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Comparison of sensible heat flux measured by large aperture scintillometer and eddy covariance in a seasonally-inundated wetland

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ABSTRACT

The eddy covariance (EC) technique has been widely used to measure ecosystem surface energy fluxes. However, with a relatively small representative area (footprint), errors are often introduced when upscaling EC data based on variables derived from large-footprint satellite products. Furthermore, EC measurements often fail to close the energy balance in ecosystems such as wetlands. As an alternative to EC, large aperture scintillometers (LAS) have been used to measure sensible heat fluxes (H) over representative areas comparable to the resolution of large-scale satellite images. However, because LAS measurements are based on semi-empirical simulations, their accuracy needs further evaluation across ecosystems. Changes in hydrology on the land surface significantly alter measurement conditions as well as the processes of energy transfer, and thus, may affect the accuracy of energy measurements from LAS. To address this issue, we compared the LAS-measured H (H_{LAS}) to EC-derived H (H_{EC}) in a seasonally inundated wetland within Everglades National Park. Overall, the H_{LAS} was 7.1 ± 0.3 (SE) % greater than H_{EC}, and the ratio of H_{LAS} to H_{EC} remained similar between the wet season, when the ecosystem was inundated, and the dry season. However, inundation, as a thermal buffer in the system, reduced the magnitude of H in the wet season and resulted in a smaller difference of seasonal H budget estimates between LAS and EC measurements. Because of the homogenous land surface at our site, the discrepancies between H_{LAS} and H_{EC} could not be explained by footprint mismatch. Compared to the energy balance closure calculated with H_{EC}, the closure calculated with H_{LAS} was improved by 6% during the dry season but remained similar during the wet season. Overall, we conclude that LAS can be a reliable approach to measure H in wetland ecosystems and its measurements were stable with seasonal hydrological changes.

1. Introduction

Ecosystem turbulent surface energy fluxes, sensible heat flux (H) and latent heat flux (LE), are important processes that strongly affect ecosystem function. To measure turbulent surface energy fluxes, the eddy covariance (EC) technique has been widely used in many ecosystems such as forests (e.g. Ikawa et al., 2015), grasslands (e.g. Wever et al., 2002) and wetlands (e.g. Malone et al., 2014a; Peichl et al., 2013). However, incoming radiative energy to an ecosystem is often not balanced by energy losses measured by EC and associated micrometeorological instruments (Wilson et al., 2002). These energy discrepancies are mainly caused by: 1) a mismatch of source area (footprint) between energy budget terms, 2) systematic bias in instrumentation and 3) technical limitations that fail to measure certain contributions to energy transfer (e.g. low and high frequency loss of turbulent fluxes, energy storage, heat advection, etc.) (Cava et al., 2008; Foken, 2008; Wilson et al., 2002).

Furthermore, fluxes measured by EC in many ecosystems, such as wetlands, grasslands and croplands, etc., usually represent a relatively small area, which strongly varies with wind direction and speed. When upscaling EC data based on variables derived from large-footprint satellite products such as Advanced Very High Resolution Radiometer (AVHRR), errors may be introduced due to a mismatch of the footprint scales between the EC measurements and satellite products (Jung et al., 2011). Therefore, there is an increasing need to develop ground-based methods to measure surface energy fluxes accurately over larger spatial scales that are comparable to the pixel size of satellite images.

As an alternative to EC, the large aperture scintillometer (LAS) can be used to measure H based on the semi-empirical Monin-Obukhov similarity theory (Chehbouni et al., 2000; De Bruin et al., 1993; Hill

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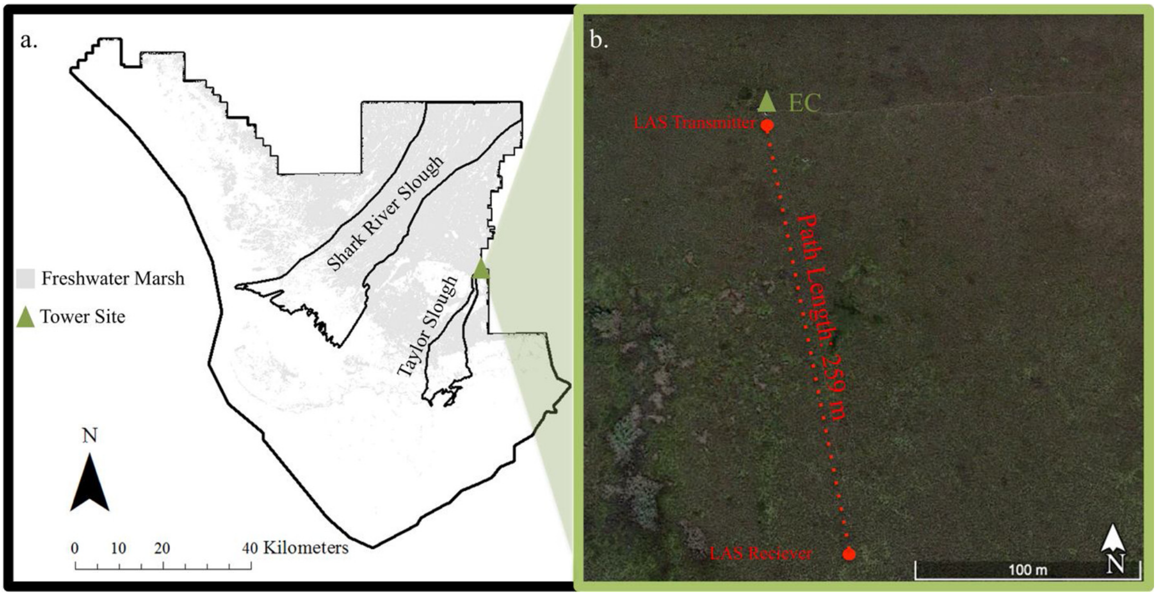

