Many thanks for handling the review process for our manuscript. The time and effort devoted to our manuscript by you and the reviewers are very much appreciated.

We have revised the manuscript carefully according to the reviewers' comments and suggestions. In the following, we provide a point-by-point response. The original reviewer comments are in black regular font. Our responses are shown in blue italic font. Quotes from the revised paper are shown in blue bold-face font. Additionally, there are a number of small grammatical and wording changes throughout the manuscript that are not specifically documented below.

REVIEWER COMMENTS

Reviewer (Raquel González Armas and Jordi Vilà-Guerau de Arellano):

1. Although the processes of entrainment and boundary layer growth is acknowledged throughout the paper, we have the feeling that is played down in the research. We realized that with a surface data set is difficult to quantify, although the mixed-layer diagrams proposed by Santanello et al. (2009) could be an adequate tool to further quantify the relevance of entrainment of warm and dry air at the different sites. Could the authors elaborate and quantify more regarding the role of entrainment?

   ➔ *The role of atmospheric entrainment in the mixing diagrams, especially for the atmospheric components, introduces drier air with higher potential temperature at the top of the growing boundary layer. The impact is strongest from 7 AM to about noon while the boundary layer is growing. Its contribution is diminished during the afternoon since boundary layer growth slows and radiative cooling of the warmer air leads to a negative tendency of thermal energy, which becomes dominant at night. On the other hand, the sensitivity is not very different over the water- and energy-limited regimes despite the large discrepancy in the boundary layer depth. These descriptions is added in Lines 521-523 and 541-543:*

   "Although the effect of atmospheric entrainment continues until continues until dissipation of the daytime boundary layer around sunset, it is obscured by the other contributions after noon."

   "Despite the PBL in water–limited regimes being about twice as deep as for energy-limited regimes, with accompanying stronger entrainment, the impact of the atmospheric entrainment over both climate regimes is similar, resulting in a positive temperature and a negative moisture tendency from 7 AM to the noon."

2. Closely connected to this, we miss key references at the introduction that can help the reader to position this research with respect to research that have already dealt with the relevance of processes happening at the sub-daily scales. For instance, Ek et al. (J. Hydro meteorology. 5, 86–99, 2004) and van Heerwaarden et al (Quarterly Journal of the Royal Meteorological Society 135, 1277-1291, 2009). Could the authors introduce these or similar references in the introduction?

   ➔ *We have added the suggested key references to address the impact of sub-daily land-atmosphere interactions on the boundary layer development using the coupled model simulation. Ek and Holtslag (2004) highlighted the influence of land surface condition (e.g., soil moisture) on the development of the boundary layer cloud and Van Heerwaarden et al. (2009) addressed the effect of dry-air entrainment on surface evaporation and the convective boundary layer. These previous studies commonly focused on the daytime land-atmosphere feedback mechanisms. This description is added in Lines 70-73:*

"In addition, the influence of soil moisture on the boundary layer cloud development has been demonstrated for the coupled L–A system with realistic daytime surface fluxes and atmospheric profiles (Ek and Holtslag, 2004) and the role of dry-air entrainment has been shown to enhance surface evaporation and induce a shallower convective boundary layer through daytime L–A feedbacks (Van Heerwaarden et al., 2009)."

3. At section 2.2 a key assumption is the use of the ERA5 to get information on the planetary boundary layer. Here, we disagree with the authors that the mesoscale variability of the boundary layer height is small compared to its temporal variability. There are clear examples in which the surface fluxes are not representative of the boundary layer development (see for instance figures 1 and 16 at Vilà-Guerau de Arellano et al (Biogeosciences 17, 2022). In that respect, there are already tools that enable us to make use of the worldwide soundings to determine the properties of the boundary layer dynamics (see Figures 3 and 4 at Hendricks et al., Geoscience Model Development 12, 2019). Although we realize that the use of this data set is beyond the scope of the paper, I believe the reader will appreciate a more elaborated and thorough sensitivity analysis on the uncertainty of ERA5 with respect to surface heterogeneity below the horizontal grid size of 31 km.

