Reply

We thank the reviewer for his/her time to provide us feedback on our study. We copied the blue the referee's comment and in black our reply.

This paper attempts to describe the formation process of vapor plumes in a tropical forest environment due to evaporation processes happening during rain events. This phenomenon is quite interesting and probably contributes to water cycling in tropical wet forests. However, I do have substantial doubts about the scientific quality and the overall rationale of the study. The various reasons are outlined below:

1. Scientific objectives / rationale: To my opinion, the scientific objective and the conclusions about the identification of visible vapor plumes in a Tropical Wet Forest are relatively weak and the measurement setup is not suitable to derive reliable evaporation estimates during these events. If any observer (or any camera) can identify the vapour plumes above the tropical forest what is the novelty of this paper? What is the contribution to the scientific knowledge about water cycling in the tropics? One scientific objective could have been to estimate the contribution of these vapour plumes to the total annual evapotranspiration (ET) flux in these environments. To achieve this, more sophisticated measurements (e.g., 3D wind components) and a detailed literature study comparing the magnitude of evaporation fluxes from vapor plumes at this site in Costa Rica to ET fluxes measured by eddy covariance at other comparable tropical sites (e.g. Puerto Rico, Amazon Basin) should have been performed (Holwerda et al., 2012; Paca et al., 2019). In addition, a modelling exercise using remote sensing data (i.e. land surface temperature) would probably have been feasible. However, the authors did not attempt to investigate the role of these plumes for the hydrological cycle.

Reply:

We understand there is some confusion on the objective of our study. Our objective is not to quantify the contribution of vapor plumes to total evaporation. This would -as the reviewer correctly mentions- require a totally different setup. The objective of our study is more preliminary and is twofold: 1) to identify vapor plumes and 2) to explain when and why these plumes occur using meteorological data.

The formation of visible vapor plumes is commonly known to happen after rain events (Page 2, line 21), but the specific conditions of how they form, has not been scientifically described yet. A detailed description of when this commonly known phenomenon occurs, and how it links to local hydrology at site level will help to understand different offsets in other processes such as interception of precipitation. Moreover, there is a lack of techniques that are able “to characterize the occurrence of these plumes close to the surface” (Page 2, line 22), and this manuscript provides a procedure that may be used to recognize the meteorological conditions needed for the formation of these visible vapor plumes.

We think understanding this is a pre-requisite before we are able to quantify such a complex process as vapor plumes. Additionally, although we would have loved to quantify the vapor contribution to total evaporation, the difficulty lies into the circumstances vapor plumes form. Visible vapor plumes that we studied, happen during rainy days and under these conditions (continuous rain events) the performance of more sophisticated instruments is compromised (Centre for Atmospheric Science, 2020). Instruments such as sonic anemometers (e.g., CSAT3, CSAT3B) and Open Path CO2/H2O Analyzers (e.g., LI-7500) are strongly affected by high humidity and rainfall (Campbell Scientific Inc., 2017, 2019, Foken et al., 2012b, LI-COR, 2016, Moncrieff et al., 2005). The presence of rain causes departures from the measurements increasing the sonic speed (Camuffo 2019, Kelton and Bricout, 1964, Peters et al., 1998) or blocking the face of the transducers (Campbell Scientific Inc., 207, 2017) causing a frequency loss during rain events (Zhang et al., 2016). These conditions trigger the need to screen the data and filter the rain events to remove poor-quality data (Mauder and Zeeman, 2018) requiring complex gap filling procedures afterwards (Moncrieff et al.,2005).

Also using remote sensing data would not be feasible since land surface temperature products have a too coarse spatial (e.g., Landsat: 60 m, MODIS: ~1 km, Aster: 90 m) and temporal resolution (e.g., Landsat: 16 days, MODIS: twice daily, Aster: twice daily). While vapor plumes occur in time windows that last minutes and cover small areas around the forest.

To the contrary, conventional measuring devices for temperature and relative humidity (e.g., HOBO sensors) are reliable when installed with multi-plate plastic shelters, registering a deviation of just 1.6 % from the mean temperature of the fully ventilated sensors under tropical conditions during sunny days (da Cunha, 2015). Meanwhile, during rainy days and night-time conditions, conventional air temperature sensors have low biases when compare against active ventilated sensors

(Terando et al., 2017). Also, measuring devices based on 3D wind components (e.g., eddy-covariance systems) are developed to measure water in gas form (Foken et al., 2012a) and are not intended to measure vapor plumes that are ascending clusters of tiny water particles (Spellman, 2012). Therefore, we decided to use conventional meteorological instruments to study vapor plumes.

