

Dear Editor,

We thank again the Editor and the referees comments which led to significant improvements of the quality of our manuscript. Please find below, the modifications made at the manuscript. The referees' comments are in black, our point-by-point responses are in red color, and the changes to the manuscript are in blue color.

Sincerely,

Alice Henkes on behalf of all coauthors

Responses to referee comments on the acp-2021-87 Manuscript "Morning boundary layer conditions for shallow to deep cloud evolution during the dry season in the central Amazon", by Henkes et al.

Referee Comments 1

We would like to thank referee 1 for his/her constructive comments on the manuscript, which have helped improve the presentation of our results. In what follows we present our point-by-point responses are in red color, and the changes to the manuscript are in blue color.

I appreciate the efforts of the authors to address my comments, revise the manuscript and add a new section for statistical analysis of more cases during two cases. I'm ok that the authors decide to focus on case study and use a new section of statistical analysis for more cases to support their conclusion. Many thanks for this comment.

1) However, in this case, I would suggest showing all individual cases throughout the analysis and focus on discussing their overall behavior as well as case-to-case variability in Section 3 (use lighter color and thinner lines to present individual cases, as well as more solid color and thicker lines for their means), instead of just means and standard deviations, as I don't think standard deviation of merely 4 cases makes sense enough.

1) Following the reviewer's suggestion, we made the new version of the figures in Section 3. However, thinking about the figures, we prefer to keep the previous version (mean and one standard deviation) as the new figures did not improve significantly for a better visualization. Therefore, we copied the new figures into our response as follows on the next page.

2) One important point concluded by the authors is that the shorter morning transition stage of ShDeep days (or delay growth of BL in ShCu days) is due to larger sensible heat flux in ShDeep days. However, I don't think this point is convincing enough as the SH difference at this stage is actually not significant before 8 LST in Fig. 4f, nor did it supported by the additional analysis in Fig. 11. This part should be more carefully discussed.

2) The sensible heat flux values (as shown in Table 2 of the manuscript) are large and early (in the cloud-free morning) at the moment of the crossover (when the sensible heat flux change from negative to positive) on ShDeep than ShCu day. For example, event 5 (20140905, ShCu) and event 7 (20140909, ShDeep) have the same time as the first positive value considering the 30 min average of ECOR sensible heat flux (of around 07 LST), but we observe 44.0 Wm^{-2} on ShDeep and 0.1 Wm^{-2} for ShCu day. The point is that this surface heating flux after crossover increases with time and with the amount of energy (released from the surface), causing the erosion of nocturnal BL thermal inversion and facilitating the growth of the mixed layer during the morning transition stage. We rewrote the paragraph in the discussion section to clarify this:

"A pronounced feature of the diurnal evolution of the sensible heat flux, often seen on ShDeep days, is the effect of sensible heat flux promoting the erosion of nocturnal BL. After the crossover, the sensible heat flux increases with time and with the amount of energy released from the surface, driving a higher growth rate of the BL in the morning transition stage than on ShCu days.[...]"

