Interactive comment on "Friagem Event in Central Amazon and its Influence on Micrometeorological Variables and Atmospheric Chemistry" by Guilherme F. Camarinha-Neto et al.

Anonymous Referee #2

We would like to thank all the reviewer's comments. Our answers are in blue font and part of them were added to the manuscript.

General comments: The manuscript studies a Friagem event during July 9 - 11, 2014 in the central Amazon region and its influences on the micrometeorology variables, local circulation, as well as the trace gas concentrations. The investigation of a cold front in the central Amazon is a relevant subject for research in current days. Using the reanalysis and the satellite data, the manuscript demonstrates the propagation of the cold front and the convection on Jul 11, 2014. The second main component of the paper is to understand the event mechanistically and its influences with the local circulation by simulating the cold front. The third component is to explore the influences of this front on the temperature and the trace gas concentrations. I trust most of the results regarding the meteorological part such as the occurrence of the cold front and its link to the convection on Jul 11. I feel the weaknesses of the manuscript is the depth of discussion and the interpretation of the chemistry part.

(1) The cold front has a lifetime of 3 ~ 5 days as presented in the manuscript, while O3 has a much shorter lifetime. It is tricky to quantitively define the influences of the cold front on O3 directly due to their different timescales. Specifically, the authors suggest that the cold pool arrives at ATTO on July 9-11. However, **(2)** the O3 mixing ratios are affected on the 9th and 11th by convective systems, not on the 10th. **(3)** To me the O3 concentrations are closely related to the convective systems not the cold pool necessarily. **(4)** In addition, the dry deposition and vertical mixing are heavily speculated to play a part in the O3 concentrations without actually being estimated.

We thank the reviewer for pointing this out. We will take the opportunity to better explain the results. We will answer in 4 parts:

(1) This is consistent with our argumentation!! From model results, we see higher O3 concentrations associated with the cold airmass entering from the south. We can show that the cold airmass is able to reach ATTO, but is not associated with high O3 anymore. The opposite is true its depleted from O3. In the manuscript we give the following explanation: “However, it should be noted that this mass of air rich in O3 did not reach the Manaus region and the ATTO-site. It is believed that the presence of the cloud cover in central Amazonia on 11th, July (Fig. 5), formed by the convergence of air (Friagem and Eastern winds), has an inhibitory effect on O3 formation (Betts et al., 2002). As O3 deposition prevails, a net loss of ozone is expected during transport under conditions of limited photochemical production. The rain forest canopy is a strong sink for ozone (Jacob and Wofsy, 1990; Fan et al., 1990; Rummel et al., 2007). Therefore, the low O3 mixing ratio in the Manaus region and the ATTO-site during the 11th July (Fig. 6-f) would be associated with cloudiness and prolonged transport over forested regions”. Flux measurements above amazon rainforests give consistently high deposition velocities of about 2 cm s^{-1} around noon (Fan et al., 1990; Rummel et al., 2007). Taking the a simple approach of deriving a lifetime of ozone with respect to deposition, i.e. deposition velocity divided by boundary layer height (Nguyen et al., 2015) gives for noon time conditions and a BL of 1000 m 13 hours and for 500 m of 7 hours, respectively.

(2) Actually on all 3 days when the Friagem event occurred in the Manaus region, clouds were present, as shown in Figure 1 of this document (July 9 and 10) and in Figure 5 of the manuscript (July 11). The presence of such cloudiness reduced incident short-wave radiation and O3 near the surface (Fig 10a and 10b of the manuscript). However, it was during 11th July when shortwave radiation suffered the greatest reduction, and therefore we used that day as a case study.

(a) (b)

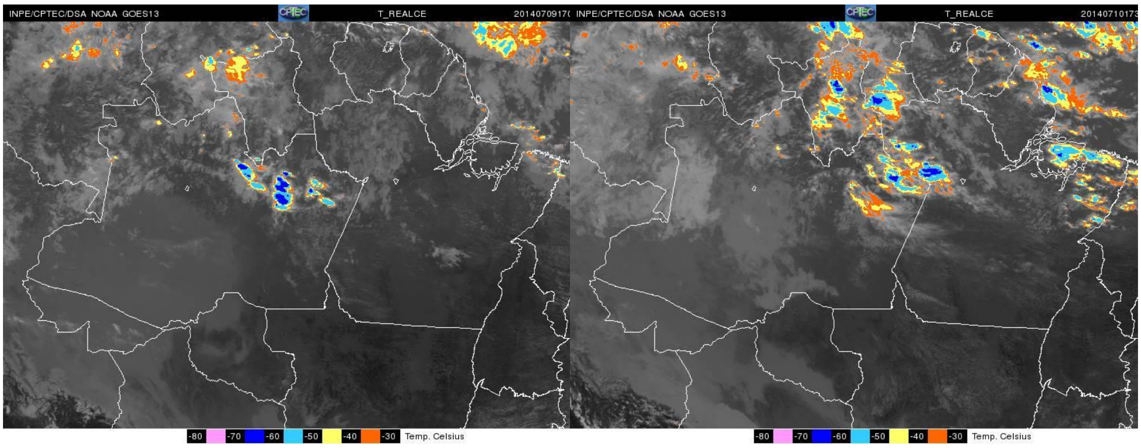


Figure 1: Enhanced images of the GOES 13 satellite in the infrared channel on: (a) July 09th at 17:00 UTC and (b) July 10th at: 17:30 UTC.

(3) We agree in parts with the reviewer. Fig. 6 of the manuscript and Fig. 4 of this document shows the values of the surface concentration of O3, obtained through ERA5, before (Fig. 6a) and during Friagem (Fig. 6b). It is possible to clearly notice that the Friagem (cold pool) carries high levels of O3 from the southwest to the central region of the Amazon. However, this air mass has its O3 concentration reduced as it approaches the surrounding region of Manaus (ATTO, T2, T3 and T0z). We believe that the cause of this reduction is the presence of strong cloudiness above this region (Fig. 5 of the manuscript), responsible for the reduction of solar radiation reaching the surface (Fig. 10a) and consequently a decrease in O3, as already highlighted in the manuscript (L: 175-184). Furthermore, a cold airmass occupying the lowest 500m of the BL was clearly identified on the 11th.

