Interactive comment on “Friagem Event in Central Amazon and its Influence on Micrometeorological Variables and Atmospheric Chemistry” byGuilherme F. Camarinha-Neto et al.

Anonymous Referee #1

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

General comments: The manuscript presents an interesting discussion of how the entry of a cold front or cold can interfere with micrometeorological conditions and the rates of trace gas mixture in central Amazonia. The combination of surface measurements with the simulations of the coupled model JULES-CCATT-BRAMS made it possible to understand the cooling effects, as well as their development and implications. Certainly, the results related to the effects on Lake Balbina are important for understanding the effects of cold on the ecosystem as a whole. In general, the work has an importante scientific contribution, as it clearly and objectively shows the ecosystem’s response to a cold event. With regard to the structure of the manuscript, it still needs adjustments in the text. Some structural modifications are needed to make it clearer to the reader around the methodological application used to achieve the proposed objectives. **(1)** The only point to be reviewed more intensively is the choice of the study period and the implications of this in the discussions. As the methodology of the work itself shows, this manuscript brings as results the case study of a particular event that occurred from July 6 to 11, 2014, however, no discussion about the meteorological characteristics of this year was held, it was also not clear whether any cold front arrival in the region will cause the same effects. The authors cite other studies on coldness in the Amazon, which are in agreement with their results, but do not make clear when these analyses were performed. **(2)** As much of the results are derived from simulations it would be interesting to discuss the possible annual variations or at least discuss whether such variations may exist or not, as well as answer whether the effects on atmospheric chemistry will always be these, or if by different conditions, such as a year with high burn rates, these results may diverge, that is, my suggestion is a small restructuring of the results to include these discussions.

We appreciate the reviewer's comments. We will respond in parts:

(1): The reasons for choosing the case study shown in the manuscript (July 6 to 11, 2014), were as follows: i) July is one of the months with the largest number of cold fronts that arrive in the South-Southeastern region of Brazil (Prince and Evans, 2018). Consequently, July is also the month where a greater number of Friagem phenomena are observed in the Amazon region (Prince and Evans, 2018). ii) Throughout 2014, intensive activities of the GoAmazon project took place (Martin et al., 2016), that is, measurements of gases and the thermodynamics of the atmosphere were carried out in several sites investigated in this work (T2, T3 and T0z), and therefore this was the motivation for choosing the year 2014 for our case study. iii) The period between 06 and 11 July was chosen, as it was observed that a Friagem event reached the city of Manaus and its surroundings in those days. It should be noted that for a Friagem event to occur, it is necessary that a mass of cold air (cold front), coming from the South reaches the North region of Brazil. Friagem events do not always have the “capacity” to reach the city of Manaus. For example, on July 25-31 2014 there was also a Friagem event in the Southwest of the Amazon, but this event was not observed in the city of Manaus.

About the meteorological characteristics of this year, according to the CLIMANALISE Bulletin (http://climanalise.cptec.inpe.br/~rclimanl/boletim/pdf/pdf14/jul14.pdf), in July 2014, precipitation in northern Brazil showed positive and negative deviations from the climatological average (Figure 1a). In addition, the deviation from the maximum temperature in relation to its climatology shows a drop in the maximum temperature from the state of São Paulo to the Southwest of the Amazon, indicating the advance of frontal systems in this region (Figure 1b).

Regarding global scale phenomena, the South Oscillation Index showed that this month remained close to neutral, that is, without the occurrence of the El Nino and La Nina phenomena.

The main characteristics of the Friagem observed in this work seem very similar to those observed by Marengo et al. (1997) and Silva-Dias et al. (2004), both cited in the manuscript.

Marengo et al. (1997) investigated the two strongest Friagem events that occurred during the year 1994, being: June 26th and July 10th. For both events they observed that the main consequence of the Friagem in the City of Manaus was greater cloud cover and consequently less solar radiation reaching the surface, which is the main cause of the fall in air temperature. In addition, they noted that Friagens produced a shallower boundary layer. That is, the results by Marengo et al. (1997) corroborate part of our results - Friagem increases the cloud cover (Fig. 4), reduces the air temperature (Fig. 6) and produces a shallower boundary layer (Fig. 11a).

The work by Silva-Dias et al. (2004) showed that during the period from 24 to 31 July 2001, the arrival of a cold air mass in the western region of the Amazon increased atmospheric pressure to sea level in this region, resulting in a pressure gradient force pointing in the opposite direction of the trade winds, which is consistent with a deceleration of the trade winds and the consequent formation of more intense breeze circulations in the Santarém region. The main consequences of this Friagem in the city of Manaus were: drop in air temperature around 5 ºC, reduction in wind speed, confluence of a cold and dry air mass coming from the South region with a hot and humid air mass coming eastern Amazon. We emphasize that part of our results are corroborated by Silva-Dias et al. (2004), which are: (1) confluence of trade winds with westerly winds in central Amazonia (Fig. 3). We show that it was this confluence that was mainly responsible for the formation of clouds and the consequent reduction of solar radiation that reached surfaces, reducing the air temperature and the O3 concentration.

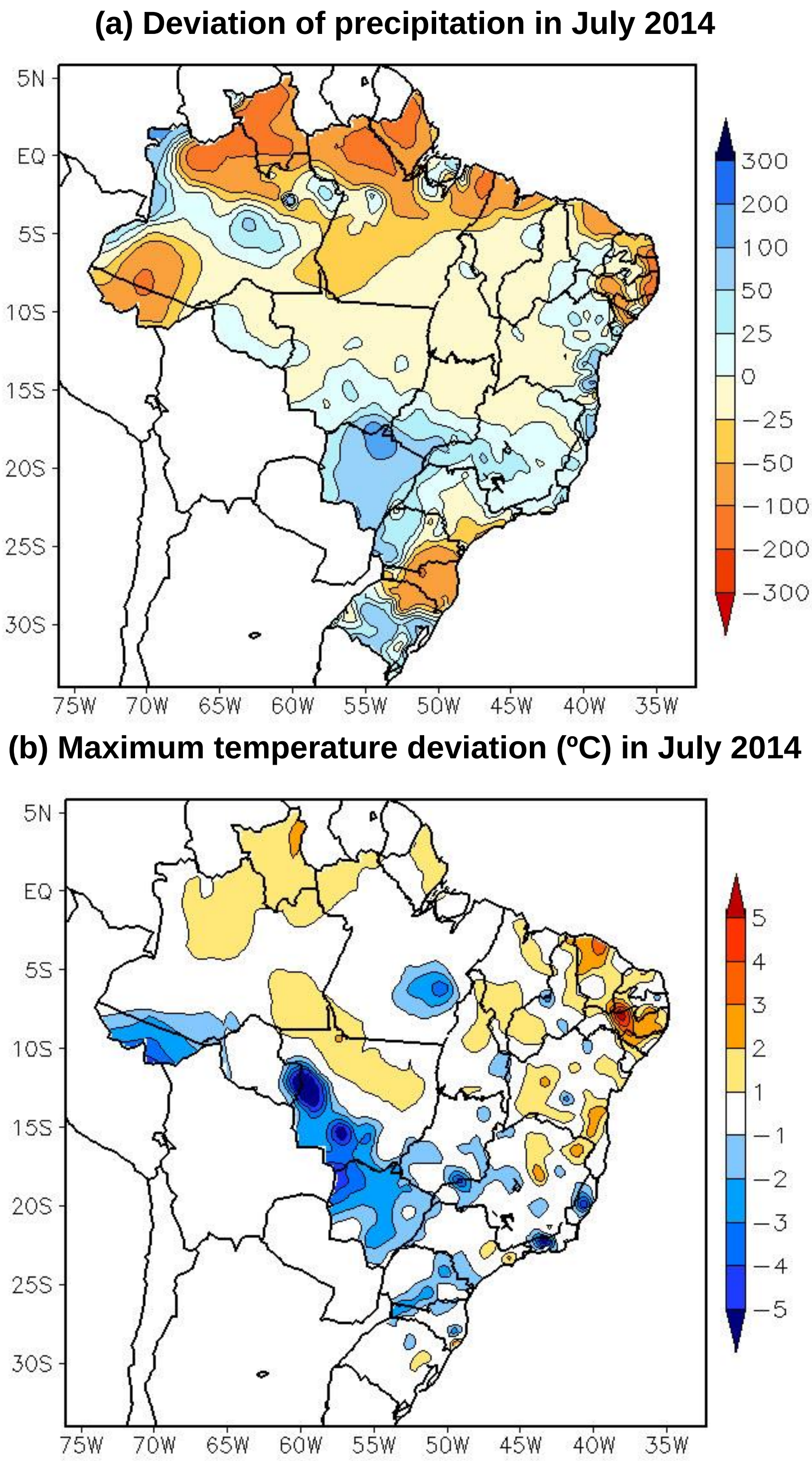

Figure 1. Behavior (a) deviation of accumulated precipitation in relation to climatological-mean (1961-1990) and (b) deviation from maximum temperature in relation to climatological-mean (1961-1990) for July 2014.

Source: Monitoring and Climate Analysis Bulletin (CLIMANASE). V. 29, No.07, July 2014. ISSN 0103-0019 CDU-555.5

(2): We agree with the reviewer that new simulations that show the impact of possible annual variations, such as the increase/decrease in precipitation and air humidity and decrease/increase in temperature, during atypical years, such as La Niña / El niño, among others, can influence the number of occurrences and the strength of Friagem events and, consequently, the chemistry and thermodynamics of the atmosphere near the surface. In addition, the performance of simulations with different burn rates conditions and consequently with different amounts of cloud condensation nuclei can influence the formation of clouds and the role of cooling above the central Amazon. However, the objective of this work is not to make comparisons between different annual conditions, but to demean a case study. The reviewer's suggestions are valuable and will be the subject of future research by this group. In addition, we will add these suggestions to the conclusions of the manuscript (suggestions for future work).

Specific comments: About the abstract: Review the first sentence of the abstract, because it practically already brings, in a more generic way, the main conclusion of the work, that is, the authors begin the work stating that the cold event influences the variables and atmospheric chemistry. I suggest changing the sentence and leaving to make this statement at the end of the abstract along with the main conclusions of the work.

We decided to move this sentence from the abstract to the conclusions section.

About the introduction: In paragraph 30, the authors evidence the influence of breezes on CO2 and O3 mixing rates, however, they mention a region of North America, Canada, and this is out of context in the manuscript because all other information collected in the introduction directly mentions works developed in the Amazon. If the authors want to talk more about these events around the world, they should include supplementary discussions on the effects of lake breezes. The last sentence of paragraph 50 is a text that describes how the objectives will be achieved, that is, a text of methodology, I suggest removing or restructuring this text since this information will appear in the methodology.

We agree with the reviewer: We rewrite the paragraph 30 and we remove the last sentence of paragraph 50 that described how the objectives will be achieved.

About the methodology: In paragraph 70 the authors say that this is a case study, it would be interesting at this moment to talk about the specific implications of this analyzed period.

We introduced a new paragraph to better explain the motivation for choosing July 2014 as case study and we made a brief comment about the specific implications of this analyzed period (L68-75).

When talking about the O3 measurements in the analyzed sites, it is observed that these measurements were performed at different heights, ATTO at 79m, T3 at 3.5m, T2 at 12m and T0z at 39m. Can these different heights interfere with the measurements? The authors can make a brief discussion about this.

Yes, different measurement heights may affect the observed O3 concentrations in some cases, due to the process of dry deposition onto available surfaces and stomatal uptake by vegetation. In the case of T2 and T3 sites, which are not forest sites, the measurement height may not have a significant influence on O3 concentrations during the day in a well mixed boundary layer, provided that the inlets were set apart from surfaces like walls, roofs and trees. At forest sites, previous studies have shown a significant O3 vertical gradient inside the canopy, especially in its lowest half part (e.g., Rummel et al., 2007; Freire et al., 2017). However, the reported O3 measurements at T0z and ATTO were taken above the canopy, where vertical gradients are expected to be close to zero if the boundary layer is well mixed. Based on previous studies, we estimate that the 40 m difference in the measurement height of ATTO and T0z may result in a 15% difference on O3 concentrations, with smaller concentrations at T0z due to the proximity of the canopy top. Nevertheless, this difference does not affect the main aspect discussed in Figure 11, which clearly shows a decrease in diurnal O3 concentrations at all sites in 2014 July 11th as a result of the influence of a cold front.

We put part of this comment in the main text of the manuscript (L95-101).

On the results: the results are presented in a very clear and objective way, the only observation is made in relation to the period of analysis. As described in the methodology of the work, this manuscript brings as results the case study of a particular event that occurred from July 6 to 11, 2014, however, no discussion about the meteorological characteristics of this year was held, it was also not clear whether any cold front arrival in the region will cause the same effects. The authors cite other studies on coldness on Amazon, which are in agreement with their results, but do not make clear when these analyses were performed.

We inserted new paragraphs in the manuscript that make the meteorological characteristics of this year (L68-75) and in our citations about other studies on coldness on Amazon we make more clear when these analyzes were performed (L181-184; L214-218)

As much of the results are derived from simulations it would be interesting to discuss the possible annual variations or at least discuss whether such variations may exist or not, as well as answer whether the effects on atmospheric chemistry will always be these, or if by different conditions, such as a year with high burn rates, these results may be different, that is, I suggest a small restructuring of the results so that these discussions are included.

We agree with the reviewer that new simulations that show the impact of possible annual variations, such as the increase/decrease in precipitation and air humidity and decrease/increase in temperature, during atypical years, such as La Niña/El niño, among others, can influence the number of occurrences and the strength of Friagem events and, consequently, the chemistry and thermodynamics of the atmosphere near the surface. In addition, the performance of simulations with different burn rates conditions and consequently with different amounts of cloud condensation nuclei can influence the formation of clouds and the role of cooling above the central Amazon. However, the objective of this work is not to make comparisons between different annual conditions, but to demean a case study. The reviewer's suggestions are valuable and will be the subject of future research by this group. In addition, we will add these suggestions to the conclusions of the manuscript (suggestions for future work).

About the figures presented in the results: In general, give more detailed information of the figures in the subtitles. The figures along with their subtitles have to be highexplanatory. Another detail that the authors have to review are the titles of the axes of the figures, as well as the title in the "colobar" when necessary.

Thank you. We reviewed the figure captions and made some minor changes (in blue). In all the figures where there is “colobar” we indicate that they represents the shaded area. The axes that do not have a title are those that indicate the North/South and East/West coordinates.

On the conclusion: In paragraph 320 the authors state that in general, the model satisfactorily reproduced the main changes caused by the cold phenomenon. Did the authors intend to evaluate the application of the model? Was that a goal, too? Just one observation in the last sentence of the conclusion: it is practically the same initial sentence in the abstract, so is necessary to restructure this fragment in the abstract.

We would like to thank the reviewer for his comments. We decided to remove the sentence "*In general, the model reproduced satisfactorily the main changes that the phenomenon brought to the environment of interest*" from the conclusion and the sentence "*that is, the Friagem event has the ability to significantly change the microclimate and atmospheric chemistry close to the surface in the Amazon central region*" of the abstract.

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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 in 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)

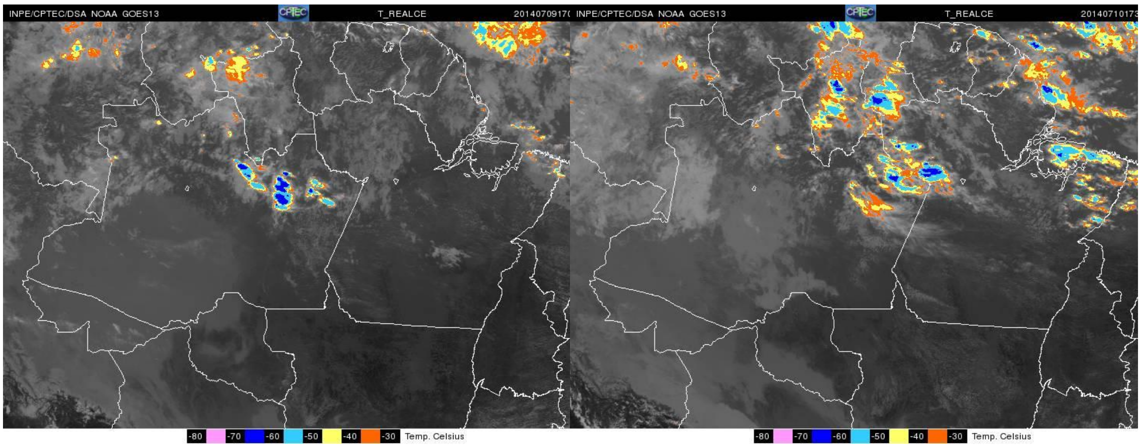


Figure 1: Enhanced images of the GOES 13 satellite in the infrared channel on: (a) July 09th at 17:00 UTC and (b) July 10th at: 17:30 UTC.