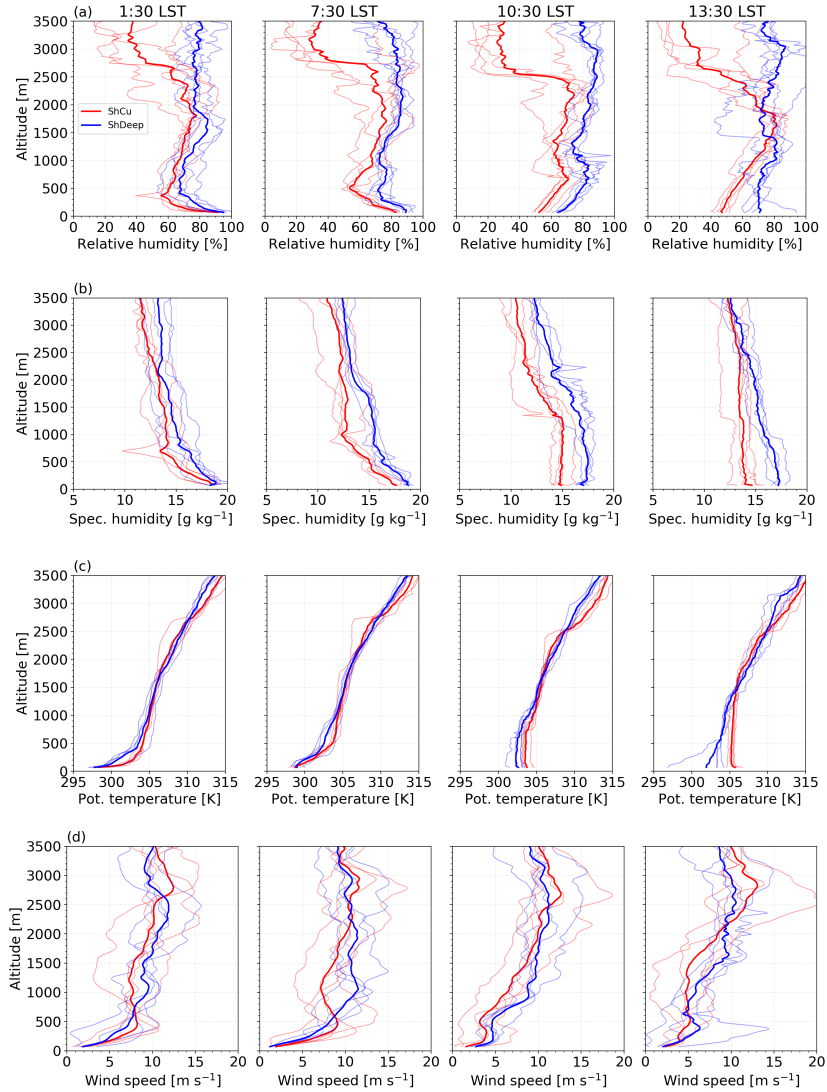


Figure 1. Vertical profiles between 50 and 3500 m of **(a)** relative humidity, **(b)** specific humidity, **(c)** potential temperature, and **(d)** wind speed from radiosondes launched at the T3 site (from left to right) at 1:30, 7:30, 10:30, and 13:30 LST. The mean (bold lines) and the case-to-case (lighter lines) are shown for shallow convective (ShCu, red) and shallow-to-deep convective (ShDeep, blue) days.

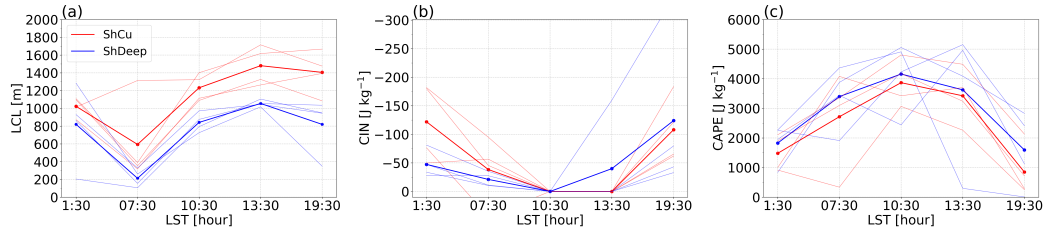


Figure 2. Time evolution of **(a)** lifting condensation level (LCL), **(b)** convective inhibition (CIN) and **(c)** convective available potential energy (CAPE) derived from radiosondes. The mean (bold lines) and the case-to-case (lighter lines) are shown for shallow convective (ShCu, red) and shallow-to-deep convective (ShDeep, blue) days.