➔ *As the reviewer states, the surface fluxes reveal the sensitivity to spatial representativeness (Vilà-Guerau de Arellano et al. Biogeosciences 17, 2020), but the boundary layer height is relatively less sensitive to that problem (see for instance Fig. 16b in the same reference). Our study employs time series of the surface fluxes from FLUXNET2015 and the other flux sites, so that we only focus on the spatial representative issue in the PBL height as a function of time. To justify the adaptation of ERA5 PBL height, we have added some references that describe the limited spatial dependency of the modeled boundary layer in the CloudRoots field experiment, and that ERA5 is the best available reanalysis product among four different reanalysis datasets against worldwide radiosonde measurements. This description is added in Lines 145-149:*

"Although there are some issues in downscaling the gridded data to the observed sites due to unresolved spatial heterogeneity in the atmospheric boundary layer, Vilà-Guerau De Arellano et al. (2020) found a satisfactory agreement between ERA5 and three independent observations, which demonstrates that the boundary layer shows similar temporal evolution on the larger regional scale. Additionally, the inter-comparison of daytime Z_{PBL} from four reanalysis datasets against globally distributed high-resolution radiosonde measurements suggests that the most accurate reanalysis product is ERA5 (Guo et al., 2021)."

4. Equation (5) describes how the pressure at the planetary boundary layer height was calculated by integrating equation (4). In doing so, the temperature must be expressed as a function of height. Assuming a linear dependency with height the following equation is reached.

$$P_{PBL} = P_{sfc} e^{-\frac{g(Z_{PBL}-2)}{R(T_{PBL}-T_{2m})}\ln\frac{T_{PBL}}{T_{2m}}}$$

In equation (5) a factor is missed inside the exponential. This factor is the inverse of the temperature lapse rate in the boundary layer, $\Gamma = \frac{T_{PBL}-T_{2m}}{Z_{PBL}-2}$. In addition, in equation (5) the exponent has units when it must be dimensionless. I highly recommend correcting for this factor or for a similar corresponding factor if other assumptions were made.

➔ *Thank you for pointing out the missing term in the definition of pressure at PBL based on the vertical pressure gradient and the ideal gas law. Based on the reviewer's comments, we have* *corrected the formulation of Eq. 5 and redone all the relevant calculations using the pressure at the PBL. Although the updated results are similar to the previous results, this has resulted in some noticeable but unsubstantial changes to Figs. 4 and 5.*

5. Along the results section in part 4.2 Diurnal mixing diagrams and 4.3 Climate regime dependence, hysteresis of the thermal process chain versus the moist process chain is discussed. Regarding the discussion of hysteresis, we have three comments:

   A. We highly encourage to define in this context the term hysteresis. Hysteresis is a word originally coined in science to describe systems which state depends on their history. The typical scientific example is the magnetic hysteresis. This refers to a magnet that is able to experience different magnetic moments when subject to the same magnetic field. Those magnetic moments depend on the previous states of the magnet. To us, using hysteresis in land atmospheric context may be misleading since the state of the system may be different between morning and afternoon because the external factors are also different. For instance, soil water content and vapor pressure deficit are generally different between morning and afternoon. Therefore, the sub-diurnal asymmetry may be attributed to it not because an inherent change on the interactions due to the previous history. Nonetheless, we acknowledge that hysteresis term is generally used in land-atmospheric interactions context. We recommend defining the term in this context. We already find a definition in conclusions section, line 417, the fact that "the evening path through the water-energy phase does not retrace the morning path". We would move or repeat the definition to results because there is where the hysteresis is widely discussed. In addition, we think it would be valuable to specify in which way we consider it a hysteresis. In essence, which system is subject to its previous history? Is it the vegetation, is it a vegetation-soil system? What are considered the external factors? Another simpler solution is to coin another term such as temporal asymmetry which does not imply previous history relations.

   ➔ *As reviewer recommends defining the hysteresis in the manuscript, we have moved its definition from the conclusion section to section 4.2, and clarify it in the Abstract as well. Before suggesting the result of the hysteresis defined by the diurnal cycle of mixing diagrams and L-A coupling, we describe that our definition of hysteresis indicates the temporal asymmetry during the entire diurnal cycle. This description is added as a modification to Lines 330-333:*

   "There is a kind of hysteresis across the diurnal cycle when the terms are plotted this way, in that the thermal process chain leads the moist process chain by 2-3 hours. As a result, the evening path through the water-energy phase space does not retrace the morning path. The thermal coupling collapses toward zero quickly in the late afternoon, while the moist coupling declines gradually throughout the evening."

   B. We highly recommend discussing the hysteresis' possible causes both on the land and the atmospheric coupling. We argue that due to many processes that peak at different times (e.g., radiation peaks around noon, sensible heat flux peaks in the early afternoon and latent heat flux which with peaks later in the afternoon), morning-afternoon asymmetry can be expected. It is not clear to us what is the added value of assessing the asymmetry or if the aim of the research is simply to characterize it. We recommend clarifying either if the paper aims to characterize them as a general characteristic observed or if the asymmetry is seen as a possible option to evaluate land atmosphere interactions.