(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.

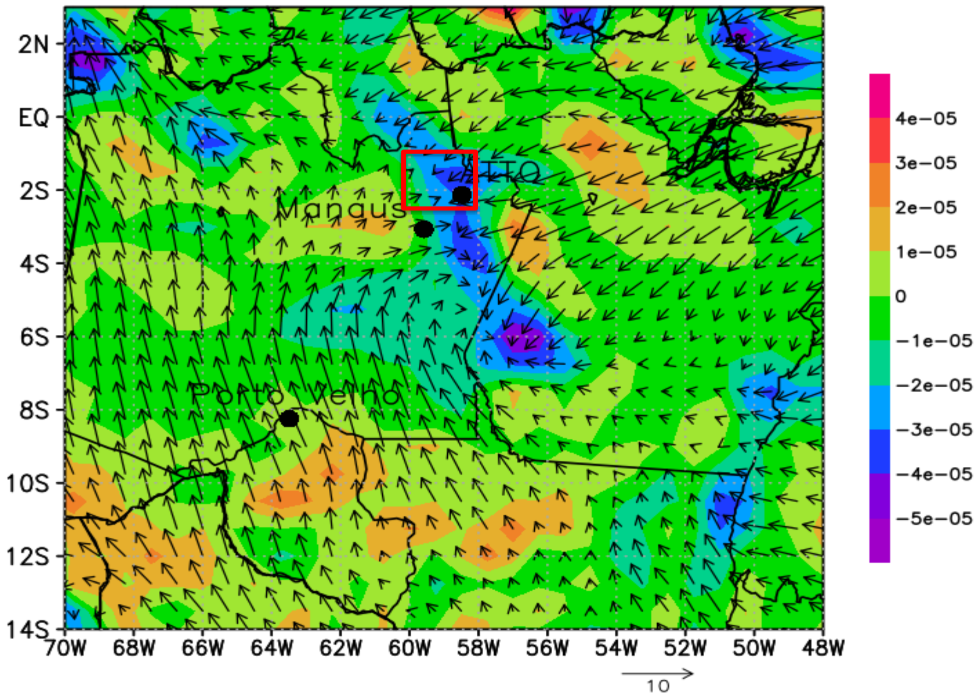
The general features of the cold front are clearly described in the manuscript such as the temperature drops and the trade wind is weakened, which accounts for the majority of the manuscript. However, the understanding and discussion of its mechanism is lacking. For example, **(1)** it is not clear how 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)



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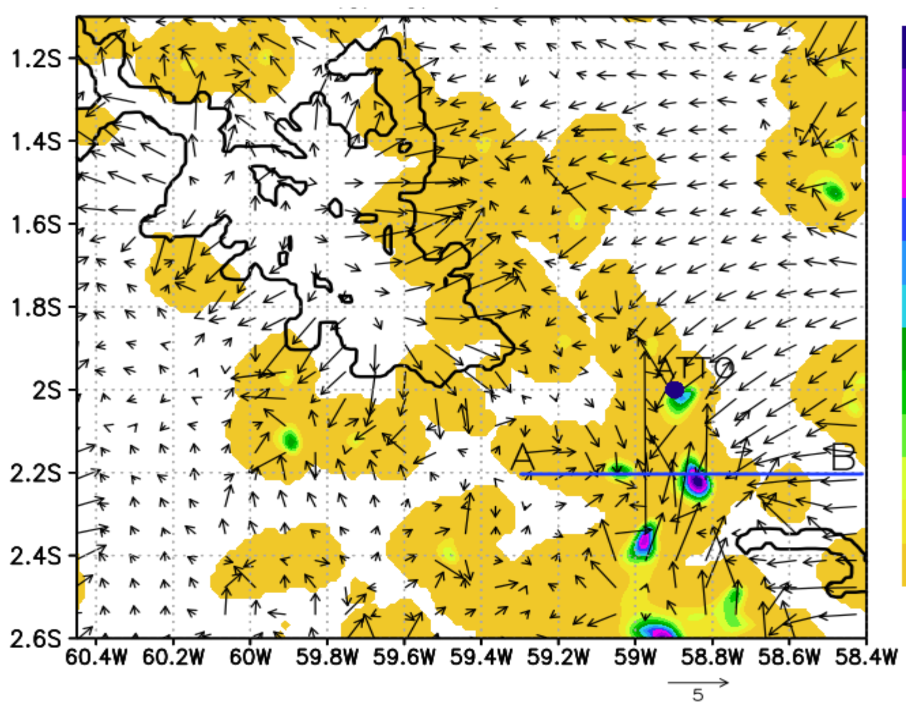


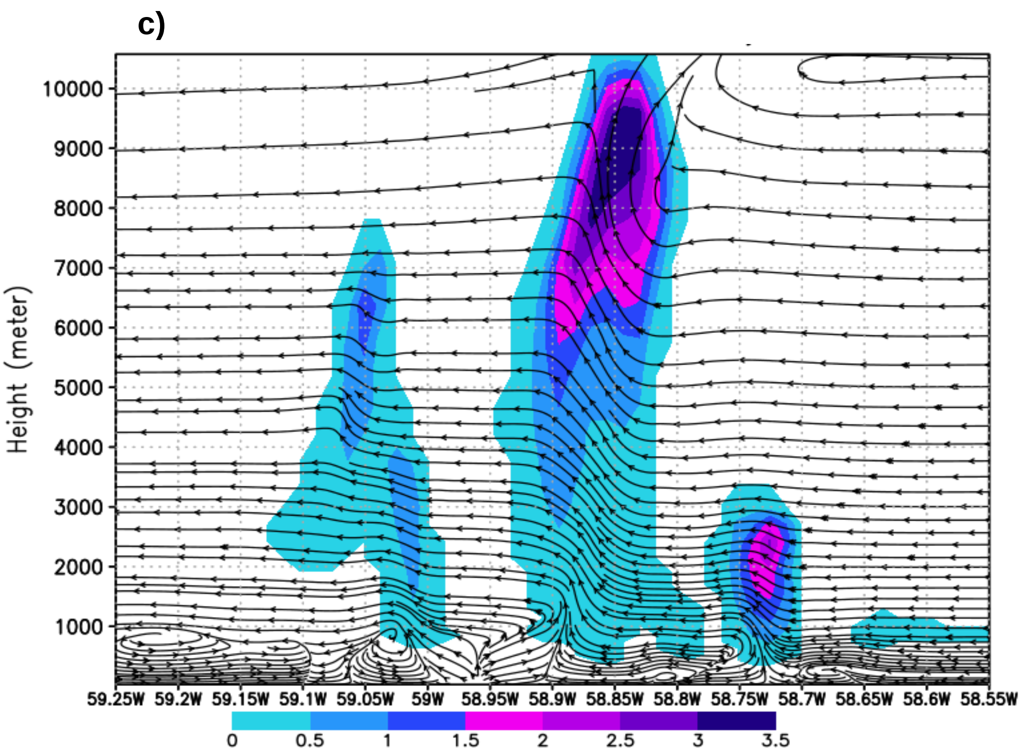


Figure 2. (a) Horizontal Wind (vector, m/s) and wind divergence (shaded, s^{-1}) at 975 hPa on July 11th, 2014 at 15:30UTC from ERA-interim reanalysis. The red square represents the domain used in model JULES-CCATT-BRAMS. (b) Horizontal distribution of rain water mix ratio (shaded, g/kg) and horizontal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

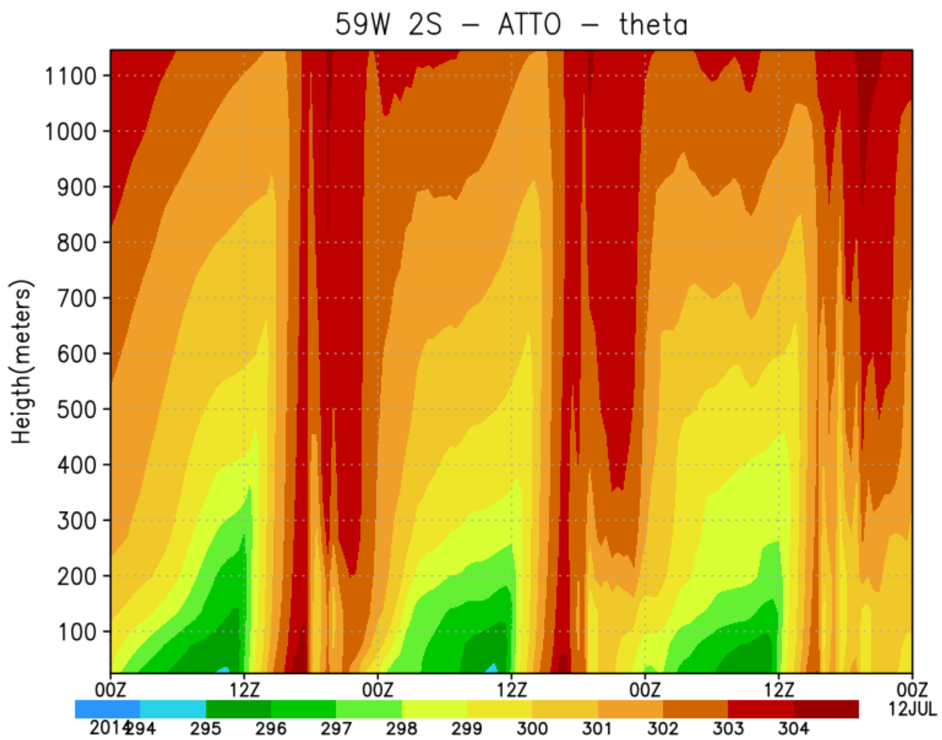


Figure 3: Potential temperature (shaded, K) profile from simulation with JULES-CCATT-BRAMS at ATTO site (2°S,59°W) on July, 6-11, 2014.

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.

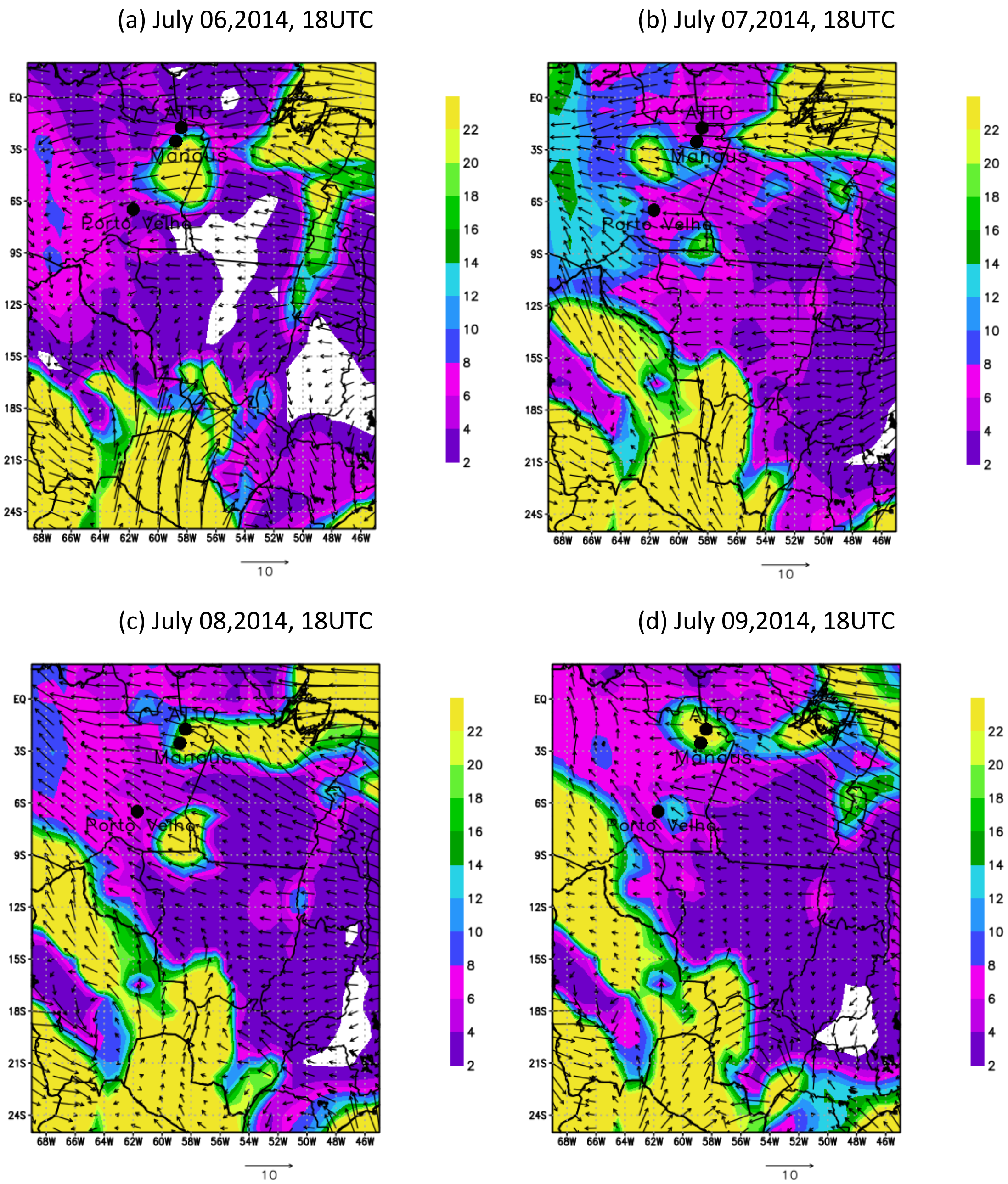
We agree with the reviewer that in Figure 3, where reanalysis data are shown, it is not possible to observe significant drops in temperature in the region of Manaus and ATTO (around 2 ºC), compared to the drop experienced in Porto Velho (around 6º C). We will rewrite the sentence in the new version of 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 5, through reanalysis data. We added a small comment on the manuscript (L172).



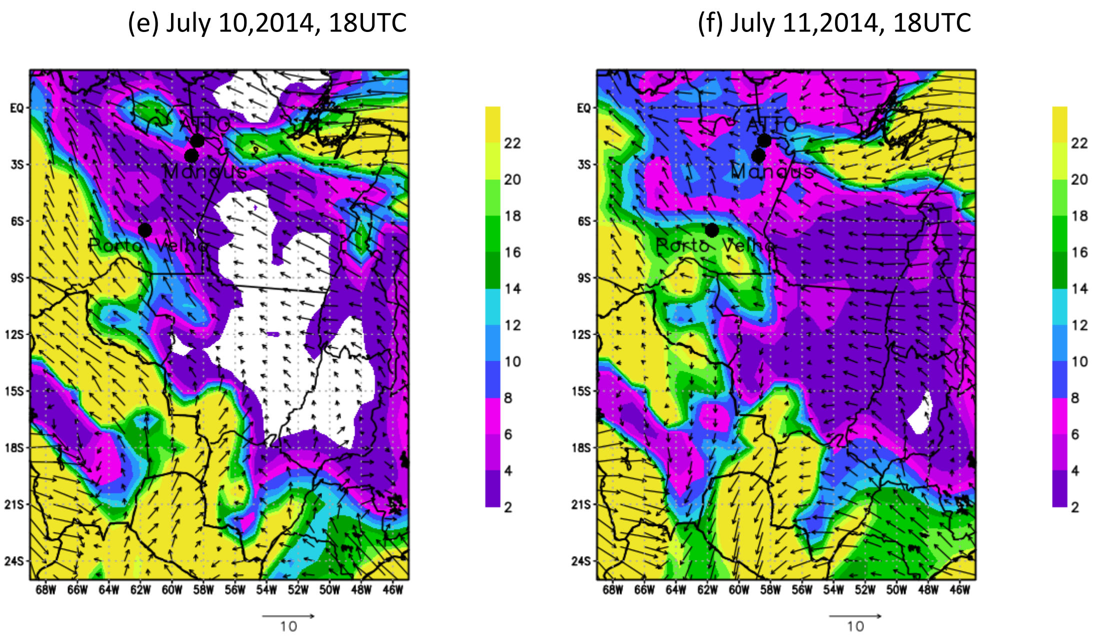


Figure 4.: - Surface wind (m s^{-1}, vectors) and ozone (ppbv, contour) on days 6-11, 2014 at 18 UTC, highlighting Porto Velho (P), Manaus (M) and ATTO site (A) obtained with the ERA-interim reanalysis.

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 O3 concentrations are expected) reduced the incident solar radiation (Fig. 10a) and therefore photochemical production of O3.

8. Line 238-241: “did not result in an increase of near surface O3”. I don’t necessarily agree with this. I think there is an increase in O3 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 O3 (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 O3 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.

