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 2

We thank you for your constructive comments and suggestions to improve our study. We have carefully addresses all comments/suggestions made by reviewer. Please find below our point-by-point responses in red color, and the changes to the manuscript are in blue color response.

This manuscript used field observations to study the shallow to deep convective cloud evolution in the central Amazon. Several transition cases are comprehensively discussed. In general, this study discussed an important issue with solid analyses. However, the limited cases may not support statistically significant conclusions. Meanwhile, the significance of this study needs to be better summarized in the conclusion section. Therefore, this paper needs major revisions before potential publication in Atmos. Chem. Phys.

The main findings are shown in the conceptual model under ShCu and ShDeep conditions, which were not discussion in details in previous work:

"This finding support the previous results (Ghate and Kollias, 2016; Zhuang et al., 2017; Tian et al., 2021), but extends the knowledge by showing in detail the different BL processes evolved in the shallow to deep convection transition. In addition, our results show that the time taken to eliminate the nocturnal stable boundary layer inversion is used to promote convection having important effect in characterizing the convective strength in the morning transition stage." Line 559–562

As suggested by both referees, we included a new section with statistical analysis of BL processes, especially during stable and morning transition stages (also note our response to the specific comment below). In summary, we rewrite part of the introduction, and we include a new section with BL processes statistics (Sec. 4) and rewrite the conclusions to be more focused on the new findings.

Specific Comments:

1. The evolution of boundary layer cloud can largely differ case by case. Therefore, the mechanism and evolution pattern observed in the several cases may not be representable enough.

   Thanks for your comment. This concern was also raised by Reviewer 1. Motivated by both suggestions, a new section with BL processes statistics based on the overview of case studies is now presented in Sect. 4 (Line 460-514).

   4. Boundary layer processes statistics during the two dry seasons of the GoAmazon 2014/5 campaign

   In order to evaluate the significance of the conceptual model built based in the case studies, a statistical analysis was performed. The statistical analysis was developed by comparing the cases of shallow and deep convective clouds using the same classification and relaxing the premise of having convection under the T3 site. ShDeep days were classified as hot-tower clouds with little external disturbances in the morning based on cloud boundaries of the RWP-WACR-ARSCL product and the precipitation properties for the domain within the 75 km radius of the T3 site estimated by S-band Radar scanning (Tian et al., 2021). ShCu days were classified as days with no precipitation in the 75 km radius of the T3 site. Using the two dry season years, 45 cases of ShDeep and 30 cases of ShCu were selected. On the majority of days, the shallow-to-deep cloud evolution did not occur at the T3 site but in the 75 km radius domain of S-Band Radar. The statistic analysis of the BL processes mainly focus on the stable to the morning transition stages as it has been shown in the conceptual model of the BL process (Fig. 10). This large number of events is robust to significantly describe the daily evolution of a typical day of ShCu and ShDeep.

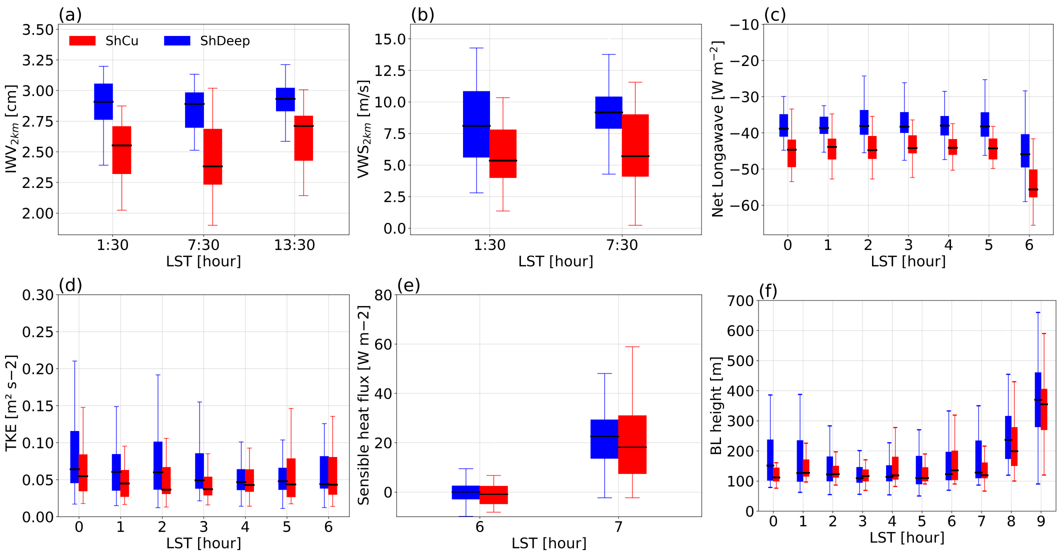
   The composites of the BL processes, discussed in detail in the previous section, are shown in Fig. 11 as box-and-whisker plots. As previously discussed, Ghate and Kollias (2016) suggested that greater fluctuation over short periods in IWV is the primary factor controlling meteorology and precipitation during the dry season. In fact, the median $IWV_{2\ km}$ composite, at the lower 2 km, shows large values and exhibits small variability in the ShDeep (blue boxes) than ShCu (red boxes) regimes since nighttime (stable stage) (Fig. 11a). In the lower troposphere, distinct variability in ShDeep conditions is also observed in $VWS_{2\ km}$ from the stable stage to the morning transition stage, with larger median values than that for ShCu (Fig. 11b). Zhuang et al. (2017) found a similar result, concluding that the contrast between ShDeep and ShCu days could be associated with weak surface wind and strong wind shear in the lower troposphere. Moreover, this result indicates that turbulent mixing may be transported from aloft down to the surface, linking to the evolution from stable to unstable BL conditions.

