AMERICAN UNIVERSITY OF BEIRUT

INTERCOMPARISON OF LATENT AND SENSIBLE HEAT FLUXES FROM EDDY COVARIANCE AND SCINTILLOMERTY OVER A SMALL VINEYARD IN A SEMI-ARID REGION

by
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ABSTRACT

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Title: Intercomparison of Latent and Sensible Heat Fluxes from Eddy Covariance and Scintillomerty over a Small Vineyard in a Semi-Arid Region

Accurate measurements of evapotranspiration and of energy fluxes between the land and the atmosphere are very important in understanding climatic patterns. Several techniques and models can measure heat fluxes and evapotranspiration including scintillometers and eddy covariance systems. In this experiment, measurements of sensible and latent heat fluxes were carried out using a boundary layer scintillometer (BLS 900) installed along an open path eddy covariance in a semi-arid climate at a vineyard located in the Beqaa valley, Lebanon. The results showed good correlation between the sensible heat flux estimates measured by both systems, sensible heat flux measured by the eddy covariance system was less than the one measured by the scintillometer by 14.13%. This difference decreased when the surface energy balance closure ratio was closer to 1 (11.12%), wind direction was perpendicular to the scintillometer beam pass (9.62%) and with high wind speed at the experimental site location (6.87%). Sensible heat fluxes measured by both systems showed better agreement when the bare soil to leaves ratio was low (Period of low NDVI). Additionally, sensible heat fluxes measured by both systems were lower during major rainfall events at the experimental site location. Good correlation was also found when comparing latent heat fluxes (LE) estimated by both systems, latent heat flux estimated by the eddy covariance system was lower than the one estimated by the scintillometer by 5%. This difference in the latent heat flux measured by each system is attributed to errors in the energy balance closure error, and to discrepancies in the net radiation or ground heat flux estimates as they are point measurements. Differences in the footprint of each system was not a major cause in the discrepancies in fluxes measured during this experiment as the source area of both systems share the same soil surface characteristic.

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CHAPTER I

INTRODUCTION

Studying the energy and water vapor interactions between the atmosphere and the land surface is of high importance in understanding terrestrial ecosystems as these interactions govern the transport of heat, humidity, and moisture in addition to the planetary boundary layer (Baldocchi, Vogel et al. 1997). Consequently, accurate estimation of turbulent heat fluxes is very crucial in managing water resources especially in arid and semi-arid regions as these areas are considered as the driest in the world (Water 2018). Turbulent heat fluxes include the latent heat and the sensible heat fluxes which are the main drivers of atmospheric circulation. Latent heat flux is affected by the availability of energy, precipitation, and soil moisture. It is directly related to the amount of evapotranspiration from the soil surface to the atmosphere which is the summation of the water amount evaporated from the soil surface and the one transpired from vegetations (Eagleson 1978).

Many approaches and equipment have been adopted for accurate estimation of the surface heat fluxes such as scintillometers and eddy covariance systems.

Scintillometers are optical devices that are used in atmospheric, hydrological, agricultural and water resources researches (Geli, Neale et al. 2012). The system consists of a transmitter and a receiver mounted in the field at a specific elevation called path height and separated by a distance called path length. Path height is determined depending on the height of the vegetation present along the path length as it should be double or triple the height of the vegetation along the path (Scintec 2019). The path length can be specified by the user depending on the study area and can vary between 0.5 up to 12 depending on the type of the equipment installed. (Scintec 2019).

The transmitter emits a beam of electromagnetic radiation of a known wavelength across the system's path, this beam is detected by the receiver after being scattered by air parcels (eddies) along the path. The receiver will be detecting the scintillations intensity induced by a continuously changing field of eddies. After that, wave turbulence and propagation theory relates first and second order statistics of the detected signal to determine the path-averages of Cn^2 and I_0 which are used to calculate the other parameters. (Scintec 2020).

Different types of scintillometers exist and are used in research. The **SLS scintillometer** is a displaced-beam laser scintillometer. It consists of a laser transmitter formed of two laser beams separated by a distance of 2.7mm directed towards a receiver where the signal is averaged. This equipment functions in the visible spectrum at a wavelength of 670 mm. Unlike other scintillometers types, SLS can measure the sensible heat flux (H) and the momentum τ flux densities over the path between the receiver and the transmitter by purely optical means without the need of additional wind speed measurements (Scintec 2020). The **Large aperture scintillometer (LAS)** and the **extra-large aperture scintillometer (XLAS)** are used to measure the structure parameter of the relative index (Cn^2), Their path length varies between one up to twelve kilometers. Both LAS and XLAS operate under the near infrared spectrum with a wavelength of 880 mm. Additional wind speed measurements are needed to calculate the sensible heat flux (H) and the momentum τ flux densities. If used along with a meteorological station all scintillometer types can calculate evapotranspiration (ET). (Scintec 2020).

Eddy covariance equipment is becoming more popular nowadays in measuring ET (Baldocchi 2014). This system does not only measure ET, but also other parameters including sensible heat flux (H), latent Heat flux (LE), carbon dioxide (CO_2), water (H_2O) and methane fluxes (CH_4) by measuring vertical turbulent fluxes within the atmospheric boundary layers (Wang, Liu et al. 2013). The flux is the total amount of air moving through a unit area in a unit time, it is the mean product of the vertical wind speed and the value of the property. Flux measurements depend on several factors such as the crossing area, the size of the areas being crossed, and the time needed to cross this area. Measuring turbulent heat fluxes using this equipment requires the usage of many sensors such as the sonic anemometer for measuring the vertical component of wind, thermocouple, soil moisture sensors, and soil heat flux plates for measuring soil heat flux, sensors for measuring air temperature and relative humidity, a net radiometer sensor for measuring net radiations in addition to a rain gauge for measuring precipitation. The accuracy of this system depends on numerous factors and it is most accurate in steady atmosphere, homogeneous underlying vegetation and when it is located on a flat terrain for an extended distance upwind (Kumar, Bhatia et al. 2017).

In this paper, field experiments were conducted on a vineyard irrigated using drip irrigation to estimate latent and sensible heat fluxes using a boundary layer scintillometer (BLS 900) from Scintec which falls under the XLAS type of scintillometers along with a meteorological station and an open path eddy covariance equipment (EC) (Scintec 2020).

The objectives of this experiment are to (1) compare the different fluxes readings estimated using a scintillometer and eddy covariance technique, and (2) discuss the differences of fluxes estimations between both systems.

CHAPTER II

LITERATURE REVIEW

A. Evaluation of Scintillometer derived fluxes.

ET equipment have been extensively evaluated in Literature. Moorhead, Marek et al. (2017) evaluated the sensible heat flux and evapotranspiration estimates using surface layer scintillometer (SLS) and a large weighing lysimeter in Brushland over irrigated sorghum and over grain corn and found poor correlation for sensible heat flux and a much better correlation for ET with an r^2 value of 0.83 and 0.87 for hour and daily ET respectively. The accuracy of the SLS was comparable to other ET sensing instruments with an RMSE of 0.13 mm·h^{-1} (31%) for hourly ET. Summing hourly values to a daily time step reduced the ET error to 14% (0.75 mm·d$^{-1)}$ (Moorhead, Marek et al. 2017).

Meijninger, Beyrich et al. (2006) tested the performance of a combined large aperture and millimeter wave scintillometer (LAS-MWS) (two wavelength method) for estimating sensible and latent heat fluxes over a moderate heterogeneous landscape having an area of 20 km × 20 km, located in Germany. The study area was dominated by forests (42%), agricultural farmlands (41%); other surfaces types are lakes (7%), meadows (5%), and villages (4%). The scintillometer system was installed at a path length of 4.7 km and a path height of 43 meters. The measured/calculated fluxes were compared with eddy covariance measurements. The results showed good agreement between LAS-MWS and EC sensible and latent heat fluxes which is the case also for the LAS sensible heat fluxes, additionally the latent heat estimated by the LAS-MWs system were 26% higher than the EC estimates. LAS-MWS results were also compared with a MWS system operating at a 94 GHz frequency, the results obtained were similar to those of Meijninger, Green et al. (2002) who compared a LAS-MWS system to a MWS system operating at a frequency of 27 GHZ. As a conclusion this study showed that the two-wavelength method and single LAS can produce accurate fluxes estimates at a scale of several kilometers. (Meijninger, Beyrich et al. 2006)

B. Evaluation of Eddy covariance derived fluxes.

Eddy Covariance principals were published in 1951, but its application was very limited because of its high hardware requirements(Monteith and Unsworth 2013). Nowadays, with the technological advancements made in computer acquisition, data analyses capacity and sensors such as the ultrasonic wind meter and the CO_2 analyzer, EC equipment are becoming more widely used as described by (Baldocchi 2003), and (Shaw and Snyder 2003). The use of EC in measuring Et requires high speed measurement sensors at a frequency ranging between 5-20 Hz (Allen, Pereira et al. 2011). In addition to the measurement of the sensible and the latent heat flux by the EC, net radiation and soil heat-flux need to be measured to estimate an energy budget of the area of interest (Tomlinson 1996). The use of the eddy covariance method requires well trained personnel with knowledge in electronics, turbulent theory, and biophysics. Additionally, EC measurements require some correction for accurate estimation of ET. Many software and programs for correction of EC data are available including EC Pack from Wageningen University, TK2 software of the University of Bayreuth (Mauder and Foken 2011), EddySoft developed at the Max-Planck-Institute for Biogeochemistry in

Jena (Kolle and Rebmann 2007) , EdiRE software from the University of Edin- burgh, and APAK by Oregon State University (Vickers and Mahrt 1997).

Despite all these correction programs many literatures showed energy balance closure error for EC data where the sum of measured LE + H does not equal measured Rn – G (Baldocchi, Hincks et al. 1988), (Twine, Kustas et al. 2000); LE + H were undermeasured relative to Rn − G by as much as 30% even after EC data correction (De Bruin, Hartogensis et al. 2005).

A 20 years overview of research on energy balance closure could be found in Foken (2008). There is evidence that closure problem arises due to issue in the documented methods and calibrated sensors rather than due to measurement error and storage terms. When exchange processes on larger scale of the landscape were included in the energy balance, closured drastically improved indicating that the scale problem affects the measurement and estimation of fluxes.

With a perfectly designed EC system, the mean uncertainty in ET measurements can be reduced to 10% (Meyers and Baldocchi 2005). Additional information on the Eddy covariance system corrections and flux calculations can be found in the following articles:(Twine, Kustas et al. 2000), (Wilson, Goldstein et al. 2002), and (Baldocchi 2003).

