Reply to Reviewer 1

Major comments

Reviewer says: *1) My main comment, which needs to be addressed before publication is due to methodology. Section 4, which is the main results section investigates turbulent fluxes and TKE during the passage of storm systems. However, I am not convinced that the data during these episodes is reliable and supports the conclusions. During rain events or with water on the transducers CSAT3 do not work very well. While light rain may be acceptable, during heavy rain (>3 or so mm/h) sonic anemometers generally produce no accurate readings. There may also be an issue with vibrations of sensor mounts and tower that affects measurements during storms. For example I find the reported values of TKE (increase by factor of ~50 during passage of cells) and H (up to -800 W/m2) questionable/ unrealistic. Can values like this be supported from the literature. The methodology does not mention any kind of data quality assurance. For example, the authors should look at turbulence spectra to check whether these look OK and eliminate data observed during rain events or during periods when sonic transducers are likely wet.*

Reply: This is a valid concern. This issue needs to be addressed to give the readers confidence in the results. We are confident in them, and these are the main reasons:

i. Precipitation was never large. Total precipitation along the entire duration of the events was 2.3, 1.0, 5.3 and 1.5 for events 1 to 4 respectively, therefore only in event 3 exceeding the limit mentioned by the reviewer for "heavy rain". We are now including this fact in the text and adding the plot below, showing precipitation evolution along each event, as a supplementary figure.

ii. Nevertheless, it did rain in all cases and there is also the issue raised by the reviewer regarding vibration of the mounts and tower. To address that, and following the suggestion from the reviewer, we plotted TKE spectra and heat flux cospectra for the 4 different portions of events 1 and 2: before the gust front (I); the period of upward heat flux that marks the gust front arrival (II); the period of large downward heat flux that corresponds to enhanced storm-generated turbulence (III) and the wake period after the event (IV). This is only done for events 1 and 2, because these are the cases when these periods can be easily identified. The plots are shown below (Figs. $R_1$2 to $R_1$5). It is clear that the TKE spectra and heat flux cospectra are, in all cases, well-organized, tending to zero in the high-frequency limit, indicating that there is reduced levels of noise. Besides, the upward or downward fluxes happen over the entire range of turbulence scales, being well organized vertically as well. It gives us a high degree of confidence in our dataset. These plots have also been included as supplementary material and a discussion referring to them has been included in the main text. In Figs. $R_1$6 and $R_1$7, the raw velocity and temperature turbulent data from events 1 and 2 are also shown, indicating the absence of spikes and random fluctuations. They have also been included as supplementary material. Paragraphs explaining that the data quality analysis is shown in the supplementary material have also been added to the main manuscript.

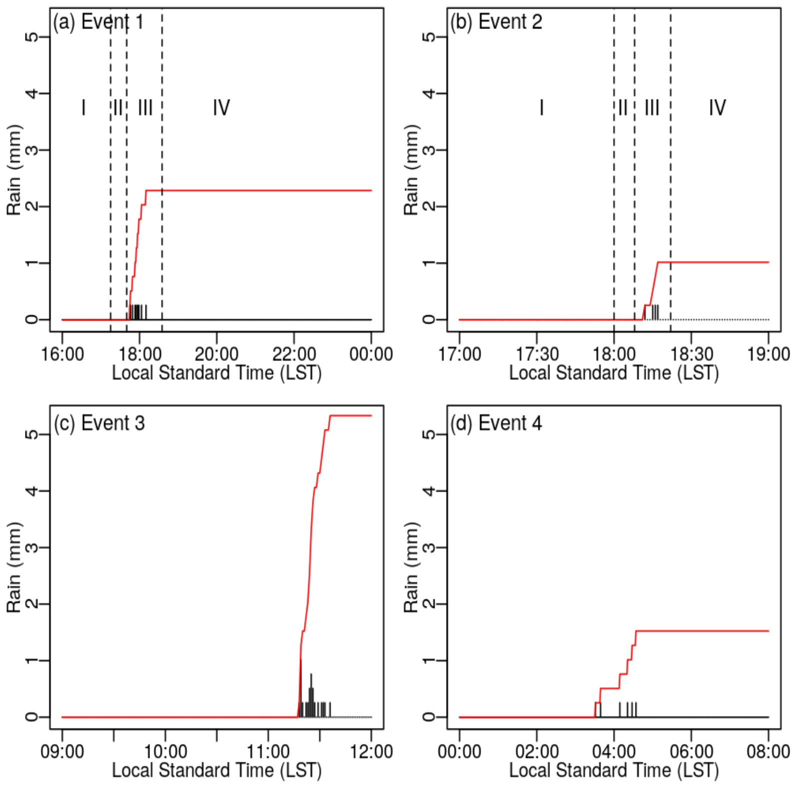

Fig. R$_1$1. 1-minute and total precipitation for each event.