During the stable stage at near surface, less radiative cooling and intense periods of turbulent mixing characterized the ShDeep composite in comparison with ShCu. The net longwave showed very similar results to the case studies (Fig. 11c) with a well-defined difference of around 5 W m^{-2} between the ShDeep and ShCu composites. The median shows more intense radiative cooling during the ShCu regime than for ShDeep. For example, Edwards et al. (2014) using large-eddy simulations showed that radiative cooling has an important effect on the morning transition and in the development of the convective BL. The mechanical turbulence is seen in Fig. 11c by the TKE. The magnitude of the TKE is comparatively higher for the ShDeep between 00:00 and 03:00 LST than those of the ShCu composite. Similar small median values occur at around 06:00 LST for both regimes when the increase in turbulence is weak, probably caused by weak wind at late night and cumulative thermal cooling inducing stable stratification near the ground through the nighttime.

In contrast to the longwave radiative cooling, the sensible heat flux showed a less pronounced difference with increasing sample size, being slightly higher in the median ShDeep values than in the median ShCu values during the crossover event (Fig. 11e). One explanation for this difference is that the sensible heat flux is affected by cloudiness and the surface thermal properties, such as the one shown in Fig 1g, on day 7 of the case studies. In that case, the sensible heat flux is influenced, before or during the morning transition, by reducing incident solar radiation, surface temperature, and therefore its magnitude and time crossover (e.g., reduce the intensity of convection). However, considering that under ShDeep conditions there is less radiative cooling, a small variation in the sensible heat flux at the time of crossover can resulting in early erosion of the nocturnal inversion that develops during the stable stage. Such cloud cover is less frequent in the ShCu regime during the early morning, if clouds are more frequent in the afternoon period attributed to the shallow cumulus cloud type (Giangrande et al., 2020).

During the stable stage, the ShDeep BL height is higher than that of the composite ShCu. The relatively high BL height values are consistent with relatively higher mechanical turbulence as the source of TKE (Fig. 11d). The hourly median BL height values from sunrise to early morning vary from about 110 to 250 m between 07:00 and 08:00 LST in the ShDeep regime (Fig 11f). For the ShCu regime, the median hourly BL height values vary from around 110 to 200 m, suggesting that the onset of convective BL is earlier in the ShDeep composite regime than in the ShCu composite regime. The BL height evolution exhibited in both regime composites is consistent with the evolution observed in the case studies during the morning transition.

The statistical analysis is in agreement with the conceptual model developed based on the case studies, even do not considering convection over the T3 site. The pronounced feature that emerges from this analysis is the clear difference between the two regimes for IWV and VWS and the BL height. This impact in the time needed to eliminate the nocturnal stable BL inversion used to promote convection having important effect in characterizing the convective strength in the morning transition stage and the rapid growth stage. This energy of BL growth is in agreement with the large, positive BL disequilibrium values on ShDeep days and the mostly negative BL disequilibrium values in early morning on ShCu days showed by Tian et al. (2021). Therefore, the enhanced water vapor at low and mid-level is important not only for the initiation of deep convection in the cloudy mixing layer stage but also for the characterization of the cloud-BL interaction from the stable to the rapid growth 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.



. Figure 11. Box-and-whiskers plot of (a) IWV$_{2\ km}$ during the stable, morning transition, and cloudy mixing layer stages, (b) VWS$_{2\ km}$ 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.

2. The impacts of humidity on the development of convective clouds have been intensively investigated in previous studies (e.g., Zhang et al. 2010, 2013). The authors need to address the differences in their findings comparing to previous studies. Thank you for the suggestion. We added references to the text. Also, we added the recent GoAmazon work about diurnal cycle of clouds of Tian et al., (2021) which expands the previous classification of Zhang and Klein (2010,2013) based on US Southern Great Plains to GoAmazon main site. This new classification of ShDeep events was used to provide statistical analysis (e.g. New Sec. 4) of our conclusions which is based in the cloudy-BL stages of conceptual model.