   ➔ *We did not deeply discuss the hysteresis in land and atmospheric couplings in Figs. 4b and 4c. Due to the lack of the description about the possible causes of those morning-afternoon* *asymmetry, it was difficult to assess what leads to the diurnal hysteresis in land and atmospheric couplings. To characterize the observed diurnal coupling behaviors, this description is added in Lines 337-339 and 344-346:*

"This results from the asymmetry of R(SWC1,LE) between developing (morning) and decaying (afternoon) phases, whereas R(SWC1,H) is relatively symmetric (not shown)."

"The diurnal atmospheric coupling hysteresis is determined by the evolution of R(H,LCL) and R(LE,LCL) and emphasized by the large daytime LCL variability. It is characterized by the diurnal maximum of LCL variance at 3-4 PM and its abrupt decaying from that maximum."

6. Omissions - Code not available yet in GitHub

   We just wanted to mention that the code is not yet available in the mentioned Github website. We guess that this may be made available after the publication. We just wanted to mention it to be sure that that was the case.

   ➔ *We have posted the source code used in these calculations and the plots included in this manuscript through GitHub. They had been left in private mode after submission – they are now publicly available.*

7. Comments about the introduction

   A. We recommend reinforcing the importance of sub-diurnal variability to understand land-atmosphere interactions at longer time scales (e.g., seasonal, and climatological). In the paragraph of the introduction that goes from line 55 to line 68, some examples are given. For instance, it is mentioned that it has been found links between morning evaporation and probability of rainfall, and between morning convective inhibition and convective initiation. If possible, we find interesting to include some more examples.

   ➔ *We omitted the specified season of the previous studies in the introduction section. Most of the previous studies examined the climatological land-atmosphere interactions and they tend to focus on the summer season when the land-atmosphere coupling is prominent. The specific description is added in Lines 63-64 and 67-69:*

   "Findell et al. (2011) established that increased morning evaporation leads to an enhanced probability of afternoon rainfall for the boreal summer season over much of the United States, …"

   "The climatological probability of summertime convective initiation was found to be more sensitive to morning convective inhibition over the southeastern United States, …"

   B. The next paragraph that goes from line 69 to line 80 states that "… thorough examinations of complete diurnal cycle of land-atmospheric interactions have been lacking". We recommend clarifying that this is the case from the climatological point of view. Detailed study cases in which the diurnal cycle of land-atmospheric interactions is researched have been previously published. What we find relevant and innovative in this research is that the thorough sub-diurnal analysis focus on the coupling terms using long temporal time series spanning from 1996 to 2020. This climatological approach may reveal more generalizable land-atmospheric interactions.

➔ *The purpose of this study is highlighted in the last paragraph of the introduction section where we mention this study investigates the climatological land-atmosphere interactions using globally distributed flux tower observations. To clarify the lack of previous studies dealing with the full diurnal cycle of the climatological land-atmosphere interactions, we amended the wording in Line 74:*

"Nevertheless, thorough examinations of the climatology of the complete diurnal cycle of L–A interactions have been lacking."

8. Comments on the methodology

   A. In line 109, the lifting condensation level is used as the variable to understand the coupling of the land with the atmosphere. We think the reader would appreciate a short sentence in which it is stated why this variable is an important indicator of the coupling to the atmosphere (e.g., because its strong relation with cloud initiation or its importance in convection schemes in atmospheric models).

➔ *This study employs the lifting condensation level to characterize the atmospheric behavior based on the readily-available near-surface atmospheric conditions. It is used to understand the atmospheric coupling and two-legged coupling from the flux tower observations. It also can be compared to the PBL height to understand cloud formation processes in terms of land-atmosphere interactions. This description is added in Lines 121-124:*

"The LCL can be characterized as a potential level of cloud base formation based on parcel theory. It can be compared to the planetary boundary layer (PBL) height to define LCL deficit (PBL height minus LCL; Santanello et al., 2011). When the PBL grows to the height of the LCL (corresponding to positive values of the LCL deficit), water may condense from the air parcel and cloud formation occurs."