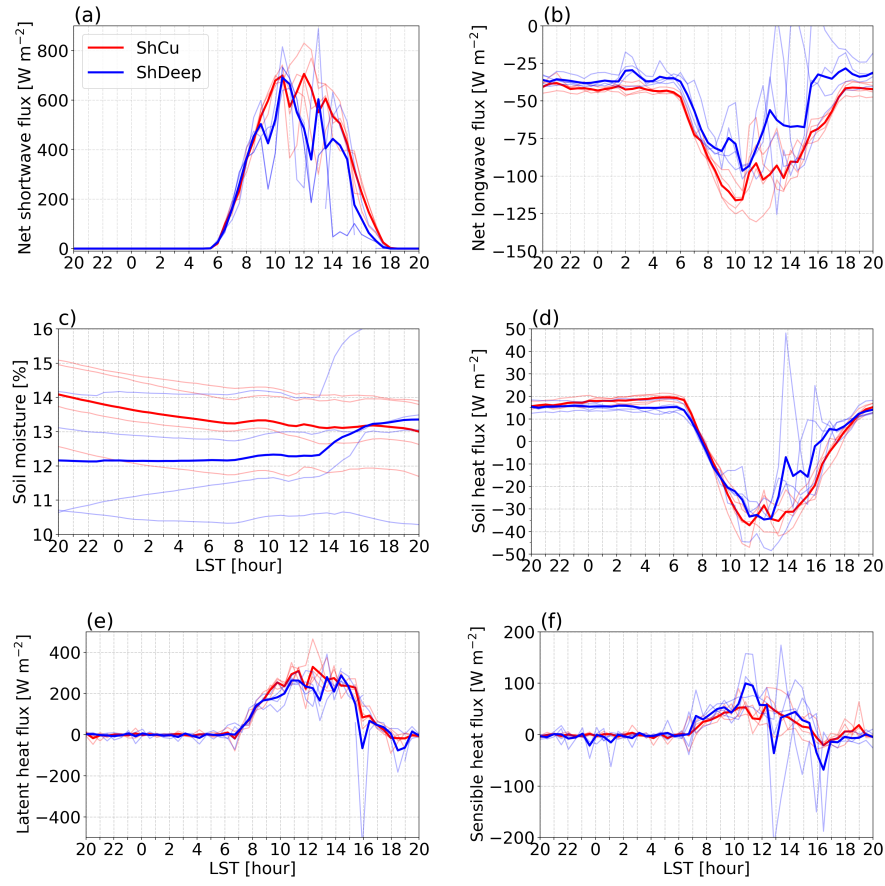


Figure 3. Time evolution of (a) net shortwave radiative flux, (b) net longwave radiative flux, (c) soil moisture at superficial layer, (d) soil heat flux, (e) latent heat flux and (f) sensible heat flux at the surface. The mean (bold lines) and the case-to-case (lighter lines) are shown for shallow convective (ShCu, red) and shallow-to-deep convective (ShDeep, blue) days.