C. Intercomparison between Scintillometer and EC fluxes.

Yee, Pauwels et al. (2015) compared surface heat fluxes derived using 2 optical and 2 microwave scintillometers in addition to an eddy covariance system. This experiment was performed at a pasture site in a semi-arid environment in New South

Wales, Australia. Fluxes estimated using EC and the optical scintillometer (LAS) showed good correlation with an $R^2 > 0.94$. On the other hand, the microwave scintillometers measured a larger LE and a lower H than EC with a bias of around 65 and 60 W/m^2 respectively. A comparison between the optical scintillometers (LAS) showed good correlation in H with an $R^2 = 0.98$ which is not the case for the microwave scintillometers (MWS) as they showed different results when operating with different frequencies and polarization. A combination of the LAS and MWS measurements (Two wavelength method) showed better results than the MWS measurements when compared to the EC readings, which is not the case for LAS measurements which showed better results that both MWS and the combination of LAS/MWS measurements when compared to EC readings. The differences between the surface heat flux derived from the EC system and those estimated using the MWS and the two-wavelength method are related to the inaccurate assignment of the structure parameter of temperature and humidity. Additionally, MWS fluxes estimates can be associated with two values of the Bowen ratios thus leading to uncertainties in the fluxes estimation. Therefore, for accurate estimation of surface heat fluxes in a semi-arid climate the optical scintillometer is recommended (Yee, Pauwels et al. 2015).

Valayamkunnath, Sridhar et al. (2018) compared evapotranspiration from eddy covariance, and scintillometers (LAS) across three ecosystems (sagebrush, cheat grass, and lodge pole pine) in a semiarid climate. This study used three years of eddy covariance and large aperture scintillometer (LAS) flux measurements and found that H_{Ec} was slightly under-estimated compared to H_{LAS} at all the three sites as at all three sites H_{LAS} was 8 to 13% higher than H_{EC}. The difference between H_{Ec} and H_{LAS} was attributed to unsaturated atmosphere conditions, energy balance closure errors, and the discrepancy in the size and the homogeneity of EC and LAS footprints. Furthermore, the statistics for H measured by both systems showed a strong correlation for sagebrush and cheat grass compared to lodge pole pine (Valayamkunnath, Sridhar et al. 2018).

Moreover, Liu, Xu et al. (2011) analyzed the seasonal variations of energy balance components measured using Eddy covariance (EC) and a large aperture scintillometer (LAS) over 3 different locations: Irrigated cropland (Yingke, Yk), alpine meadow (A'rou, AR), and spruce forest (Guantan, GT) in the Heihe river basin between 2008 and 2009. Additionally, source areas of the EC and LAS measurements were determined using a footprint model for each site. Concerning the EC equipment, the source areas were estimated to be within a radius of 250 m at all the study sites. On the other hand, the source area of the LAS (with a path length of 2390 meters) stretched along a line of approximately 2000 m long and 700 m wide. Surface characteristics in the source areas changed with different seasons at each site, and seasonal variations in the energy balance components were observed at all the sites. This study showed that the sensible heat flux was the main component of the energy budget during the dormant season, but during the growing season the latent heat flux was the main component in the energy budget. The sensible heat flux readings measured by LAS (H_{LAS}) were higher at AR compared with H_{Ec} readings measured at the same site and at the same time which is caused by the energy imbalance phenomenon and the difference between the source areas of the LAS and EC measurements (As the EC source areas were within a radius of 250 m and the main source area for the LAS equipment stretched along an area of 2000 meters long and 700 meters wide).

Odhiambo and Savage (2009) presented measurements of sensible heat flux for an extended period using surface layer scintillometer (SLS) and eddy covariance (EC) and supplemented by Bowen ratio measurements for a mixed grassland community on the eastern seaboard of South Africa. These measurements were compared with those obtained using EC for a wide range of Bowen ratio (*β*). Additionally, an analysis of the different forms of the Monin–Obukhov similarity theory (MOST) functions used in micrometeorology and suggested by various authors was also presented. Moreover, Structure parameter of air Temperature (C_T^2) measured by the SLS and corrected for β was compared to uncorrected C_T^2 also measured by the SLS. The result showed good correspondence with a slight bias highlighting on the importance of correcting SLS measurements for *β* in preventing any error in H measurements especially in humid areas. After comparing scintillometer measurements to Eddy covariance Sensible heat flux estimates (H) with averaging periods between 1 and 120 minutes, (Odhiambo and Savage 2009) found that short-time averaging periods resulted in underestimated H_{EC}. The EC measurements for 60 and 120-min averaging periods were sometimes inconsistent with SLS measurements. In addition, a sensitivity analysis indicated that measuring H using both EC and SLS equipment is affected by the Bowen ratio (*β*). In fact, for $0 < \beta < 0.2$, the correction to H_{SLS} is more than 10% compared to 20% for H_{EC}. A comparison of H_{EC} and H_{SLS} measurements for 0.1 intervals of *β* between 0 and 4.3 shows reasonable correlation for $\beta > 1$, and for $0 < \beta < 1$ the linear regression slope of the H_{SLS} and H_{Ec} scatterplot (H_{SLS} on the y axis) decreased from 1.25 to nearly 1 for β increasing from 0 to 1. A comparison between H_{SLS} measurements corrected for *β* and computed using various empirical stability function used by MOST, and H_{EC} measurements also corrected for β showed a difference of 20% (overestimation of H_{SLS} for some methods and underestimation for others). Long term use of the recommended MOST stability functions for the SLS readings resulted in reasonable correspondence between the sensible heat flux measured using SLS and the one measured using EC equipment for a wide range of atmospheric conditions (Odhiambo and Savage 2009).

Liu, Xu et al. (2013) compared ET measurements from eddy covariance systems and large aperture scintillometers (LAS) in the Hai River Basin “China”. ET observation were made for three years (2008-2010) in typical underlying surfaces across the Hai River Basin. The ET readings ranged from 510-730 mm for the EC measurements and 430-560 mm for the Scintillometer. The differences in the ET readings among the years and sites were linked to the differences in the crop growing conditions. The difference in the source areas of EC and LAS measurements and the heterogeneity in their source areas are the primary causes of the discrepancy between EC and LAS measurements. The EC and LAS readings were also compared to the field water balance calculation method and remote sensing techniques for determining Et ($Modis_{16}$); The average difference was 0.85% (mean relative error) and 33.80 mm (root mean square error) between the EC measurements and field water balance method calculations, and 7.72% and 47.08 mm between LAS measurements and MOD16 ET from 2008 to 2010 at the three sites.

D. Advantages and Disadvantages of EC and Scintillometer:

Eddy covariance and scintillometers have many advantages and disadvantages. Both systems are non-disruptive, fully automated, simple to operate and maintain and can get ET data over large area. Contrary to the eddy covariance technique which uses direct turbulent measurements, Scintillometers rely on the semi empirical Monin-Obukhov similarity theory (MOST) for the calculation of surface fluxes and any bias in Rn or G representativeness transfer into inaccurate Et calculations. Scintillometers are used for accurate error estimation of remote sensing and satellite estimations of sensible heat flux due to their path length as it is larger than the EC footprint (Lee, Lee et al. 2015). EC systems requires substantial fetch and have energy balance closure error ranging from 10 to 30%. In addition to that, both systems are expensive and may require some post-processing correction (Hoedjes, Chehbouni et al. 2007).

CHAPTER III

MATERIALS AND METHODS

This experiment was conducted in a vineyard at the premises of the American University of Beirut's Agricultural Research and Education Centre "Arec", between October 2020 and February 2021. This chapter will explain the procedures carried out in this experiment.

A. Site Description

The study area is located in the Beqaa area in Lebanon (33° 55'20''N, 36° 04' 36''E) at an elevation of 994 meters above the sea level. The vineyard where the experiment was conducted is flat with no clear slope. The geographical location of the experiment site is presented in Figure 1.

1600 wine grape plants are planted in the site. The varieties of the plants are Viognier, Syrah, Sauvi-Blanc, Tempranillo, Muscat, Grenach, and Cinsault. The plants are planted in fourteen rows, with a between row spacing of 2.5 meters and an in-row spacing of 1 meter. Note that the plants were planted three years ago, in spring 2018.

The experimental location is known by its semiarid climate with dry and hot summer (from May to September), and cold winter in addition of an average annual grass reference evapotranspiration of 1.5 meters. The average annual precipitation is 520 mm/year, with a coefficient of variation of 0.31 (Jaafar, Khraizat et al. 2017).