   B. 3.3 Mixing diagrams section. Along this section mixing diagrams are introduced. It is stated that for computing them, 2-m temperature and humidity or vapor pressure deficit are used. In the last paragraph of the section, some shortcomings of this approach are addressed. For instance, it is mentioned that embedded in this method it lies one hypothesis. The hypothesis that 2-m measurements reflect mixed-layer values. We find this hypothesis to be dubious for certain ecosystems. For instance, in vegetated areas whose trees are taller than 2-m, the measurements fall into the in-canopy range. Many forests have trees that surpasses this height. Therefore, unlike many of the observations in other land types, observations in forests lie inside the canopy. In the research 102 from 230 sites (approx., 44 %) are classified as forests. Consequently, for forests sites, we wonder how much sensitive the land and surface couplings are to the height in which the surface heat fluxes, temperature and humidity are measured. We would expect that using measurements located right above the canopy would reflect different land and atmospheric coupling. We do acknowledge the challenge of comparing the diverse land-types considered in the study within the same methodological framework. Nonetheless, we would appreciate a justification of using the 2-m height measurements for forests or at least addressing the special advantages and shortcomings of such approach for forests. In addition, we wonder how the inclusion of these observations affect the general conclusions for the land-atmospheric interactions. For instance, are patterns more easily generalizable (in figures 2, 3, 4 and 5) when forests are excluded?

➔ *Flux tower observations from FLUXNET2015 include the surface air temperature, humidity, air pressure, vapor pressure, surface fluxes above the canopy layer and sometimes within it.*

However, the documentation generally does not provide the canopy information needed to compare it with the reference height of the measurements. Although this limitation is a shortcoming of the usage of these flux tower datasets, we have assumed the variables are measured from 2 meters above the canopy. So, we added this description for the flux measurements in Lines 116-120, 199, and 201-202:

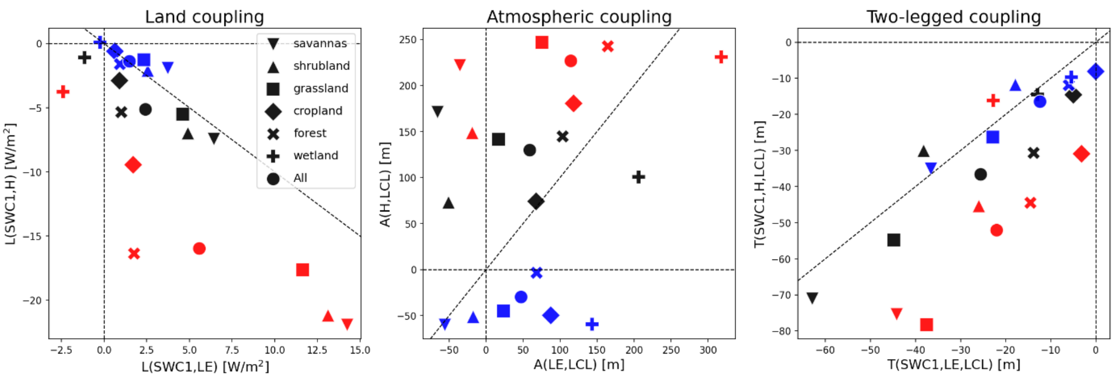
"Except for SWC1, the other variables are assumed to have been measured a few meters above the canopy while acknowledging that the canopy height varies among sites. However, the flux observations generally do not contain the canopy information necessary to compare to the reference height of the sensors, which is a shortcoming of using flux tower data, especially for forested locations."

"Flux sites provide surface air temperature …"