(4) The argumentation is not speculative because if we argue that photochemistry is absent just the transport and deposition terms of the budget equation remain. Furthermore, it has been shown for the Amazon rainforest that at “very low” NOx-levels (rainy season), the O3 budget is controlled by downward transport (i.e. vertical mixing) and deposition to the canopy (Jacob and Wofsy, 1990). Additionally, there is a small photochemical loss (Jacob and Wofsy, 1990). Due to increase cloudiness,

> this contribution will be also small in our case. For the dry season ("higher-NOx") O3 vales have been found to be mainly controlled by photochemistry and by deposition to the forest (Jacob and Wofsy, 1988). Again consistent with the argumentation, that if photochemistry is reduced due to increased cloudiness the deposition term will persist and increase loss of O3.

The referee is right that we do not provide numbers, but the observed phenomena are consistent with the argumentation. The argumentation that reduced vertical mixing is (at least partly) is responsible for very low O3 values refers to the situation on the 11th as with the largest drop in surface O3 at the same time large accumulation of CO2 (emitted by the forest) was observed. The large CO2 values are difficult to explain by the action of convective systems, but they fit to the reduced O3 values due to reduced vertical mixing (generally convective systems also increase surface O3 by downward transport). Furthermore, for the 11th there evidence from a) the wind field in the BRAMS model (fig 12a in manuscript), b) the potential temperature profiles of the BRAMS (Fig. 3 in this document) and the boundary layer height of just 500 m from ERA5 that there is a colder air mass (cold pool) near the surface (fig 12b in manuscript), that traps trace gases close to the surface.

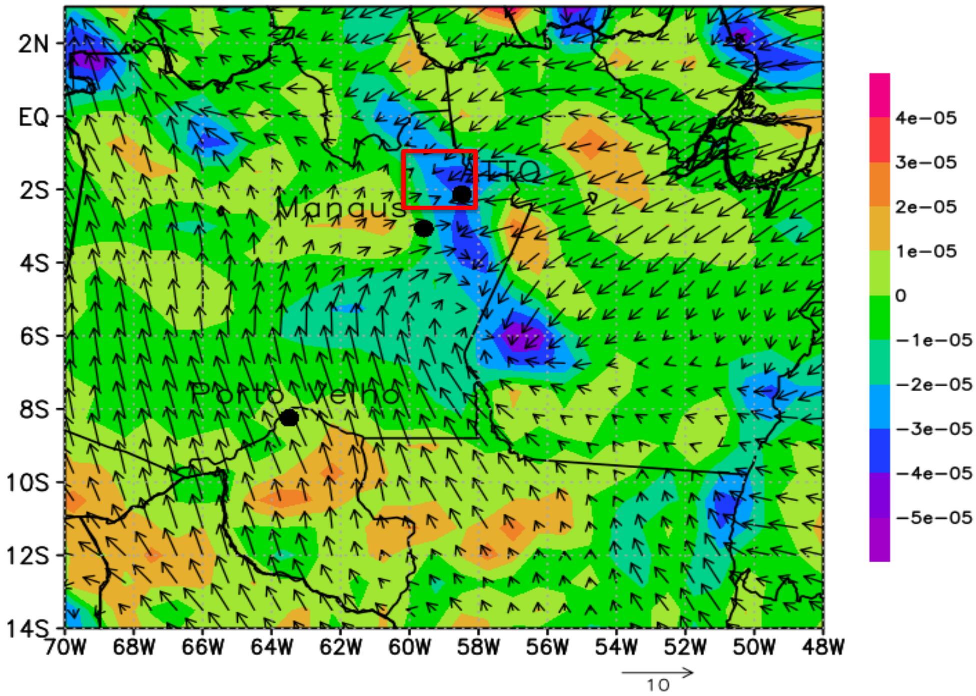
The general features of the cold front are clearly described in the manuscript such as the temperature drops and the trade wind is weakened, which accounts for the majority of the manuscript. However, the understanding and discussion of its mechanism is lacking. For example, **(1)** it is not clear how the cold front induces the convection on July 11 that affects the O3, and thus it's still unclear to what extent Friagem affects O3 in general without knowing its influences on inducing convections. **(2)** In addition, the cold pool and the subsequent weakened vertical mixing are not well demonstrated because of the lack of vertical profiles of meteorological variables. I believe these can be fixed by further exploring the model results.

(1) We believe that the arrival of Friagem in the central region of the Amazon (region around Manaus and the ATTO site) brings with it a layer of cold, dry air that meets the hot and humid air coming from the Eastern Amazon region (L152-158 of the old vertion of manuscript). This will favor the formation of convective clouds in this region. Marengo et al. (1997) draw attention to this effect (page 1565): "*Based on the observations of wind speed and direction and cloudiness, along with the air temperature data, it is suggested that cold-air advection is the main mechanism for cooling in Ji-Paraná where maximum and minimum air temperatures fell substantially and the sky remained cloud free. At Marabá and Manaus increased cloudiness (probably middle-level clouds or shallow cumulus), associated with the colds, meant that the cooling took the form of reduced maximum temperatures and reduced diurnal temperature range*."