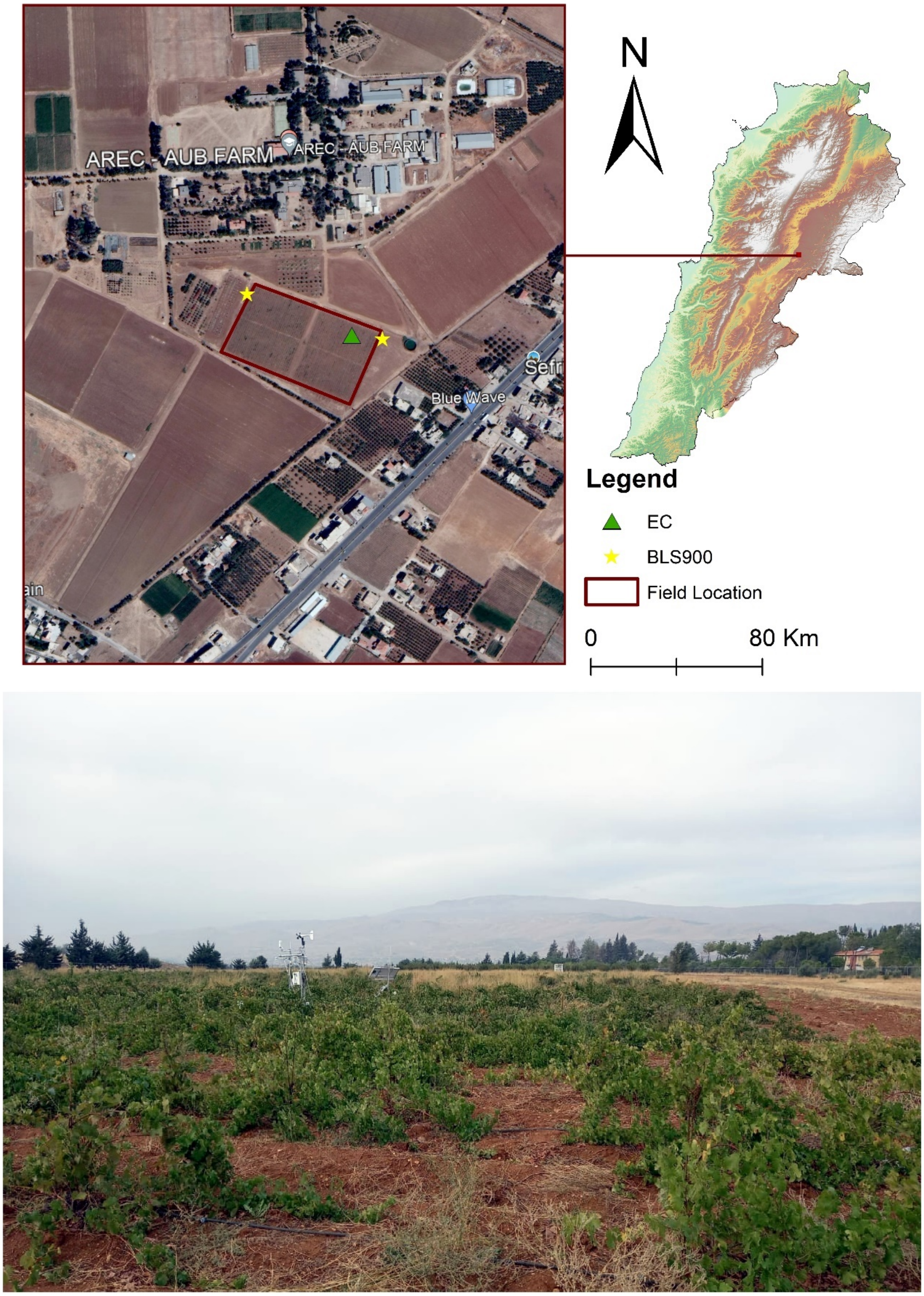

Figure 1:Location of the study area in the Beqaa area, Lebanon

B. Flux measurements

1. Boundary Layer Scintillometer Data Processing

The BLS 900 scintillometer is commercially available from Scintec (Rottenburg, Germany). This scintillometer has two transmitters that are tangent to each other and one receiver with a diameter of 0.15 meters and operates at a wavelength of 800nm (Scintec 2020). The BLS equipment was installed in the Vineyard with a path length of 191 meters, and a path Height of 2.55 meters (elevated using tripods). A real-time evapotranspiration extension was also installed in the vineyard in a way not to interfere with the BLS beam path (Figure 2).

The real-time evapotranspiration extension includes a wind monitor sensor installed at an elevation of 2.5 meters, a two-way pyrradiometer sensor (measuring outgoing and incoming solar radiation) installed at an elevation of 2 meters, a temperature and humidity sensor installed at a height of 1.8 meters, upper temperature sensor installed at the same level, a lower temperature sensor installed at 30 cm above surface, two soil heat flux sensors for determining the soil heat flux (G) (Hukseflux) installed at a depth of 5 cm, and a rain Gauge. All the sensors are wired to a Campbell Scientific data logger which is connected along with the receiver to the BLS SPU. Data was collected from the SPU at a 15-minute averaging period using the BLS configuration and processing software (SRun) (version 1.64) (provided by the manufacturer) by connecting it to a laptop using an ethernet cable.

The BLS 900 derives the turbulent intensity after measuring the relative index of air C_n^2 ($m^{-2/3}$).

$$C_n^2 = 1.12\sigma_{ln\,I}^2 D^{7/3} L^{-3} \quad (1)$$

Where, $\sigma_{ln\,I}^2$ is the variance of the natural logarithm of intensity fluctuations, D is the aperture diameter (m), and L is the path length (m).

Any variation in temperature and humidity causes fluctuations in the relative index of air (C_n^2), so C_n^2 is related to the temperature structure parameter C_T^2($K^2\ m^{-2/3}$), humidity C_q^2 ($kg^2\ m^{-6}\ m^{-2/3}$), and the covariance term C_{Tq} ($K\ kg\ m^{-3}\ m^{-2/3}$) (Wesely 1976). As a simplification, Wesely (1976) showed how the temperature structural parameter is related to the relative index of air for LAS systems operating at the near infrared wave by the following equation:

$$C_T^2 = C_n^2 \left(\frac{T^2}{-7.87\times10^{-7}P}\right)^2 \left(1+\frac{0.03}{\beta}\right)^{-2} \quad (2)$$

Where, T is the air temperature (K), P is the air pressure (Pa), and β is the Bowen ratio.

According to the Monin–Obukhov similarity theory (MOST), the sensible heat flux is calculated using the following equations:

$$\frac{C_T^2\,(Z_{LAS}-d)^{2/3}}{T_*^2} = f_T\left(\frac{Z_{LAS}-d}{L_{Ob}}\right) \quad (3)$$

$$H_{LAS} = \rho_a C_P U_* T_* \quad (4)$$

$$U_* = \frac{K_v U}{\ln\left(\frac{Zu-d}{Z_{0m}}\right) - \psi_m\left(\frac{Zu-d}{L_{Ob}}\right) + \psi_m\left(\frac{Z_{om}}{L_{Ob}}\right)} \quad (5)$$

where z_{LAS} is the effective height of the LAS (m), d is the zero-plane displacement height (m), which is calculated from the simple relationship between d and the vegetation canopy height h_c,, L_{Ob} is the Obukhov length (m), f_T is the stability function, C_p is the specific heat capacity of air at constant pressure ($J\ kg^{-1}\ K^{-1}$), ρ_a is the density of air ($kg\ m^{-3}$), u_* is the friction velocity ($m\ s^{-1}$), T_* is the temperature scale

(K), k_v is the von Kármán constant (0.40), u is the wind speed (m s^{-1}), z_u is the measurement height of the wind speed (m), z_{0m} is the aerodynamic roughness length (m), and Ψ_m is the stability correction function for the momentum transfer (Paulson and Climatology 1970), (Webb 1970).

After calculating the sensible heat flux (H), the latent heat flux can be estimated as a residual of the energy balance:

$$\mathrm{LE} = \mathrm{Rn} - \mathrm{H} - \mathrm{G} \quad (6)$$

Where Rn is the Net radiation (W.m^{-2}), LE is the latent heat flux (W.m^{-2}), H is the sensible heat flux (W.m^{-2}), and G is soil heat flux (W.m^{-2}) (Meijninger, Hartogensis et al. 2002).

Equation (6) explains the exchange in radiant energy between the sun, earth, and the atmosphere. Four important processes are involved, which are the following: absorption and reflection of radiation by the surface (where Rn is the absorbed radiation), the absorbed energy can be conducted as thermal heat within the surface (G), transferred as heat energy toward or away of the surface (H), and finally used as energy to evaporate water from the soil surface (LE). Rn is positive when radiations are approaching towards the surface, G is positive when the flux is directed toward the ground (away from the surface), H is positive when the flux directed away from the surface (toward the atmosphere), and LE is positive as the flux moves towards the surface (Monteith and Unsworth 2013).

Hourly LE_{BLS} data was corrected by replacing the net radiation data measured by the BLS system with the one measured by the EC. Additionally, ground heat data measured by the EC system were used in LE-BLS calculations because the latter is more accurate in G estimation as it relates between the temporal change in soil temperature, soil water content and G estimations.

2. Eddy Covariance Data processing

The eddy covariance equipment used in this experiment is an open path system. It was installed in the vineyard 20 meters away from the real-time evapotranspiration extension installed with the scintillometer (Figure 2). The system is composed of an IRGASON Open-path gas analyzer, a 3D sonic anemometer, and a temperature and relative humidity probe, mounted to an EC 100 data logger form Campbell Scientific and installed at an elevation of 1.75 meters. Other sensors were also mounted to a VOLT 116 and a CR6 data loggers which are the following: three averaging soil thermocouple probes (TCAV) for measuring the average temperature of the soil installed horizontally at a depth of 2, 4 and 6 cm, three water content reflectometer (CS65X) installed horizontally at different depths (5 to 15 cm) to measure the soil water content, three soil heat plates installed at a depth of 8 cm in a way to represent the area under study with the side having a red label facing the sky (HFP01), a relative humidity probe (HMP115A) installed at an elevation of 2.25 meters, and a 4-way net radiometer (NR01) installed at an elevation of 2 meters. Note that all data from the sensors were stored in the CR6 data logger at a 30-minute averaging period and were retrieved using a flash card which can be replaced after transferring the data to a computer. The eddy covariance system requires continuous power supply for uninterrupted day night operation. To meet this requirement solar panels were installed in the field on tripods (Figure 2).

The sensible heat flux derived from the EC system is computed as the covariance between fluctuations of vertical wind speed and fluctuations of temperature (Van Dijk, Moene et al. 2004),

$$H = \rho C_p \overline{w'T'} \tag{7}$$

Where ρ is air density Cp is the specific heat capacity of air, w T is the covariance between vertical wind speed (w) and air temperature (T), and the overbar indicates time averaging (Moncrieff, Massheder et al. 1997). No corrections were done on the EC data as the Easy flux program was uploaded on the EC CR6 data logger which is a CRBasic program that enables the CR6 data logger to collect fully corrected data including latent heat flux (LE), sensible heat flux (H), and ground surface heat flux from the open path Eddy Covariance system mounted along energy balance sensors (2020).

Figure 2:Layout of the deployed Boundary layer Scintillometer and Eddy Covariance system in the experimental site.

C. Statistical analyses

In this paper the Nash-Sutcliffe efficiency coefficient (NSE) (Equation 8), the percentage bias (PBIAS) (Equation 9), and the correlation coefficient (r) (Equation 10) were used to study the relation between the different parameters measured/calculated by the EC and the BLS systems. R^2

$$NSE= 1-\frac{\sum_{i=1}^{n}(OBSi-SIMi)^2}{\sum_{i=1}^{n}(OBSi-\overline{OBS})^2}. \quad \text{(Nash and Sutcliffe 1970)} \qquad (8)$$

- OBS_i = Observation value.
- SIM_i = Forecast value.

- OBS= Average of observed values.

$$PBIAS = \frac{\sum_{i=1}^{n}(Pi-Oi)}{\sum_{i=1}^{n}Oi}. \quad \text{(Yapo, Gupta et al. 1996)} \qquad (9)$$

P_i = Predicted values.

O_i = Observed Values.

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{(n\sum x^2-(\sum x)^2\,(n\sum y^2-(\sum y)^2}} \quad \text{(Asuero, Sayago et al. 2006)} \qquad (10)$$

- r = the correlation coefficient.
- n = number in the given dataset.
- x = first variable in the context.
- y Second variable in the context.

CHAPTER IV

RESULTS

A. Sensible heat flux comparison (H-BLS VS H-EC)

The comparison between the sensible heat flux measured using both eddy covariance and BLS-900 is shown in figures 3 and 4. The scatter plots show good correlation between these two variables. The hourly dataset comparison showed a correlation coefficient (R) equals to 0.906 (Figure 3, a), the daily dataset comparison showed an R of 0.942 (Figure 3, b), the weekly data set comparison showed an R of 0.952 (Figure 3, c), and the monthly dataset comparison showed an R of 0.967 (Figure 3, d). The daily dataset comparison had the best 1:1 association between H-BLS and H-EC with an NSE coefficient of 0.846 (Table 1). H-EC was lower than H-BLS as shown in figure 4, and H-EC hourly data were 14.13% lower than H-BLS which is also the case for daily, weekly, and monthly datasets having a bias percentage of 15.2, 15.2, and 12.38 % respectively (Table 1).