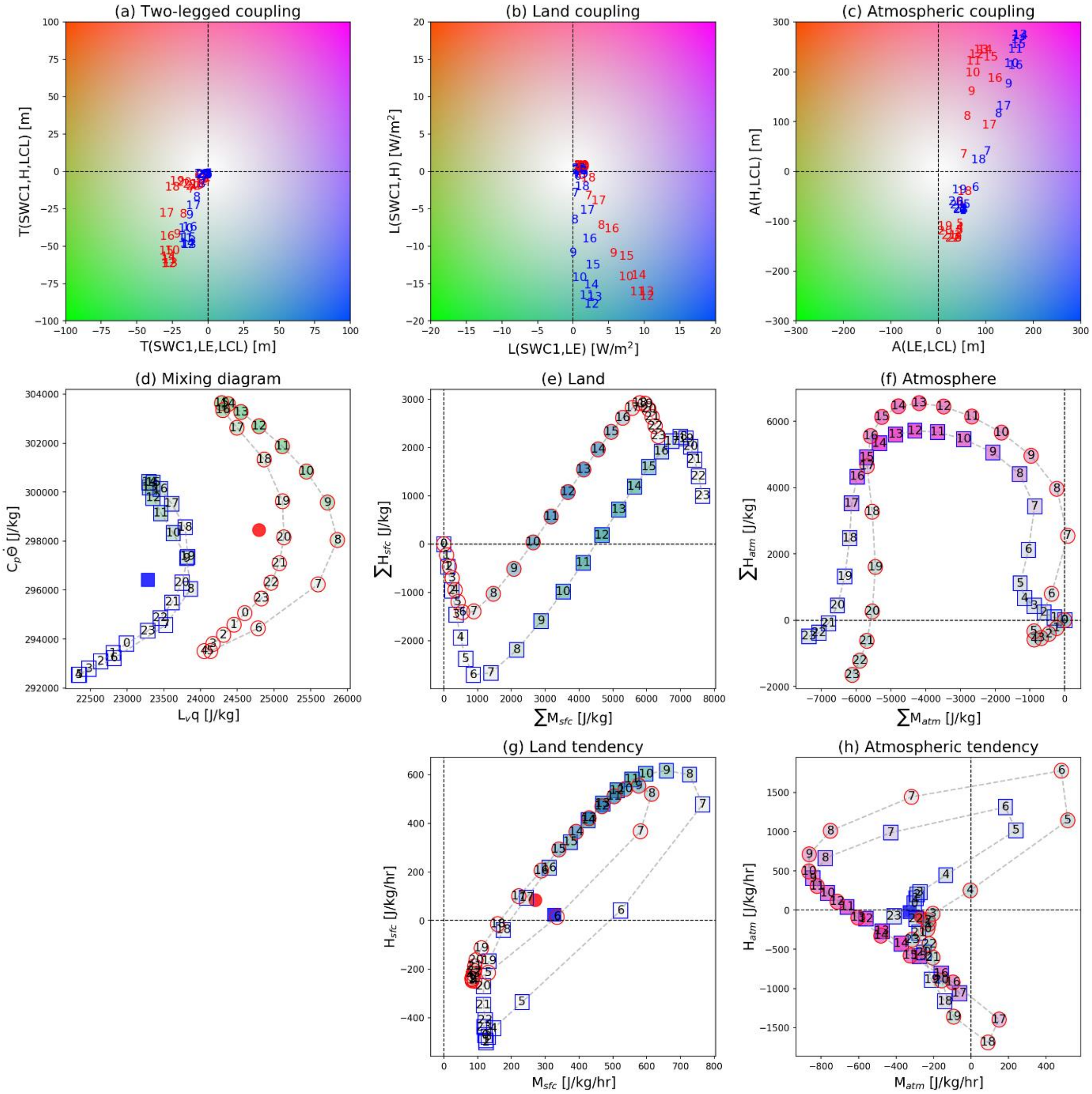
"As the instrument height may vary among flux towers, this study assumes that the observations are taken 2 meters above the canopy."

➔ *To understand the possible impact of sub-canopy measurements in the diurnal mixing diagram, we have additionally employed the meteorological data from the Discovery Tree at the Andrews Experimental Forest in Oregon, USA, which provides vertical temperature and humidity observation at 1.5- (below canopy) and 56-meter (above canopy). Although the result of the diurnal mixing diagrams is from only this single site in a forest, it can give some insight and necessity to understand not only the below- but also above-canopy physics. Thus, we add the new analysis (Fig. 6) and its description in section 2.1 (Lines 125-132), section 4.4 (Lines 426-449), and section 5 (Lines 533-541). It exposes the shortcomings of the standardized FLUXNET2015 dataset (and similar data, e.g., AmeriFlux) for such land-atmosphere studies, as there are clear contrasts between different heights within and above the canopy. The data we used represents an extreme case (in a very tall, dense, old growth forest) – perhaps other sites will show less contrast.*

➔ *To account for the contribution of the forest regions to the overall climatological result, we have reproduced the analysis in Fig. 3, but sorted by vegetation type. The result shows the forest does not reveal any distinctive characteristics in the comparison of segmented couplings across the types of vegetated land cover. For instance, wetlands generally agree with the results of wet and cold climate, and the savanna is consistent with the result of dry and warm climate. Of course, there is correlation between climate regime and the vegetation that can grow there.*



The diurnal cycle of mixing diagrams and land-atmosphere couplings (Fig. 5) is also reproduced by separating forest sites (site count is 102 and indicated by blue squares) to the other (site count is 128 and indicated by red circles). The results show that the sensitivity of the forest land cover to the diurnal cycle of the land-atmosphere interaction is not clear, but the forest sites are placed mainly in the energy-limited regimes which indicates some sensitivity *to the background state. Again, the climate signal is necessarily convolved with vegetation.*



