationship on DoY 131 (Figs 3 and 6) when wind is more or less perpendicular to the beam path. Wind speed plays a role in atmospheric stability and on DoY 131 the atmospheric condition was near-neutral while on DoY 107 the atmospheric condition was unstable.

IV. FOOTPRINT ANALYSIS

To aid in the interpretation of the surface area responsible for the flux estimations by the two methods (EC and SLS), a footprint analysis was carried out. The model developed by Hsieh et al. (2000), and corrected and modified by Savage et al. (2004), was used to estimate relative contributions from areas at various upwind distances $x$. Wang et al. (1978) used a bell-shaped spatial weighting function applied to $C_n^2$ to account for the fact that scintillations near the centre of the beam contribute more greatly than those nearer the receiver and those nearer the transmitter. Three-dimensional surface colour maps of the footprint function for the surface layer scintillometer beam were created using the Origin (version 7.5) software. The contour was defined as:

$$C(f, x, y) = f(x) \times \text{W}(y)$$  \hspace{1cm} (2)

where $f(x)$ is the footprint function as a function of distance $x$ perpendicular to the scintillometer beam and $\text{W}(y)$ is the beam path weighting function based as a function of distance along the beam measured from the transmitter. The function $\text{W}(y)$ is based on Eq. 2.8.

The footprint function, $f(x)$ (m$^{-1}$), used was based on the Hsieh et al. (2000) and modified by Savage et al. (2004).

$$f(x) = \left(2 \frac{x_{\text{max}}}{x^2}\right) \times \exp(-2 \frac{x_{\text{max}}}{x})$$  \hspace{1cm} (3)
where $x_{\text{max}}$ is the peak of the footprint given by
\[
x_{\text{max}} = \frac{D \cdot \beta}{2k^2}
\]
and the beam path weighting function $W(y)$ given approximately by (Meijninger, 2003):
\[
W(y) = \left(\frac{y}{L_{\text{beam}}} \cdot \frac{1 - y}{L_{\text{beam}}}\right)^{5/6}
\]

In Figs 7 a and b, the weighted footprint plots for the SLS method against horizontal distance for two different stability conditions are shown. A clear picture that emerges from the plots is that atmospheric stability influences the peak position of footprint with the peak footprint position being further from the measurement position when the atmospheric stability condition is closer to stable as denoted by the Obukhov length of -5 and closer to the measurement point for convectively unstable atmospheric conditions as shown by the Obukhov length of -30. Figures 7 a and b, show that a larger fetch is required when the atmosphere is convectively unstable as indicated by the contours plotted on top of the footprint plots.

These findings agree well with those of Kljun et al. (2004) who also show that the footprint peak location ($x_{\text{max}}$) varies with atmospheric stability conditions, with the location being further from the measurement point when the atmospheric stability condition is neutral and nearer the measurement position when the atmospheric condition is strongly convective. This therefore means that when the atmosphere is stable, the source area associated with the SLS method is greater than when the atmospheric stability condition is convectively unstable. This may influence how well the measurements obtained by the two methods (EC and SLS) agree. In Figs 8 to 5.23 the different locations for the peak of footprint as well as the footprint magnitude estimated by the footprint plots for EC and SLS are shown, with Figs 8 and 10 showing the agreement plots for DoY 131 and 107 when the agreement in sensible heat flux measurements by the two methods seem to deviate more than for DoY 275 for which the measurements by the two methods appear to be very good ($r^2 = 0.945$, and slope = 1.046). The footprint magnitude for SLS measurement is also larger than for the EC. For these two days (DoY 107 and 131) therefore, the two methods appear to have differing associated sensible heat flux source areas. For DoY 275, the peak location of the footprint for the two methods appear closer, with EC footprint peak being 4.64 m and that of SLS 6.74 m. As noted earlier, the wind direction on this day (DoY 275) was predominantly perpendicular to the SLS beam path compared to DoY 107 when the prevailing wind direction was more random. Wind direction and atmospheric stability condition seem to have a similar effect on the agreement between the sensible heat flux measurements by the EC and SLS methods. On DoY 131, wind speed was lower as is indicated by the short length of the wind direction and wind velocity plots in Fig. 5. The footprint plot for DoY 131 (Fig. 8) indicates that the source area and peak location of the two methods are different confirming further the effect of wind speed on the measurements from both EC and SLS methods.