To clarify to the reader why we did not quantify the contribution of vapor plumes, we will add the reasoning, as described above. Consequently, we proposed the following changes to the manuscript follows:

Add to the introduction in page 2, line 23:

> "… to the surface. Visible vapor plumes are classified as ascending clouds formed by clusters of tiny particles of water in liquid form (Spellman, 2012). This characteristic makes difficult to measure them with sophisticated systems based on 3D wind components (e.g., eddy-covariance systems) that are developed to measure water in gas form (Foken et al., 2012a). This type of measurements are sensitive to rainy and high humidity conditions (Camuffo 2019, Foken et al., 2012b, Kelton and Bricout, 1964, Moncrieff et al., 2005, Mauder and Zeeman, 2018, Peters et al., 1998) making difficult to use them to identify the occurrence of visible vapor plumes in forested ecosystems. This mismatch between measurement systems and target phenomena, underlines the need to identify the conditions under which visible vapor plumes are formed. This type of methodological constraints requires an innovative data analysis approach, which is the focus of this paper."

Improve the manuscript aims as follows:

> "This work aims (1) to test an innovative approach to link visual information and conventional meteorological data describing a local hydrological phenomenon. Also, (2) to identify the meteorological conditions when visible vapor plumes are present in a Tropical Wet Forest, and it tries (3) to explain the processes involve on the formation of these visible vapor plumes. The data analysis is based on conventional meteorological data vertically distributed along the forest canopy layer and time-lapse videos during day-time conditions."

Add in Page 3, line 19:

> "… H21-USB). Meteorological data collected along the tower and soil temperature data were recorded with 1 min and 5 min averages, respectively. All data was summarized in 5 min time intervals for the analysis. A Bushnell® … "

2. Experimental setup: According to the paper, the vertical air temperature profiles using the Hobo sensors were not actively aspirated, which, however, should be the case to achieve sufficient accuracy when measuring vertical air temperature profiles.

Reply:

It is true that the sensors were not actively aspirated. However, the use of the radiation shields together with HOBO air temperature sensors allows keeping the mean absolute error during day time below 0.3 ºC (da Cunha, 2015, Terando et al., 2017) in warm tropical ecosystems. In addition, the measurement of minimum or night-time temperatures does not require the cover of the radiation shield to keep low biases on the mean temperature (<0.5 ºC) due to the reduced or total absence of solar radiation (Terando et al., 2017). Also, the shelter provided by the forest canopy for the measurements carried out at 2 m helps to record similar temperatures to the surrounding near-surface environment (Lundquist & Huggett, 2008).

We added this explanation to the manuscript in Page 3, line 14 as follows:

> "The use of radiation shields together with conventional air temperature sensors allows keeping a mean absolute error during day time in warm tropical ecosystems below 0.3 ºC (da Cunha, 2015, Terando et al., 2017). Also, the shelter provided by the forest canopy for the measurements carried out at 2 m helps to record similar temperatures to the surrounding near-surface environment (Lundquist & Huggett, 2008). Meanwhile, the measurement of minimum air temperatures or night-time temperatures does not require the cover of the radiation shield to keep low biases (<0.5 ºC) on the mean air temperature due to the reduced or total absence of solar radiation (Terando et al., 2017)."

Additionally, wind speed measurements were apparently entirely lacking (or were made at 10m height only, according to Jiménez-Rodríguez et al., 2020). For this type of analysis, a vertical wind speed profile within and above the canopy or 3D wind components should be measured.

Reply:

We agree that measurements of a 3D sonic anemometer would have been better under normal circumstances. However, we study the temperature gradients under humid conditions and highly rainy conditions, where sonic anemometers often have their limitations (Camuffo 2019, Foken et al., 2012b, Kelton and Bricout, 1964, Moncrieff et al., 2005, Mauder and Zeeman, 2018, Peters et al., 1998). Also, the main analysis is based on temperature gradients, where vertical wind speed measurements are not required as the reviewer mentions.