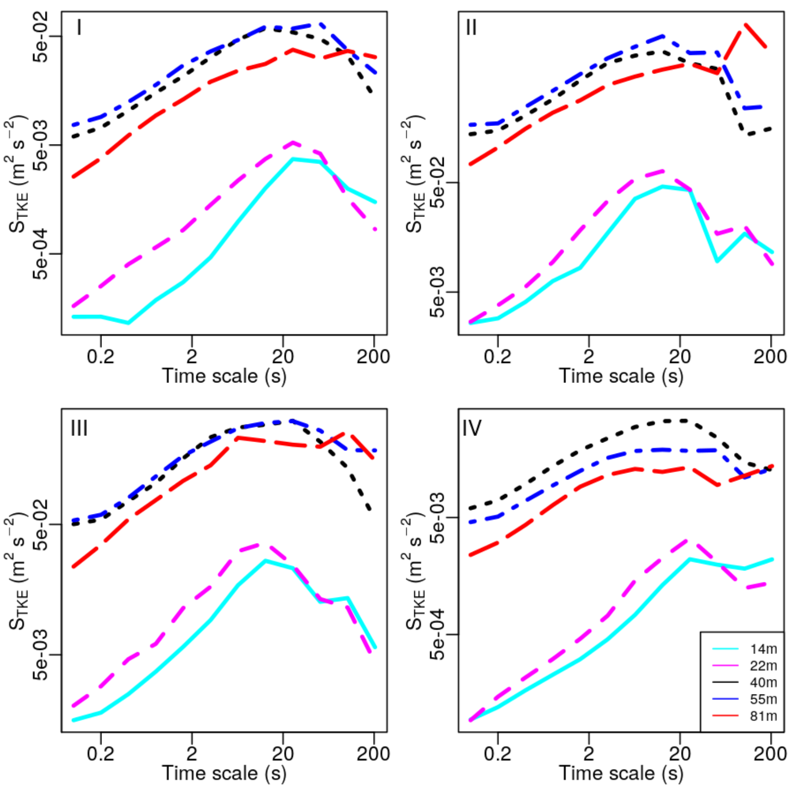

Fig. R$_1$2. Multiresolution TKE spectra for the 4 periods of event 1.

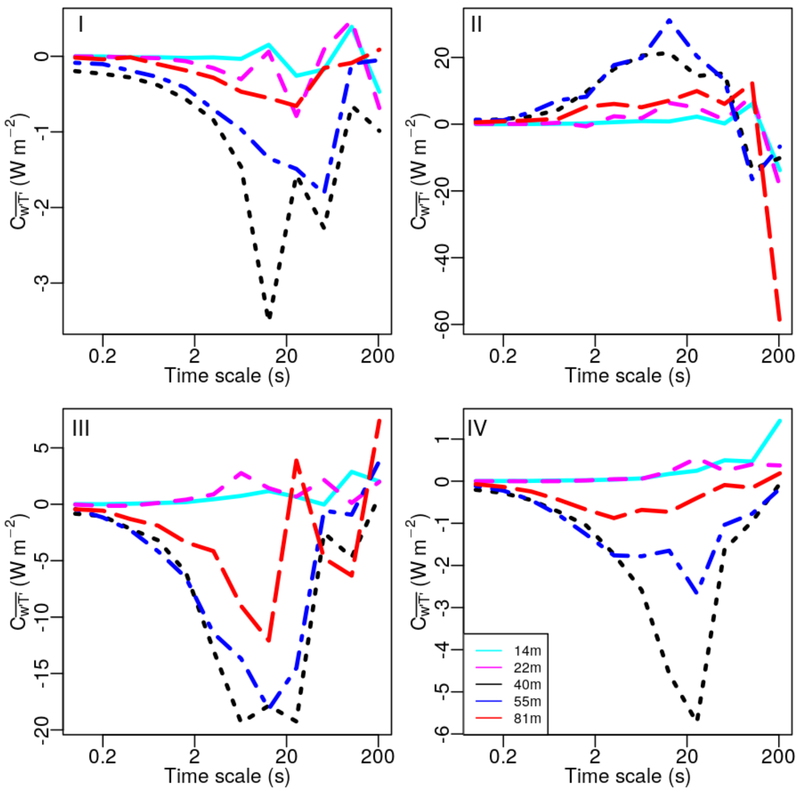

Fig. $R_1$3. The same as in Fig. $R_1$2, but for heat flux cospectra.