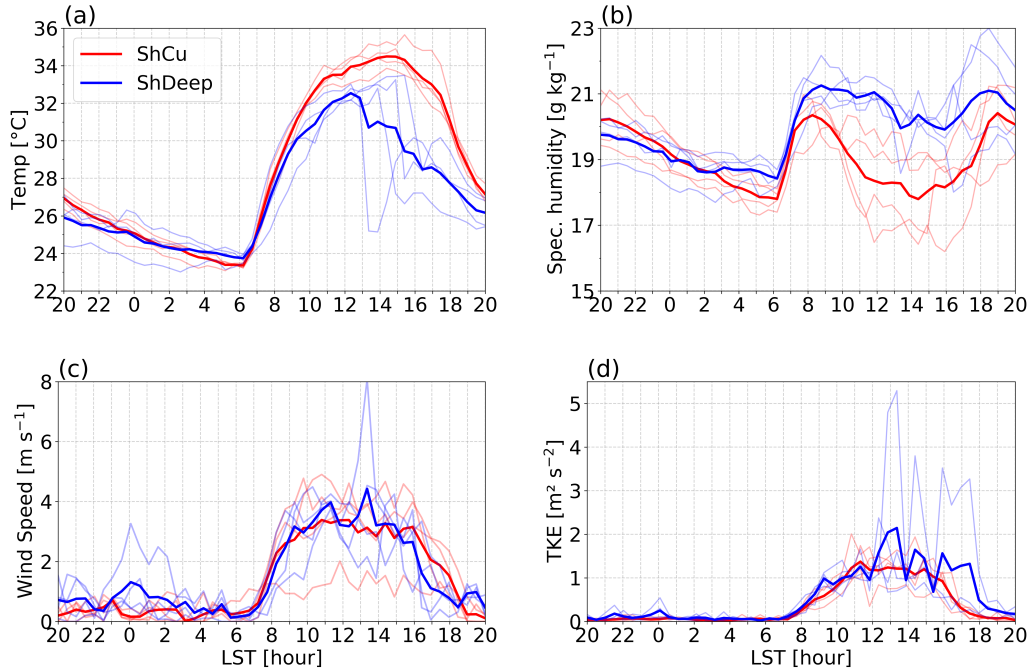


Figure 4. As in Fig. 3 but for (a) surface air temperature, (b) specific humidity, (c) wind speed estimated by surface meteorological system, and (d) turbulent kinetic energy estimated by ECOR.

40 In this version of revision, I still find a lot of long and awkward sentences, grammatic error, incorrect reference to Figures and numbers. I suggest the authors should check the manuscript more carefully again and improve the English writing. Besides these, I'm overall satisfied with the response addressing my other comments. My recommendation is a major revision.

Line 1: "two dry season years" "dry seasons of two years". **We changed the text accordingly.**

45 Line 5: "Atmosphere" "Atmospheric". **Corrected.**

Line 8-9: recommend revision: "decreased duration of ... is associated with ...". **We rephrased the sentence: "Results show that the decrease in time duration of the morning transition on ShDeep days is associated with high humidity and well established vertical wind shear patterns."**

Line 13-16: This sentence is too long and hard to understand, please rephrase. Also, I did not recall seeing an analysis for the impact of morning transition duration on convection strength and subcloud processes.

We rephrased the sentence:

'Under these conditions, the time duration of morning transition is used to promote convection, having an important effect on the convective BL strength evolution leading to the formation of shallow cumulus clouds and their subsequent evolution into deep convective clouds.'

55 Line 26: "others" "other". **Corrected.**

Line 35: "between land-atmosphere" "between land surface and atmosphere". **We changed the text accordingly.**

Line 52: add "convection" after "shallow to deep". **We added accordingly.**

Line 52-53: suggested revision: "Comparing the days with ... to those with ...". **Corrected.**

Line 61-63: do you mean shallow cumulus clouds and deep convective clouds represent 22.1% and 5.2% of the total cloud cover year round, respectively, while for the dry season, the numbers are reduced to 16.6% and 1.5%, respectively? In addition, why are these numbers so small? Are these fraction of total cloud cover or cloud frequencies? **Because this numbers refers to**

the cloud frequencies of cloud types occurrence of seven categories (shallow, deep convection, cirrus, cirrostratus, congestus, altostratus, altocumulus). We rephrased the sentence as:

65 They found that shallow cumulus clouds and deep convective clouds represent 22.1% and 5.2% of the total cloud frequencies of cloud type occurrence year round, respectively. While for the dry season, the numbers are reduced to 16.6% and 1.5%, respectively.

Line 66-67: not sure what this means. Are you explaining the new criteria used in Tian et al. 2021? Please rephrase.

We rephrased the sentence as: Their criteria associated days with local deep convective clouds to a presence or not of pre-existing or external disturbance.

70 Line 76: what is attributed to enhanced shallow and deep convection? Or do you just mean during the diurnal cycle of convective BL in the dry season, the enhanced shallow and deep convection are related to increased humidity in the lower free troposphere. The sentence was changed accordingly.