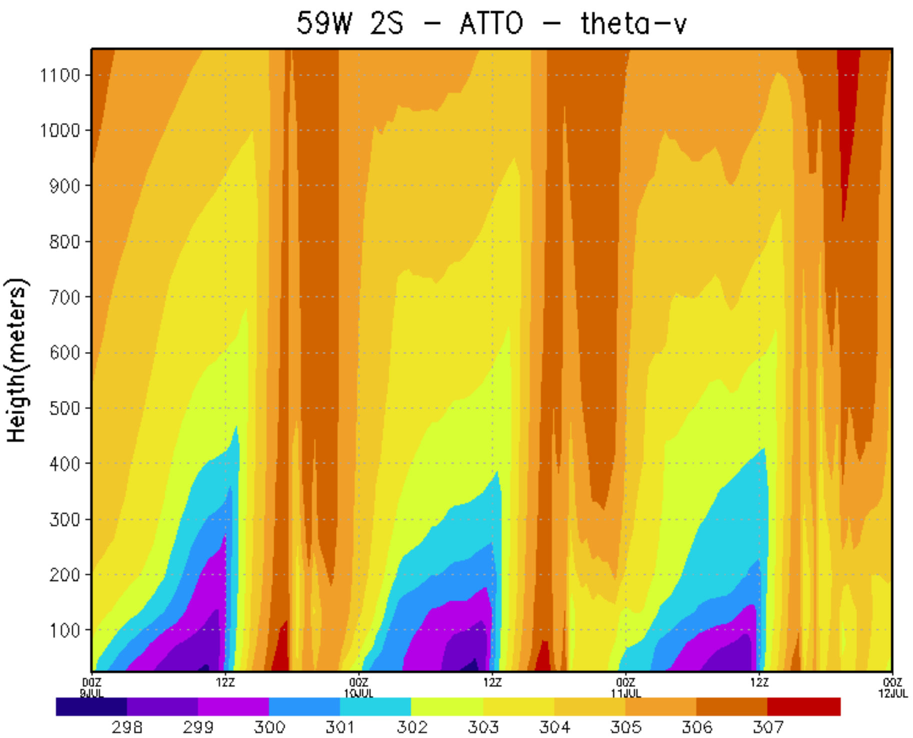
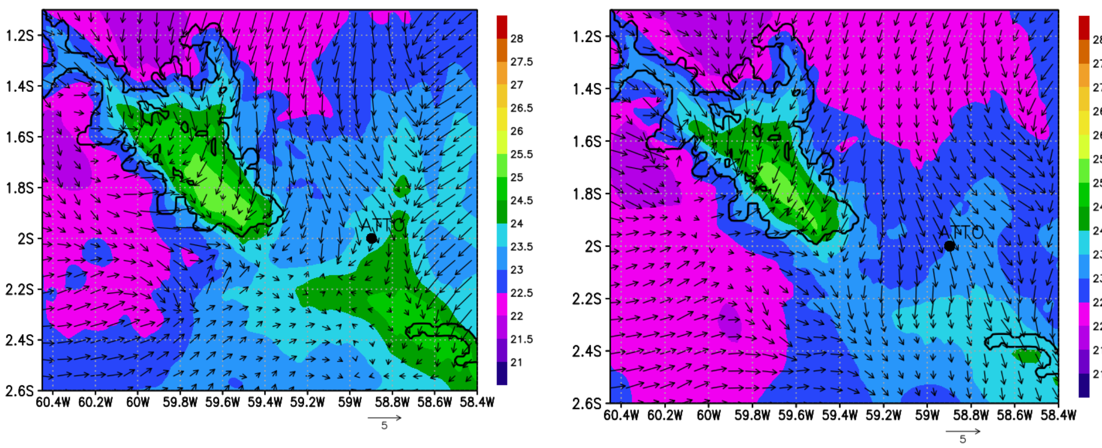


Figure 5: Virtual Potential temperature (shaded, K) profile from simulation with JULES-CCATT-BRAMS at ATTO site (2°S,59°W) on July, 9-11, 2014.

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.

(a) July 11, 2014 03UTC (b) July 11, 2014 05UTC



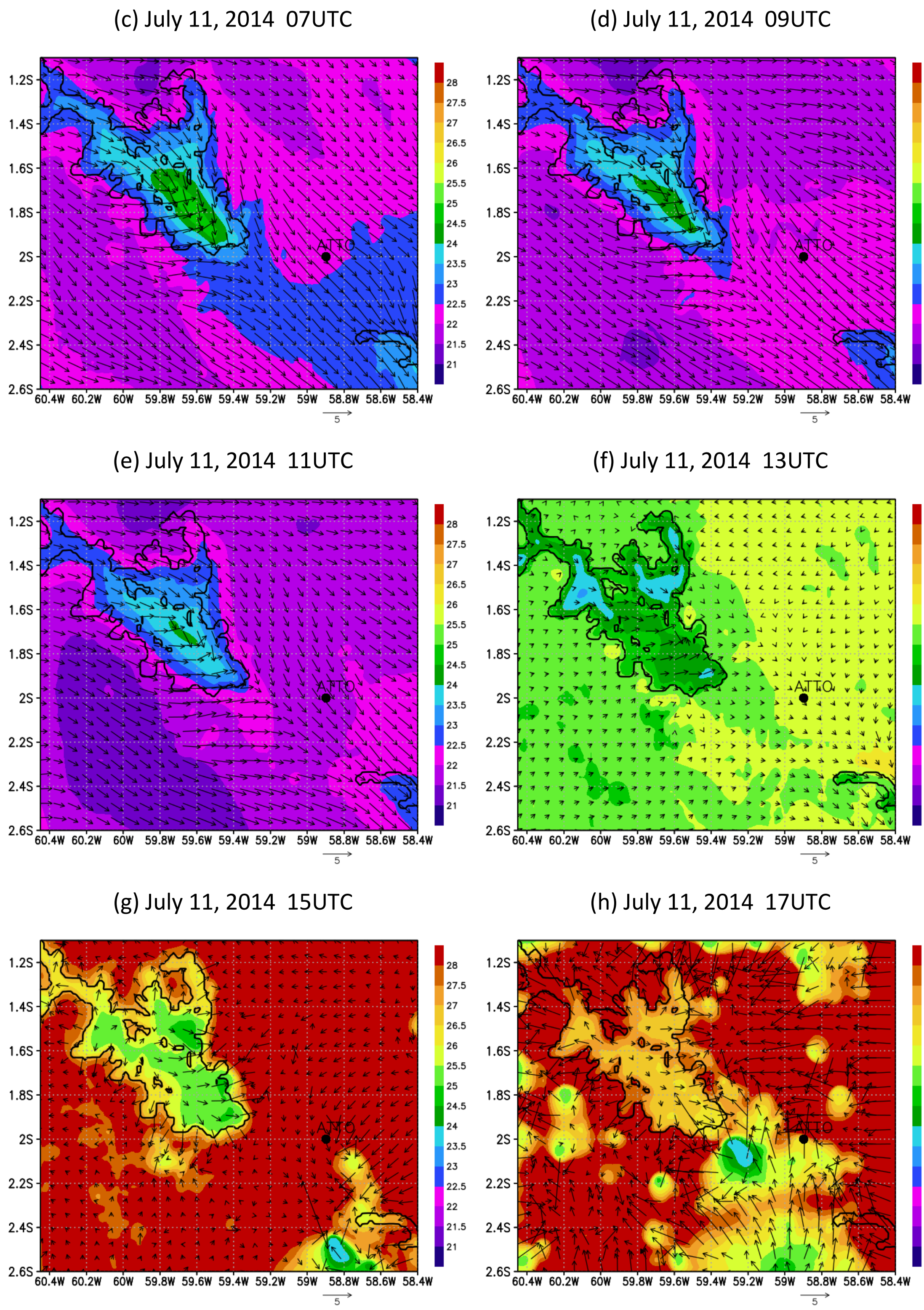


Figure 6: Evolution of air temperature (◦C, shaded) at 76.8 m and horizontal wind (m s−1, vector) at 134.5 m, on July 11th, 2014 at: (a) 03 UTC, (b) 05 UTC, (c) 07 UTC, 09 UTC, (e) 11 UTC, (f) 13 UTC, (g) 15 UTC and (h) 17 UTC. Balbina Lake (black contour) and ATTO site (black dot) are indicated.

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.

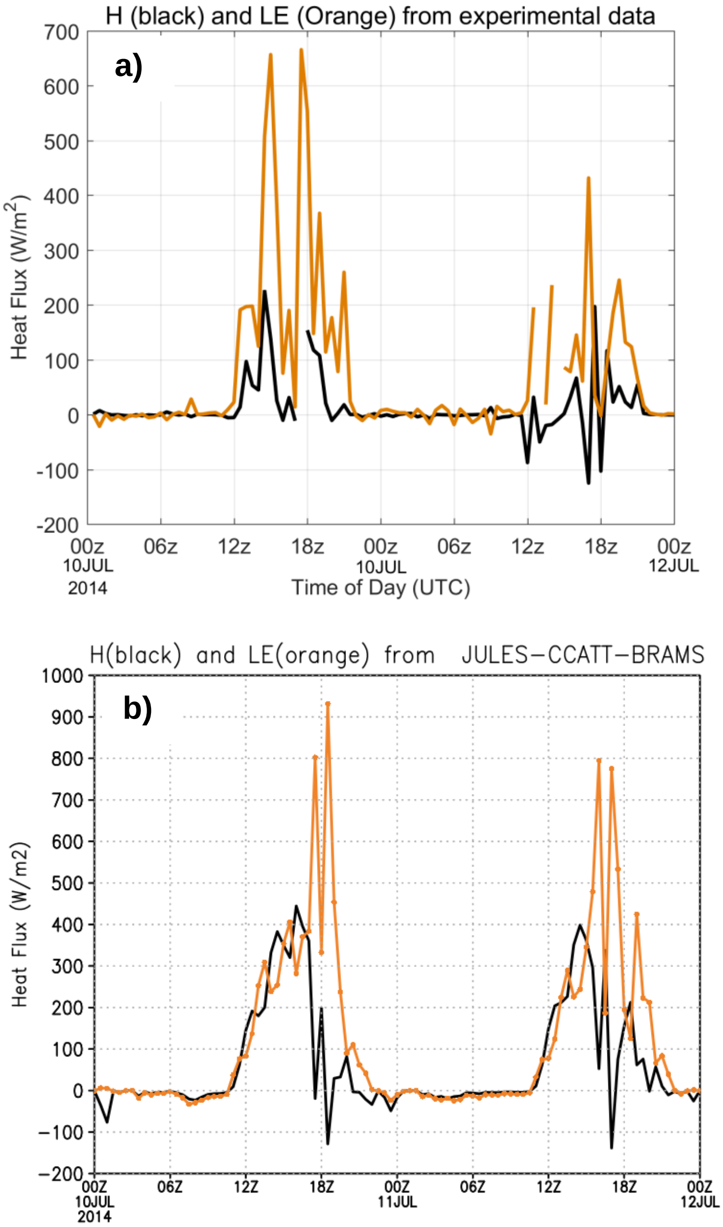


Figure 7: Latent and sensitive heat on July 10-11th, 2014 at ATTO site: (a) measured in the ATTO tower; (b) obtained from JULES-CCATT-BRAMS simulation.

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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LIST OF ALL RELEVANT CHANGES MADE IN THE MANUSCRIPT

Referee #1

1) We move the first sentence of the abstract to the conclusions section
2) We rewrite the paragraph 30 and we remove the last sentence of paragraph 50 that described how the objectives will be achieved.
3) We introduced a new paragraph to better explain the motivation for choosing July 2014 as case study and we made a brief comment about the specific implications of this analyzed period (L68-75).
4) Regards O3 measurements in the analyzed sites We add some comments in the main text of the manuscript (L95-101).
5) We inserted new paragraphs in the manuscript that make the meteorological characteristics of the year 2014 (L68-75) and in our citations about other studies on coldness on Amazon we make more clear when these analyzes were performed (L181-184; L214-218)
6) We decided to remove the sentence "*In general, the model reproduced satisfactorily the main changes that the phenomenon brought to the environment of interest*" from the conclusion and the sentence "*that is, the Friagem event has the ability to significantly change the microclimate and atmospheric chemistry close to the surface in the Amazon central region*" of the abstract.

Referee #2

1) 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).

2) Figures 3 and 4 were merged into one (in the new version of the manuscript Fig.3)
3) We will rewrite the sentence about the role of Friagem on air temperature (L188-191)
4) 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).
5) Figure 12: The simulated figures at the height of 24.4 m were replaced by the simulated figures at the height of 76.8 m.
6) We change the sequence of Figure 7: Porto Velho, Manaus and ATTO.

Friagem Event in Central Amazon and its Influence on Micrometeorological Variables and Atmospheric Chemistry

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Abstract. In the period between July 9^{th} and 11^{th}, 2014 a Friagem event reached the Amazon region. On July 11^{th}, the southwest flow related to the Friagem converged with the easterly winds in the central Amazon. The interaction between these two distinct air masses formed a convection band, which intensified over the Manaus region and the Amazon Tall Tower Observatory (ATTO) site. The satellite images show the evolution of convective activity on July 11^{th}, which lead to 21 mm of precipitation in the ATTO site. Moreover, the arrival of the Friagem caused a sudden drop in temperature and a predominance of southerly winds, which could be seen in Porto Velho between July 7^{th} and 8^{th} and in Manaus and ATTO site from July 9^{th} to 11^{th}. The results of ERA-Interim reanalysis and Brazilian developments on the Regional Atmospheric Modeling System (BRAMS) simulations show that this Friagem event coming from the southwest, carries a mass of air with higher O_3 and NO_2 mixing ratios and lower CO mixing ratio compared to the airmasses present at the central Amazon. At lake Balbina the Friagem intensifies the local circulations, such as the breeze phenomena. At the Manaus region and ATTO site, the main effects of the Friagem event are: a decrease in the incoming solar radiation (due to intense cloud formation), a large temperature drop and a distinct change in surface O_3 and CO_2 mixing ratios. As the cold air of the Friagem was just in the lower 500 m the most probable cause of this change is that a cold pool above the forest prevented vertical mixing causing accumulation of CO_2 from respiration and very low O_3 mixing ratio due to photochemistry reduction and limited mixing within the boundary layer.

1 Introduction

The Amazon region suffers from the incursion of cold waves from the high latitudes of the Southern hemisphere (SH), with a relatively common occurrence mainly in the less rainy season, between June and September. These events are denominated locally and in literature as Friagem and about 70% of the cases of Friagem occur in this period of the year (Brinkmann and Ribeiro, 1972; Marengo et al., 1997; Fisch et al., 1998; de Oliveira et al., 2004; Caraballo et al., 2014). Brinkmann and Ribeiro (1972) observed 2 to 3 Friagem events per year, preferably in the less rainy season, in the central Amazon. This was one of the first studies to explore frontal system (FS) interference in central Amazon.

Silva Dias et al. (2004) showed that the arrival of a Friagem event in the West of the Amazon generates a pressure gradient force whose direction is opposite to the trade winds, thus causing a weakening of these winds. These authors observed that the weakening of the trade winds enables the development of vigorous local circulations in the region of Santarém - PA.

Moura et al. (2004), who used data collected at the shores of Lake Balbina (central Amazon), concluded that without the influence of large-scale flow it is possible to observe the dynamics of breeze circulations influencing the ozone (O_3) mixing ratio with more clarity. According to these authors, the O_3-mixing ratio changes are larger when the flow occurs in the direction from the lake to the forest, that is, during the occurrence of the lake breeze. Trebs et al. (2012), using data from central Amazon region, concluded that the transport and dispersion of O_3-mixing ratio are strongly affected by local wind systems, such as the breeze.

Marengo et al. (1997) compared the effects of the Friagem at Manaus (central Amazon) and Ji-Parana (south of the Amazon River), that are around $1,200\ km$ apart. They observed that the Friagem was strongly modified during its passage over the Amazon basin. For example, the lower temperatures in Ji-Parana could be associate to cold air advection, whereas in Manaus they were mainly caused by reduced solar radiation due to increased cloudiness.

Several studies have already shown the effect of the Friagem on the surface meteorological components (Marengo et al., 1997; Fisch et al., 1998; Moura et al., 2004; Silva Dias et al., 2004). However, we are not aware of any study investigating the accompanied changes in trace gas concentrations and atmospheric chemistry in the Amazon Basin. Besides that, it is know that the presence of the Friagem phenomenon can alter the conditions of the local microclimate, allows the opportunity to better understand the dynamics of local circulations pattern and, consequently, influence local measurements carried out in Amazonian ecosystems, since they also cause the weakening of the predominant large-scale (trade) winds blowing from the East in the study region (Silva Dias et al., 2004).

Therefore, the objective of this study is to investigate the effects of Friagem on micrometeorological variables measured in the Manaus region and in the forest region of the Amazon Tall Tower Observatory (ATTO) site (Andreae et al., 2015), as well as to evaluate the influence of this phenomenon on the local circulation dynamics and its role in the dispersion of trace gases at ATTO site and Balbina lake.