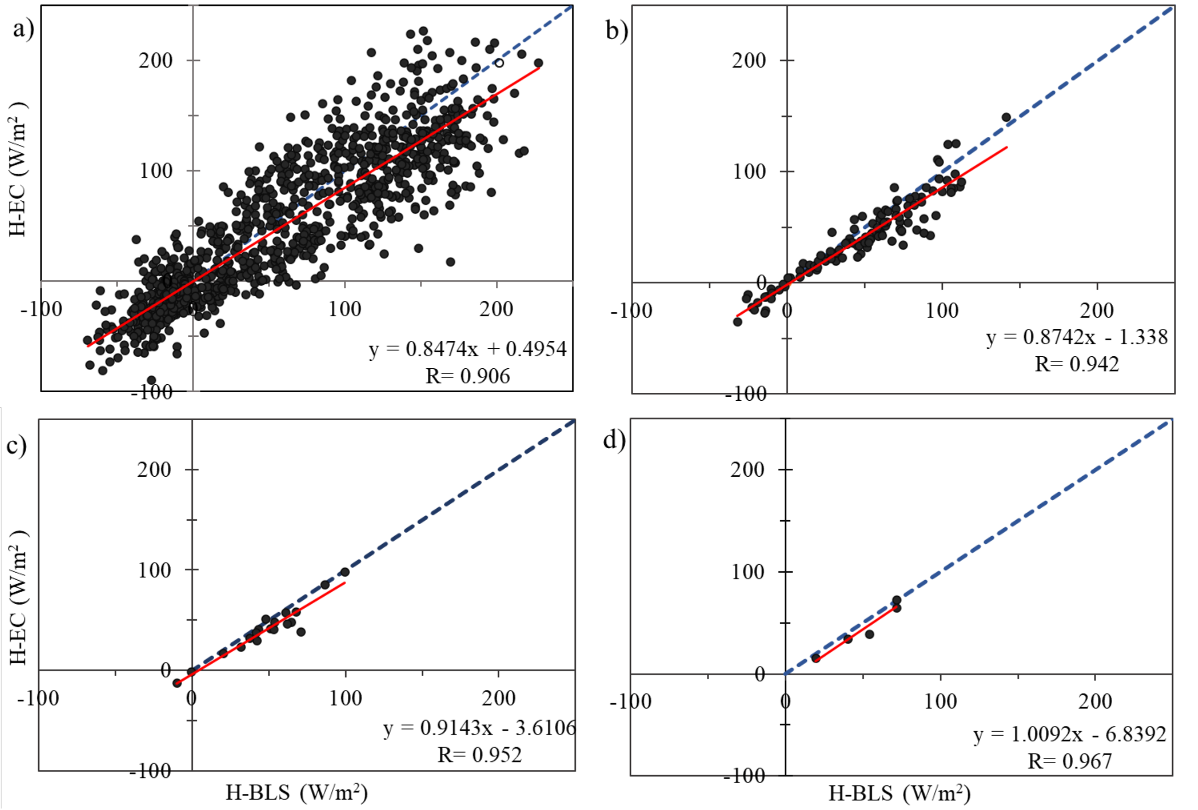

Figure 3:Comparison of a) Hourly, b) Daily, c) Weekly, and d) Monthly sensible heat flux measured by EC and BLS systems. Note that the statistics shown in the figure represent the best fit line (line in red).

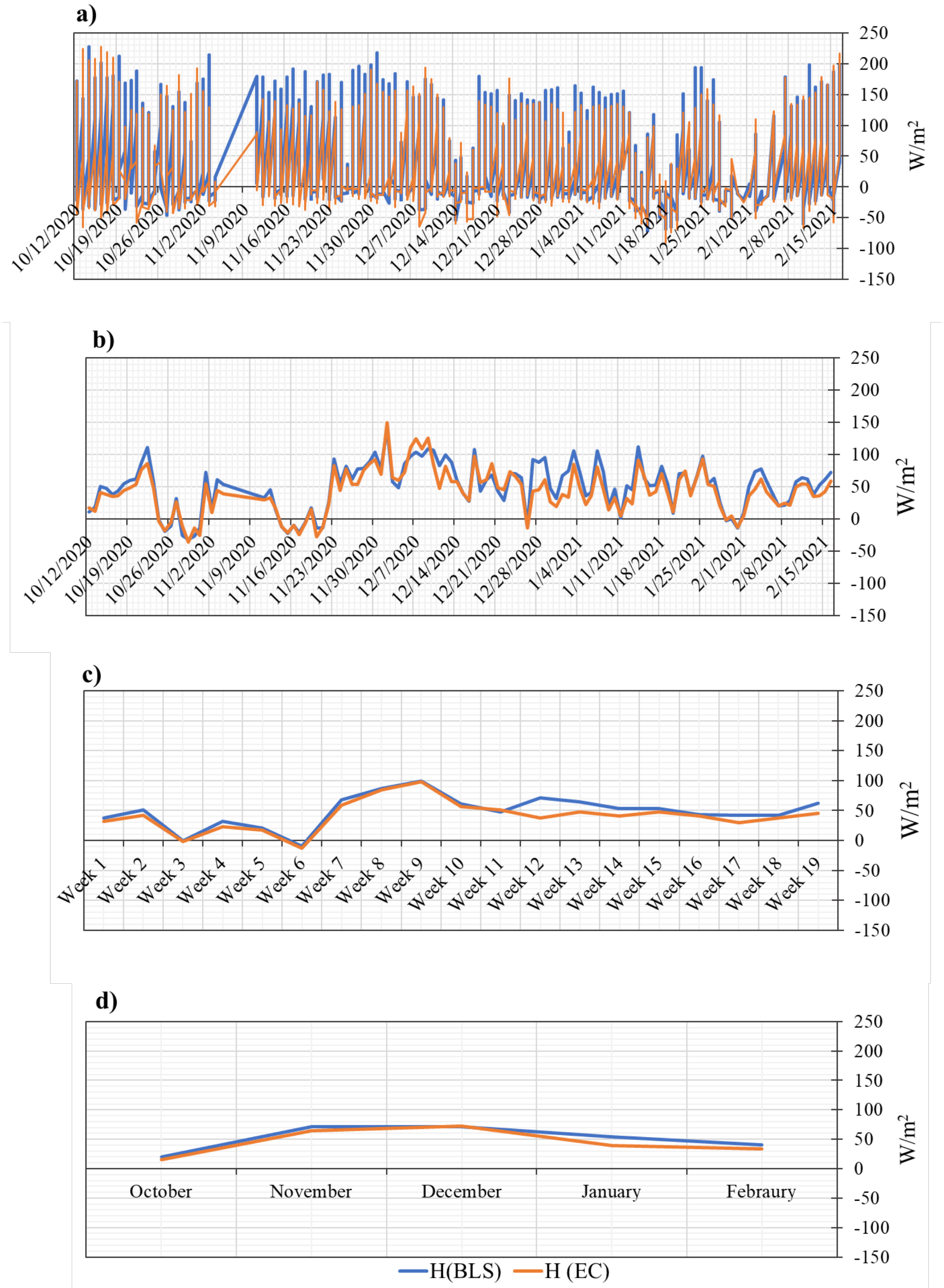

Figure 4: a) Hourly, b) Daily, c) Weekly, and d) Monthly sensible heat flux variation with time.

Table 1: H-BLS vs H-EC statistical analysis.

	R	NSE	PBIAS
H (Hourly)	0.906	0.806	14.13
H (Daily)	0.942	0.846	15.2
H (Weekly)	0.952	0.815	15.2
H (Monthly)	0.967	0.826	12.38

B. Surface energy balance closure error

Figure 5 shows the sum of the measured LE and H (LE+H) plotted against the net radiation Rn minus the ground heat flux G (Rn-G). The studied parameters showed good correlation with $(LE+H)_{EC} = 0.9641\ (Rn\text{-}G)_{EC} - 5.31$, and a correlation coefficient (R =0.921). Additionally, the EC data show surface energy imbalance of 9.42% as (LE+H) are smaller by 9.42% compared to (Rn-G).

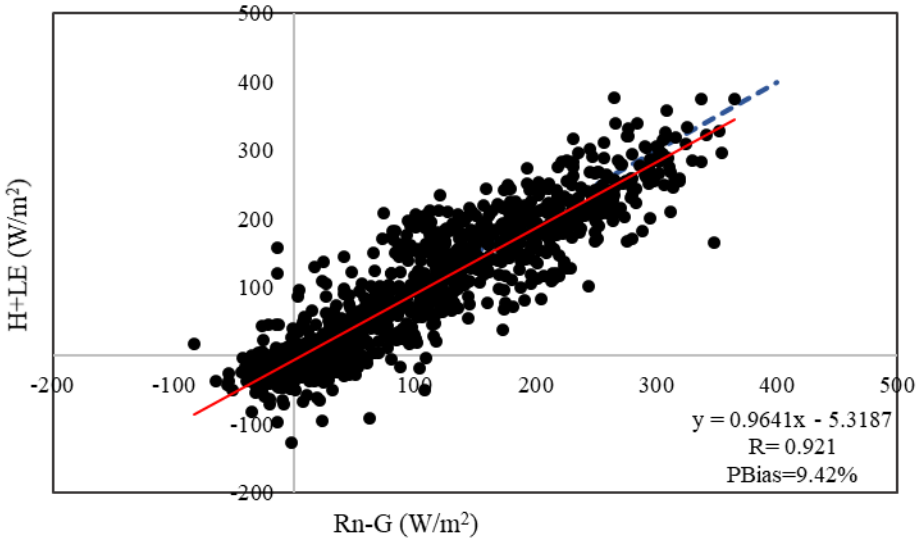

Figure 5: EC (H +LE) vs EC (Rn − G), Each point is a 1-hour measurement. Note that the statistics shown in the figure represent the best fit line (line in red).

C. Energy balance ratio effect on sensible heat flux measurements

Sensible heat fluxes readings from EC and BLS were studied with respect to the energy balance ratio (EBR). H-EC and H-BLS were compared to each other when EBR was high (greater than 0.75) and when EBR was low (less than 0.75) (Figure 6). It is noticeable that H-EC and H-BLS show better agreement when EBR<0.75. When EBR<0.75, H-BLS and H-EC had a correlation coefficient R= 0.92, When EBR <0.75, H-BLS and H-EC showed a lower correlation coefficient R = 0.87. On the other hand, a lower PBias was recorded between H-BLS and H-EC when EBR>0.75 with a PBias =11.12% compared to a PBias of 49.4% when EBR<0.75.