Line 84: I think you mean “adopt” not “adapt”. Corrected

75 Line 86: I recommend to delete “until the last stage when shallow clouds evolve to deep,” for clarity. We deleted this part of sentence.

Line 130: please rephrase. We rephrased the sentence as:

"The retrieval approach determines the layers associated with the aerosol backscatter gradient profile as possible BL height candidates."

Line 131: do you mean “high aerosol concentration”? Corrected

80 Line 148: “allow estimating” “estimates” Corrected.

Line 150: “ and distant” “which is” Corrected.

Line 159: If this stage includes (1) the sunrise, then why it “occurs two hours after sunrise”? We rephrased the sentence as:

The complete erosion of the nocturnal BL, during dry season in Amazon region, usually occurs two hours after sunrise (Carneiro et al., 2020)

85 Line 164: should it be “It corresponds to the occurrence of a cloudy mixing layer ...”? The sentence was changed accordingly.

Line 177: delete “day” Done

Line 180: “around 2km”? around or under? Corrected.

Line 192: “former” “latter”? Corrected.

90 Line 193: “shallow-to-deep” “shallow to deep” - Changed

Line 201: “allowed” “allowed us”. Corrected

Line 203: “significant number”? Do you mean “larger number”? We changed the text accordingly.

Line 217: “difference ... important”? consider use “apparent” or “larger” . We changed "important" to "apparent" in the text.

95 Line 265: “stronger diurnal cycle” than what? “increase in” “diurnal cycle of” Corrected

Line 266: “relatively” “ is relatively”. Corrected

Line 269: “overlap of these two zones”, what zones? We rephrased the sentence.

Line 280: should be “diurnal evolution of convective clouds” Corrected.

Line 282: add “in ShDeep days” after “cloud cover” Done

100 Line 291: do you mean “as the cloud fraction difference between them increases”? Corrected.

Line 295: should be “Fig. 4c” not “Fig. 4d”. Corrected

Line 298: should be “Fig. 4d” not “Fig. 4c” Corrected

Line 307: should be “Fig. 4e” not “Fig. 4c” Corrected

Line 312: “surface”? or “surface warming”? Corrected

105 Line 320: I don’t think the sensible heat flux in morning transition stage (I suppose it’s 6 to 8) show significant difference between the two regimes large enough to explain the delay of BL growth in ShCu days. We rephrased the sentence:

"A pronounced feature of the diurnal evolution of the sensible heat flux, often seen on ShDeep days, is the effect of sensible heat flux promoting the erosion of nocturnal BL. After the crossover, the sensible heat flux increases with time and with the amount of energy released from the surface, driving a higher growth rate of the BL in the morning transition stage than on ShCu days."

110

Line 324: I don't see sensible heat flux on ShCu days larger than that on ShDeep days in your Fig. 4f.
 We rephrased the sentence:
 'On the other hand, the more entrainment of dry air from the free tropospheric into the BL on ShCu days may be a response to BL turbulence and more sensible heat flux during the cloudy mixing layer stage.'

115 Line 334: "1.1°C and 2.3°C" are not "rates", please correct the units. **Corrected**
 Line 336: I think you mean "than ShCu days" not "unlike ShCu days" **Corrected**
 Line 339: "noon" for "ShDeep days", 15 LST for "ShCu days" **We changed the text accordingly.**
 Line 340: "drop of 3°C" during? **We rephrased the sentence:**
 [...] a drop of $\sim 3.0^{\circ}\text{C}$ is observed during the cloud mixing stage due to the latent cooling from rain evaporation.

120 Line 346: "on the order of -1.0" "by about 1.0" **Corrected**
 Line 356: I don't think there is a square root in the equation. **Corrected**
 Line 363: "at the time the gust front ..."? **We corrected the sentence:** "arrived at the observational site".
 Line 374-375: I don't see a BL depth increase around 7. **We rephrased the sentence:** [...] after 7 [...], there is a slight increase in the BL depth.