2 Data and Methodology

2.1 Study area

The Sustainable Development Reserve (SDR) of Uatumã, São Sebastião do Uatumã county where the ATTO site is located ($02°\,08'\,38''\,S$ - $59°\,00'\,07''\,W$) is about 140 km northeast of Manaus in the state of Amazonas, Brazil. The village of Balbina, in Presidente Figueiredo county as well as the Balbina dam lake ($01°\,52'\,S$ - $59°\,30'\,W$), are located to the northwest of the ATTO site (Fig. 1). The ATTO site is structured in a dense terra firme forest, where plateaus prevail, with a maximum elevation of 138 m (Andreae et al., 2015). The artificial lake of Balbina is a flooded area of approximately $1,700\ km^2$, with an average depth of 10 m (Kemenes et al., 2007).

Additionally, near surface measurements of O_3 made at T2 ($03.1392°\,S$ - $60.1315°\,W$), T3 ($03.2133°\,S$ - $60.5987°\,W$) and the forest site T0z ($02.6091°\,S$ - $60.2093°\,W$) experimental sites, at a distance of 8, 70, and 60 km from Manaus, respectively, were used (Fig. 1). These sites were deployed in the Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) experiment (Martin et al., 2016). Due to its location, site T2 is heavily impacted by the Manaus urban plume as well as emissions from brick factories and to a minor extent by local pollution sources such as shipping or burning of household waste and wood near the site (Martin et al., 2016). The site T3 is typically downwind of Manaus city, influenced by urban air masses in 38.5% of time (Trebs et al., 2012; Martin et al., 2016; Thalman et al., 2017). The site T0z, typically upwind Manaus (Rizzo et al., 2013), is situated in the Cuieiras Biological Reserve ("ZF2") that has been a central part of Amazonian ecology and climate studies for over 20 years (Araújo et al., 2002). Differently T2 and T3, the T0z site is subject to minimal antopogenic interference. These five sites will enable us to better understand the role of Friagem at near surface O_3-levels in different parts of the central Amazon, some of them in the Manaus pollution plume (Cirino et al., 2018).

2.2 Data

A Friagem event that occurred between July 9^{th} and July 11^{th}, 2014 in the region of the ATTO experimental site was identified and used as a case study. The two main motivations for choosing this period were: i) July is one of the months with the largest number of cold fronts that arrive in the South-Southeastern region of Brazil and consequently, July is also a month with high number of Friagem events in the Amazon region (Prince and Evans, 2018). ii) Throughout 2014, the intensive activities of the GoAmazon (Observations and Modeling of the Green Ocean Amazon) project took place (Martin et al., 2016), that is, measurements of gases and thermodynamics of the atmosphere were carried out in various sites investigated in this work (T2, T3 and T0z). We also emphasize that the month of July 2014 did not show significant changes in precipitation and air temperature in relation to other years' july. In addition, in 2014 there were no El Nino and La Nina phenomena (http://climanalise.cptec.inpe.br/~rclimanl/boletim/pdf/pdf14/jul14.pdf).

The data were collected at the ATTO site and at the international airports of Manaus ($03°\,02'\,08''\,S$ - $60°\,02'\,47''\,W$) and Porto Velho ($08°\,42'\,50''\,S$ - $63°\,53'\,54''\,W$), for July 2014. Air temperature data, as well as wind direction and wind speed, in 30 min intervals were obtained from airport weather stations. The cities of Porto Velho (about 930 km southwest of ATTO)

Figure 1. Google Earth map of the location of the ATTO site, Balbina lake, T2, T3 and T0z (white circles). The dashed red line indicates the distance from the ATTO site in relation to the Balbina lake and the city of Manaus (copyright: © Google Maps). The yellow lines represent the roads and the blue lines represent the network of the rivers in this region.

and Manaus (about 150 km southwest of ATTO) were chosen with the purpose of evaluating the impacts of the advance of the Friagem towards the region of the ATTO site.

The ATTO site air temperature, wind speed, wind direction, incident short-wave radiation and precipitation were measured at the 81 m high walk up tower ($02° \, 08.6470' \, S$ - $58° \, 59.9920' \, W$) at different heights (see table 1). CO_2 and O_3 measurements were taken at 81 and 79 m above ground, respectively. The measurements of CO_2 and O_3 mixing ratios were conceived respectively by an infrared gas analyzer (IRGA, LI-7500A model, LI-COR inc., USA) and (TEI 49i model, Thermo Electron Corp, USA).

The data acquisition at the tower was performed by data loggers CR1000 and CR3000 (Campbell Scientific inc., USA), with instantaneous measurements taken every minute for meteorological variables and at high frequency for CO_2 (10 Hz) and O_3 (30 s) mixing ratio, subsequently processed every 30 min. The variables used in this study and their respective sensors are presented in more detail in Table 1.

The O_3 data at T3 site were obtained as part of the U.S. Department of Energy Atmospheric Radiation Measurement Program (ARM, http://www.arm.gov/measurements) during the GoAmazon 2014/5 project (Martin et al., 2016). O_3-mixing ratios were measured with an ultra violet gas analyzer (TEI 49i model, Thermo Electron Corp, USA). The instrument was installed at a height of 3.5 m above the ground (Dias-Júnior et al., 2017). At T2 and T0z, O_3-mixing ratios were also measured with the same analyzer model (Thermo 49i) at a height of 12 m a.g.l. and 39 m a.g.l., respectively.

Table 1. Variables used in this study, their respective measuring instruments and height in the micrometeorological tower at ATTO site.

VARIABLES	INSTRUMENTS	HEIGHT
Air Temperature	**Thermo-hygrometer** (CS215, Campbell Scientific, USA)	**81 m**
Wind Speed and Direction	**2D Sonic Anemometer** (Windsonic, Gill Instruments Ltd., UK)	**73 m**
Incident Short Wave Radiation	**Pyranometer** (CMP21, Kipp and Zone, Netherlands)	**75 m**
Rainfall	**Pluviometer** (TB4, Hydrological Services Pty. Ltd., Australia)	**81 m**
CO_2**-mixing ratio**	**Infrared Gas Analyzer** (IRGA, LI-7500/LI-7200, LI-COR inc., USA)	**81 m**
O_3**-mixing ratio**	**Ultraviolet Gas Analyzer** (TEI 49i, Thermo Electron Corp, USA)	**79 m**

The O_3 measurements were performed at different heights in the sites investigated here. These heights may affect the observed O_3 concentrations in some cases, due to the process of dry deposition onto available surfaces and stomatal uptake by vegetation. In the case of T2 and T3 sites, which are not forest sites, the measurement height may not have a significant influence on O_3 concentrations during the day in a well mixed boundary layer. At forest sites, previous studies have shown a significant O_3 vertical gradient inside the canopy, especially in its lowest half part (Rummel et al., 2007; Freire et al., 2017). However, the reported O_3 measurements at T0z and ATTO were taken above the canopy, where vertical gradients are expected to be close to zero if the boundary layer is well mixed.

The European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis was used at intervals of 6 h, with the objective of evaluating the evolution of the Friagem event investigated in this work. The ERA-interim model and the ECMWF reanalysis system present spatial resolution with 60 vertical levels, harmonic spherical representation for the basic dynamic fields, and reduced Gaussian grid with uniform spacing of approximately 79 km for the surface (Berrisford et al., 2011). Furthermore, enhanced images of the infrared channel of the GOES-13 satellite were used, with the purpose of analyzing the formation and passage of convective systems in the study area.

2.3 Experimental design

The numerical simulations of the present study were made using the BRAMS (Brazilian Regional Atmospheric Modeling System) mesoscale model version 5.3 (Freitas et al., 2017). BRAMS represents a Brazilian version of the Regional Atmospheric Modeling System (RAMS) (Cotton et al., 2003) adapted to tropical conditions. This version of BRAMS contains the coupling of the JULES (Joint UK Land Environment Simulator) (Best et al., 2011; Clark et al., 2011) and CCATT (Coupled Chemistry-

Aerosol-Tracer Transport) models (Longo et al., 2010; Freitas et al., 2009), making BRAMS a new and fully-coupled numerical system of atmosphere-biosphere-chemical modeling, called JULES-CCATT-BRAMS (Moreira et al., 2013).

The integration time of the model was 72 hours, starting at 00 UTC on July 9^{th}, 2014. The numerical experiment was performed using only a grid whose horizontal resolution was 1.5 km, with 185 points on x, 140 points on y, and 39 points on z. The vertical grid resolution was variable with the initial vertical spacing of 50 m, increasing by a factor of 1.1 up to the 1.2 km level, and from that point forward this spacing was constant to the top of the model (around 16 km). The domain covered by this grid, the distribution of the main rivers and topography can be observed in Fig. 2.

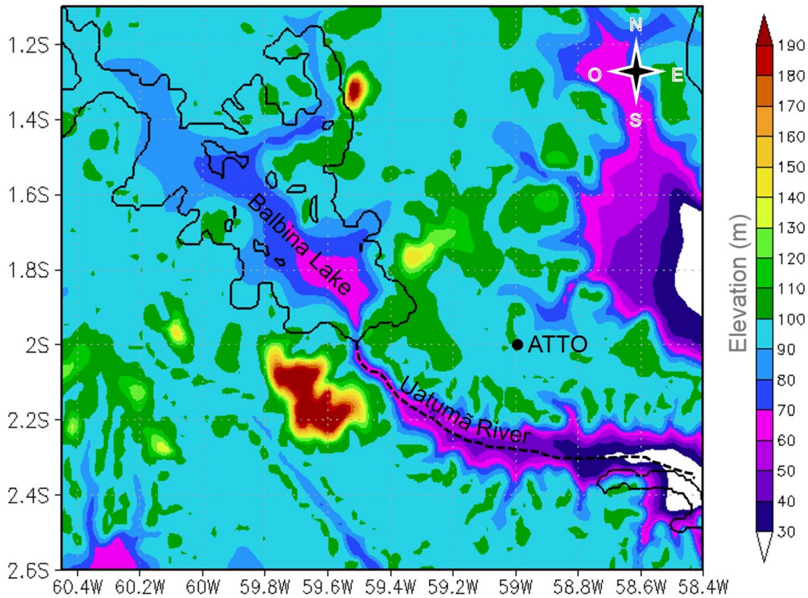


Figure 2. Domain of the grid used in JULES-CCATT-BRAMS simulation showing the distribution of the topography (m) and location of the Balbina lake (black line), ATTO site (black point) and Uatumã river (dashed line)

The initialization of the model was heterogeneous, using the ECMWF- ERA Interim reanalyses (www.ecmwf.int/en/forecasts/datasets/reanalysis) every 6 hours in a quarter-degree spatial resolution. Seven soil layers were defined up to the depth of 12.25 m and the assumed soil humidity was heterogeneous, as described in Freitas and Freitas (2006). Soil texture data were originally obtained from the Food and Agriculture Organization of the United Nations (UN FAO) and were adapted for the Brazilian territory by INPE (Rossato et al., 2004).

In this simulation, cloud microphysics uses the Thompson cloud water single-moment formulation, which consists of the separate treatment of five classes of water that are then mixed in a single treatment for each type of cloud (Thompson et al., 2008; Thompson and Eidhammer, 2014). In addition, it includes the activation of aerosols in the cloud condensation nuclei (CCN) and ice nuclei (IN), thus, it predicts the concentration of the number of water droplets in the clouds, as well as the concentrations of two new aerosol variables, one for CCN and one for IN. These variables are grouped into hygroscopic aerosols called "water friendly" and non-hygroscopic aerosols are "ice friendly" (Freitas et al., 2017).

The parameterization of the long and short wave radiation used was the Carma (Community Aerosol and Radiation Model for Atmospheres) (Toon et al., 1989). This scheme solves the radiative transfer using the two-flux method and includes the main molecular absorbers (water vapor, CO_2, O_3 and O_2) and treats the gas absorption coefficients using an exponential sum formula (Toon et al., 1989). The JULES-CCATT-BRAMS radiation schemes are coupled online with the cloud and aerosol microphysics models to provide simulations of aerosol-cloud-radiation interactions (Freitas et al., 2017). The physical and optical properties of the cloud in the radiative scheme of Carma were parameterized according to Sun and Shine (1994) and Savijärvi et al. (1997); Savijärvi and Räisänen (1998) using liquid and ice water content profiles provided by the JULES-CCATT-BRAMS cloud microphysics scheme (Freitas et al., 2017).

3 Results and discussion

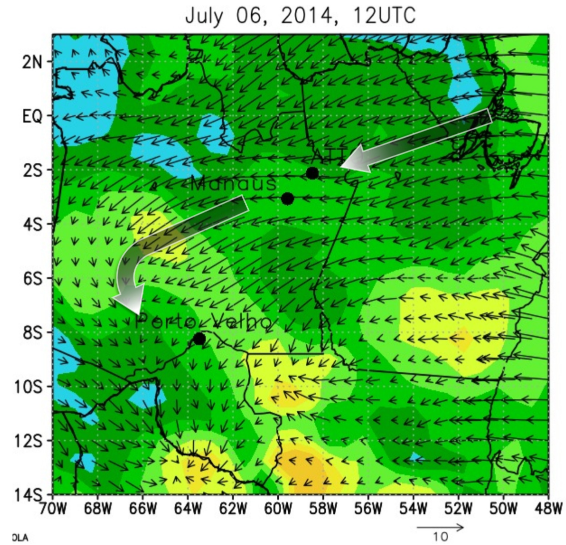
3.1 Environmental characteristics in the Amazon basin scale

From the ECMWF ERA-interim reanalysis the evolution of the horizontal wind and air temperature near the surface, in the north region of Brazil, between July 6^{th} and 11^{th}, 2014, at 12 UTC (Local Time = UTC - 4 h) (Fig.3) can be obtained. On the 6^{th} it is observed that the mean temperature was of the order of $24\ ^{\circ}C$ in three places of interest of this work, being: Porto Velho; Manaus and ATTO site (Fig. 3a). The dominant wind direction was from East in practically the entire Amazon region. The surface temperature and wind direction represent the standard normally found in this region (Fisch et al., 1998; Pöhlker et al., 2019). However, on July 7^{th}, the dominant wind direction becomes South-Southeast in the region of Porto Velho, as is evidenced by the presence of a mass of air with a lower temperature (around $18\ ^{\circ}C$) approaching this city (Fig. 3b).

In the course of the days, between July 8^{th} and 9^{th}, the mass of cold air advanced even more towards Porto Velho, just as the dominant wind direction changed to South in all western regions of the state of Amazonas, as well as to the southern regions of Manaus and the ATTO site (Fig. 3c, d). On July 10^{th}, the southerly winds arrive in the Manaus region and the ATTO site, characterizing the arrival of Friagem in the area of interest of this work (Fig. 3e, f). For this period, the CPTEC technical bulletin reported the penetration of a polar air mass in the subtropical and tropical Brazilian region that advanced in the Southeast-Northwest of Brazil, giving origin to the cold waves of the South, as well as causing the Friagem phenomenon in the Amazon (http://tempo.cptec.inpe.br/boletimtecnico/pt).

Therefore, the arrival of the Friagem phenomenon in the Amazon region is characterized by the change in the wind direction in the Southwest and central regions of the Amazon and by abrupt drops in the values of temperature, especially in the Southwest. Similar results were also found by other authors (Marengo et al., 1997; Fisch et al., 1998; de Oliveira et al., 2004).

The wind behavior throughout the Amazon basin before and during the Friagem event is represented in Fig. 3a and 3f, respectively. Interestingly, at the time the Friagem was present in the Manaus and ATTO site region, there was convergence of the easterly winds with the westerly flow associated to the Friagem (Fig. 3f). The easterly flow carries humidity from the Atlantic coast to the central region of the Amazon, while the southerly flow, associated with the Friagem event, transports masses of dry and cold air from high latitudes to the Amazon region (Marengo et al., 1997).