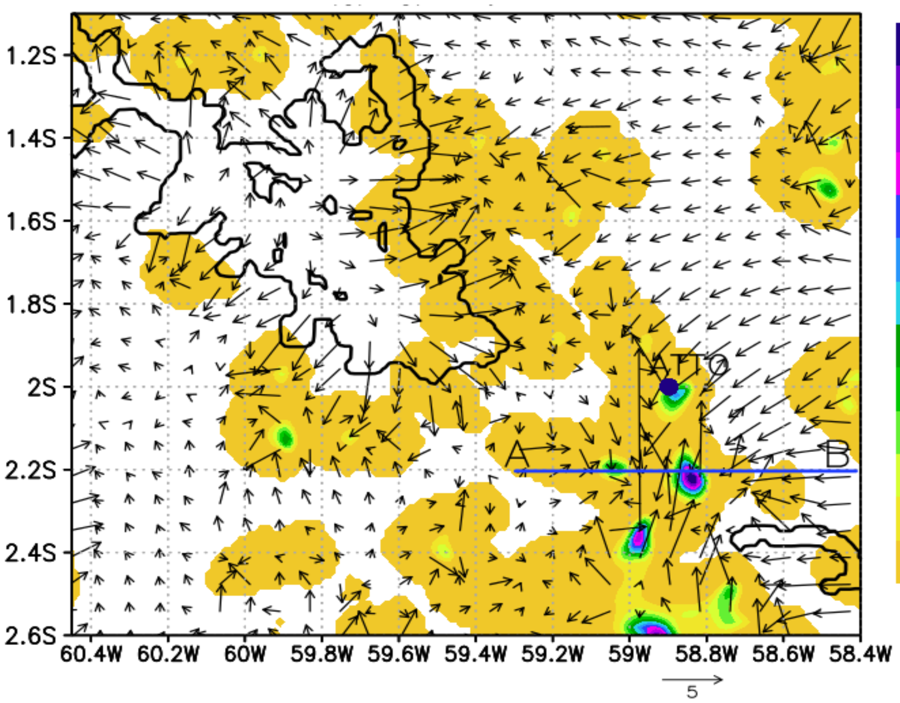
The satellite images (Fig. 5 of the manuscript) show the presence of clouds during the arrival of the Friagem at the ATTO site. With the help of the BRAMS simulations we will explain the formation of these clouds a little better. Fig. 3a of this document shows the divergence of the horizontal wind obtained by the reanalysis of Era5 on July 11th at 12UTC, where there is also a red square demarcating the area of the domain used in the simulation with the JULES-CCATT-BRAMS model. There is a band of convergence of the westerly and easterly winds, passing through the region of the ATTO site, where convective activity was also formed, as seen in Figure 5 of the manuscript. Fig. 3b shows the distribution of precipitation and the horizontal wind at 15:30 UTC on the 11th of July (simulated with the JULES-CCATT-BRAMS model). These results make it possible to visualize the circulation of the Lake Balbina breeze and some storms formed nearby of the ATTO site. In addition, even though the domain of the grid used in the simulation is much smaller than the area studied with the reanalysis, it is possible to observe the formation of the storms in the convergence of the southwesterly wind with easterly wind in the same way that was observed in Figure 3a . Fig. 3c (cross-section - line AB in Figure 3b) shows the behavior of current lines u, w together with rain water mix ratio. In the layer from the surface to the level of 1000 meters, the westerly flow converges with the easterly flow in the region where the mature convection is located.

We know that in the presence of solar radiation, volatile organic compounds (VOCs) and nitrogen dioxides (NO + NO2 = NOx), O3 is photochemically produced (Davidson, 1993; Wakamatsu et al. 1996; Gerken et al., 2016). Therefore, the presence of a large cloud cover in the central region of the Amazon, during the Friagem, reduced the arrival of solar radiation on the surface and consequently the surface concentrations of ozone (Fig. 11 of the manuscript).

a)



(b)



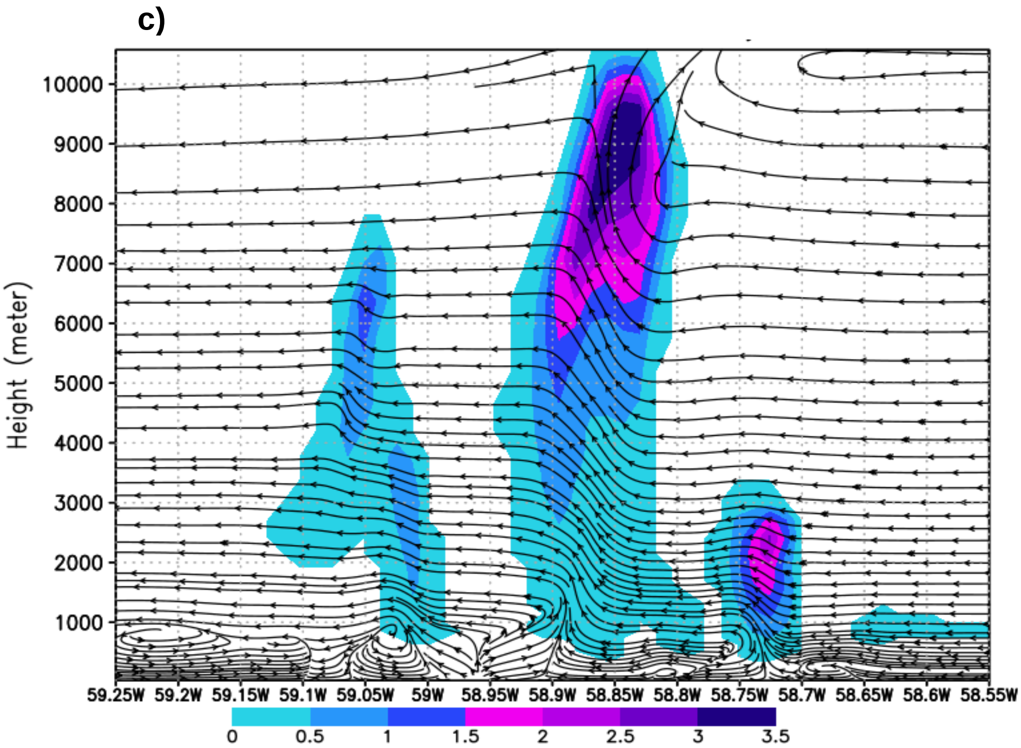


Figure 2. (a) Horizontal Wind (vector, m/s) and wind divergence (shaded, s^{-1}) at 975 hPa on July 11th, 2014 at 15:30UTC from ERA-interim reanalysis. The red square represents the domain used in model JULES-CCATT-BRAMS. (b) Horizontal distribution of rain water mix ratio (shaded, g/kg) and horizontal wind (vector, m/s) at 134.5 meters and (c) Vertical cross-section at 2.2°S (AB line in Figure 3b) showing the streamlines of u,w and liquid water content (shaded, g/kg) on July 11th, at 15:30UTC from simulation with JULES-CCATT-BRAMS.