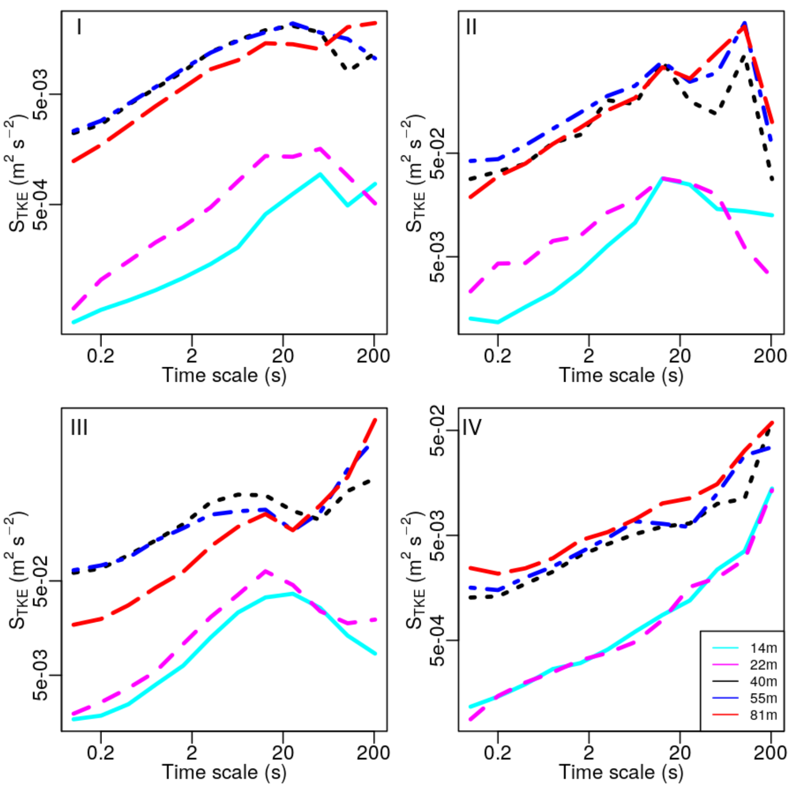

Fig. $R_1$4. The same as in Fig. $R_1$2, but for event 2.

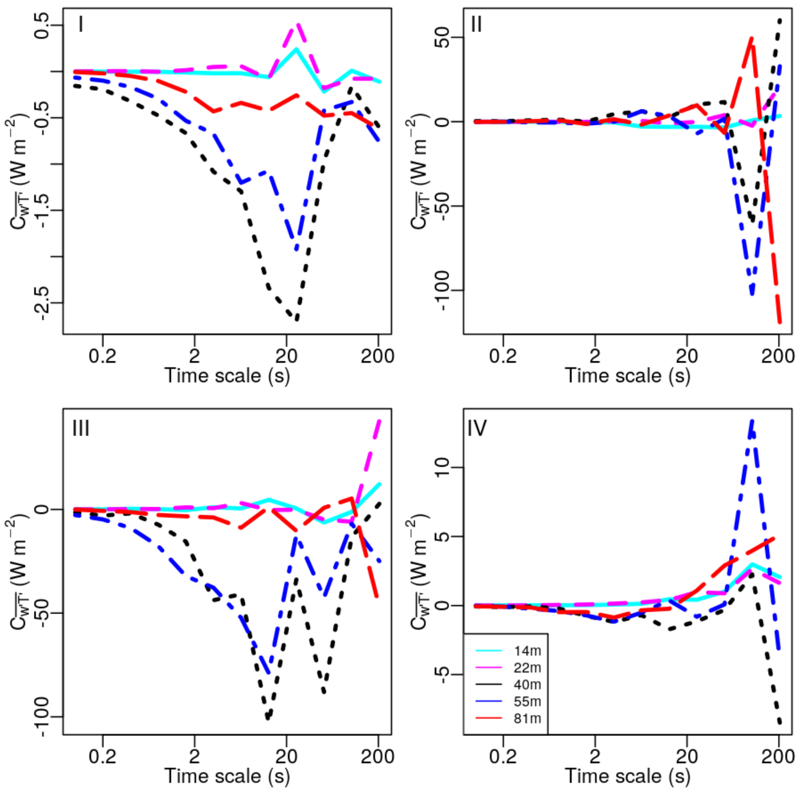

Fig. R$_1$5. The same as in Fig. R$_1$3, but for event 2.