July 06, 2014, 12UTC
ATTO
Manaus
Porto Velho
2N
EQ
2S
4S
6S
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10S
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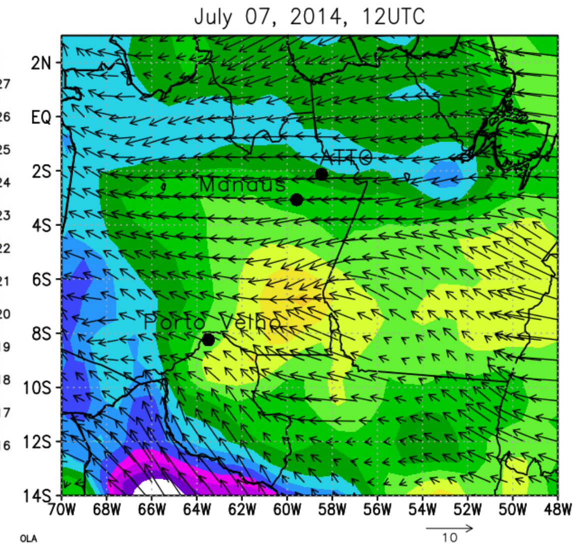
70W 68W 66W 64W 62W 60W 58W 56W 54W 52W 50W 48W
27 26 25 24 23 22 21 20 19 18 17 16
10

(a)


July 07, 2014, 12UTC
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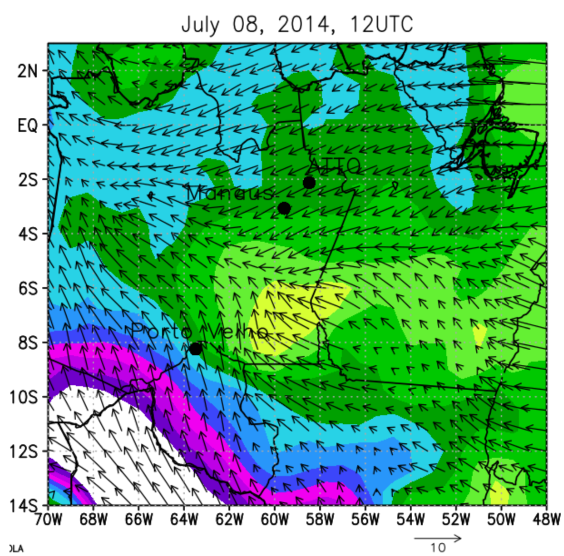
(b)


July 08, 2014, 12UTC
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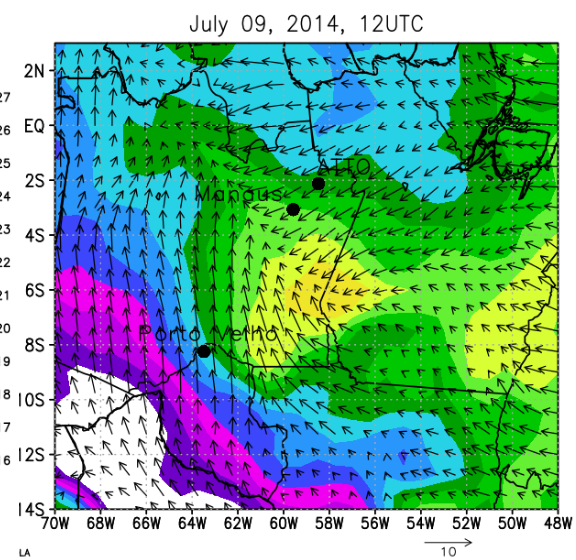
(c)


July 09, 2014, 12UTC
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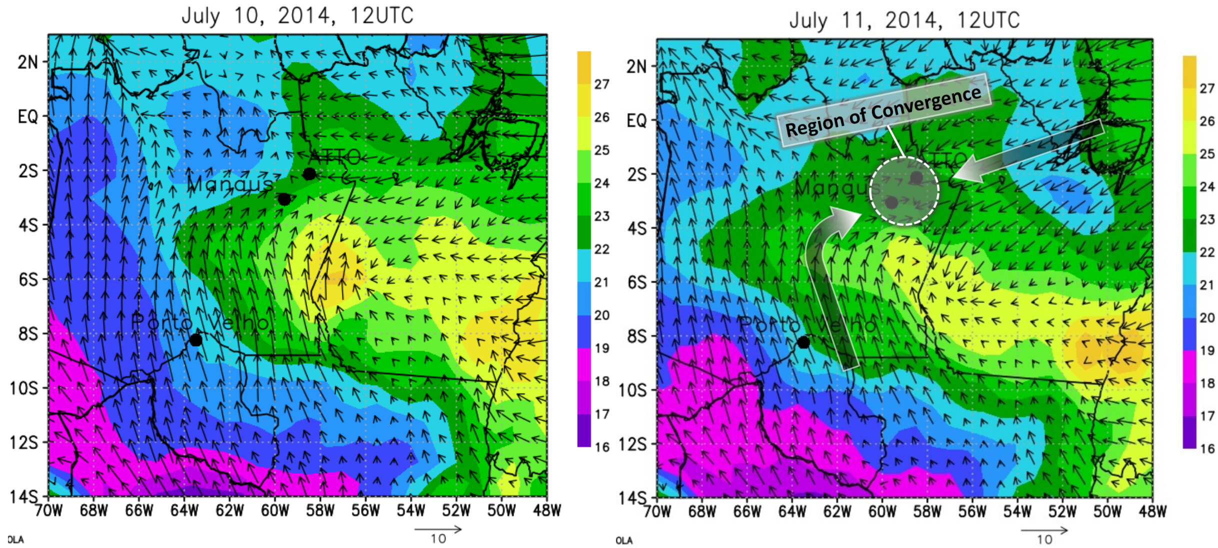
27 26 25 24 23 22 21 20 19 18 17 16
10

(d)

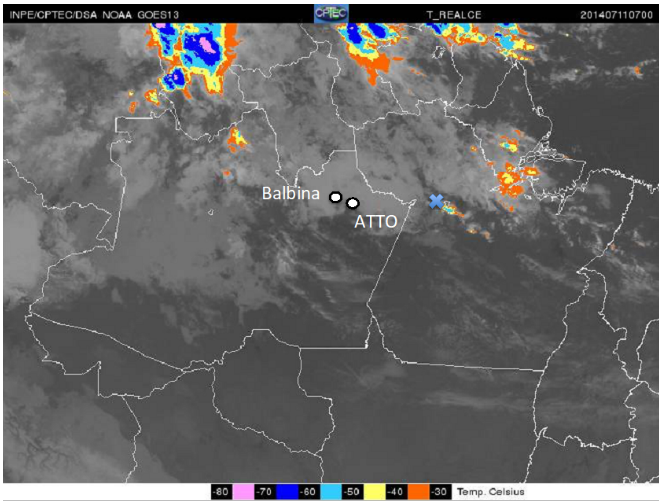


(e) (f)

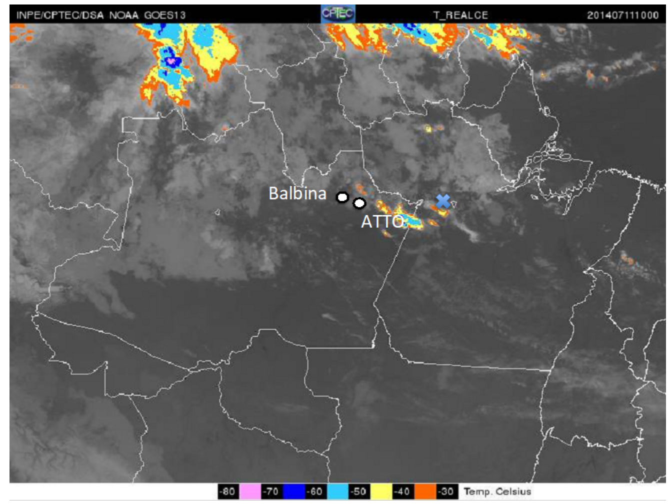
Figure 3. Distribution of air temperature (°C, shaded) and wind (ms^{-1}, vector) at the surface, in the localities of Porto Velho, Manaus and ATTO site, at 12 UTC between days 6^{th} and 11^{th} of July 2014 obtained with the ERA-interim reanalysis. Grey arrows indicate the predominant wind flow and the dashed circle highlights the region of convergence of the winds in the Manaus and ATTO region.

Figure 4 shows the satellite images before and during the Friagem event in the central Amazon. Convection in the confluence between Amazonas and Tapajós rivers region was observed at dawn, on July 11 at 07 UTC (Fig 4a). This convection propagated in the West direction, arriving in the ATTO site region at 13 UTC (Fig 4c). Since this convective system is not associated to the squall lines that form along the coast (Cohen et al., 1995; Alcântara et al., 2011; Melo et al., 2019) it is possible to state that this convection has its formation associated with the convergence of these two air masses with different properties (Fig 3f). It is noteworthy that during the propagation of this convection on July 11^{th}, it intensified and caused the highest rainfall (starting at 12:30 UTC) registered at the ATTO site during the month of July 2014, with a record rainfall of 21 mm.

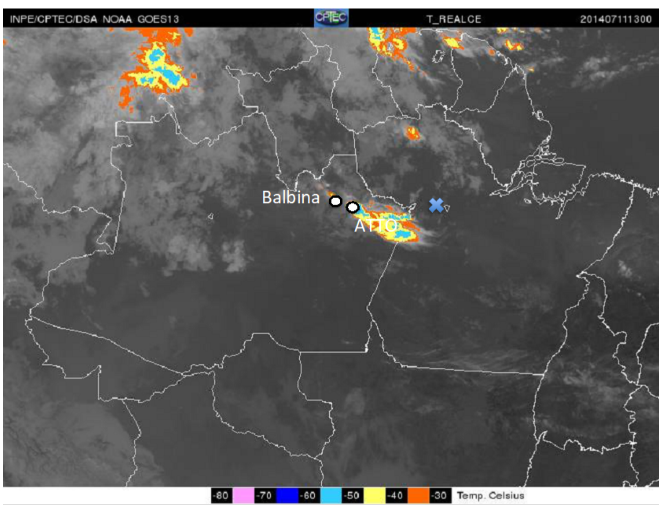
The evolution of the horizontal wind and O_3-mixing ratio near the surface (both from ECMWF ERA-interim reanalysis), during July 7^{th} and 11^{th}, 2014, at 18 UTC can be seen in Fig. 5. On July 7^{th} onward the Friagem event carries air rich in O_3 from Southeastern of the Brazil (not shown here) to northwards (Fig. 5a). This airmass reaches the state of the Amazonas on July 8^{th} (not show here). On July 11^{th} at 12 UTC (not shown here) the air mass influenced by the Frigaem has the shortest distance from the study region (ATTO-site). On July 11^{th} at 18 UTC the Friagem begins to dissipate (Fig. 5b). However, it should be noted that this mass of air rich in O_3 did not reach the Manaus region and the ATTO-site. It is believed that the presence of the cloud cover in central Amazonia on 11^{th}, July (Fig. 4), formed by the convergence of air (Friagem and Eastern winds), has an inhibitory effect on O_3 formation (Betts et al., 2002). As O_3 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



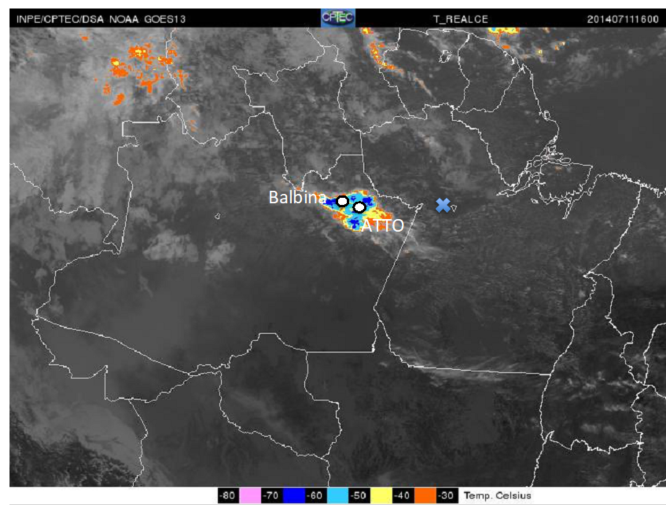
(a)



(b)



(c)

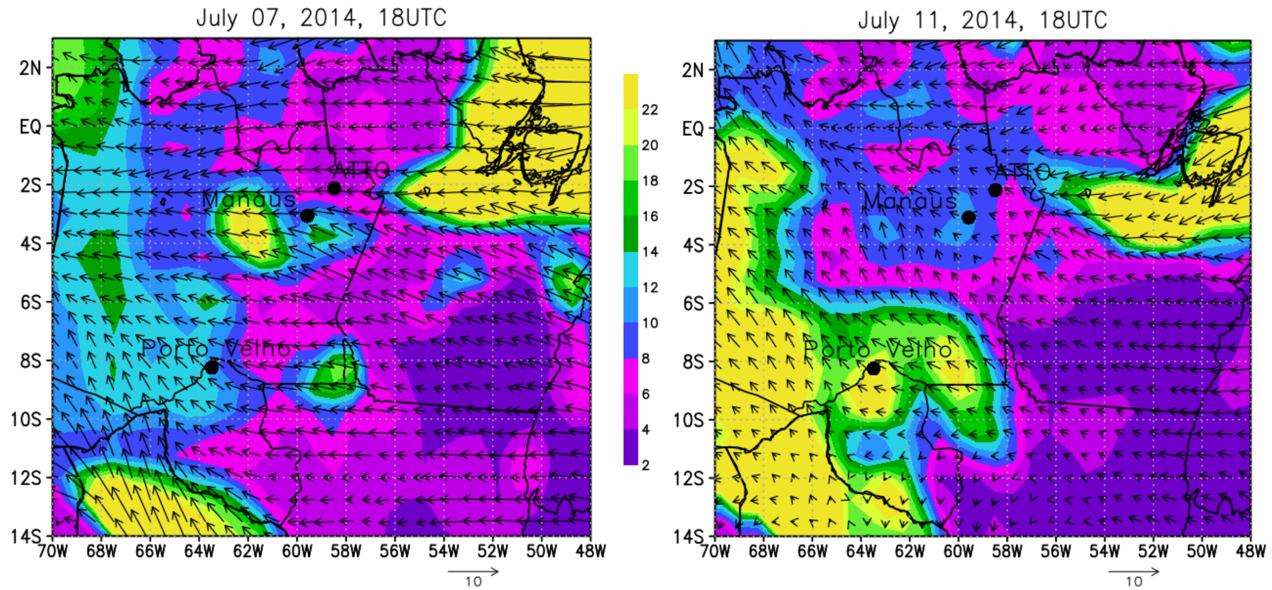


(d)

Figure 4. Enhanced images of the GOES 13 satellite in the infrared channel on July 11^{th}, 2014 at: (a) 07 UTC, (b) 11 UTC, (c) 13 UTC and (d) 16 UTC, which is openly accessible (http://satelite.cptec.inpe.br/acervo/goes.formulario.logic?i=br). Including the approximate locations of the ATTO site and Balbina lake (white circles) and the confluence region of the Amazon and Tapajós rivers (blue X).

and Wofsy, 1990; Fan et al., 1990; Rummel et al., 2007). Therefore, the low O_3 mixing ratio in the Manaus region and the ATTO-site during the 11^{th} July (Fig. 5-f) would be associated with cloudiness and prolonged transport over forested regions.

Marengo et al. (1997) investigated the two strongest Friagem events that occurred during the year 1994, being: June 26^{th} and July 10^{th}. They did not show the impact of Friagem on O_3 levels but showed that for both events the main consequence of the Friagem in the city of Manaus was greater cloud cover and consequently less solar radiation reaching the surface, which was the main cause of the fall in air temperature, corroborating part of the results find here (Figs. 3, 4 and 6)



(a)

(b)

Figure 5. Surface wind ($m\ s^{-1}$, vectors) and ozone (ppbv, contour) on days: (a) 7^{th} and (b) 11^{th} of July, 2014 at 18 UTC, highlighting Porto Velho, Manaus and ATTO site obtained with the ERA-interim reanalysis.

3.2 Air temperature during the Friagem event

Figure 7 shows the air temperature values near the surface at Porto Velho (Fig 6a), Manaus region (Fig 6b) and above the forest canopy at the ATTO site (Fig 6c), between July 6^{th} and 11^{th}, 2014 (black line) together with the air temperature hourly average for the month of July 2014 (orange line). 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 8^{th}) was 7 $°C$ (from 31 to 24 $°C$), whilst in Manaus region and at ATTO site the differences were in the order of 4 $°C$ (from 30 to 26 $°C$ and 29 to 25 $°C$, respectively) during July 11^{th}. The temperature starts to fall in Manaus region and ATTO around one day after the temperature fall observed in Porto Velho.

At Porto Velho, both the maximum and minimum values of air temperature were substantially reduced during the presence of the Friagem. However, at Manaus region and the ATTO site, the decrease was mainly observed in the maximum temperature values. Although the decrease was not so evident at the time of the diurnal minimum (at least on the 10 th and 11 th) the whole diurnal cycle was disturbed with (much lower) minima than the average at different times of the day.

Similar behavior was observed by Marengo et al. (1997) for the Southwest and Central Amazon regions during an episode of Friagem. Therefore, it is noted that due to the occurrence of the Friagem, the southernmost regions of the Amazon present more intense reductions in temperature values, compared to the regions located more in the center of the Amazon basin.

Additionally, the ATTO site is located in a forest region, 58 km from the Balbina dam lake and Manaus region is under the influence of intense urbanization (de Souza and Alvalá, 2014) and is located in the proximity of rivers. Thus, there is evidence that both the ATTO site and Manaus region may be under the influence of lake (Moura et al., 2004) and rivers breezes (dos Santos et al., 2014), respectively, which could offer them a greater thermal inertia.