Fig. 1. Location of freshwater marsh study site in the Everglades (a) and layout of the eddy covariance tower (EC), the large aperture scintillometer (LAS) transmitter and receiver at the site (b).

et al., 1980). The LAS system measures the amount of scintillations in the infrared at 880 nm wavelength in terms of the optical turbulence structure parameter of the refractive index of air (C_N^2). The H is then derived from C_N^2 with other corresponding meteorological variables (e.g. air temperature, wind speed, etc.). The advantage of LAS is that it provides average H along a horizontal path, typically with a distance of a few hundred meters to 12 km, a scale that is comparable to the pixels from satellite images such as Moderate Resolution Imaging Spectroradiometer (MODIS) or AVHRR (Bai et al., 2015; Tang et al., 2011). With a fixed measurement path between the transmitter and receiver, the footprint of LAS measurements is less variable compared to that of EC measurements. At the same time, with a different theoretical basis from that of EC, LAS may overcome some of the limitations of EC. For example, Von Randow et al. (2008) found LAS is able to sample more eddies, especially those with lower frequency, than EC in the same time interval, and thus, may result in a better ecosystem energy closure. However, since the LAS measurements are based on semi-empirical simulations, their accuracy still needs further evaluation across ecosystems that differ in land surface and environmental conditions.

To date, LAS has been applied to measure H in a range of sites, including forests (Von Randow et al., 2008), grasslands (Kleissl et al., 2008), agricultural lands (Kleissl et al., 2009; Meijninger et al., 2002), deserts (Xu et al., 2013; Zeweldi et al., 2010) and other complex terrain (Chehbouni et al., 2000; Liu et al., 2011). Previous studies have also measured H using LAS over water surfaces in coastal areas (Lee et al., 2015; Lee, 2015); however, without validating the outputs with other methods, the accuracy of LAS measurements over water surfaces is still uncertain and establishes a need for additional studies.

Wetlands represent a land surface that varies significantly in hydrological conditions. Changes in hydrology, e.g. seasonal inundation, may significantly alter measurement conditions as well as the processes of energy transfer, and thus may affect the accuracy of energy measurements from LAS. Therefore, it is important to consider the variability in water conditions when evaluating H derived from LAS, especially in wetlands.

Despite some drawbacks, the EC technique is still considered to be the most appropriate and reliable approach for H measurements, especially over homogenous surfaces (Alekseychik et al., 2017; Jung et al., 2011). In this study, we compared the sensible heat flux measured by LAS with the measurements from a nearby EC system in a seasonally-inundated wetland over a three-year period (2013–2015) to answer the following questions: 1) are sensible heat flux measurements from LAS comparable to EC measurements under different hydrological conditions (i.e. inundated vs non-inundated)? 2) what factors influence the measurement differences between LAS and EC? 3) does the LAS-measured H improve the energy balance closure compared to H measured by EC? The results provide insights for utilizing LAS measurements in wetland ecosystems while potentially reducing uncertainties in the energy balance of the ecosystem.

2. Methods and materials

2.1. Site description

This study was carried out at a short-hydroperiod freshwater marsh (25°26' N, 80°35' W) within the Taylor Slough region on the eastern edge of Everglades National Park from January 1, 2015–December 31, 2017. The site is co-located with the Florida Coastal Everglades long-term ecological research (FCE-LTER) program site TS/Ph1B. The vegetation is dominated by sawgrass (*Cladium jamaicense* Crantz) and muhly grass (*Muhlenbergia filipes* M.A. Curtis) with an average canopy height of ~0.73 m and a leaf area index (live + dead) of ~1.8 (Schedlbauer et al., 2010). The site is generally homogenous and flat. Annual mean temperature is 23.9 °C and precipitation is on average 1380 mm annually, with ~70% of rainfall occurring from June to November (Davis and Ogden, 1994). The water inputs into the ecosystem are controlled by a combination of precipitation and active water management through a complex system of levees and canals. As a result, the study area is usually inundated for 4–6 months during the wet season (~May–October) with water levels 20–30 cm above soil surface, while water levels stay below the soil surface for the remaining months (~November–April) (Malone et al., 2014b; Schedlbauer et al., 2010). In this study, we define the wet season as the period when the site was continually inundated and the dry season as the period without inundation.

2.2. Instrumentation

A LAS system (LAS 150, Kipp & Zonen Inc., Delft, Netherland) was installed to measure the sensible heat flux at the study site in December 2012. It has a 259 m path length between the transmitter and receiver oriented roughly from north to south (Fig. 1). This path length met the