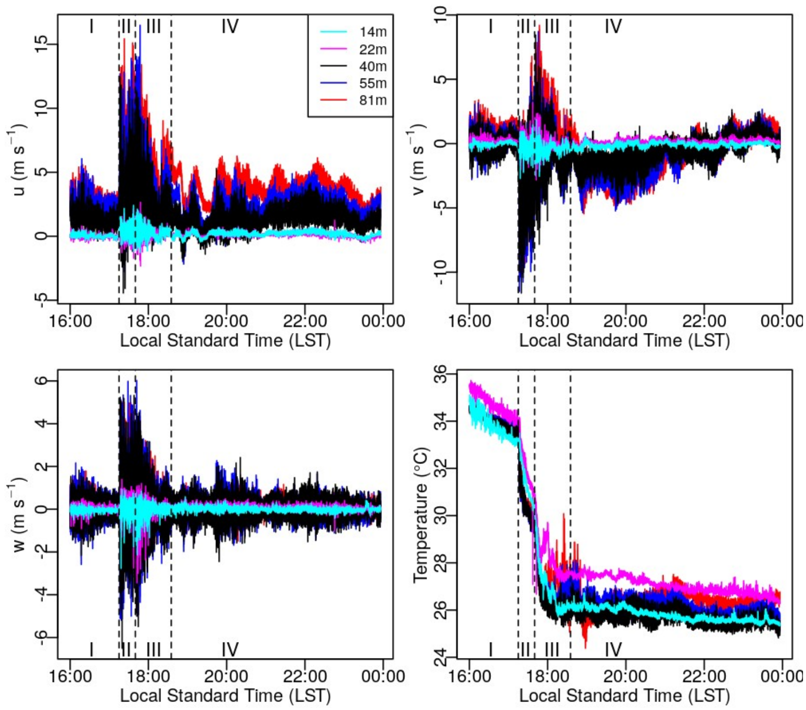

Fig. R$_1$6. Time series of the velocity components and temperature along event 1.

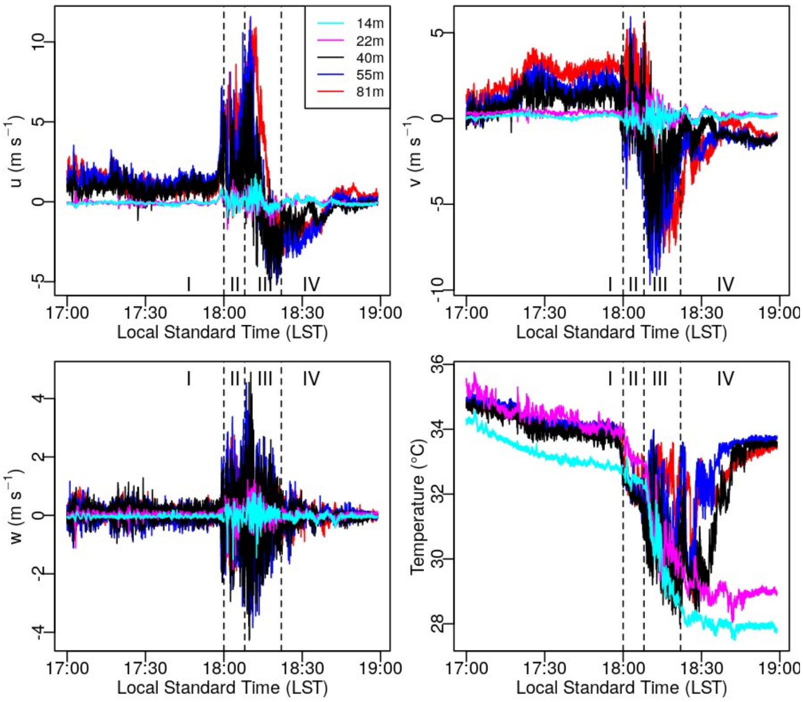

Fig. $R_1$7. Time series of the velocity components and temperature along event 2.