C. Equations (6 and (8), page 7. We find misleading the notation Hsfc and Hatm to term the hourly land and atmospheric vector component. H is generally used to depict a sensible heat surface flux. Therefore, in our opinion, a subindex to it would be a logical notation to indicate a partitioning of the flux. Nonetheless, in the notation used in the manuscript, the subindex is not indicating a partitioning of the flux itself but a partitioning of a slightly different variable. In this case instead of being a flux of energy per square meter (such H), Hsfc and Hatm refer to the amount of energy contained in a kilogram of air that has been introduced in a certain time (in this case one hour) due to either surface of atmospheric processes. Since the units and the physical variable are different, we recommend finding another symbol such M was used for the moisture vector components.

➔ *We replace the notation for the heat fluxes within the energy budget in the mixing diagrams with F_{sfc} and F_{atm} over the entire manuscript.*

9. Asymmetry of L(SWC1,H)

p9, line 241 "This means that the asymmetry of L(SWC1,H) in the sub-daily time scale is larger than that of L(SWC1,LE), a characteristic that is explored in more detail later" we see that this is mentioned afterwards, but we recommend to indicate already here what processes may be affecting this asymmetry. These processes seem to be mostly diurnal. We think some interpretation of the physical processes, when possible, in the results may be enriching.

➔ *The diurnal sign shift of H is from positive during the daytime to negative during the nighttime. It is the major factor for the larger asymmetry of L(SWC1,H) in the sub-daily time scale compared with that of L(SWC1,LE). This description is added in Lines 268-269:*

"This means that the asymmetry of L(SWC1,H) in the sub-daily time scale is larger than that of L(SWC1,LE), which is mainly attributed to the diurnal reversal of H (positive during the day and negative at night). This characteristic is explored in more detail later."

10. Definition of significant relationships

p9, line 244 "The relationship between A(H,LCL) and A(LE,LCL) is not significant during midday due to their opposite relationships on either side of A(LE,LCL) = 0" What is specifically meant by "not significant"? It can be identified the two peaked distribution of A(LE,LCL) with one peak more predominantly in the region A(LE, LCL) > 0 and another less predominant in the region A(LE, LCL) < 0. What is the specific criteria to classify as "no significant"? Is it the fact that two feedbacks are identifiable? We would consider clarifying this point.

➔ *We meant to address that the p-value calculated from the correlation between the 230 sampled values of A(H,LCL) and A(LE,LCL) is large though "not significant". This is clarified in Lines 271-272:*