3. As a key parameter, this study discussed the positive role of sensible heat flux on shallow-to-deep convective clouds. However, strong sensible heat also can lead to strong entertainment at the boundary layer top, which would induce dry air masses into the boundary layer. Thus, sensible also may negatively affect cloud development. Moreover, besides the impacts of sensible heat on cloud development, clouds can significantly alter sensible heat. Thus, this issue needs to be discussed more carefully. We agree. We added the information to the text about sensible heat flux on clouds and entrainment during the ShCu and ShDeep conditions:

   Line 315-321 "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 driving a higher growth rate of the BL in the morning transition stage than on ShCu days. At the cloudy mixing layer stage, for ShDeep days, clouds affect the surface sensible heat flux, either positively by increasing the sensible heat flux due to processes associated with the arrival of the gust front or negatively by diminishing the sensible heat flux due to the transport of cool air from aloft into the BL (e.g. Oliveira et al., 2020). On the other hand, the large sensible heat flux during the cloudy mixing layer stage on ShCu days may be a response to BL turbulence and more entrainment of dry air from the free tropospheric into the BL (that drives more sensible heat flux)"

   Line 345-349 [...] "While on ShCu days, the surface specific humidity is maximum around 08:00 LST followed by a drying throughout the rapid growth stage and cloudy mixing layer stage of around 2.0 g kg^{-1} until the sunset, followed by a later maximum at 19:00 LST. These findings are consistent with those of Zhang and Klein (2013), where a large sensible heat flux during the cloudy mixing layer were observed to contribute to greater entrainment of dry air into the BL in ShCu in the SGP site.

4. Some variations in the meteorological data may not cause by natural variability, but due to the instrument deficiency. In Figure 4-5, some signals seem a little bit noisy. In Figure 4f, there are some sharp decreases in sensible heat during the daytime. The authors may clarify these odd variations.

We agree that some plots of Fig. 4 and Fig. 5 in the same panel seem to have more variability. This variability is due to the different time interval resolution used in the plot, such as 1 min for the surface meteorological system and 30 min for ECOR. However, we do not believe that it is due to instrument deficiency since, for the analysis, we have used all good-quality flagged by the ARM user facility. To clarify this point, we have changed the time interval of the surface meteorological system by 30 min on average since it does not alter the results of our discussion. Thus, we have updated and replaced Figures 4-5.

References

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, e2020JD032 550, 2020.

Edwards, J., Basu, S., Bosveld, F., and Holtslag, A.: The impact of radiation on the GABLS3 large-eddy simulation through the night and during the morning transition, Boundary-layer meteorology, 152, 189–211, 2014.

Ghate, V. P. and Kollias, P.: On the Controls of Daytime Precipitation in the Amazonian Dry Season, J. Hydrometeorol., 17, 3079–3097, https://doi.org/10.1175/JHM-D-16-0101.1, 2016.

Giangrande, S. E., Wang, D., and Mechem, D. B.: Cloud regimes over the Amazon Basin: perspectives from the GoAmazon2014/5 campaign, Atmos. Chem. Phys., 20, 7489–7507, https://doi.org/10.5194/acp-20-7489-2020, 2020.

Oliveira, M. I., Acevedo, O. C., Sörgel, M., Nascimento, E. L., Manzi, A. O., Oliveira, P. E., Brondani, D. V., Tsokankunku, A., and Andreae, M. O.: Planetary boundary layer evolution over the Amazon rainforest in episodes of deep moist convection at the Amazon Tall Tower Observatory, Atmos. Chem. Phys., 20, 15–27, https://doi.org/10.5194/acp-20-15-2020, 2020.

Tian, Y., Zhang, Y., Klein, S. A., and Schumacher, C.: Interpreting the diurnal cycle of clouds and precipitation in the ARM GoAmazon observations: Shallow to deep convection transition, Journal of Geophysical Research: Atmospheres, 126, e2020JD033 766, 2021.

Zhang, Y. and Klein, S. A.: Factors controlling the vertical extent of fair-weather shallow cumulus clouds over land: Investigation of diurnal-cycle observations collected at the ARM Southern Great Plains site, Journal of the Atmospheric Sciences, 70, 1297–1315, 2013.

Zhuang, Y., Fu, R., Marengo, J. A., and Wang, H.: Seasonal variation of shallow-to-deep convection transition and its link to the environmental conditions over the Central Amazon, J. Geophys. Res. Atmos., 122, 2649–2666, https://doi.org/10.1002/2016JD025993, 2017.