(2) We believe that the West-Northwest and Southerly winds at low levels (up to approximately 500 m) and a boundary layer that did not exceeded 500 m (Fig. 12 of the manuscript) are already strong indications of the presence of a cold pool during the occurrence of Friagem. However, we are presenting Fig. 3 that shows the potential temperature profile simulated by JULES-CCATT-BRAMS for the ATTO site. It is possible to notice that in the afternoon of July 11th (the moment when the Friagem was most intense in the region) the potential temperature of the air layer located between the surface up to approximately 500 m is lower than the temperature of the layer immediately above (residual layer). That means that the presence of the cold pool was well captured by the BRAMS model.

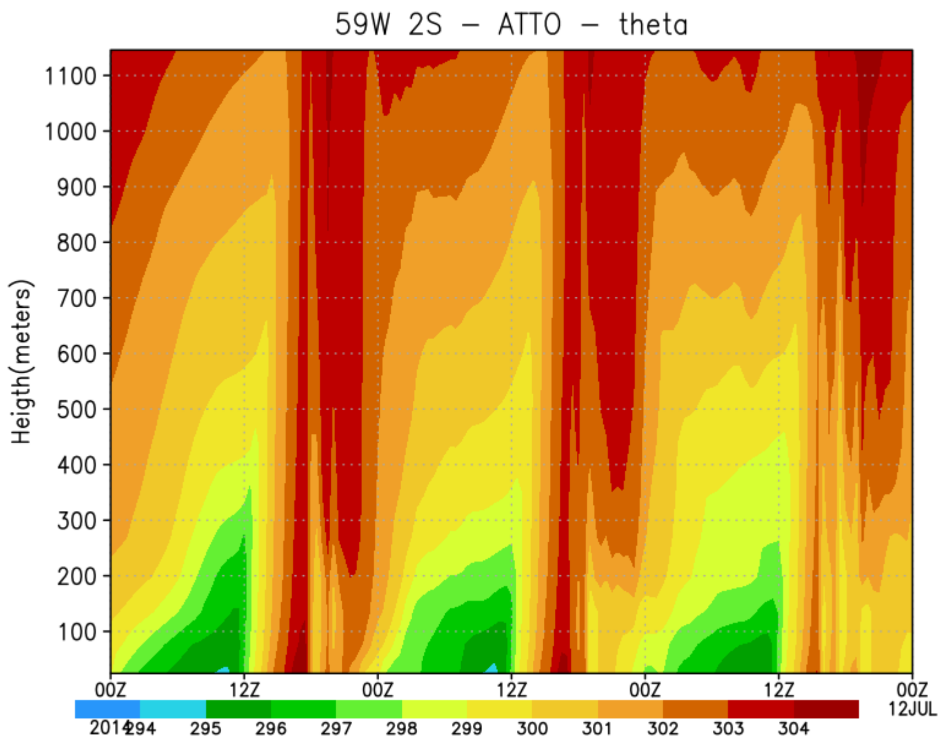


Figure 3: Potential temperature (shaded, K) profile from simulation with JULES-CCATT-BRAMS at ATTO site (2ºS,59ºW) on July, 6-11, 2014.

Major comments

1. Line 145: Figure 3 suggest that the changes in temperature are not that significant for Manaus and ATTO, somewhere within 2 degrees.

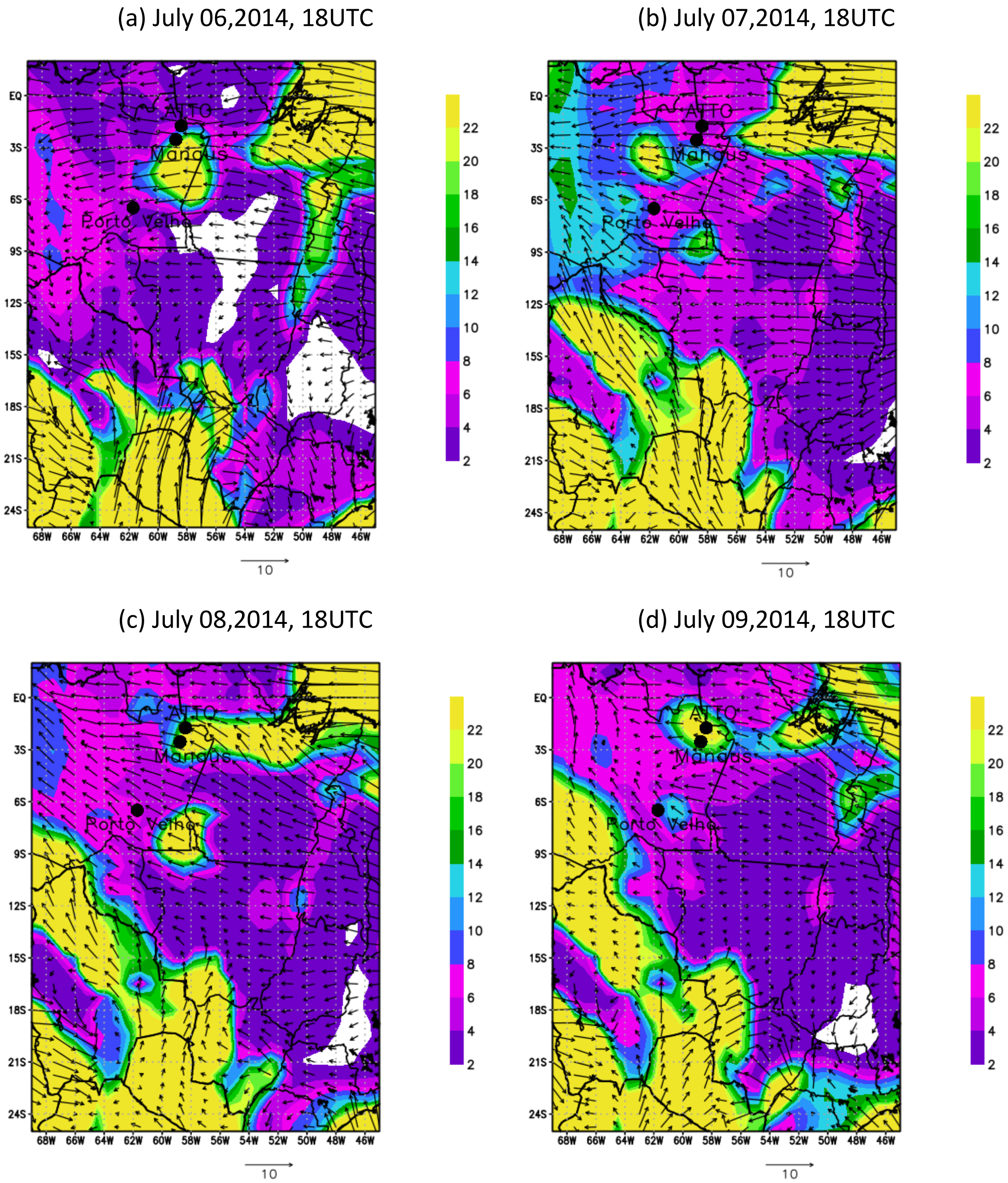
We agree with the reviewer that in Figure 3, where reanalysis data are shown, it is not possible to observe significant drops in temperature in the region of Manaus and ATTO (around 2 ºC), compared to the drop experienced in Porto Velho (around 6º C). We will rewrite the sentence in the new version of the manuscript (L155-157). However, in Figure 7 of the manuscript, the air temperature values measured experimentally in Manaus and at the ATTO site are shown, where it is noted that the decrease in air temperature was in also of the order of 4 ºC during the Friagem event.