iii. Regarding the large observed values of both TKE and heat flux, it is important to stress that these values refer to transient events, and they have been determined using 1-min time windows. The spectra and cospectra shown in Figs. $R_1$2-5 show that this time window captures the majority of the turbulent fluctuations. Transient events such as these may, indeed, have very large magnitudes, and still be genuine. Certainly, the average flux determined over a more typical 30-min window in would have a much smaller magnitude in these cases, but it would miss all the dynamics of the event passage. There are previous observations from the literature that support these values. Hohenegger and Bretherton (2011) reported observed values of PBL-averaged TKE during cases of deep convection in ARM and KWAJEX experiments. TKE values that exceed 10 m^2/s^2 are common during cases of deep convection. We have not found published observations of vertical sensible heat fluxes as large as those we are reporting, but this is precisely one of the main objectives of the paper: to report this type of observations for the first time. However, in a previous study of our group, we reported similarly high transient fluxes of sensible heat in the horizontal direction, this time caused by the advance of an air mass with distinct characteristics along the surface of a river (Acevedo et al., 2007). Besides, we also have observations taken during GO-Amazon project that show heat flux evolutions and magnitudes that are similar to those being presently reported (Fig. 6.2 in Oliveira (2017), in Portuguese). This is the Doctorate thesis of one of the coauthors, Pablo Oliveira, where these GO-Amazon events have also been simulated using a simple column model that uses K-theory to predict the fluxes, indicating that the very large thermal gradients and wind speeds observed during the transient events may indeed drive very large fluxes, although for a very brief period. TKE is also very large in these observations, reaching 12 m^2/s^2.

Reviewer says: *2) The paper presents 4 events (mostly with time series of theta, U and other variables during the course of the event), but it is not clear to what extent atmospheric behavior during these events is generalization. Are these events the norm, or are they unusual. I feel that this severely limits the knowledge that can be gained from this work.*

<u>Reply</u>: Yes, the reviewer is correct. We have added the following sentences at the end of the conclusion to make it clear that we are not claiming that the results are general:

> Despite the consistency found among the events analyzed, it is important to stress that the study is based on a reduced number of events (4) and that a more detailed analysis with a larger number of cases is necessary to validate the conclusions. They will be possible along ATTO project, when continuous turbulence observations will be available from the surface to 320 m.

Reviewer says: *Specific: P2L12: "Much of the knowledge on the effects of DMC on PBL evolution has been gained from research based on the GARP" > I suggest to modify this statement, as it sounds as if this experiment delivered a majority of knowledge on the topic.*

<u>Reply</u>: Yes, the reviewer is correct, although we believe GATE was extremely relevant in the early developments on the field. We reworded it to "*Much of the initial knowledge on the...*"

Reviewer says: *Section 2.1: Given that the study concerns DMC, the authors should expand here on their treatment of periods with rain. Rainfall and water on CSAT3 transducers impacts turbulence measurements. How was this dealt with? Are there any longer datasets available? For example, the work described in Fuentes et al has 9 levels of turbulence between 0.5 and 55 m and data is collected for _ 1 year.*

<u>Reply</u>: The issue regarding rainfall has been addressed in the reply to major comment (1), above. The dataset used in this paper comes from an Intensive Operating Period (IOP) at the ATTO site. This was carried out before most of the instruments were deployed for the continuous measurements (scheduled to happen in the upcoming months). Although data from the GO-Amazon project could be used for comparison, it has not been done. It presently focuses on case studies, and for this purpose the ATTO IOP dataset has the advantage of a deeper vertical coverage as compared to GO-Amazon. Such a comparison is certainly a good idea for future work.

Reviewer says: *P4L3: "The study period extended from 29 October 2015 to 20 November 2015" I have a question regarding the study period. I know that this site is used extensively for research (mainly Atmospheric Chemistry). I am a bit surprised that there is only 1 month of data available for turbulence measurements. Could the authors elaborate on the deployment of the CSAT3s.*

<u>Reply</u>: As mentioned previously, the dataset correspond to an IOP carried out in 2015. As of October 2019, the full micrometeorological instrumentation have not yet been deployed, and the continuous observations are scheduled to start early in 2020. Although some levels have operated continually for a long time, it is only during this IOP that there has been multiple CSATs operating simultaneously. In reply to comment 2, above, we have added a sentence stating the relevance of the upcoming continuous measurements for the generalization of the present results. It has also been added to the manuscript that the period of observations corresponded to an IOP.