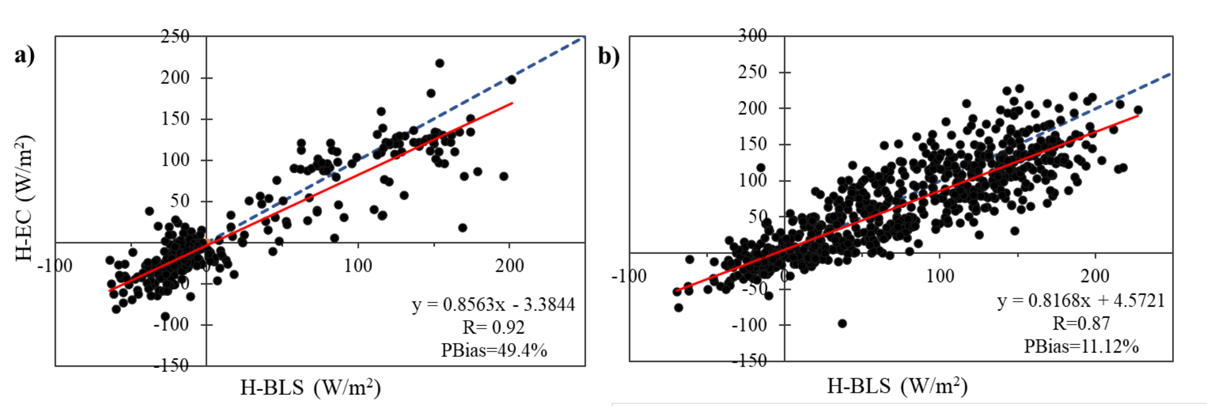

Figure 6:H-BLS and H-EC comparison when a) EBR<0.75, and when b) EBR>0.75, Each point is a 1-hour measurement. Note that the statistics shown in the figure represent the best fit line (line in red).

D. Wind speed/Direction effect on sensible heat flux estimates.

Sensible heat flux readings from EC and BLS were studied with respect to wind direction and wind speed. H-EC and H-BLS were compared to each other when wind direction was perpendicular to the BLS beam pass (Figure 7, a) and when the wind direction was random (Figure 7, b). The same parameters were also compared to each other when wind speed was high and when wind speed was low (Figures 8 and 9).

As it is noticeable in figure 7, H-BLS and H-EC showed better agreement when wind direction was perpendicular with a correlation coefficient R= 0.915, a PBias of 9.42% and a NSE coefficient of 0.832, compared to when wind direction was random having an R =0.9, a PBias equal to 18.04% and an NSE Coefficient of 0.798.

According to figure 8, with perpendicular wind direction and high wind speed, H-BLS and H-EC showed a higher correlation coefficient R= 0.921, a lower PBias (6.87%) and a higher NSE coefficient (0.84) compared to the fluxes recorded when wind speed was low (R= 0.915, PBias=21.32%, and NSE=0.78).

Figure 9 compare the measured sensible heat flux measurements when wind speed was high (Figure 9, a) and when wind speed was low (Figure 9, b) with random wind direction. H-BLS and H-EC also showed better agreement when wind speed was high with a correlation coefficient R =0.918, a PBias of 8.7% and an NSE of 0.831 compared to when wind speed was low (R= 0.852, PBias= 24.1%, and NSE= 0.643).

1. ***Wind direction analysis:***

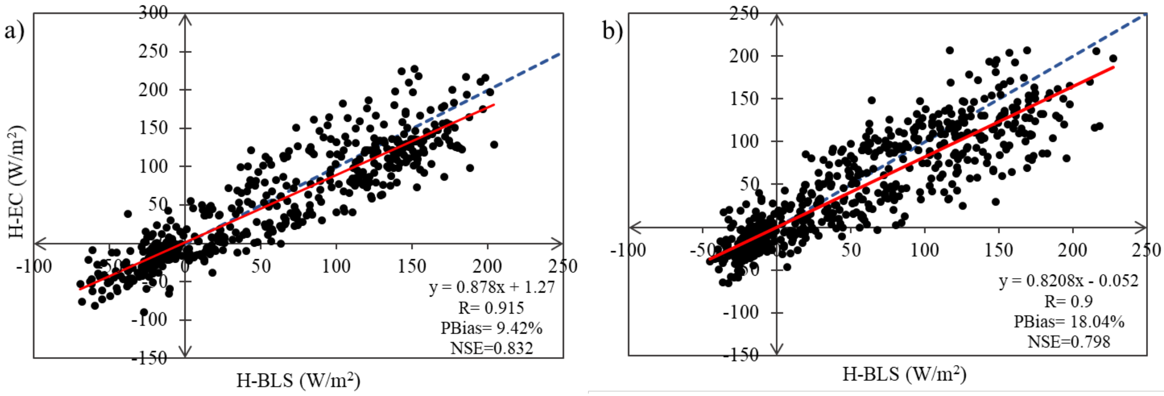

Figure 7:H-BLS and H-EC comparison when a) Wind direction was perpendicular to the BLS beam path, and when b) wind direction was not perpendicular with respect to the BLS beam path (Random wind direction), Each point is a 1-hour measurement. Note that the statistics shown in the figure represent the best fit line (line in red).

2. Wind speed analysis:

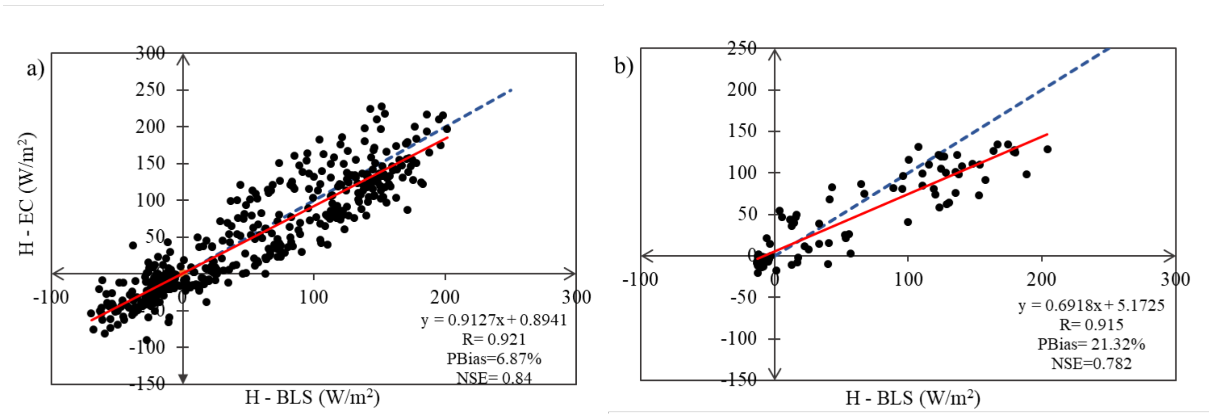

Figure 8: H-BLS and H-EC comparison when a) Wind speed was high, and when b) Wind speed was low, with perpendicular wind direction to the BLS beam path, each point is a 1-hour measurement. Note that the statistics shown in the figure represent the best fit line (line in red).

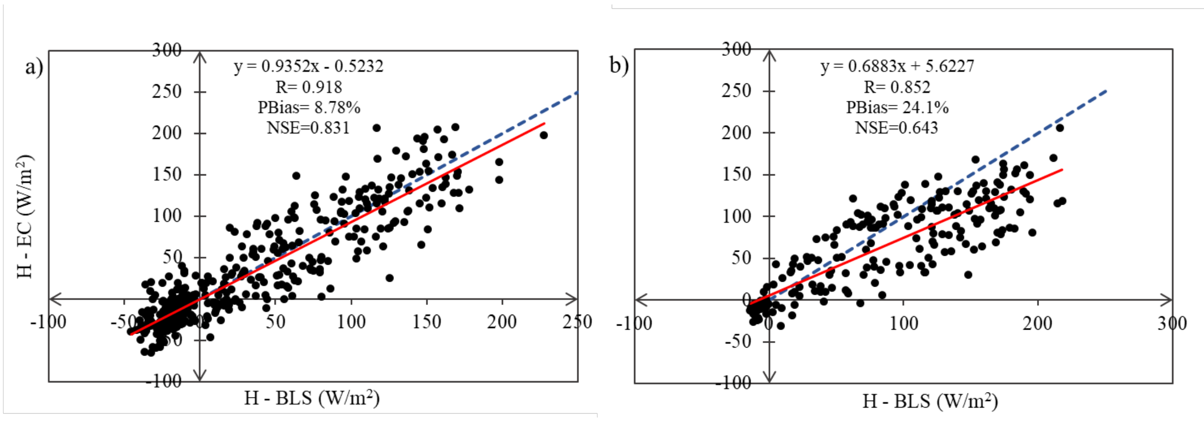

Figure 9: H-BLS and H-EC comparison when a) Wind speed was high, and when b) Wind speed was low, with random wind direction with respect to the BLS beam path, each point is a 1-hour measurement. Note that the statistics shown in the figure represent the best fit line (line in red).

E. Rainfall effect on sensible heat flux estimates.

Sensible heat flux estimates from the BLS and the EC systems were studied with respect to precipitation depth recorded by the BLS system. As shown in figure 10, H-BLS and H-EC values decreased during major rainfall events. Between 10/25/2020 and 10/30/2020 a major rainfall event occurred at the experimental site location and during this time the sensible heat flux recorded by both systems was low (ranging between -

32.15 and 31.6 (W/m^2) for the BLS system and between -35.3 and 26.3 (W/m^2) for the EC system. Two other major rainfall events occurred throughout the experiment and as it is shown in figure 10, a drop in the H-BLS and H-EC values was also recorded during that period (between 12/21/2020 and22/12/2020, and between 1/31/2021 and 2/2/202).

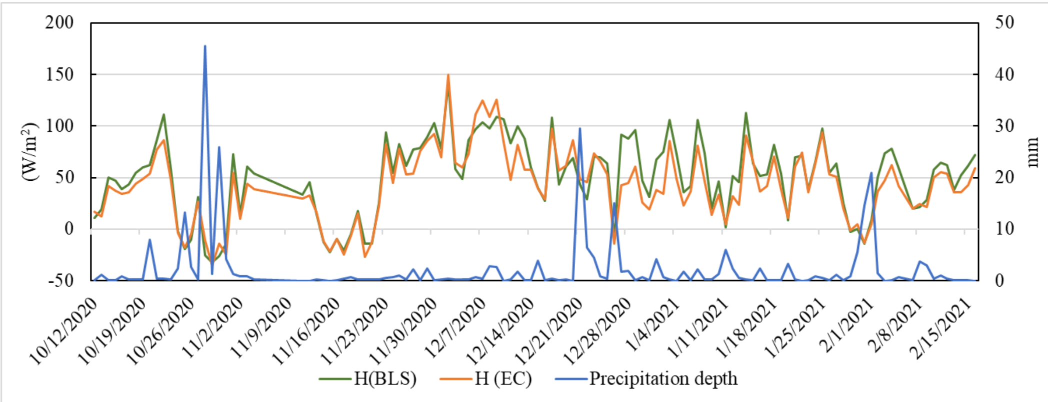

Figure 10: H-BLS, H-EC, and precipitation depth daily variations.