2. Figure 4: Is the same data in Fig. 4 as in Fig. 3a and 3f? I wouldn't show the same data twice.

Figures 3 and 4 were merged into one (in the new version of the manuscript Fig.3)

3. Line 160 “carries air rich in O3”: What is (are) the source(s) of the O3?

We believe that Friagem carries O3 from the Southeastern region of the Brazil (very polluted) towards the Amazon region, as shown in Figure 4, through reanalysis data. We added a small comment on the manuscript (L172).



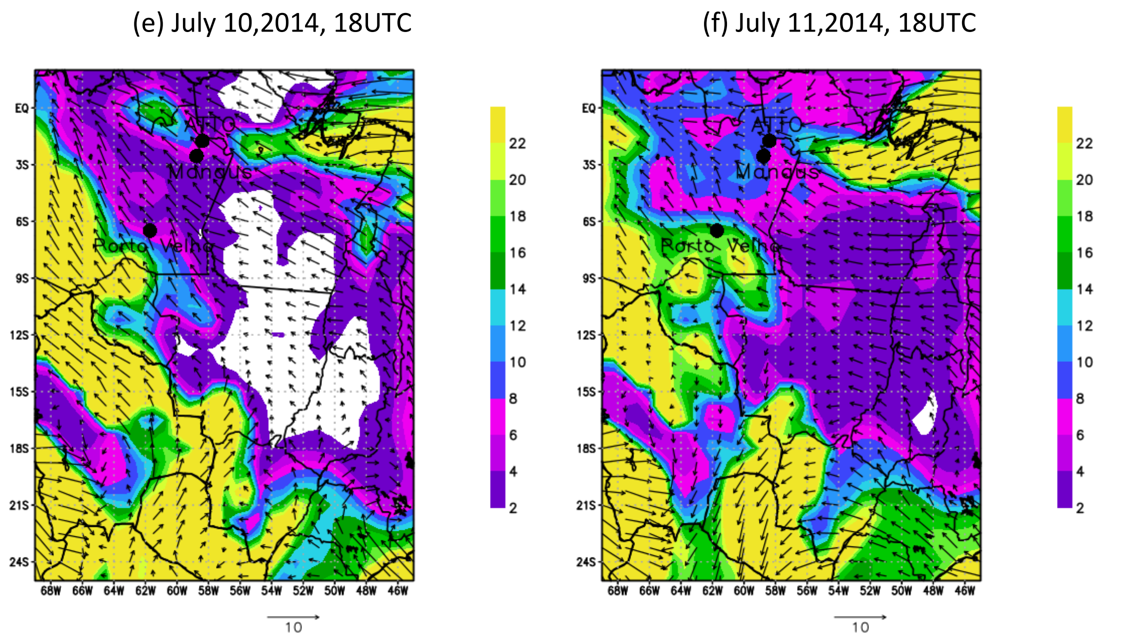


Figure 4.: - Surface wind (m s^{-1}, vectors) and ozone (ppbv, contour) on days 6-11, 2014 at 18 UTC, highlighting Porto Velho (P), Manaus (M) and ATTO site (A) obtained with the ERA-interim reanalysis.

4. Line 166-167: The chemical reactions with terpenes emitted by the forest might be important for O3 loss too. The estimate of the lifetime of the O3, which is a function of dry deposition and chemical reactions is needed for this argument "As O3 deposition prevails, a net loss of ozone is expected during transport under conditions of limited photochemical production".

The loss by chemical reactions with terpenes in the BL above the amazon rainforest has not yet been directly quantified (to our knowledge). The deposition velocities given are the net deposition and therefore not only consider dry deposition, but also within canopy chemical reactions (including terpenes). From own calculations (unpublished) and also literature (e.g. (Freire et al., 2017)) the contribution of terpenes for this layer is negligible. As Fluxes (from which deposition velocities were derived) were measured shortly above canopy (~ 40 m above ground level) the chemical reactions are just considered for the volume below this height. The loss of O3 by these reactions considering the whole mixed layer is therefore uncertain. One can argue that these compounds are emitted by the forest and therefore concentrations at ground level are highest and their contribution to O3 loss diminishes with height. Therefore, the above given estimates of the lifetime with respect to deposition should serve as qualified guess of the total loss rate.