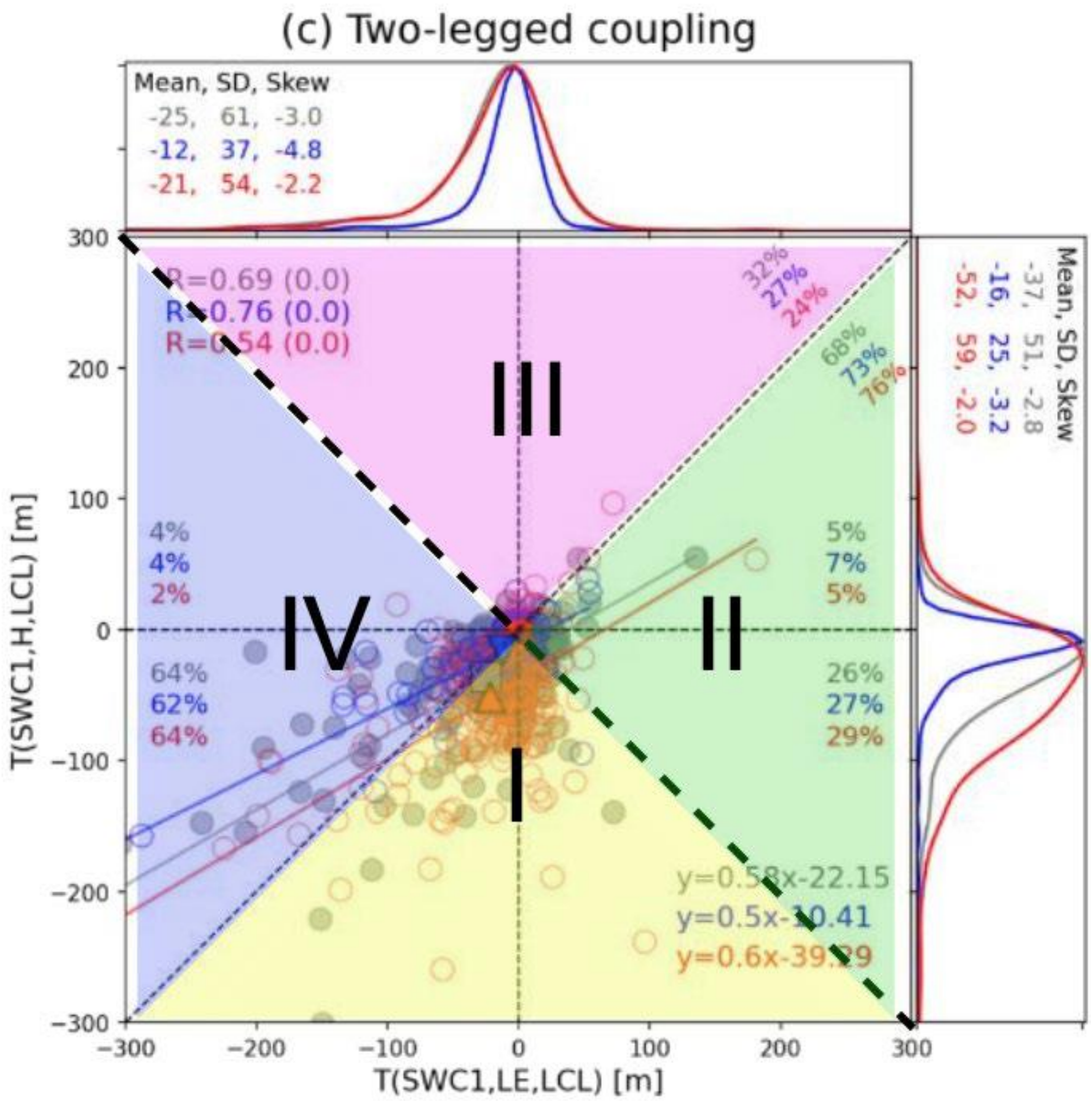
"The relationship between A(H,LCL) and A(LE,LCL) is not significant during midday, based on a high p-value along with low correlation, …"

11. Strength of the couplings

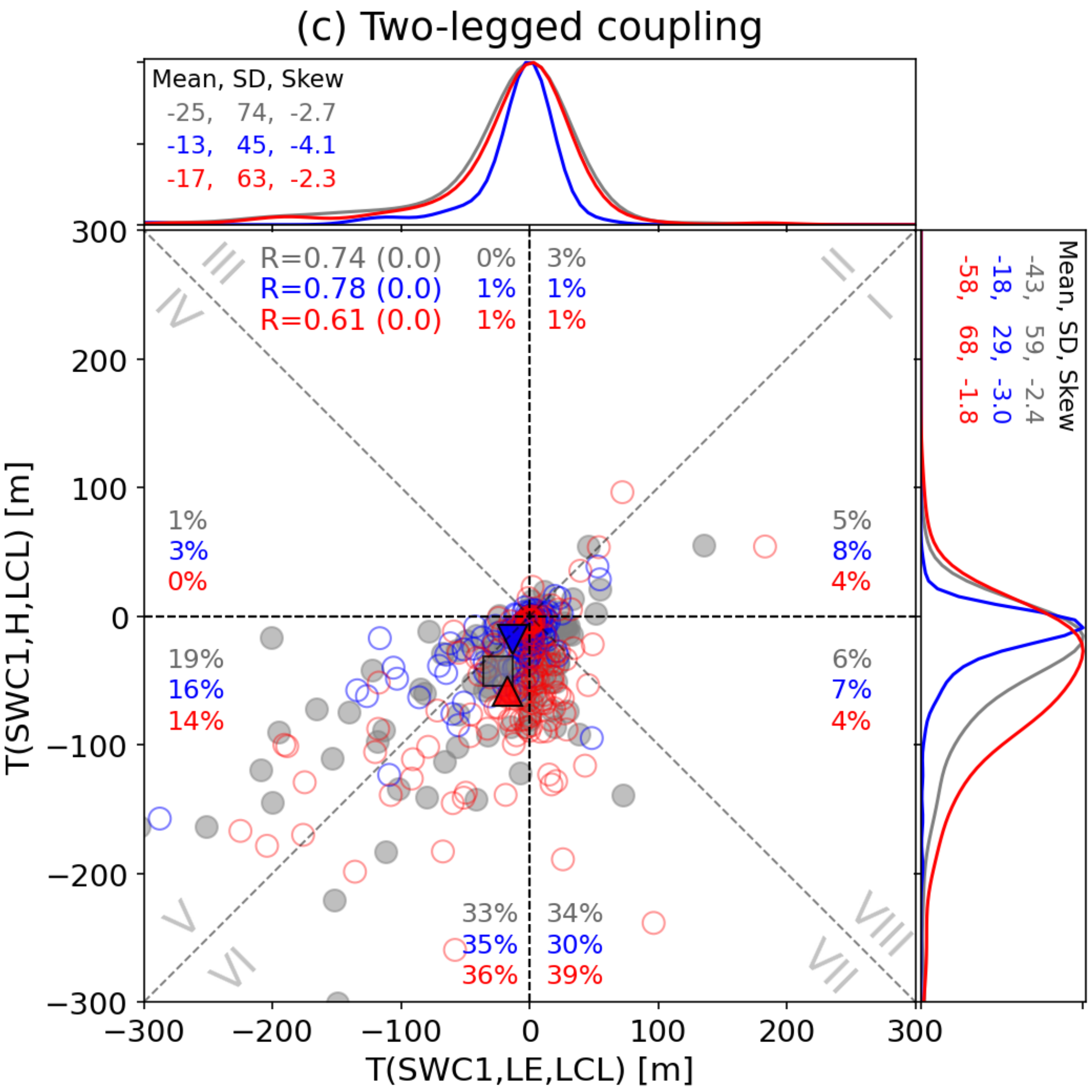
p9, line 256 Referring to figure 2c "Points on the right of the diagonal x=y line indicate stronger two-legged coupling through LE than trough H, which arise mainly from the larger correlation terms of land and atmosphere coupling via LE."