3.3 ATTO site wind direction

In addition to the changes observed in the daily air temperature cycle at the ATTO site, changes were also observed in the local wind direction during the Friagem period (Fig 7). Before the arrival of this phenomenon, between July 6^{th} and 8^{th}, it was observed that the direction of the horizontal wind was predominantly Southeast and Northeast. On the other hand, on July 9^{th} the wind direction was well distributed among the four cardinal points, and on July 10^{th} and 11^{th} the wind flow had higher frequencies of West, North and Southwest, when the Friagem arrived at ATTO site. The general wind directions before and after the Friagem are consistent with long term observations at ATTO (Andreae et al., 2015). The low frequency of observed wind directions from the westerly directions (based on 2.5 years of data) led to the conclusion that effects of local circulation (due to Uatumã River ≈ 12 km and Balbina Lake ≈ 58 km) are not important or could not be observed (Andreae et al., 2015). At least not on regular basis.

Silva Dias et al. (2004) showed that during the period from 24^{th} to 31^{th} July 2001, the arrival of a cold air mass in the western region of the Amazon. The main consequences of this Friagem in the region were: increased atmospheric pressure to sea level, decrease the air temperature around $5\,°C$, reduction in wind speed, confluence of a cold and dry air mass coming from the South region with a hot and humid air mass coming eastern Amazon. We emphasize that part of our results are corroborated by Silva Dias et al. (2004). The increased atmospheric pressure to sea level resulting in a pressure gradient force pointing in the opposite direction than the trade winds, which would be consistent with a slowdown of the easterly winds. In this way, these authors were able to observe with greater clarity the occurrence of river breeze circulations in this region. Following this hypothesis, the behavior of the wind at the ATTO site was analyzed every two hours, during the period in which the Friagem was active in this region (Fig. 8).

On the 9^{th} of July it is observed that the direction of the wind was essentially from East until the end of the morning (14-16 UTC), when the wind changed to Southeast and Southwest directions until the late afternoon and early evening (22-00 UTC), which corresponds to the flow associated with the arrival of Friagem in this region. From 00 UTC of July 10^{th} to 14 UTC it is observed that the prevailing wind was from the West, indicating a deviation from the general flow, which would normally be from the East. In the early afternoon (16 UTC), the wind changed to the North direction until the early morning (12 UTC) of July 11^{th}. This change in wind direction to the West and to the North observed during the morning of July 10^{th} and 11^{th},

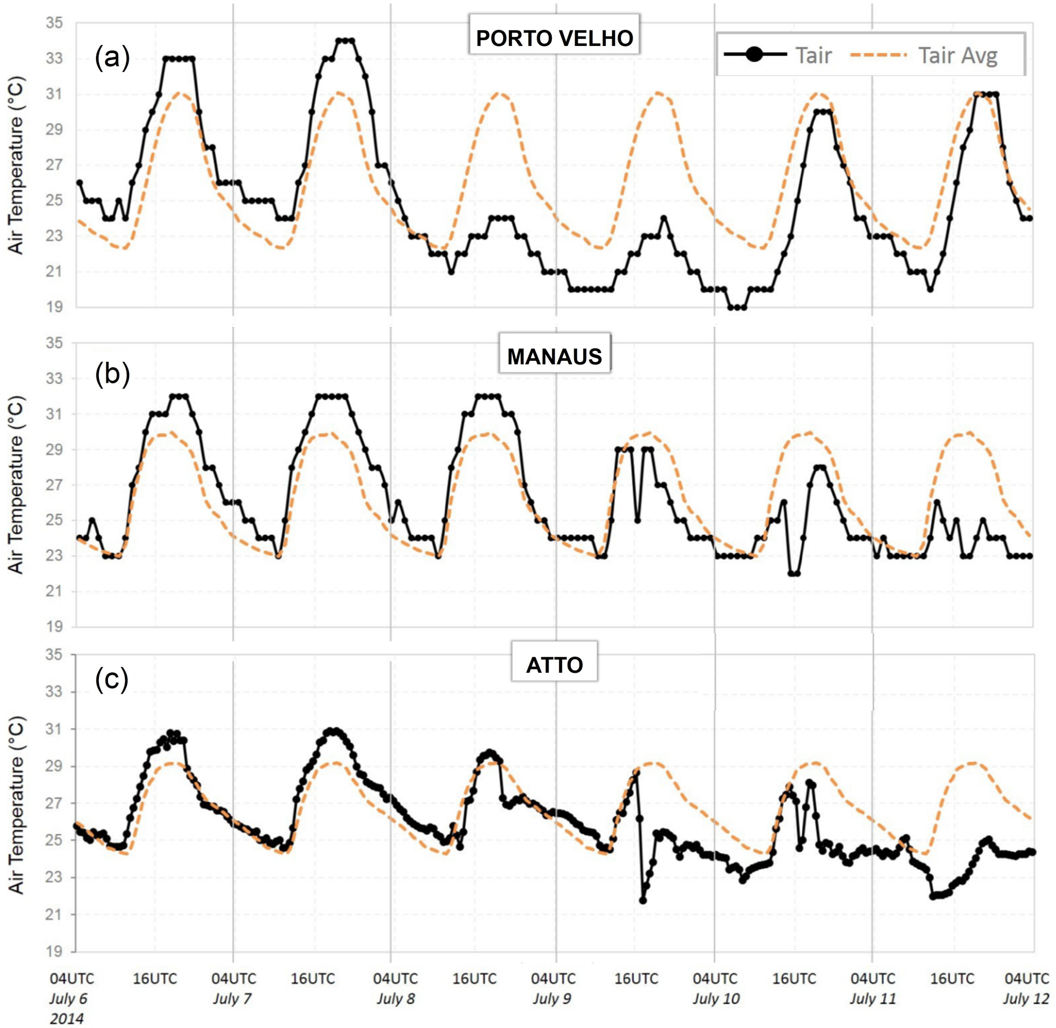


Figure 6. Daily cycle (black line) and monthly average (orange line) of the observational air temperature data from July 6^{th} to 11^{th}, 2014, at: (a) Porto Velho, (b) Manaus region and (c) ATTO site.

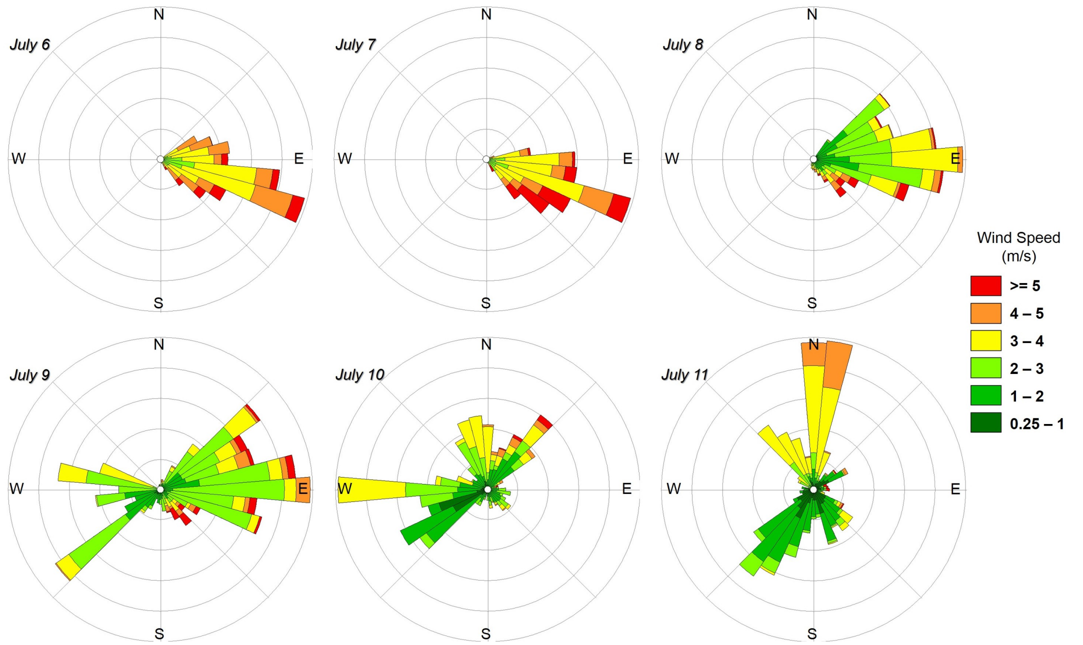


Figure 7. Experimental horizontal wind speed and direction at $73\ m$ above ground measured at the ATTO site between July 6^{th} and 11^{th}, 2014

respectively, does not correspond to the expected direction during the occurrence of the forest breeze towards Lake Balbina, which should be from East-Southeast. Therefore, it is believed that the flow related to the Friagem phenomenon overlapped with that of the breeze circulation observed by Moura et al. (2004), or that the forest-lake breeze circulation does not present the capacity to reach the micrometeorological tower of the ATTO site in $58\ km$ distance (In line with results from Andreae et al. (2015)). This aspect will be discussed in the next section where the results of the simulation with JULES-CCATT-BRAMS model will be analyzed.

3.4 Radiation, ozone and CO_2 during the Friagem event

Figure 9 shows the values of incident short wave radiation (SW_{in}), O_3 and CO_2 measured at the ATTO site, between July 6^{th} and 11^{th}, 2014, respectively (black line). The SW_{in} values decrease during the morning of July 11^{th} when Friagem arrives at the ATTO site (Fig 9a). Moreover, the maximum value ($\approx 450\ W\ m^{-2}$) of SW_{in} occurred at approximately 19 UTC (15 LT), whereas the average monthly daily maximum SW_{in} (orange line) usually occurs at 16 UTC ($\approx 800\ W\ m^{-2}$).

Before the arrival of Friagem at ATTO site region, between July 6^{th} and 8^{th}, it is observed that the values of O_3 (black line) were close to the monthly average (orange line), with minimum values occurring around 10 UTC (06 LT) and maximum around 17 UTC (Fig 9b). This result is consistent with those observed in other studies conducted in the Amazon (Betts et al., 2002; Gerken et al., 2016; Dias-Júnior et al., 2017; Melo et al., 2019). However, during the occurrence of Friagem, between

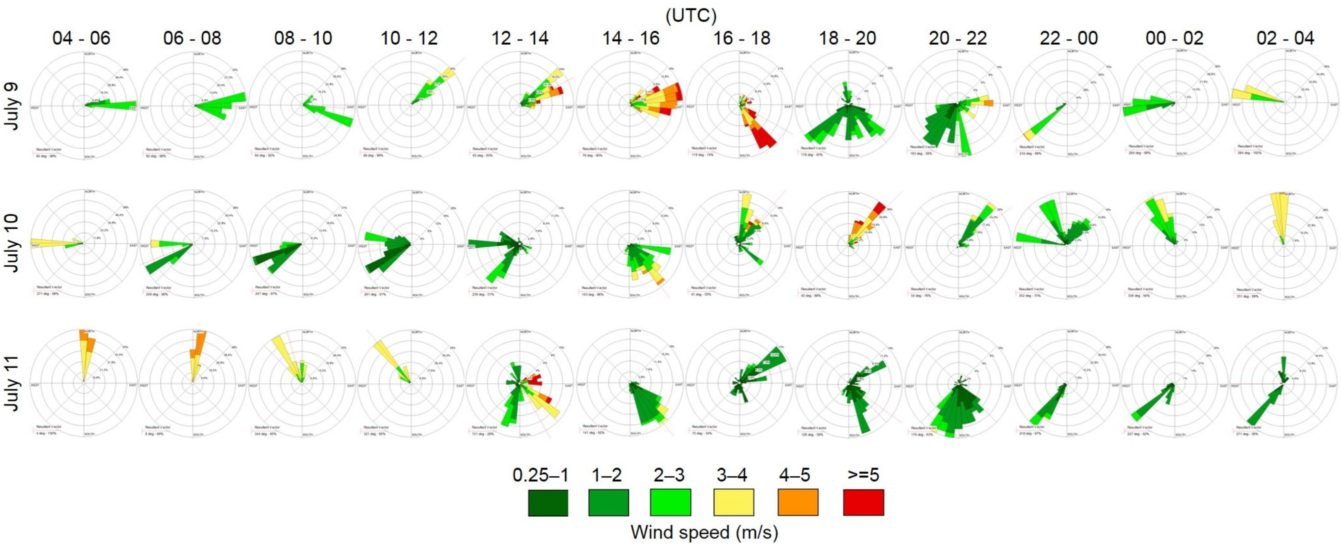


Figure 8. Experimental wind speed and direction at the 73 m above ground measured at the ATTO site, in 2 hour intervals, between July 9^{th} and 11^{th}, 2014.

July 09^{th} and 11^{th}, there was a sharp drop in O_3 mixing ratio at the times when the highest mixing ratio of this trace gas were expected (17 UTC).

Figure 10 shows the O_3 mixing ratio data from 4 different stations around the city of Manaus. All stations show reduced O_3 values during the passage of the Friagem event (black dotted rectangle). Furthermore, stations affected directly by the pollution of the city of Manaus (Iranduba - T2, Manacapuru - T3) show clear influence of increased O_3 formation compared to ATTO and ZF2-T0z. These differences are much smaller during the Friagem event, probably due to reduced photochemistry (Fig. 9a) in this region.

The reduction of the incident short-wave radiation values observed on the 11^{th} (Fig 9a) was possibly associated to the presence of convective systems in this region, as shown in Fig 4. It is known that cloudiness is a determinant meteorological factor in the daily O_3 cycle (Gerken et al., 2016).

It is interesting to note that the rain event during July 11^{th} did not result in an increase of near surface O_3 as observed by others authors (Betts et al., 2002; Gerken et al., 2016; Dias-Júnior et al., 2017). It is believed that the convective cloud formed during the Friagem event was not as deep as the clouds investigated by Betts et al. (2002) and Gerken et al. (2016), which, through their downdrafts, transport O_3 from the high troposphere to the surface.

The values of CO_2 mixing ratio between July 06^{th} and 11^{th} are shown in Fig 9c. It is observed that between July 06^{th} and 10^{th}, CO_2 values for the daily cycle (black line) were very close to the monthly average values (orange line), with a maximum molar fraction around 420 ppm approximately at 10 UTC and minimum of less than 390 ppm (de Araújo et al., 2010). However, on July 11^{th} at 14 UTC, a significant increase of CO_2 (≈ 470 ppm) was observed in relation to the monthly average. This increase may be related to the incident radiation attenuation due to increased cloudiness which reduces the efficiency of the forest in absorbing CO_2 gas via photosynthesis (Ruimy et al., 1995). Also limited vertical mixing as discussed below is a potential reason.

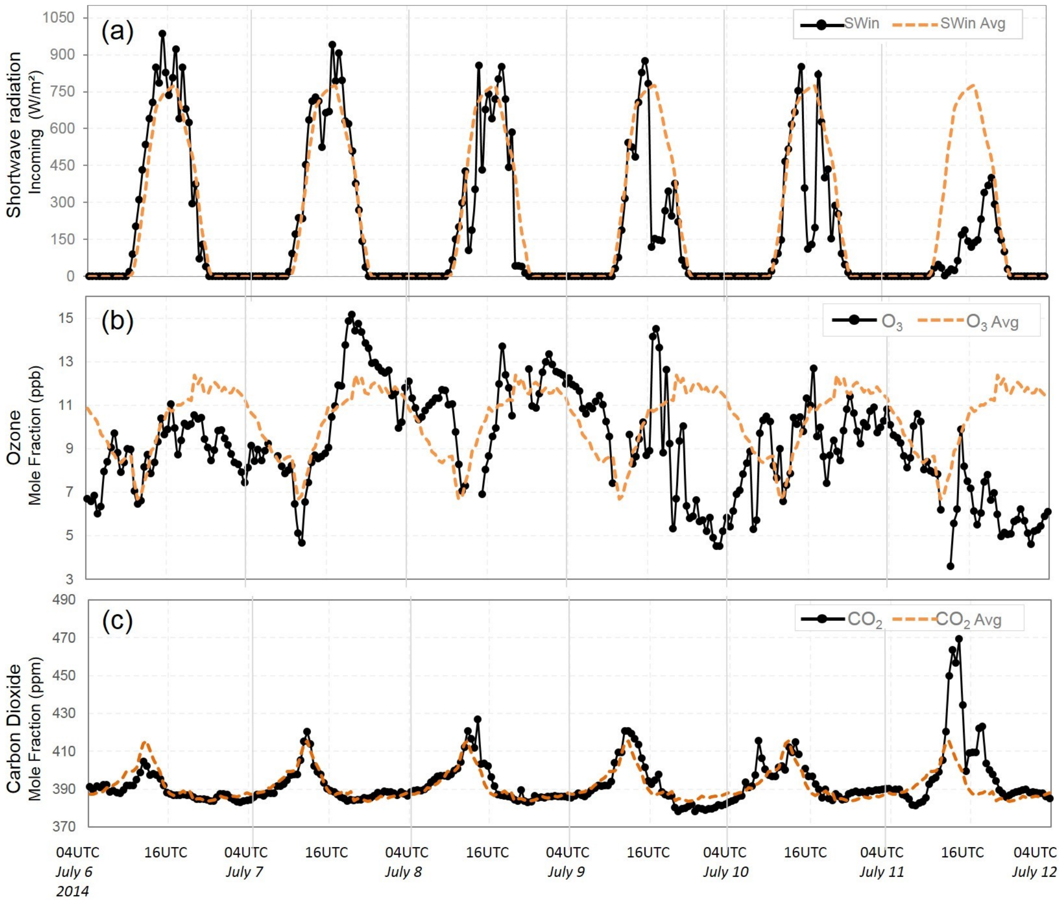


Figure 9. Daily behavior (black line) and monthly average (orange line) of the experimental data : (a) incident short wave radiation (SW_{in}), (b) Ozone (O_3) and (c) Carbon Dioxide (CO_2) mixing ratio from July 6^{th} to 11^{th}, 2014 at the ATTO site.