V. CONCLUSION

Measurements of sensible heat flux ($F_h$) by EC and SLS methods over a mixed grassland experimental site were compared for wind directions approximately perpendicular to the SLS beam path and wind directions either random or approximately parallel to the beam path.

For those days with wind directions approximately perpendicular to the beam, the $F_h$ agreement between the EC and SLS methods was better compared to random wind directions or directions approximately parallel to the SLS beam path. Wind speed also seems to influence the $F_h$ estimates by the two methods since the agreement in the $F_h$ values obtained by the two methods is greater when wind speed is higher compared to times of the day when the wind speed is lower.

The atmospheric stability influences the peak position of footprint. The peak footprint position being further from the measurement position when the atmospheric stability condition is closer to stable as denoted by the Obukhov length of -5 and closer to the measurement point for convectively unstable atmospheric conditions as indicated by the Obukhov length of -30. A larger fetch was also shown to be required when the atmosphere is convectively unstable as indicated by the contours plotted on top of the footprint plots. The footprint for the two methods (EC and SLS) differ more when the wind direction is random compared to when the wind direction is mainly perpendicular to the beam and this may be part of the reason why the sensible heat flux comparisons between the two methods improved for wind directions mainly perpendicular to the SLS beam path than for directions more random or parallel to the beam.

REFERENCES


Figure 1. (a) Wind vector variation between 06h00 to 18h00 for DoY 275. The arrows point to the wind direction and wind speed is indicated by the length of the arrows. On this particular day wind direction was nearly perpendicular to the SLS beam; and (b) wind vector variation between 06h00 to 18h00 for DoY 287 for which the wind direction was random in the morning hours of the day and nearly perpendicular to the SLS beam path in the afternoon.

Figure 2. (a) Wind direction between 06h00 to 18h00 for DoY 131 for which wind direction was nearly perpendicular to the SLS beam path but with low wind speed and (b) wind vector variation between 06h00 to 18h00 for DoY 107 for which the wind direction was random.

Figure 3. (a) Comparison of 2-min sensible heat flux measured by EC and SLS methods for DoY 275 for which wind direction is nearly perpendicular to the SLS beam path and (b) diurnal plot of 2-min SLS- and EC-measured sensible heat flux for DoY 275 for which wind direction is nearly perpendicular to the SLS beam path.


Figure 4. (a) Comparison of 2-min sensible heat flux measured by EC and SLS methods for DoY 275 for which wind direction is nearly perpendicular to the SLS beam path and (b) diurnal plot of 2-min SLS- and EC-measured sensible heat flux for DoY 275 for which wind direction is nearly perpendicular to the SLS beam path.

Figure 5. (a) Comparison of 2-min sensible heat flux measured by EC and SLS methods for DoY 275 for which wind direction is nearly perpendicular to the SLS beam path and (b) diurnal plot of 2-min SLS- and EC-measured sensible heat flux for DoY 275 for which wind direction is nearly perpendicular to the SLS beam path.

Figure 6. Depiction of the SLS beam-weighted footprint function for (a) Obukhov length \( L \) of -30 m and (b) Obukhov length of -5 m. Also shown is the contour for a view of the footprint function, in the horizontal plane, at the top of the footprint plot.
Figure 7. Depiction of the SLS beam-weighted footprint function for (a) Obukhov length ($L$) of -30 m and (b) Obukhov length of -5 m. Also shown is the contour for a view of the footprint function, in the horizontal plane, at the top of the footprint plot.

Figure 8. Daytime footprint peak location estimated by the calculations for EC and SLS mid-point beam position for DoY 107, 12h00. On this day the wind direction was random and (b) daytime footprint peak location estimated by the calculations for EC and SLS mid-point beam position for DoY 275, 12h00. For this day the wind speed was nearly perpendicular.