It is true that the points on the right of the diagonal y = x indicate that T(SWC1,LE,LCL) > T(SWC1, H, LCL). Nonetheless, in our opinion, that does not immediately mean that the two legged coupling is stronger because the coupling can be either positive (meaning a correlation between SWC1 and LCL through that pathway) or negative (meaning an uncorrelation between SWC1 and LCL through that pathway). To me, what indicates the strength of the coupling is the absolute value, that is: |T(SWC1,LE,LCL)| > |T(SWC1,H,LCL)|.

We have inserted a figure where the four regions that arise when the absolute values are considered are colored. Following that logic, the coupling following the LE pathway would be stronger for the regions II and IV. On the contrary, the coupling following the H pathway would be stronger for the regions I and III. In that case, by naked eye, the strength of both couplings seems comparable, and it depends mainly on the density of points in regions I and IV. We would even argue that probably the coupling via the sensible heat flux pathway is stronger because in figure 4a, all values of the part where both couplings are negative are in the half corresponding to region I. In fact, in lines 292-294 it is accurately described this by stating: "During the daytime, both two-legged couplings are negative, with T(SWC1, H, LCL) being almost three times as strong as T(SWC1,LE,LCL) around midday, showing the importance of sensible heating for ML growth".



➔ *We have typically focused on the quadrant where both two-legged couplings are negative as the realm where land surface state variability directly affects the atmosphere. But, as the reviewer mentioned, the absolute comparison between both couplings can suggest the comprehensive interpretation for which mediative land fluxes highly contribute to LCL variability (or are at least related if not causal) regardless the coupling sign. Thus, we have modified the Fig. 2c by removing regression lines [which erroneously implied y=f(x)] and separating the quadrants into an 8-piece domain of triangles separated by y=x and y=-x lines as well as y=0 and x=0. The percentages denote the population in each octant. The updated figure is shown below and its description is in Lines 282-288 and Lines 323-324.*



"The observed two-legged couplings from soil moisture to LCL, mediated by H and LE, are mostly placed on the left side of the y=-x line (Fig. 2c). Most couplings are negative, which means LCL height is anticorrelated with soil moisture regardless of the pathway of the coupling. To the left of the y=-x line (octants IV through VII), points in octants VI and VII indicate stronger two-legged coupling of soil moisture control on potential cloud base through H rather than through LE. Locations presenting stronger coupling through H are almost two times more than through LE throughout the entire day. This arises mainly from the larger correlation in the terms of land and atmosphere coupling via H; the LCL is less sensitive to LE variability compared with H, particularly in dry land conditions (not shown)."

"It is consistent with the result of three times more locations exhibiting stronger two-legged coupling of soil moisture to LCL through H than through LE (c.f., Fig. 2c)."