125 Line 375- 377: These numbers (240 and 290 W m⁻²) don't match with Fig. 4. In Fig. 4a, SW at 8:00 is nearly the same for two regimes, while in Fig. 4b, LW at 8:00 had a difference smaller than 20Wm⁻². How can the net radiation difference be 50W m⁻² here? **These number refers to the different time of net radiation 240 W m⁻² at 8:00 (ShDeep) and 290 W m⁻² at around 8:45 LST (ShCu).** "This stage ends around 08:00 LST, at which time the net radiation is $\sim 240 \text{ W m}^{-2}$ and the sensible heat flux is about 39 W m^{-2} . Moreover, on ShCu days, the BL depth grows slowly from the approximately same time and ends
 130 0.75 h later (around 08:45 LST), at which time the net radiation is $\sim 290 \text{ W m}^{-2}$ and the sensible heat flux is about 42 W m^{-2} ."

Line 386: "low-troposphere" "lower troposphere" **Corrected**
 Line 388: I think the BL depth for ShDeep days is only about 1800-1900m at 10 LST according to Fig. 6. **Corrected**
 Line 392: "influence" "can influence" . **Corrected**
 Line 395-396: please provide reference for this statement. **Done**

135 Line 403-405: sentence too long and hard to follow, please rephrase. **We removed this sentence since this information is shown in the caption of Table 2.**
 Line 414: where are these number (19 and 12 g kg⁻¹) from? **We added the information on the sentence as follow:** [...] as reported by the soundings profile [...]
 Line 438: "agreement" between what? **We rephrased the sentence:** [...]a good agreement of the early onset observed between
 140 SODAR and the ceilometer on ShDeep days
 Line 439: which is later than which by how long?
 Line 445: these numbers look incorrect for me when compare to Table 2 last column, please check **We revised this numbers as suggested and it is corrected with wind speed maximum of LLJ now.**
 Line 450-451: suggested revision: "It indicates a positive ...". **We changed the text accordingly:** It indicates a positive
 145 association of a high rate-of-change of the BL height due to the high values of IWV_{1km} and VWS

Line 468: "focus" "focuses" **Corrected**
 Line 469: delete "significantly" **Done**
 Line 472: "meteorology"? please indicate more specifically or just remove it. **We deleted the word.**
 Line 473: "large ... small" "larger ... smaller". **We changed the text accordingly.**

150 Line 473: is there any particular reason to change the vertical range from 1km to 2km for IWV and VWS (Fig. 9 and 11). If not, please keep consistent. **We explore the IWV during dry season of the the two years between surface and 1km, surface and 2 km, and surface and 3 km on statistical analysis (not shown). We note that IWV, VWS are higher during the ShDeep in all layers, although the larger differences were found at layer between surface and 2 km.**
 "For the dry seasons of two years, higher IWV and VWS were found in 2 km than 1 km as in the case studies, reflecting the
 155 variability through the progression of the dry season."

Line 484: should be "Fig. 11d" not "Fig. 11c" **Corrected**
 Line 488: I would suggest to test if there is a significant difference between ShCu and ShDeep for each pair of bars in Fig. 11. **We included the statistically significant differences on the text (Table 1-4). However, we note that sensible heat flux do not show significant difference, since it is very sensitive to cloud cover and the time of crossover:**

160 "Also, the statistical two-sided Student's t test showed that statistically significant differences are present for all times of
IWV, VWS, longwave radiative cooling, and TKE only for at 3 LST at the 95% confidence level between ShDeep and ShCu
days. The BL height during the morning transition was statistically significant at the 95% confidence level at 7LST, at the 89%
confidence level for 8 LST consistent with the difference of erosion time of BL between ShDeep and ShCu days."