3.5 Simulation of local circulation and its effect at the ATTO site

In order to better understand the local circulation and its role on the measurements made at ATTO site region, this section presents the results of a numerical simulation made with JULES-CCATT-BRAMS coupled model. Figure 11a shows the vertical profile of the horizontal wind at a grid point near the ATTO site ($02°\ S$ - $59°\ W$) during model integration. At low levels (near $80\ m$), the Easterly wind is observed until the first hours of July 10^{th}. Then the wind has a predominant West-Northwest direction until the afternoon of July 11^{th} and afterwards the wind comes from the South. Therefore, it is observed that the simulation captured the horizontal wind behavior measured at a height of $73\ m$ at the ATTO site, as shown in Fig 8. In addition,

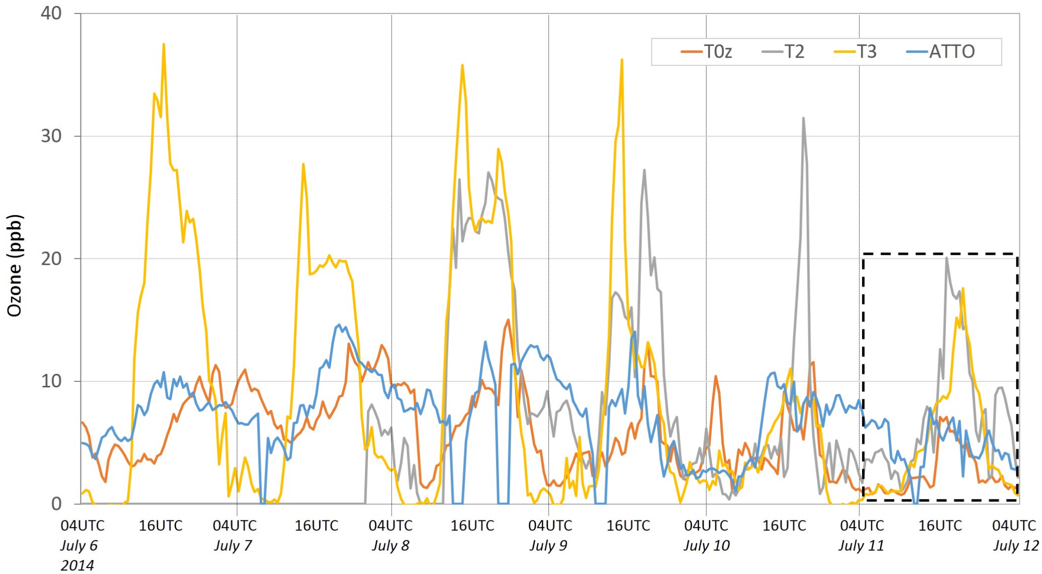


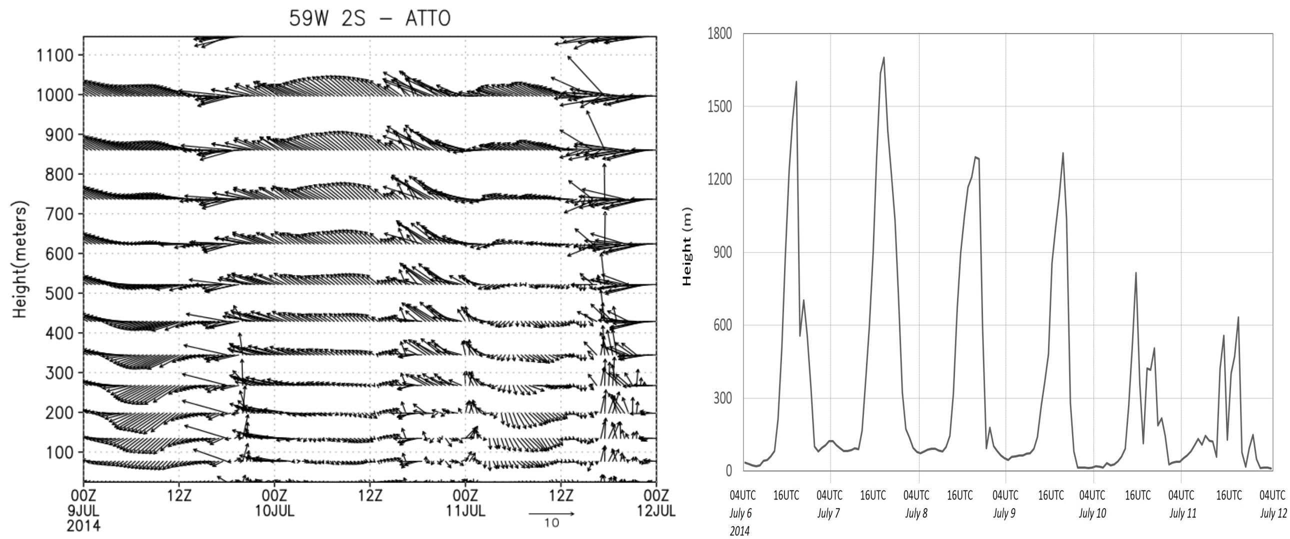
Figure 10. O_3-mixing ratio [ppbv] from 4 different stations around Manaus: ATTO-site (blue line), ZF2 forest - $T0z$ (red line), Iranduba - $T2$ (grey line), Manacapuru - $T3$ (yellow line). The black rectagle indicate the occurrence of the Friagem event. $T2$ are affected directly by the polluted air from the city of Manaus.

above 500 m the flow is essentially from the East during the whole period of integration of the model. Apparently, the Friagem changes only the flow within a small layer adjunct to the ground. Figure 11b shows the values of the boundary layer height (BLH) obtained form ERA5 at a grid point near the ATTO site (02.10° S - 59.06° W). It is possible to note that before the Friagem event the maximum BLH values were greater than 1000 m. However, during the Friagem event, the maximum BLH value was around 600 m.

The large temperature drop Fig. 6a together with the information that the cold air of the Friagem was just in the lower 500 m (Fig. 11), points to the formations of a cold pool above the forest that prevents vertical mixing. As incoming solar radiation was low (Fig. 9a) the surface heating might not be sufficient to break the inversion or at least a very shallow boundary layer was formed as evidenced by the ERA5 data (Fig.11b). This would explain high CO_2 (accumulation of soil emissions) and very low O_3 (limited transport from aloft) at the same time at the ATTO site in addition to the reduced radiation (see section 3.3).

Figure 12 shows the evolution of the temperature at 76.8 m ($°C$, shaded) and horizontal wind ($m\ s^{-1}$, vector) at 134.5 m on July 11^{th}. Between 03 and 11 UTC, the air temperature is higher on Balbina Lake compared to that above the forest area. This temperature gradient induces the formation of a forest breeze towards the lake with the wind converging towards the center of the lake (Fig 12a-e). At 13 UTC the temperature gradient reverses its direction and induces the formation of the lake breeze towards the forest that at 15 UTC is more clearly defined along the southeastern shores of Balbina Lake (Fig 12g).

Another interesting aspect is the entry of cooler air through the Northwest quadrant starting at 03 UTC, which is transported in Southeast direction. From 3 to 11 UTC a corridor of warmer air is established from Lake Balbina to the Southeast quadrant



(a) (b)

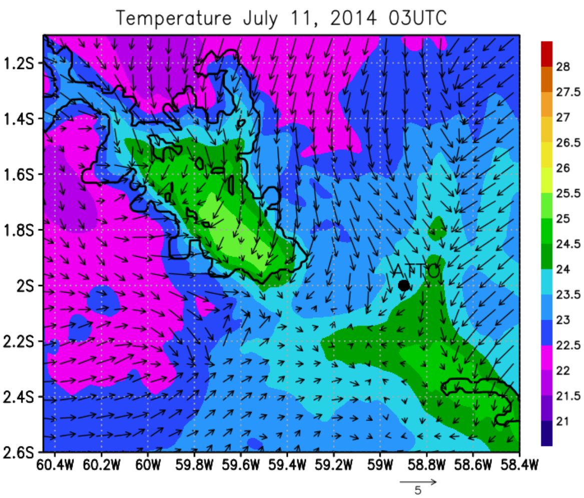
Figure 11. (a) Vertical profile of the horizontal wind ($m\ s^{-1}$) obtained by JULLES-CCATT-BRAMS simulation for the ATTO site from 00 UTC from the 9^{th} to 00 UTC of July 12^{th}, 2014. (b) Boundary layer height (m) obtained from ERA5 for the ATTO site from 04 UTC - July 6^{th} to 04 UTC - July 12^{th}, 2014.

of the domain along the Uatumã River whose width is less than 1 km and can not be captured by the horizontal resolution in this simulation. The gradual drop in temperature and predominance of Northwest winds shown in this simulation at the grid points near the ATTO site agree with the observational data from this site (Fig. 6 and 7).

Although the Balbina lake breeze was established, it did not reach the ATTO site until 15 UTC (Fig 12g). In addition, precipitation in the simulation occurred in the following hours, similar to that observed in satellite images (Fig 4), which in turn disrupts the environment propitious to vigorous breezes that could reach the ATTO site. Although the Friagem phenomenon causes the weakening of the trade winds, which in turn would allow the establishment of more intense breezes as proposed by Silva Dias et al. (2004), the cooler and drier air mass flow of Friagem in the central region of the Amazon was dominant over the lake and forest breeze circulation. Possibly, the establishment of more vigorous river breeze circulations observed by Silva Dias et al. (2004) is possible due to the Friagem phenomenon not reaching that region and interfering with the signal of the breeze and causing intense rainfall.

Figure 13 shows the behavior of modeled water vapor, O_3, CO and NO_2 on July 11^{th}, 2014, at the moment of incursion (a, c, f, g) and dissipation (b, d, f, h) of the Friagem in the study area. The mixing ratios of water vapor near the surface at 02 UTC (Fig. 13a) were lower in the regions where cooler air was observed entering this domain, indicating that the Friagem brought cold and dry air to the ATTO site and Balbina Lake.

O_3-mixing ratios are higher above the lake and its surroundings, for both times shown (Fig. 13c and d). The O_3-mixing ratio within the limits of the simulation domain are mostly below 11 ppbv, whereas above the lake these mixing ratios exceed 20


Temperature July 11, 2014 03UTC
1.2S
1.4S
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2.2S
2.4S
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60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
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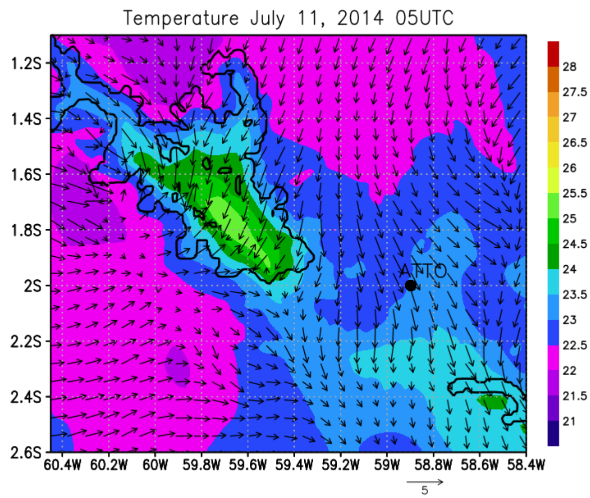
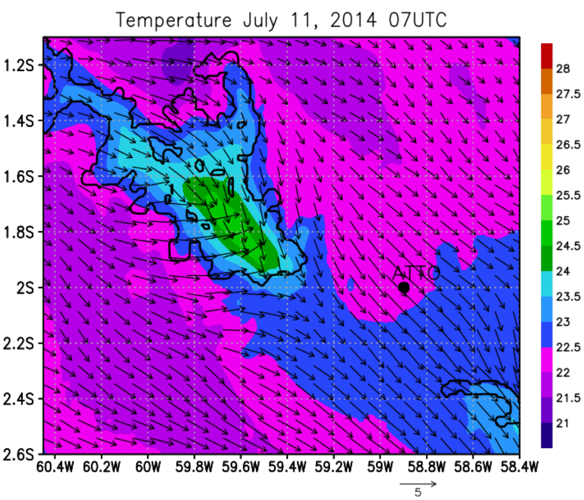
21

(a)


Temperature July 11, 2014 05UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
5
28
27.5
27
26.5
26
25.5
25
24.5
24
23.5
23
22.5
22
21.5
21

(b)


Temperature July 11, 2014 07UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
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24.5
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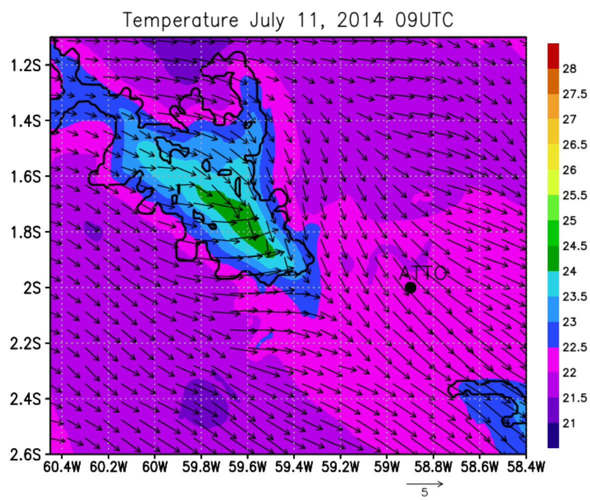
22.5
22
21.5
21

(c)


Temperature July 11, 2014 09UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
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27.5
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24.5
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22.5
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21.5
21

(d)