F. Effect of bare soil to leaves ratio on sensible heat flux estimates.

An NDVI timeseries of the field was estimated throughout this experiment using Sentinel 2 imagery (Main-Knorn, Pflug et al. 2017) (Figure 11). Based on the mean NDVI timeseries, we define two time periods: From 11 December 2020 until 10 January 2021 [lowest mean NDVI], and from 12 October until 10 December and from 11 January until 16 February [Higher mean NDVI values]. The first period where NDVI was low indicates higher bare soil to leaves ratio. When NDVI was low (Figure 12a), H-BLS and H-EC showed better agreement (R= 0.913, NSE=0.822) compared to high NDVI (Figure 12b) (R= 0.9, NSE= 0.8).

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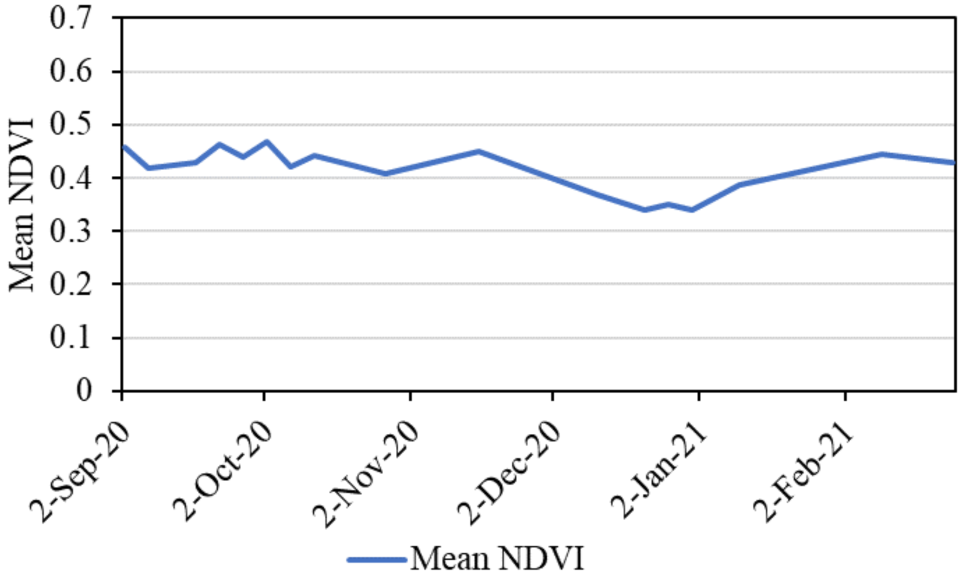

Figure 11: Mean NDVI variation with time over the experimental site.

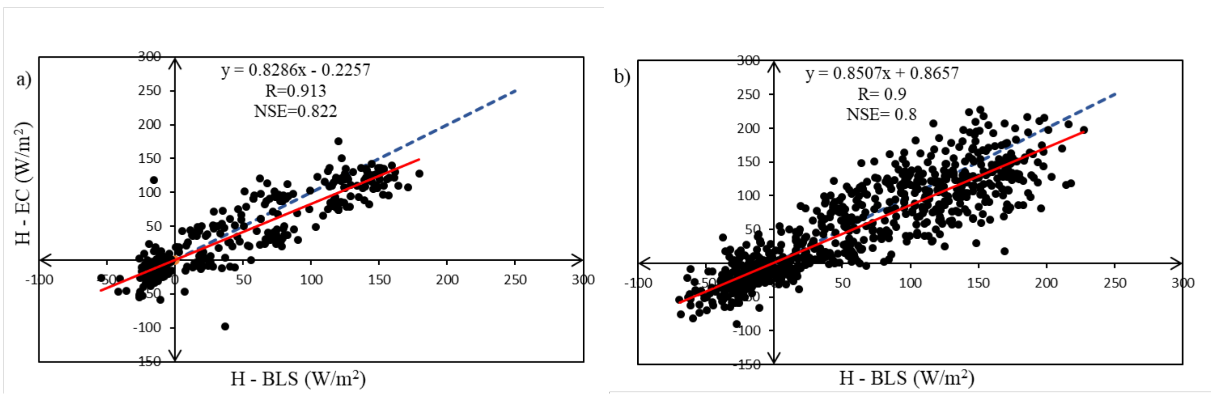

Figure 12: H-BLS vs H-EC comparison when a) NDVI was low, and when b) NDVI was high, each point is a 1-hour measurement. Note that the statistics shown in the figure represent the best fit line (line in red).

G. Latent heat flux comparison.

The comparison between LE-BLS and LE-EC is shown in the figure 13 and 14. Note that Rn-EC was used instead of Rn-BLS for the calculation of the hourly LE-BLS data. The Scatter plots show good correlation between LE-BLS and LE-EC for the daily, weekly, and monthly datasets having an R of 0.805, 0.903, and 0.923 respectively (Figure 13). The hourly data set had the lowest NSE coefficient (0.248) which kept on increasing to reach 0.809 in the monthly dataset comparison. (0.63 and 0.8 for daily and weekly dataset respectively). LE-BLS estimated throughout this experiment was higher than LE-EC by 4.99% (PBias =4.99%).

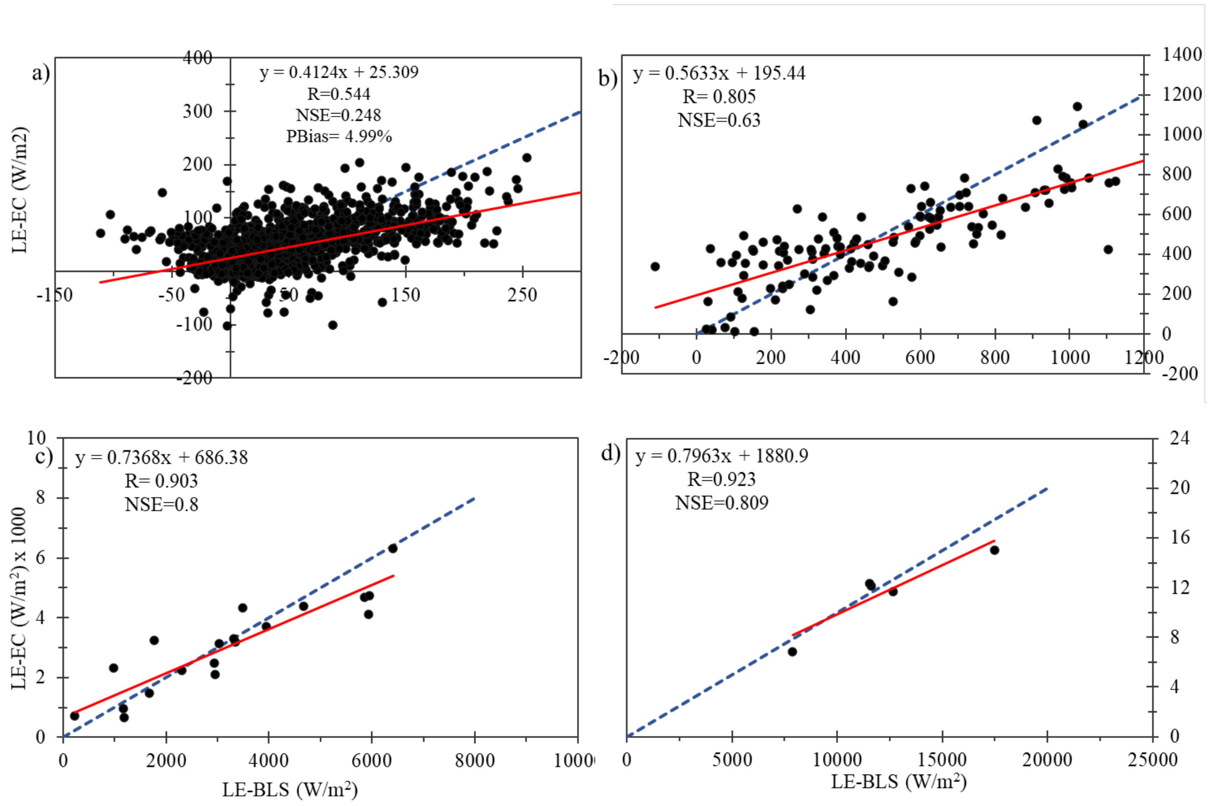

Figure 13:Comparison of a) Hourly, b) Daily, c) Weekly, and d) Monthly latent heat flux measured by EC and BLS systems. Note that the statistics shown in the figure represent the best fit line (line in red).