Figure 8: please explain what the lowest cloud base data come from in the caption. We rewrote the caption in Fig. 8:
165 [...] but for the height of the BL and lowest cloud base (black dots) from ceilometer on (a–d) ShCu days and (e–h) ShDeep
days [...].

Table 1. Absolute values from Student's t tests for the differences between composite means of IWV (Fig. 11a) and VWS(Fig. 11b) from radiosonde vertical profiles on ShDeep and ShCu days.

	IVW(01:30LST)	IVW (07:30LST)	IWV (13:30LST)	VWS (01:30LST)	VWS (07:30LST)
t-value	7.12	7.01	5.50	3.93	4.30
p-value	3.16e-09	1.98e-08	1.03e-06	1.92e-4	6.79e-05

Table 2. Absolute values from Student's t tests for the differences between hourly composite means of TKE(Fig. 11c) and hourly longwave radiative(Fig. 11d) on ShDeep and ShCu days.

	LW (0 LST)	LW (1 LST)	LW (2 LST)	LW (3 LST)	LW (4 LST)	LW (5 LST)	LW (6 LST)
t-value	6.23	6.36	6.16	5.91	5.99	5.23	5.96
p-value	3.16e-08	1.83e-08	4.27e-08	1.38e-07	1.43e-07	1.86e-06	1.13e-07
	TKE (0 LST)	TKE (1 LST)	TKE (2 LST)	TKE (3 LST)	TKE (4 LST)	TKE (5 LST)	TKE (6 LST)
t-value	1.38	1.13	1.81	2.67	1.34	0.86	0.25
p-value	0.16	0.26	0.07	0.009	0.18	0.38	0.79

Table 3. Absolute values from Student's t tests for the differences between hourly composite means of sensible heat flux (SH, Fig. 11e) on ShDeep and ShCu days.

	SH (06 LST)	SH (07 LST)
t-value	-1.71	0.68
p-value	0.09	0.49

Table 4. Absolute values from Student's t tests for the differences between hourly composite means of BL Height (BLH, Fig. 11f) on ShDeep and ShCu days .

	BLH (0 LST)	BLH (1 LST)	BLH (2 LST)	BLH (3 LST)	BLH (4 LST)	BLH (5 LST)	BLH (6 LST)
t-value	2.36	0.78	0.64	0.32	0.52	-0.63	0.93
p-value	0.02	0.43	0.52	0.6	0.52	0.86	0.35
	BLH (7 LST)	BLH (8 LST)	BLH (9 LST)				
t-value	2.01	1.57	0.97				
p-value	0.05	0.11	0.33				