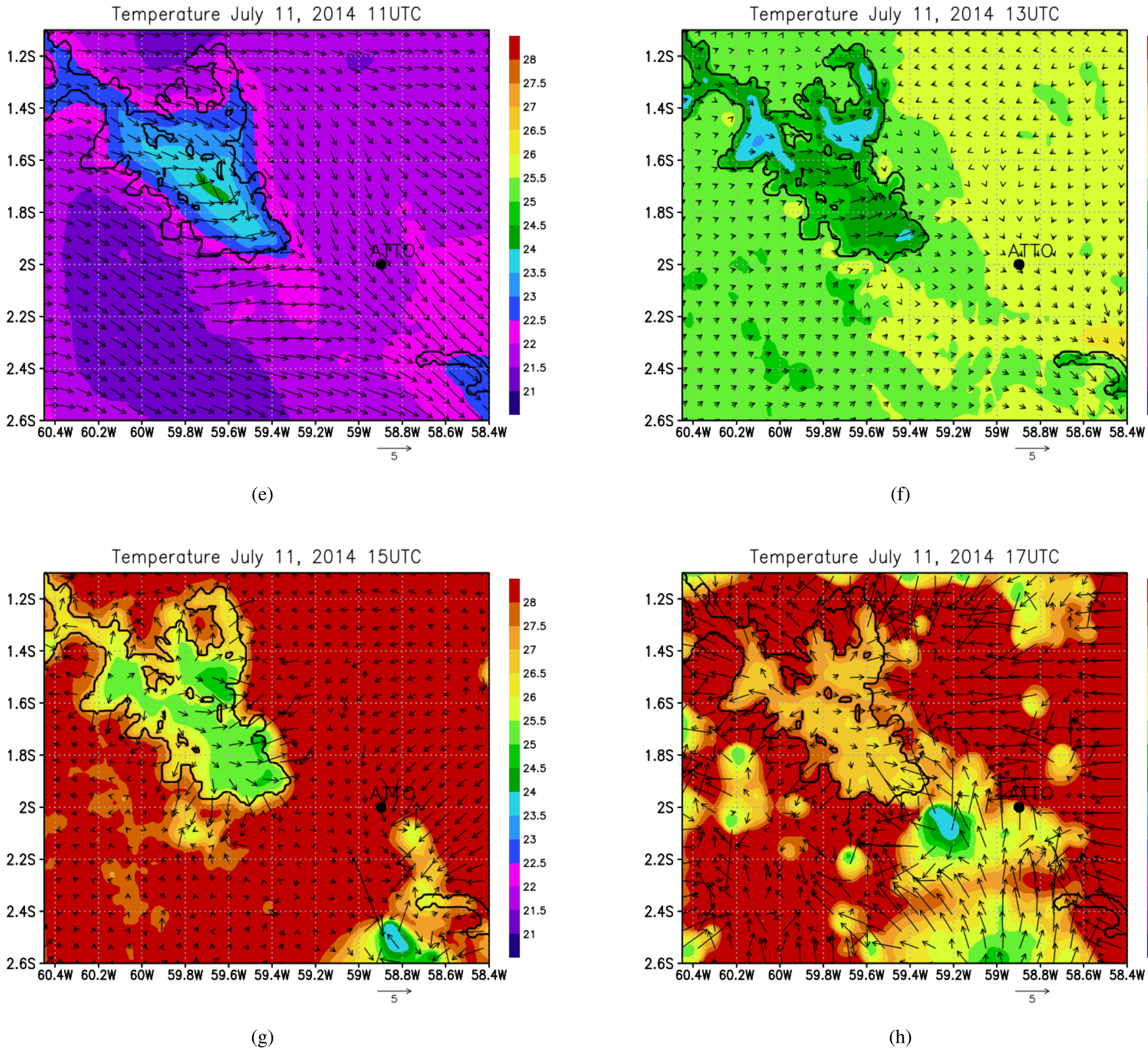
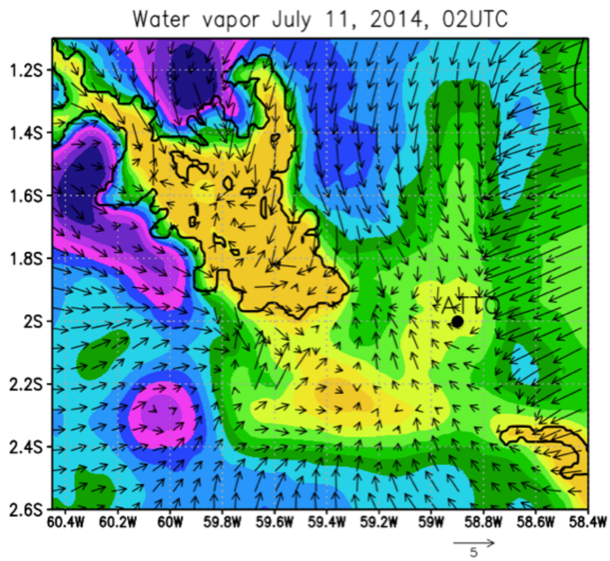
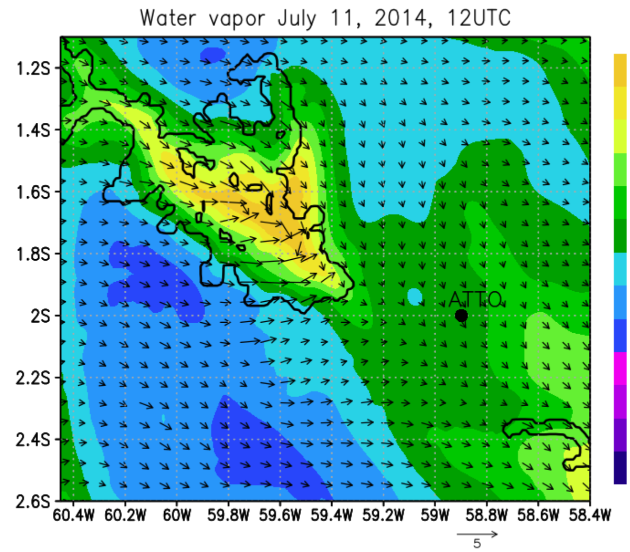


Figure 12. Evolution of modeled air temperature ($^{\circ}C$, shaded) at $76.8\ m$ and horizontal wind ($m\ s^{-1}$, vector) at 134.5 m, on July 11^{th}, 2014 at: (a) 03 UTC, (b) 05 UTC, (c) 07 UTC, (d) 09 UTC, (e) 11 UTC, (f) 13 UTC, (g) 15 UTC and (h) 17 UTC. Balbina Lake (black contour) and ATTO site (black dot) are indicated.



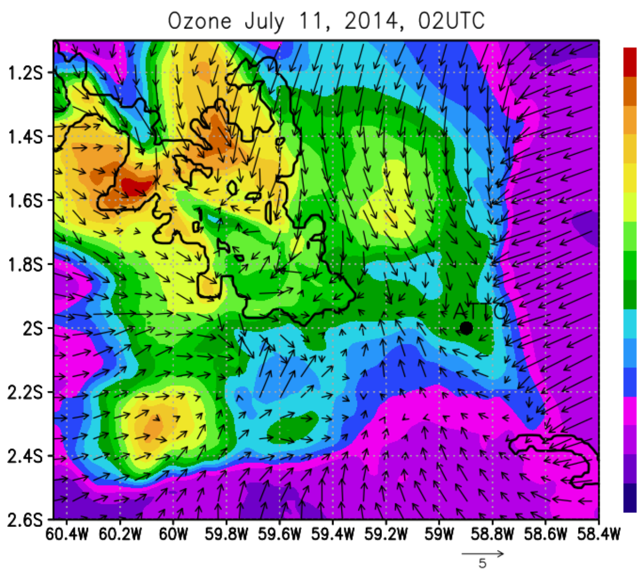
Water vapor July 11, 2014, 02UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
5
18.8
18.6
18.4
18.2
18
17.8
17.6
17.4
17.2
17
16.8
16.6

(a)



Water vapor July 11, 2014, 12UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
5
18.8
18.6
18.4
18.2
18
17.8
17.6
17.4
17.2
17
16.8
16.6

(b)



Ozone July 11, 2014, 02UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
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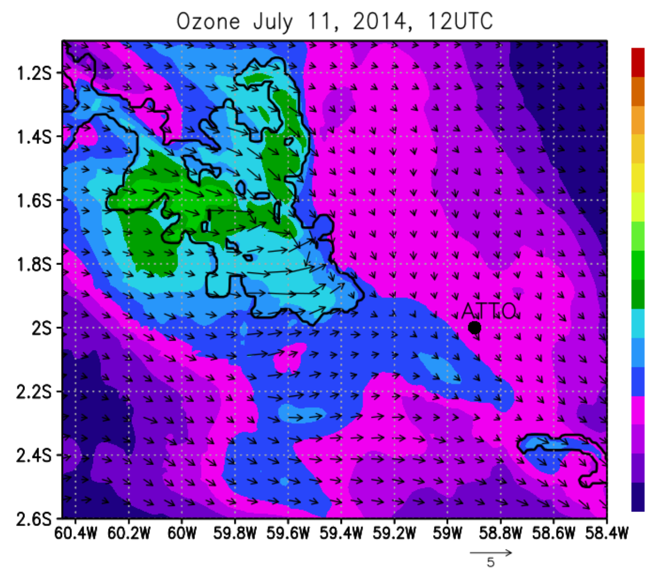
13
12
11
10
9
8

(c)



Ozone July 11, 2014, 12UTC
1.2S
1.4S
1.6S
1.8S
2S
2.2S
2.4S
2.6S
60.4W 60.2W 60W 59.8W 59.6W 59.4W 59.2W 59W 58.8W 58.6W 58.4W
ATTO
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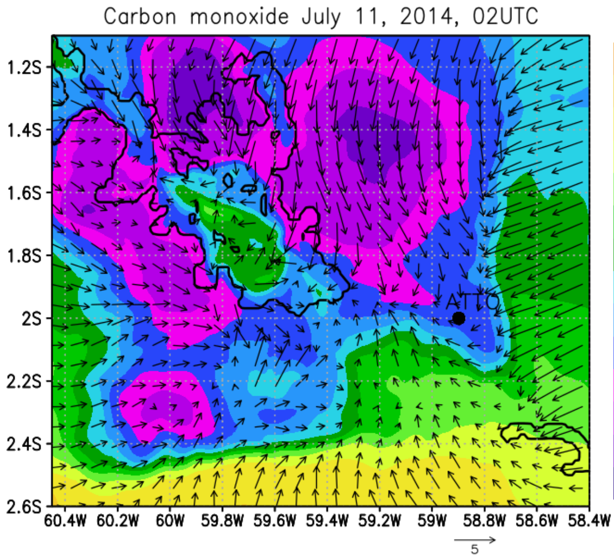
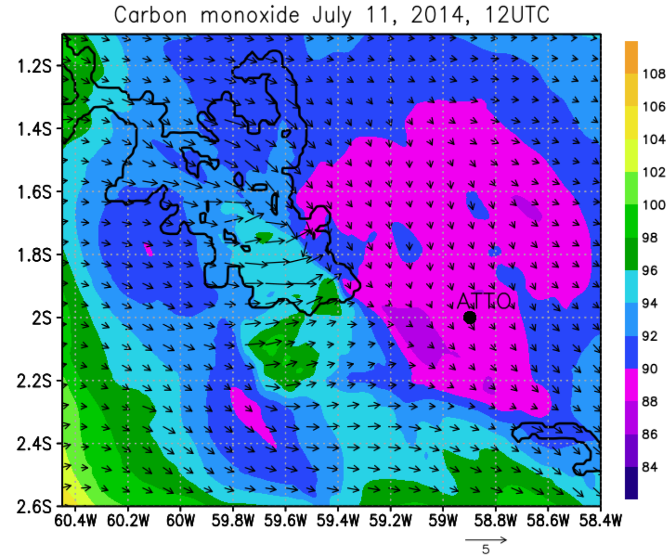
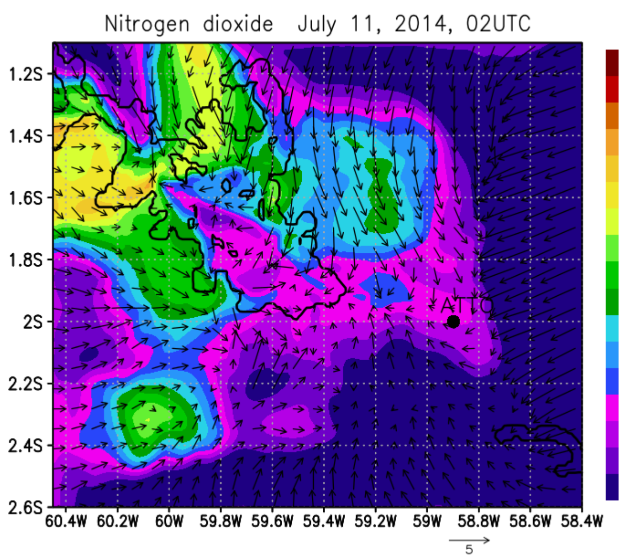
(d)



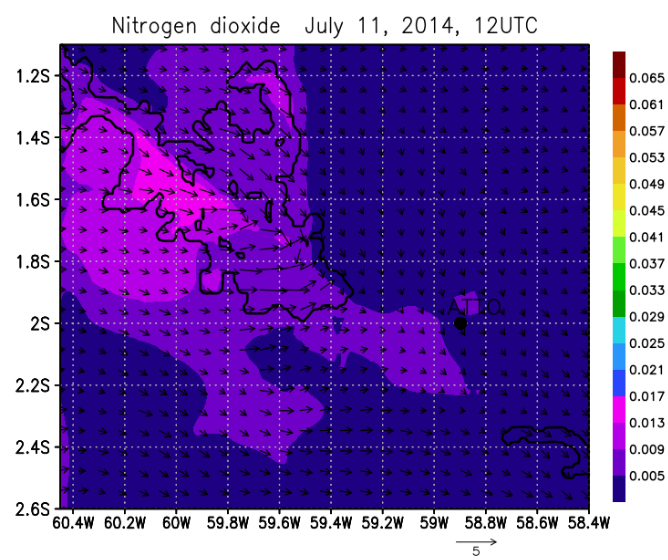
(e)



(f)



(g)



(h)

Figure 13. simulated horizontal wind at 134.5 m on July 11th, 2014 for: (a, b) water vapor mixture ratio ($g\ kg^{-1}$, shaded); (c, d) ozone mixing ratio (ppbv, shaded); (e, f) carbon monoxide mixing ratio (ppbv, shaded) and (g, h) nitrogen dioxide mixing ratio (ppbv, shaded) at $24.4\ m$, when the Friagem was arriving at the study area (a, c, e, g) and at the moment of its dissipation (b, d, f, g). Balbina Lake (black outline) and ATTO site (black dot) are indicated

ppbv at certain points, especially at 02 UTC. The effect responsible for higher O_3-mixing ratio both during the day e night may be associated with the fact that deposition is very much reduced over the open water compared to the forest (Ganzeveld et al., 2009). It can also be seen that the Friagem extended in the direction of ATTO, but probably due to the onset of rain (Fig. 4) was not clearly detected at ATTO.

In regards of CO gas, it can be observed that its concentration on the center of the lake at 02 UTC (Fig. 13e) is higher than in the regions near the margins of the lake, however, calls attention at this time the transport of CO arriving with the South and Northeast winds, approaching the ATTO site. However, it is noted that the entire region of the simulation domain presents low CO mixing ratio at the time the Friagem is dissipated (Fig. 13f). Apparently, the Friagem event "expels" the polluted air mass in the South and Southeast of the ATTO site (around Manaus city), "cleaning" the atmosphere, or preventing this pollution from reaching ATTO site and Balbina lake.

NO_2 gas is an important precursor of O_3, and is mainly related to emissions from fires and vehicles. The emission of precursor gases in the formation of O_3 mixing ratio can increase of this trace gas to levels harmful to the forest, since the ozone can damage the stomatal functions of the leaves (Pacifico et al., 2015). In spite of this, it is observed that the higher NO_2 mixing ratio at 02 UTC (Fig. 13g) seem to have their origin in the region where higher O_3 mixing ratios are found and presented lower NO_2 during the time of dissipation of the Friagem (Fig. 13h).

4 Conclusion

In the period of July 9^{th} to 11^{th}, 2014 a Friagem phenomenon reached the central region of the Amazon. Through the ECMWF ERA-interim reanalysis it was possible to verify that this phenomenon ventured the Amazon region from Southwest to Northeast, bringing a strong cold, dry, ozone-rich air mass in the West quadrant, which dominated the wind field in the central region of the Amazon.

Through the observational data it was possible to verify that the passage of the Friagem in central Amazon had its most significant effects on July 11^{th}, in region of the Manaus city, such as: Balbina Lake; ATTO site and others sites (T2, T3 and T0z).

From the observational data collected at the ATTO site, it was observed that the 11^{th} was marked by a sudden fall in air temperature, a weakening of the typical East flow and a predominance of South, West and North winds. In addition, on the 11^{th} the interaction between the Friagem air mass and the trade winds flow gave origin to convection bands, which in turn caused a significant reduction of the incident short wave radiation, besides a record rain of the month. With the BRAMS simulations we found that the cold air of the Friagem was just in the lower 500 m. These information leads us to the conclusion that there is a cold pool above the forest that prevents vertical mixing and consequently contributes to a increase in CO_2 mixing ratio and abrupt drop in O_3 mixing ratio above the forest canopy.

Also, through the simulations of the JULES-CCATT-BRAMS it was possible to evaluate the main impacts that the Friagem phenomenon caused both in the thermodynamic characteristics and in the atmospheric chemistry of the central region of the

Amazon. In addition, the breeze circulations between Lake Balbina and the forest were well represented in the simulations, however, it was not possible to verify the influence of this breeze in trace gas concentrations at the ATTO site.

With the observational results and the simulations, it can be concluded that the Friagem phenomenon can interfere deeply in the microclimatic conditions and the chemical composition of the atmosphere, in a region of dense forest, in the center of the Amazon.

Data availability. The ATTO data used in these study are stored in the ATTO databases at the Max Planck Institute for chemistry and the Instituto Nacional de Pesquisas da Amazônia. Data access can be requested from Stefan Wolff, who maintains the O3 mixing ratios dataset (stefan.wolff@mpic.de) and Alessandro Araújo who maintains the micrometeorology dataset (alessandro.araujo@gmail.com). The GoAmazon data used in these study can be requested from Luciana Rizzo (luvarizzo@gmail.com)

Author contributions. GFCN, JCPC and CQDJ designed the study and wrote the article with the assistance of MS and JHC. SW, RAFS and PA maintain the greenhouse gas measurement system at ATTO and provided the CO_2 and O_3 data. AA and MS operate and maintain the micrometeorology equipment at ATTO and provided the data which was fundamental for this study. LVR provided the O3 data from GoAmazon sites. PAFK and JCPC assisted with BRAMS simulations.

Competing interests. The authors declare that they have no conflict of interest

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