The authors propose to improve the following sentences to clarify this:

Add in Page 6, line 10:

> "… gradient $\left(\frac{\Delta\theta}{\Delta z}\right)$ due the absence of wind profile measurements to determine the atmospheric stability parameter along the tower. Values of …"

Add the reference (Stull, 2017) in page 6, line 11.

And specify some details of data collection adding this in Page 3, line 19:

> "… H21-USB). Meteorological data collected along the tower and soil temperature data were recorded with 1 min and 5 min averages, respectively. All data was summarized in 5 min time intervals for the analysis. A Bushnell® … "

3. Methodology: According to my understanding, the method used to calculate the evaporation flux within and above the forest canopy violates fundamental micrometeorological theory. The energy balance (EB) equation was used to derive evaporation within and above the canopy according to Jiménez-Rodríguez et al., 2020, although none of the EB components were directly measured in the field.

Reply:

The method used to calculate evaporation is based on the Energy Balance Method as it is described in detail by Jiménez-Rodríguez *et al*. (2020). It was not possible to measure directly the different components of the energy balance method due to constraints of instrumentation availability for a trial study. However, our aim was also not to exactly quantify evaporation. We just used the estimated evaporation by Jiménez-Rodríguez *et al*. (2020) as a proxy.

Aiming to prevent any confusion between the manuscript objectives and the source of evaporation data, we propose the following:

Eliminate equation 8 and the information contained in page 6 between the lines 18 and 23. Adding the following text instead:

> "An estimation of the evaporation during the monitored period was retrieved from Jiménez-Rodríguez *et al.* (2020). This estimation was just used as a proxy and is based on the vertical transport and neglects the advected energy on the forest canopy and is used as a reference of the evaporation process during the monitoring period."

Change the caption of table 1 as follows:

> "Table 1. Daily summary of precipitation and evaporation at 43 m, 8 m and 2 m height according to Jiménez-Rodríguez *et al.* (2020) for the experimental site during the monitoring period."

Modify the caption of Figure 3 as follows:

"Figure 3. Virtual potential temperature (ϑ_v), lifting condensation level (z_{lcl}) in an untransformed semi–logarithmic scale, and temperature gradient $\left(\frac{\Delta\theta}{\Delta z}\right)$ at 43 m, 8 m and 2 m height. Additionally, precipitation (P) and soil moisture (Θ) are also shown during the visual monitoring between 2018-03-21 and 2018-03-25. Evaporation (*E*) measurements were retrieved from Jimenez-Rodriguez, *et al.* (2020). Background colored areas denoted the three categories in which the photographs were classified: Clear View, Mist and Plumes."

Add the reference (Jiménez-Rodríguez *et al.,* 2020) in page 7, line 11.

The term in the energy balance equation refers to evapotranspiration, which also includes transpiration. How can it be justified that transpiration was indeed zero under these conditions?

Reply:

The authors consider important to highlight the evaporation definition used in this manuscript (Page 1, line 13). We used the term forest evaporation as the "*mixture of water vapor originated from water intercepted on plant surfaces, soil water and plant transpiration (Roberts, 1999; Savenije, 2004; Shuttleworth, 1993)*". Consequently, we included all water vapor sources that originated the measured evaporation. Also, the authors never considered the transpiration to be zero, instead we mentioned that transpiration "*is likely reduced by the low vapor pressure deficit*" (Page 11, line 5) but not stopped (this manuscript). Also, the evaporation data was retrieved from Jiménez-Rodríguez *et al.* (2020) who mentioned that 44.2 % of the evaporated precipitation corresponds to canopy transpiration and the accumulation of 29.4% of the leaf area index increases the potential sources of transpiration. Moreover, we propose that the main source of water vapor feeding the formation of vapor plumes is linked to the evaporation of intercepted water in plant surfaces on the canopy depressions due to two reasons:

1. the splash droplet evaporation process does not need extra energy to occur,
2. the low leaf area index of the canopy depressions can be translated into a reduced contribution of transpiration to the formation of vapor plumes,
3. the canopy depressions allow a free vertical path for the water vapor to ascend and from the buoyant cloud after reducing its potential air temperature.