5. Line 178-179: How the maximum air temperature is defined here? Seems like it is part of the diurnal cycles, which to me is not an appropriate metric for evaluating the intensity of the Friagem.

We would like to thank the reviewer for the opportunity to better clarify the role of Friagem on air temperature. Agreeing with the reviewer that the difference between maximum and minimum temperature is not an appropriate metric to define the temperature drop produced by a Friagem event. However, we would not like to associate intensity of the Friagem with a drop in temperature, as we believe that such intensity would be associated with several other parameters.

We will rewrite the sentence as follows:

"*At Porto Velho the difference between the maximum mean air temperature (maximum average daily cycle value) and the maximum air temperature during the Friagem (July 8th) was 7 ºC (from 31 to 24ºC), whilst in Manaus region and at ATTO the differences were in the order of 4 ºC (from 30 to 26 ºC and 29 to 25 ºC, respectively) during July 11th*." (L188-191)

6. Line 213-215: not clear. Clarify.

During the occurrence of the forest breeze towards Lake Balbina it would be expected that the wind direction would be from East-Southeast, and not from West or North, as noted in Fig. 9 of the manuscript.

We will added a short comment to the sentence clarify this (L230).

7. Line 228: Any explanations for the decreases in O3?

We believe that we have already answered this question in this document. In summary, we answered that the presence of heavy cloudiness around 13 LT (where maximum O_3 concentrations are expected) reduced the incident solar radiation (Fig. 10a) and therefore photochemical production of O_3.

8. Line 238-241: “did not result in an increase of near surface O_3”. I don’t necessarily agree with this. I think there is an increase in O_3 from roughly 6 ppbv to 10 ppbv. To validate if this increase is due to the convection, you can calculate the virtual potential temperature as in Gerken et al. (2016).

In the work of Gerken et al. (2016) the virtual potential temperature was not calculated, but equivalent potential temperature (θe). However, Dias-Júnior et al. (2017), used data from Manacapurú (T3, central Amazon) and showed that the correlation between the θe drop is not well correlated with the superficial increases in O_3 (Fig. 6 by Dias-Júnior et al. (2017)), during the occurrence of downdrafts. Also according to Dias-Júnior et al. (2017) a parameter that best represents the superficial increases in O_3 is a ΔCAPE (difference between the CAPE values immediately before the downdraft and the value after the downdraft). Unfortunately, we do not have data to enable us to calculate CAPE for the period investigated in this work for ATTO site.

9. Line 247 and 262: The vertical mixing can be evaluated by the vertical profiles of the virtual potential temperature.

We do not have temperature profiles for the data period used in this work. Figure 5 shows the virtual potential temperature profiles obtained from JULES-CCATT-BRAMS simulation. On 11th July the virtual potential temperature of the air layer located between the surface up to approximately 500 m is lower than the temperature of the layer immediately above (similar to that shown in Fig. 3), that is, the vertical mixing will be reduced in the presence of Friagen events.

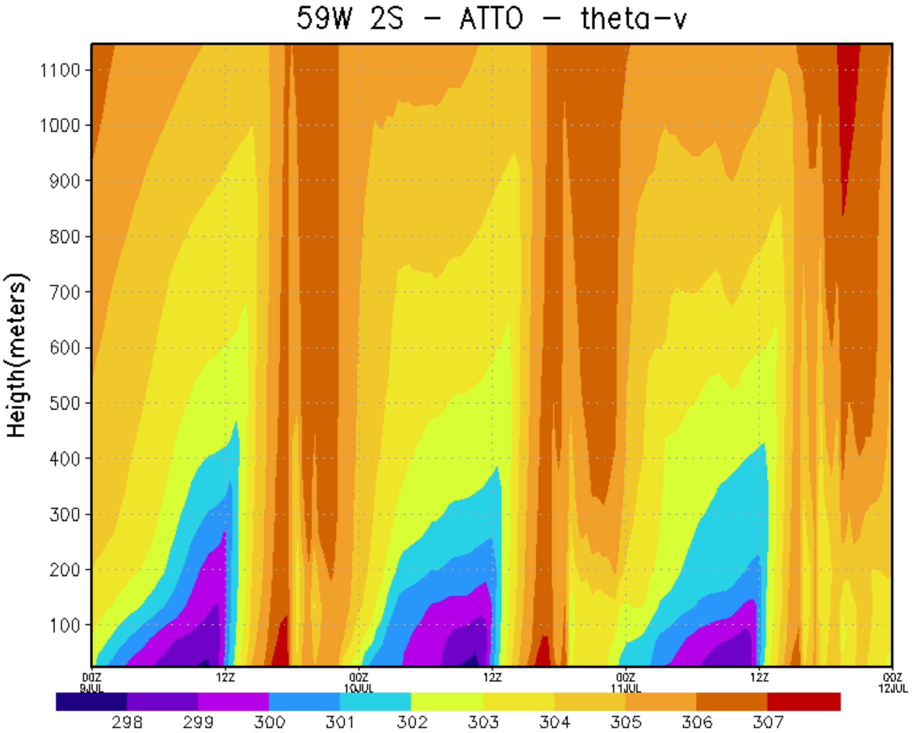
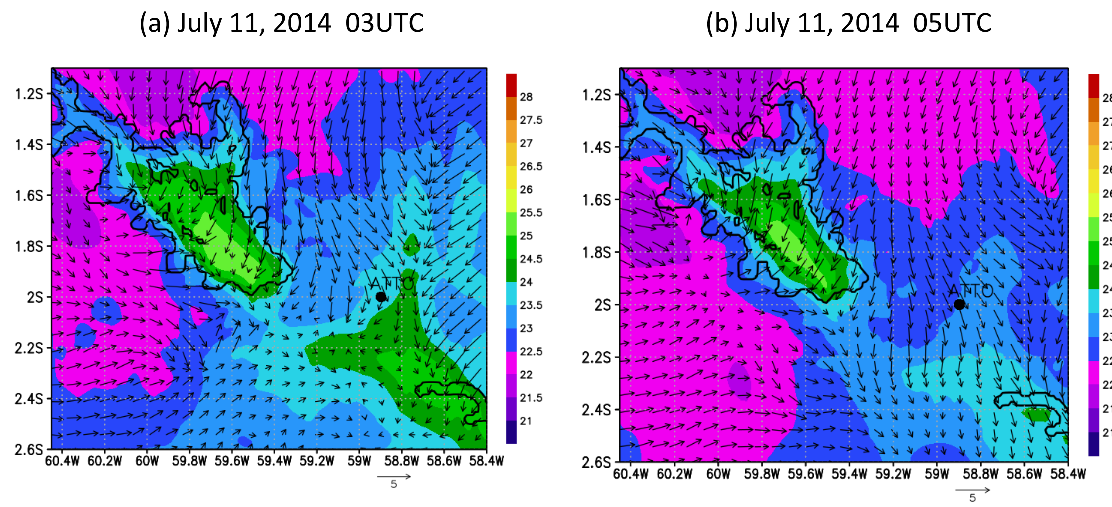