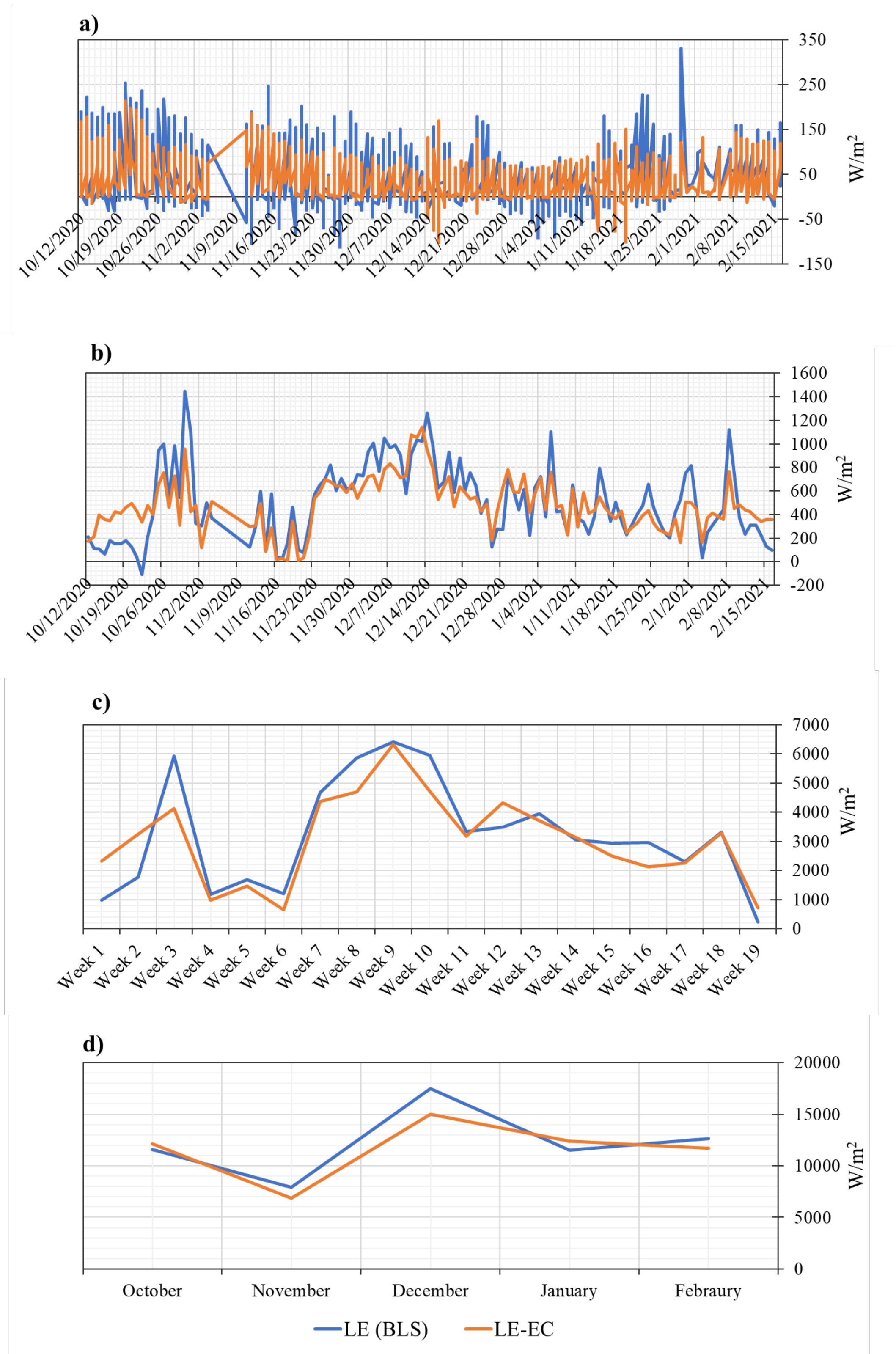

Figure 14: a) Hourly, b) Daily, c) Weekly, and d) Monthly Latent heat flux variation with time.

H. Evapotranspiration estimates comparison

According to figure 15, ET-BLS was the higher than ET-EC throughout this experiment. In fact, according to Table 2, the total cumulative ET-BLS recorded during this experiment was 97.53mm compared to 92.66 mm measure by the EC system.

EC recorded a cumulative ET of 19.41, 10.9, 23.95, 19.72, and 18.68 during October, November, December, January, and February and the BLS recorded a cumulative ET of 18.51, 12.58, 27.88, 18.39, and 20.18 mm for the same months (Table 2).

After comparing ET-EC with ET-BLS, we can notice that ET-BLS was higher by 5% (Table 2).

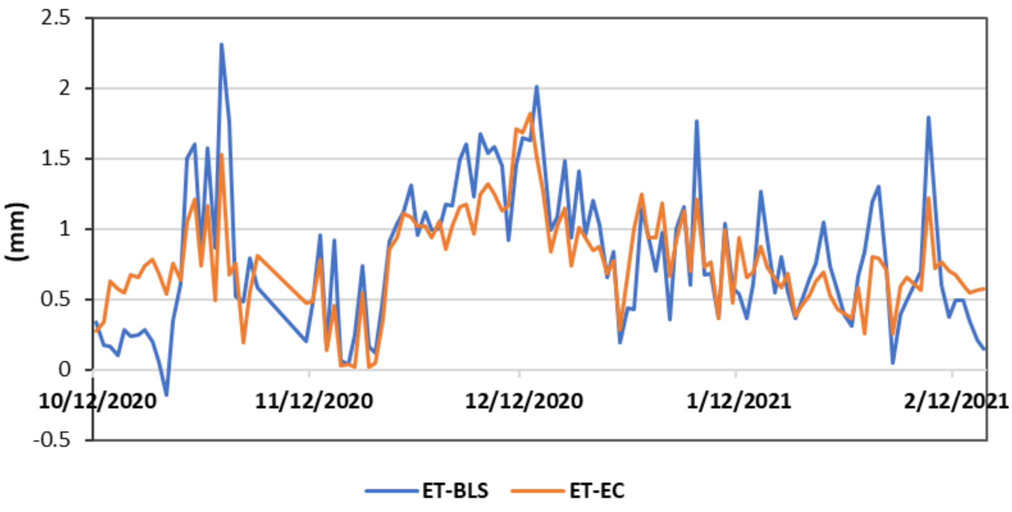

Figure 15: ET-BLS and ET-EC daily variations with time.

Table 2: ET-BLS vs ET-EC (Cumulative data).

Month	**ET-BLS (mm)**	**ET-EC (mm)**
October	18.51	19.41
November	12.58	10.90
December	27.88	23.95
January	18.39	19.72
February	20.18	18.68
SUM	**97.53**	**92.66**

CHAPTER V
DISCUSSION

A. Sensible heat flux

As presented in Chapter IV (Section A), H-EC and H-BLS showed good correlation with an R of 0.906 for hourly data, but H_{BLS} values were larger than H_{EC} values by 14.13% as also observed by Liu, Xu et al. (2011) (H-LAS larger than H-EC by 13%) who compared eddy covariance and Scintillometer measurements with respect to the energy balance closure problem and Valayamkunnath, Sridhar et al. (2018) (H-LAS lager than H-EC by 8-13%) who compared EC and Scintillometer data in a semiarid climate.

This difference can be caused by energy balance closure errors as also found by (Hoedjes, Chehbouni et al. 2007) or by errors in calibrated sensors.

The reasons of this difference between the Sensible heat fluxes measured by both systems were investigated by many researchers. Odhiambo and Ain (2011) found that wind direction and wind speed can also affect H agreements between EC and BLS equipment.

B. Surface energy balance closure error and its effect on sensible heat flux estimates

The Eddy Covariance tower showed a surface energy imbalance of 9.42% where (LE+H) were smaller than (RN-G) (Chapter IV – Section B).

Meijninger, Beyrich et al. (2006) studied Energy balance closure for EC in his experiment and found an energy imbalance of almost 30%, similar to Mauder, Liebethal et al. (2006). This difference in the surface energy balance closure may be caused by errors in measurement of Rn and G, by in turbulent fluxes from sonic anemometer, unaccounted energy loses, or inadequate accounting of other storage terms. Additionally, in this experiment we measured the soil heat flux using soil moisture and ground heat plates installed at a single point, so the ground heat flux storage estimated may not be representative of the study area (Yee, Pauwels et al. 2015).

H-BLS and H-EC showed better agreement when the energy balance ratio was smaller than 0.75. On the other hand, the percent bias between both datasets was smaller when EBR>0.75, (7.59% when EBR> 0.75, and 18.61% when EBR<0.75) (Chapter IV-Section C), which shows that the surface energy balance closure errors affect the sensible heat flux estimates measured by both systems. This result was also found by (Liu, Xu et al. 2011) who concluded that H-EC was underestimated compared to H-BLS especially for EBR<0.75.

C. Effect of wind speed/Direction on the sensible heat flux estimates.

For days when wind direction was perpendicular to the BLS beam path, the sensible heat fluxes measured by BLS and EC system showed better agreement compared to when wind direction was random, which is also the case when wind speed was high compared to when wind speed was low (Chapter IV– Section D). Similar results were observed by (Odhiambo and Ain 2011), who studied the effect of wind direction and wind speed on the sensible heat flux readings of an EC and a SLS system.

D. Effect of rainfall on the sensible heat flux.

As presented in chapter IV (section E), sensible heat flux estimated by the BLS and the EC systems decreased during major rainfall events as observed in figure 10. During a rainfall event the temperature of the canopy will be lower than air temperature which induces a downward flux of sensible heat causing sensible heat flux estimates to decrease. Similar relationship between sensible heat flux estimates and rainfall events were also observed by (Mizutani, Yamanoi et al. 1997), who studied sensible heat transfer measurement using eddy correlation method under rainfall conditions.

E. Effect of bare soil to leaves ratio on the sensible heat flux.

H-BLS and H-EC were compared when the mean NDVI over the vineyard was low, and when a higher mean NDVI in the experimental field location was recorded (Chapter IV, Section F). Better agreement was observed between H-BLS and H-EC during period of low NDVI with a higher R and NSE coefficients compared to high NDVI period. With a higher bare soil to leaves ratio (Low NDVI), transpiration in the field tend to decrease, so soil moisture will be more uniform across the field and the vegetation growth variability will decrease which result in a more homogeneous underlying surface leading to a better agreement between the sensible heat flux measured by the EC and the BLS system.

Geli, González-Piqueras et al. (2020) studied the effect of surface heterogeneity on scintillometer measurements and related the difference in the sensible heat fluxes measured by both systems to surface heterogeneity due to non-uniform soil moisture and plant growth variability.

F. Latent heat flux.

The comparison between the latent heat flux calculated using BLS 900 and the one measured by the EC showed weak correlation for the hourly dataset (Chapter IV-Section G). Additionally, LE-BLS was higher by 4.99% % compared to LE-EC.

Meijninger, Beyrich et al. (2006) compared latent heat fluxes estimated using scintillometer and eddy covariance equipment over a heterogeneous land. In their experiment Meijninger, Beyrich et al. (2006) found that the latent heat flux calculated by the scintillometer was higher by 26% compared to the LE-EC which is also the case for (Meijninger, Green et al. 2002) (overestimated by 8% only). Additionally, Yee, Pauwels et al. (2015) found a poor correlation between LE-EC and LE-BLS where LE-EC values were lower than LE-BLS.

There are several possible explanations for this result, in fact this difference may be due to the underestimation of LE by the EC system which has been previously observed by (Ward, Evans et al. 2015). This difference may be also caused by the energy balance closure error, or by discrepancies in the net radiation or in the ground heat flux measured throughout the experiment. The BLS 900 measures the sensible heat flux in addition to the net radiation and the ground heat flux and use these datasets to solve for LE following the surface energy balance equation, so any bias in the measurement of these two parameters can highly affect LE-BLS estimations.

G. Evapotranspiration

After comparing the different evapotranspiration estimates (ET-BLS, ET-EC) (Chapter IV, section H), we can notice ET-BLS was higher than ET-EC by 5%. This difference is caused by differences in sensible heat flux estimation between the EC and the BLS as it is affected by wind direction, wind speed, and energy balance closure error, in addition to difference in the source area of flux measurements and the heterogeneity of the underlying surface as found by (Liu, Xu et al. 2013).

E- Footrping analysis.

Vertical heat fluxes measured by scintillometers and Eddy covariance systems are affected by the footprint of each system and the homogeneity of its underlying surface (Valayamkunnath, Sridhar et al. 2018). Footprint's shape, size, and orientation are variable as they are affected by instruments height, BLS path length, wind speed, wind direction, surface conditions, and the atmospheric stability (Bai, Jia et al. 2015).