The authors propose to add the following to clarify the source of water vapor for the formation of vapor plumes:

Add in Page 8, line 1:

"… soil moisture. These days were characterized by cumulus clouds crossing the sky above the forest canopy in day time. Any water vapor ascending from the forest canopy will need to reach a height of more than 100 m to form visible vapor plumes (Figure 3). Also, on …"

Add in Page 8, line 26:

"The visible vapor plumes can be spotted on the canopy depressions surrounding the tower (Figure 1). These depressions are characterized by a low leaf area index and shorter canopy height, which translates into areas with low potential to produce transpiration during rain events. This implies that the main source of water vapor is linked to water evaporated from wet surfaces and soil evaporation, while transpiration may contributes to a lesser extent."

Add in Page 8, line 32:

"… As plumes are not stagnant and continue moving upwards thanks to air convection, the water vapor is removed from the understory towards higher altitudes. The water condensation at the canopy level drastically reduced the volume of water vapor due to the phase change (Makarieva et al., 2013). This allowed the ambient air to remain unsaturated and keeping the "splash droplet evaporation" process providing continuously more water vapor. "

The calculation of net radiation (Rn) components within the canopy is quite complex due to multiple extinction processes. Applying the equations give in the appendix of Jiménez-Rodríguez et al., 2020 does not seem to be reasonable to derive an in-canopy profile of Rn. Furthermore, the sensible heat flux within and above the canopy was calculated by applying flux-profile relationships, which involves estimation of the aerodynamic resistance. Flux-profile relationships are typically expressed by formulations based on-the Monin-Obukhov similarity (MOST) theory within the lowest 10% of the atmospheric boundary layer where exchange fluxes are considered to be constant with height. According to MOST, the aerodynamic resistance can only be calculated in cases when a logarithmic profile of the horizontal wind speed is present (Thom, 1975; Foken, 2017) - typically some meters above the canopy. Hence, the equations applied inside the canopy are invalid. Moreover, wind speed measurements are required to derive the aerodynamic resistance. As atmospheric turbulence is random, the use of parameterizations based on ancient wind speed measurements is not feasible. Due to these fundamental aspects, the numbers provided in the paper are only a crude approximation and do not provide a basis to derive a solid scientific conclusion.

Reply:

We agree that our evaporation estimates are not precise. As said before, we use the evaporation estimates just as a proxy. However, our main analysis focuses on the vapor plumes formation. This process is based on the virtual potential air temperature (Θ_v), lifting condensation level (Z_{lcl}), and temperature gradient $\left(\frac{\Delta\theta_v}{\Delta z}\right)$ that are estimated based on the continuous measurements of air temperature, soil temperature, and air humidity. None of these variables were estimated from old data or based on approximations but were all measured at the site during the study period. Also, the estimation of these variables (equations 1 to 7) does not depend on the aerodynamic resistance. This issue of the aerodynamic resistance applies only to the estimation of evaporation carried out in other paper used as a source of information (Page 6, line 21). We clarified in the manuscript that evaporation is only used as an indication and that our analysis focused on the temperature gradients that are not making use of MOST-assumptions. It is important to acknowledge the need for more studies focusing on this process now that the main elements of the formation of visible vapor plumes were identified in this paper. These studies should focus on (1) the quantification of the water vapor linked to the visible plumes, (2) the frequency of occurrence in a yearly basis in tropical and non-tropical regions, and (3) improve the identification procedure of visible vapor plumes through more detailed monitoring processes. Consequently, we recommend to:

Add in Page 10, line 20:

> "The description of the formation process of visible vapor plumes provides a first step on the understanding of this phenomenon within forest hydrology. This description helps to identify the timing when this phenomenon occurs, allowing to screen existing data sets in other tropical research sites to analyze its frequency of occurrence. However, is important to test if the conditions required to form visible vapor plumes are the same in other latitudes and ecosystems. Also, new developments in air temperature monitoring techniques such as distributed temperature sensing (Euser *et al*., 2014; Heusinkveld *et al*., 2020; Izett *et al*., 2019; Schilperoort *et al*., 2018) or thermal infrared imagery (Costa *et al.,* 2019, Egea *et al.*, 2017, Nieto *et al.,* 2020, Lapidot *et al*., 2019) may contribute to accurately quantify the contribution of visible vapor plumes as local recyclers of forest evaporation. These methods are suitable alternatives to eddy-covariance systems that are sensitive to rainy conditions when visible vapor plumes occur."

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