Figure 5: Virtual Potential temperature (shaded, K) profile from simulation with JULES-CCATT-BRAMS at ATTO site (2^{o}S,59^{o}W) on July, 9-11, 2014.

10. Figure 13: Why the temperature at 24.4 m is used? It is within the canopy if I understand correctly, which I think would be very different (presumably lower) from above-canopy temperature.

Thank you very much for the comments. The simulated figures at the height of 24.4 m were replaced by the simulated figures at the height of 76.8 m.



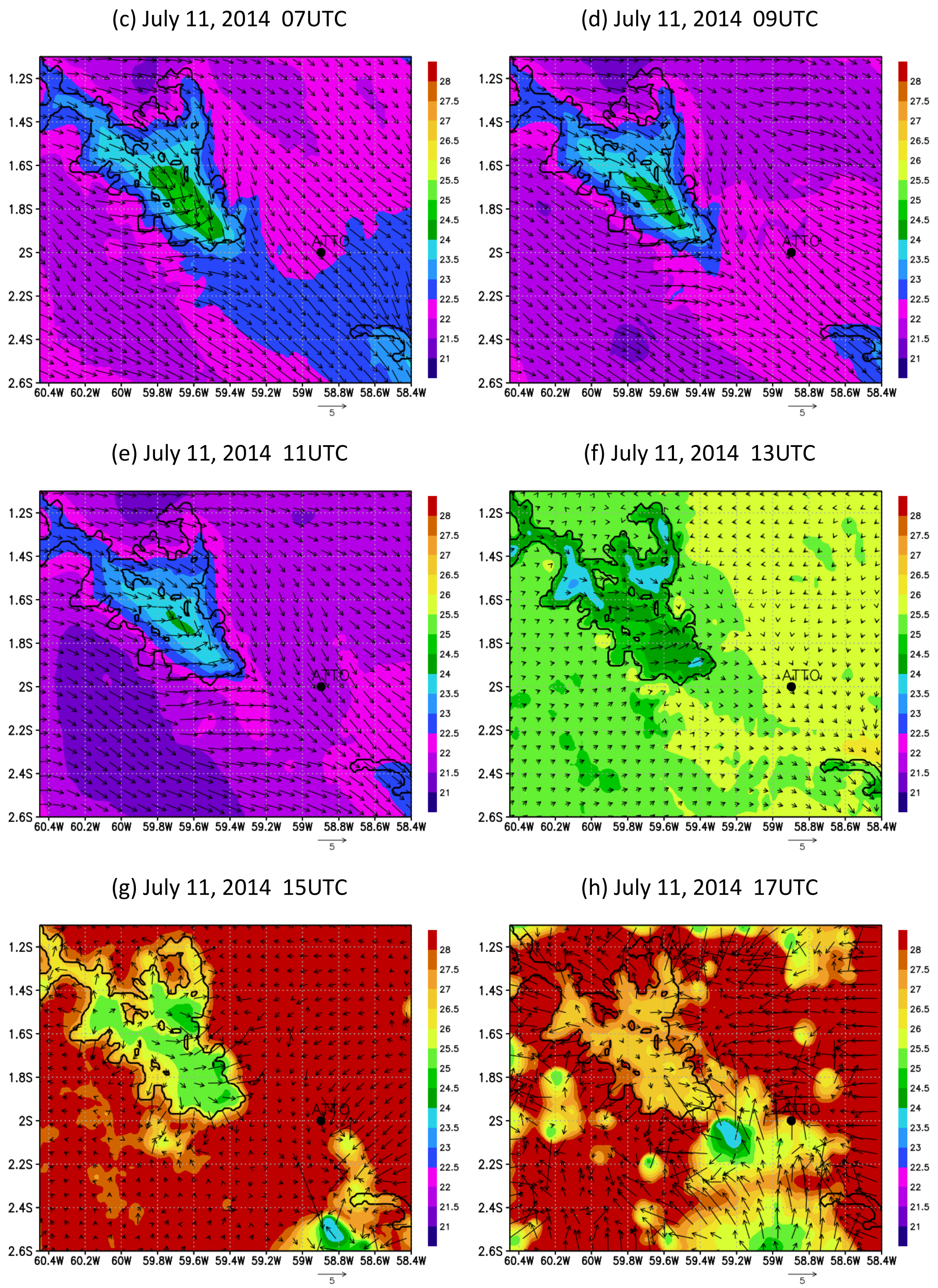


Figure 6: Evolution of air temperature (◦C, shaded) at 76.8 m and horizontal wind (m s−1, vector) at 134.5 m, on July 11th, 2014 at: (a) 03 UTC, (b) 05 UTC, (c) 07 UTC, 09 UTC, (e) 11 UTC, (f) 13 UTC, (g) 15 UTC and (h) 17 UTC. Balbina Lake (black contour) and ATTO site (black dot) are indicated.