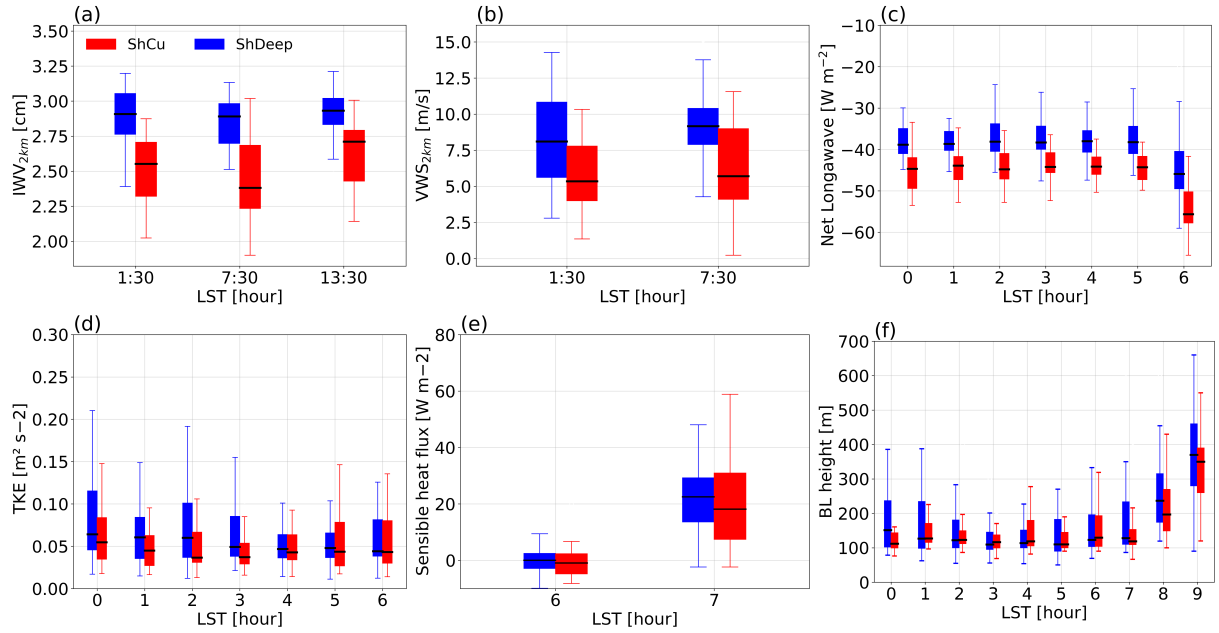


Figure 5. Box-and-whiskers plot of (a) $IWV_{2\text{ km}}$ during the stable, morning transition, and cloudy mixing layer stages, (b) $VWS_{2\text{ km}}$ at stable stage and morning transition, (c) radiative cooling during the stable stage, and (d) TKE during the stable stage, (e) sensible heat flux crossover, and (f) BL height from stable to onset of convective BL. In each box, the central bar is the median and the lower and upper limits are the first and the third quartiles, respectively. The lines extending vertically from the box indicate the spread of the distribution with the length being 1.5 times the difference between the first and the third quartiles. The red and blue boxes correspond to shallow convective (ShCu) and shallow-to-deep convective (ShDeep) days, respectively.

Responses to referee comments 2 on the acp-2021-87 Manuscript “Morning boundary layer conditions for shallow to deep cloud evolution during the dry season in the central Amazon”, by Henkes et al.

Referee Comments 2

The authors have well addressed most of my comments. However, I still have an important concern about the mechanism behind ShDeep. Non-local factors (e.g., synoptic pattern and large-scale advection) should play critical roles in the transition. The authors should add more discussions about the separate contributions from local and non-local factors.

Thank you for this comments. We rewrote the paragraph in the discussion section to clarify this:

During the dry season, the trigger mechanism of ShDeep days is a local effect; however, it only happens when there is enough IWV, and this is controlled by non-local factors. The IWV for ShDeep is explained by the synoptic patterns as suggested by Biscaro et al. (2021). Also, Ghate and Kollias (2016) shows that large-scale moisture advection can control the relationship between local land-atmosphere interactions and diurnal precipitation. Here, we show that the enhanced water vapor at low and mid-levels is important for the characterization of the cloud-BL interaction from the stable to the rapid growth stage and triggering local deep convection in the cloudy mixing layer stage. This feature, observed during the dry season over Central Amazonia, was corroborated by Chen et al. (2020) who showed that large-scale advection is vital for characterizing land-atmosphere interactions both in magnitude and type of relationships in the transition from clear-sky to precipitation clouds over the U.S. SGP site.

References

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- 190 Carneiro, R. G., Fisch, G., Borges, C. K., and Henkes, A.: Erosion of the nocturnal boundary layer in the central Amazon during the dry season, *Acta Amaz.*, 50, 80–89, <https://doi.org/10.1590/1809-4392201804453>, 2020.
- Chen, J., Hagos, S., Xiao, H., Fast, J. D., and Feng, Z.: Characterization of Surface Heterogeneity-Induced Convection Using Cluster Analysis, *Journal of Geophysical Research: Atmospheres*, 125, e2020JD032550, 2020.
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