Reviewer says: *P5L9: "Following the aforementioned procedure, four DMC events were selected for investigation" It would be good if the authors could provide some measure of how many systems there were in total. I understand that this work more or less presents case studies, but I feel some quantification of events should be done.*

Reply: The 4 cases described are the only occurrences found during the IOP. As described in the manuscript, "*Only storms that produced detectable impacts on the evolution of meteorological variables at the tower site were selected.*"

Reviewer says: *Table 1: Are there other measures that could be included, such as cloud brightness temperature/ cloud top height or precipitation to get a sense of the strength. The Table caption should indicate where Vh and theta_v where measured, as well as location of RAOBS.*

Reply: Total precipitation for each event has been included to the table.

Reviewer says: *LP6L18: "In this situation, the establishment of a shallow, cool near-surface stable layer occurs earlier than it would be the case for a typical undisturbed diurnal cycle." > This may or may not be true, but 18 LST is roughly the time of sunset, so I am not sure to what extent this really constitutes and "early nightfall" because from this work, we don't know what the normal transition looks like.*

Reply: The reviewer is correct for the cases shown when the event happens near 1800 LST, but the idea is still valid for earlier events. For that reason, we reworded the sentence to "*In this situation, the establishment of a shallow, cool near-surface stable layer may occur earlier than it would be the case for a typical undisturbed diurnal cycle.*"

Reviewer says: P6L30: *"As the gust front impacted the tower after sunset, an early nightfall effect was also observed, similar to event 1." I don't understand this. I thought an early nightfall means that there is no recovery since there is no additional energy input in the system that can lead to recovery, but this Figure 3b does show that theta recovers.*

Reply: It is a valid point. The sentence has been removed.

Reviewer says: *P7L8: "very stable stratification" > can this be quantified. if not, I suggest to remove the "very"*

Reply: "Very" has been removed from the sentence.

Reviewer says: *P8L2: "An "attempt" of a recovery phase was observed as a slight increase in theta_v around 04:00" > I don't find this very convincing. What is different at 4:00 to lets say 5:00.*

Reply: It is not much different, but the first "attempt", at 04:00 was longer and had a larger change in θ_v, being therefore mentioned.

Reviewer says: *Figure 3d: Why does theta_v at 55m and 40m behave so differently, between 3:30 and 5:00. Can you make sure that this is not an issue with the data.*

Reply: The data at 40 m were, indeed, faulty. This line has been removed from the plot.

Reviewer says: *Section 4: I feel that there are very likely methodological issues with this section. We know that CSAT3 analyzers don't work well during (strong) rain. Also, storms might introduce vibrations to tower and sensor mounts that affect 'observed' H. In summary much care needs to be taken to make sure that the findings in this section are robust. I feel that the increase in H is consistent with the cooling of the air and a surface response. At the same time, I find sustained fluxes of -800 W/m2 for several minutes surprising (Figure 4b). Especially since before and after the passage of the front, fluxes are +/- zero. I would feel much more confident, if the authors could back up their findings with a comparison to H fluxes observed during other studies. Also if fluxes are integrated to 30 minutes (which is the conventional standard). Do they make sense? This problem affects Figures 4,6,7 as all these rely on data from the CSAT3s. One indication of issues with the data is for example, that Vh changes from ~3-4 to 10m/s (factor of 3) during the passage from the first storm, but observed TKE goes from 0.1 (?) to 6 m2/s2, which is a factor of 60. I am don't think that this is real.*

Reply: This issue has been addressed in the reply to major comment 1, above.

Reviewer says: *Technical: P2L10: "into the surface" > "into the ABL" or "towards the surface" P3L8: "engender the venting" > affect the venting P4L34: "BLIS" > consider writing out for readability. I had already forgotten what BLIS stood for and had to look it up. P6L17: "an effective" > this does not work very well in English (since it sounds as if the nightfall is effective" Maybe: "a situation akin to an early nightfall" ?*

Reply: Done.

REFERENCES:

Acevedo, O.C., O.L. Moraes, R. da Silva, V. Anabor, D.P. Bittencourt, H.R. Zimmermann, R.O. Magnago, and G.A. Degrazia, 2007: Surface-to-Atmosphere Exchange in a River Valley Environment. J. Appl. Meteor. Climatol., 46, 1169–1181, https://doi.org/10.1175/JAM2517.1

Hohenegger, C. and Bretherton, C. S.: Simulating deep convection with a shallow convection scheme, Atmos. Chem. Phys., 11, 10389-10406, https://doi.org/10.5194/acp-11-10389-2011, 2011.

Oliveira, P. E. S. (2017) Estudo da turbulência atmosférica na floresta Amazônica - análise de dados micrometeorológicos e modelagem numérica (Doctoral dissertation). Available at http://repositorio.ufsm.br/handle/1/14596