11. How well the surface layer is represented by the JULES-CCATT-BRAMS model in general? How about in this study? Any comparisons between the modelled and the observations to evaluate the fidelity of the model for surface layer?

The formulations of the JULES surface scheme include dynamic vegetation, photosynthesis and plant respiration, carbon storage and soil moisture. The JULES surface scheme has been coupled to the CCATT-BRAMS modeling system using an explicit scheme. This coupling is two-way in the sense that, for each model time step, the atmospheric component provides to JULES the current near-surface wind speed, air temperature, pressure, condensed water and downward radiation fluxes, water vapor and trace gas mixing ratios. After its processing, JULES advances its state variables over the time step and feeds back to the atmospheric component the sensible and latent heat and momentum surface fluxes, upward short-wave and long-wave radiation fluxes, as well as a set of trace gas fluxes (Moreira et al, 2013).

Figures 7a-b show the values of the sensible (H) and latent (LE) heat obtained through experimental data above the ATTO site (80 m) and through the JULES-CCATT-BRAMS simulation, respectively (76.8 m). It is possible to notice that the simulation overestimates the values of both flows. However, it is noted that the LE values are higher than the H values, mainly for the daytime period. This result is expected for a forested surface, such as the Amazon rainforest.

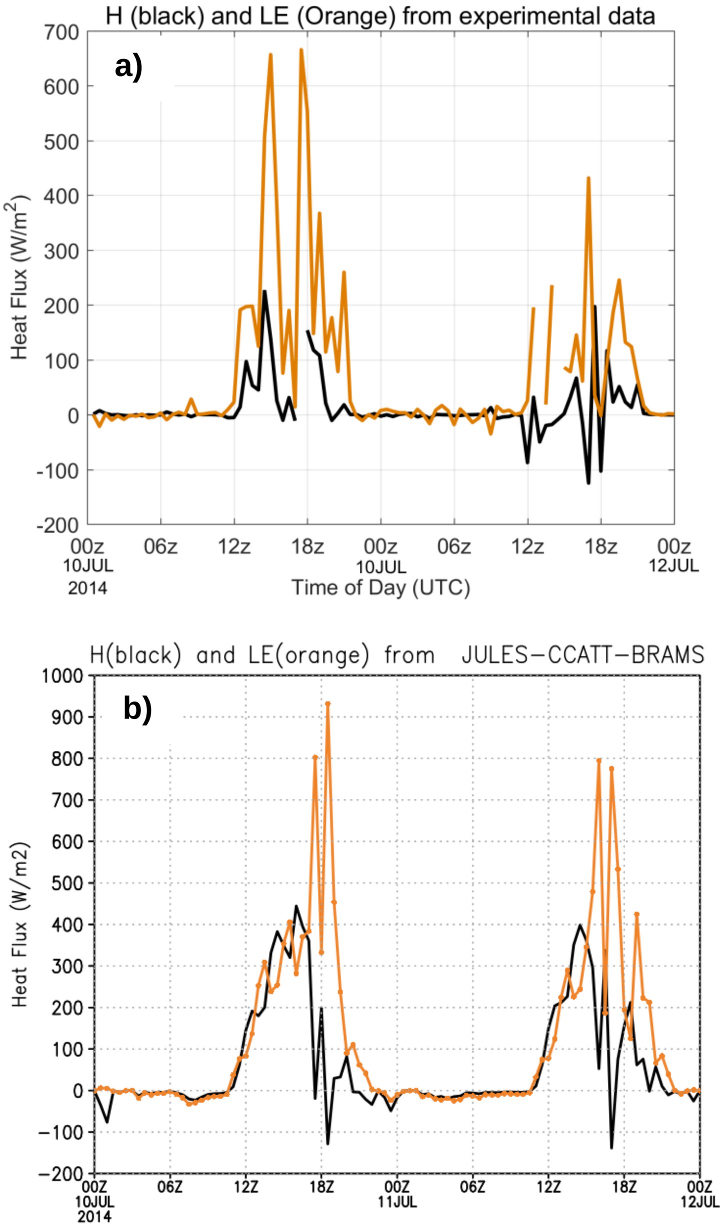


Figure 7: Latent and sensitive heat on July 10-11th, 2014 at ATTO site: (a) measured in the ATTO tower; (b) obtained from JULES-CCATT-BRAMS simulation.

12. Line 318-319: The suppressed vertical mixing might play a part in the decreased O3 mixing ratios, but it's not the only or main reason here.

As outlined above there is evidence from several sources that the lowest 500 m are occupied by a colder air mass and therefore vertical mixing is suppressed on the 11th. In parallel to reduced O3 mixing ratios we observed accumulation of CO2 which gives further evidence for trapping of trace gases in this layer. In absence of considerable photochemical activity, the situation can be seen as similar to the nocturnal boundary layer where consistently (vast body of literature) loss of O3 by deposition and chemical reactions is observed and increases in concentration are due to intermittent vertical mixing esp. by occurrence of low level jets.

Therefore, we think that the reduced vertical mixing has a strong influence on the near surface values, but to clarify that it might not be the sole reason we now write that it "contributes" to the reduced values. (L334).

Minor comments

1. Line 66: I'd cite more relevant studies regarding O3 at the T3 site.

Was done. Thank you.

2. Line 67: I'd point out the minimal anthropogenic influences at the ZF2 site to contrast the other sites.

Was done. Thank you.

3. Table 1: What is the canopy height at ATTO site?
The average height of trees at ATTO site is approximately 37 m (Andreae et al., 2015).

4. Figure 7: I'd present the data in the order of Porto Velho, Manaus, and ATTO.

Was done.

5. Line 207: There are some editorial/technical issues to be fixed. For example, the parentheses are missing for "Fig. 9".

Was corrected. Thank you.

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