The source area of the eddy covariance tends along the prevailing wind direction. On the other hand, the source area of the scintillometer prolong along its path length and its exact shape depends on wind direction and speed at the experimental site, so usually scintillometers have a larger source area compared to eddy covariance systems (Liu, Xu et al. 2011).

In this experiment the BLS path length was 191 meters only, and the EC system was installed 20 meters away of BLS path (Figure 2). So, the footprints of both systems had similar land surface characteristics. Even when the prevailing wind direction was from the north, both systems footprints included an area from outside the vineyard in their source area, so the difference in the footprint area between both systems is not a major cause of the difference in the fluxes data estimated by both sensors.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

This study compared sensible and latent heat fluxes measurements derived from a boundary layer scintillometer and an eddy covariance system. A boundary layer scintillometer (BLS 900) from Scintec was installed along with an open path eddy covariance system from Campbell Scientific, in a vineyard at the premises of the American university of Beirut's agricultural research and education center "Arec" between October 2020 and February 2021.

Based on the results of this study, sensible heat flux estimates showed good correlation between both systems but H-EC was underestimated by 14.13% compared to H-BLS. This difference in the sensible heat flux estimates is caused by the surface energy balance closure errors, the effect of wind speed and wind direction, and the effect of bare soil to leaves ratio in the study area as H-BLS and H-EC showed a lower percent bias when the energy balance closure error was close to one, and a better agreement when wind direction was perpendicular to the BLS beam path, when wind speed was high (>1.49m/s), and when the mean NDVI over the vineyard was low; as during this period (low NDVI), the area under study in more homogeneous in terms of soil moisture and plant growth variability.

The effect of rainfall on the sensible heat fluxes estimated by both systems was also tested. The sensible heat fluxes measured by both systems dropped during rainfall events which is caused by a change in the temperature gradient inducing downward fluxes.

Latent heat flux estimates showed good agreement between both systems but LE-BLS was overestimated by 4.99% compared to LE-EC which could be caused by the energy balance closure error, or by discrepancies in the net radiation and ground heat flux measurements.

Evapotranspiration estimates were calculated by dividing the latent heat flux estimates by the latent heat of vaporization, so the same results presented for the latent heat flux estimates apply for the evapotranspiration readings.

A footprint analysis showed that the underlying surface of both systems are more or less homogeneous in this experiment, as the EC system was installed at a close distance from the BLS beam path which had a length of 191 meters only.

Finally, we can conclude that boundary layer scintillometer is a reliable system for measuring sensible heat flux in semi-arid climate. With availability of accurate measurements of ground heat flux and solar radiation, and a good experimental design, scintillometers can calculate accurate readings of latent heat flux and thus evapotranspiration.

BIBLIOGRAPHY

(2020). Easy Flux DL. C. SCintific.

Allen, R. G., et al. (2011). "Evapotranspiration information reporting: I. Factors governing measurement accuracy." Agricultural Water Management **98**(6): 899-920.

Asuero, A. G., et al. (2006). "The correlation coefficient: An overview." Critical reviews in analytical chemistry **36**(1): 41-59.

Bai, J., et al. (2015). "Characterizing the footprint of eddy covariance system and large aperture scintillometer measurements to validate satellite-based surface fluxes." **12**(5): 943-947.

Baldocchi, D. D. (2003). "Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future." Global change biology **9**(4): 479-492.

Baldocchi, D. D., et al. (1988). "Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods." Ecology **69**(5): 1331-1340.

Baldocchi, D. D., et al. (1997). "Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest." **83**(1-2): 147-170.

Baldocchi, D. J. G. c. b. (2014). "Measuring fluxes of trace gases and energy between ecosystems and the atmosphere–the state and future of the eddy covariance method." **20**(12): 3600-3609.

De Bruin, H., et al. (2005). "Regional advection perturbations in an irrigated desert (RAPID) experiment." Theoretical and applied climatology **80**(2): 143-152.

Eagleson, P. S. J. W. R. R. (1978). "Climate, soil, and vegetation: 1. Introduction to water balance dynamics." **14**(5): 705-712.

Geli, H. M., et al. (2020). "Effects of surface heterogeneity due to drip irrigation on scintillometer estimates of sensible, latent heat fluxes and evapotranspiration over vineyards." **12**(1): 81.

Geli, H. M., et al. (2012). "Scintillometer-based estimates of sensible heat flux using lidar-derived surface roughness." Journal of Hydrometeorology **13**(4): 1317-1331.

Hoedjes, J., et al. (2007). "Comparison of large aperture scintillometer and eddy covariance measurements: Can thermal infrared data be used to capture footprint-induced differences?" Journal of Hydrometeorology **8**(2): 144-159.

Jaafar, H., et al. (2017). "Determining water requirements of biblical hyssop using an ET-based drip irrigation system." **180**: 107-117.

Kolle, O. and C. Rebmann (2007). EddySoft: documentation of a software package to acquire and process eddy covariance data.

Kumar, A., et al. (2017). "Eddy covariance flux tower: a promising technique for greenhouse gases measurement." Adv Plant Agric Res **7**: 00263.

Lee, S.-H., et al. (2015). "Estimation of turbulent sensible heat and momentum fluxes over a heterogeneous urban area using a large aperture scintillometer." Advances in Atmospheric Sciences **32**(8): 1092-1105.

Liu, S., et al. (2013). "Measurements of evapotranspiration from eddy-covariance systems and large aperture scintillometers in the Hai River Basin, China." Journal of Hydrology **487**: 24-38.

Liu, S. M., et al. (2011). "A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem." Hydrology and Earth System Sciences **15**(4): 1291-1306.

Main-Knorn, M., et al. (2017). Sen2Cor for sentinel-2. Image and Signal Processing for Remote Sensing XXIII, International Society for Optics and Photonics.

Mauder, M. and T. Foken (2011). "Documentation and instruction manual of the eddy-covariance software package TK3."

Mauder, M., et al. (2006). "Processing and quality control of flux data during LITFASS-2003." Boundary-Layer Meteorology **121**(1): 67-88.

Meijninger, W., et al. (2006). "Scintillometer-based turbulent fluxes of sensible and latent heat over a heterogeneous land surface–a contribution to LITFASS-2003." Boundary-Layer Meteorology **121**(1): 89-110.

Meijninger, W., et al. (2002). "Determination of area-averaged water vapour fluxes with large aperture and radio wave scintillometers over a heterogeneous surface–Flevoland field experiment." Boundary-Layer Meteorology **105**(1): 63-83.

Meijninger, W., et al. (2002). "Determination of area-averaged sensible heat fluxes with a large aperture scintillometer over a heterogeneous surface–Flevoland field experiment." **105**(1): 37-62.

Meyers, T. P. and D. D. Baldocchi (2005). "Current micrometeorological flux methodologies with applications in agriculture." Micrometeorology in agricultural systems **47**: 381-396.

Mizutani, K., et al. (1997). "Applicability of the eddy correlation method to measure sensible heat transfer to forest under rainfall conditions." **86**(3-4): 193-203.

Moncrieff, J., et al. (1997). "A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide." **188**: 589-611.

Monteith, J. and M. Unsworth (2013). Principles of environmental physics: plants, animals, and the atmosphere, Academic Press.

Moorhead, J. E., et al. (2017). "Evaluation of sensible heat flux and evapotranspiration estimates using a surface layer scintillometer and a large weighing lysimeter." Sensors **17**(10): 2350.

Nash, J. E. and J. V. J. J. o. h. Sutcliffe (1970). "River flow forecasting through conceptual models part I—A discussion of principles." **10**(3): 282-290.

Odhiambo, G. and M. Savage (2009). "Sensible heat flux by surface layer scintillometry and eddy covariance over a mixed grassland community as affected by Bowen ratio and MOST formulations for unstable conditions." Journal of Hydrometeorology **10**(2): 479-492.

Odhiambo, G. O. and A. Ain (2011). Comparison of surface layer scintillometer and Eddy covariance footprint and sensible heat flux estimates for different wind directions. 2nd International Conference on Environmental Science and Technology.

Paulson, C. A. J. J. o. A. M. and Climatology (1970). "The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer." **9**(6): 857-861.

Scintec (2019). Boundary Layer Scintillometer: installation and operation manual.

Scintec (2020). Scintillometers: Theory manual.

Shaw, R. and R. Snyder (2003). Evaporation and eddy covariance, Marcel Dekker, New York**:** 235-237.

Tomlinson, S. A. (1996). "Comparison of Bowen-ratio, eddy-correlation, and weighing-lysimeter evapotranspiration for two sparse-canopy sites in eastern Washington." Water-Resour. Invest. Rep: 96-4081.

Twine, T. E., et al. (2000). "Correcting eddy-covariance flux underestimates over a grassland." Agricultural and forest meteorology **103**(3): 279-300.

Valayamkunnath, P., et al. (2018). "Intercomparison of surface energy fluxes, soil moisture, and evapotranspiration from eddy covariance, large-aperture scintillometer, and modeling across three ecosystems in a semiarid climate." Agricultural and forest meteorology **248**: 22-47.

Van Dijk, A., et al. (2004). "The principles of surface flux physics: theory, practice and description of the ECPACK library." **99**: 525.

Vickers, D. and L. Mahrt (1997). "Quality control and flux sampling problems for tower and aircraft data." Journal of atmospheric and oceanic technology **14**(3): 512-526.

Wang, K., et al. (2013). "Comparison between eddy covariance and automatic chamber techniques for measuring net ecosystem exchange of carbon dioxide in cotton and wheat fields." Biogeosciences **10**(11): 6865-6877.

Ward, H., et al. (2015). "Infrared and millimetre-wave scintillometry in the suburban environment–Part 2: Large-area sensible and latent heat fluxes." Atmospheric Measurement Techniques **8**(3): 1407-1424.

Water, U. (2018). "2018 UN World Water Development Report, Nature-based Solutions for Water."

Webb, E. K. J. Q. J. o. t. R. M. S. (1970). "Profile relationships: The log-linear range, and extension to strong stability." **96**(407): 67-90.

Wesely, M. L. J. J. o. A. M. (1976). "The combined effect of temperature and humidity fluctuations on refractive index." **15**(1): 43-49.

Wilson, K., et al. (2002). "Energy balance closure at FLUXNET sites." Agricultural and forest meteorology **113**(1-4): 223-243.

Yapo, P. O., et al. (1996). "Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data." **181**(1-4): 23-48.

Yee, M. S., et al. (2015). "A comparison of optical and microwave scintillometers with eddy covariance derived surface heat fluxes." Agricultural and forest meteorology **213**: 226-239.

Rn_{EC} was used instead of Rn_{BLS} in LE_{BLS} calculations

G_{EC} was used instead of G_{BLS} in LE_{BLS} calculations