Response to referee comments and suggestions on acp-2018-323 by C. Pöhlker et al.: "Land cover and its transformation in the backward trajectory footprint region of the Amazon Tall Tower Observatory"

Manuscript format description:
Black text shows the original referee comment, red text shows the authors response, and blue text shows quoted manuscript text. We used bracketed comment numbers for referee comments (e.g., [R1.1]) and author's responses (e.g., [A1.1]). Line numbers refer to the discussion/review manuscript.

David Fitzjarrald as Referee #1
Received: 28 June 2018

General comments:

[R1.1] The ATTO team delivers manuscript that reads like notes from a committee white paper. Clearly a lot of work has been done by some of the authors, but I sure would have been happier had more effort gone in to dealing with the ostensible topic of the paper, the utility of the backward trajectories that lead to the ATTO.

[A1.1] We appreciate the honest criticism by the referee and can confirm that all text was specifically written for this paper. We are further confident that the text of the manuscript has a higher quality than just a collection of "notes". With respect to the backward trajectories, the referee indeed pointed out some deficits in clarifying crucial aspects of the analysis as specified in detail in our response [A1.3] to [A1.5]. We are grateful for these hints.

[R1.2] To demonstrate the importance of their effort, the authors offer up a litany of examples of Amazon Basin land cover change and deforestation, but, sadly, too many of these are references to the situation in the SW portion of the Basin, *not* upwind of the ATTO. (One fine exception is the authors' noting of the location and importance of the Renca Reserve, which is upwind of the ATTO, a site that may or may not be a new locus for mining, depending on politics in Brazil.)

[A1.2] We are somewhat confused by the referee's comment that "sadly, too many of these are references to the situation in the SW portion of the Basin, *not* upwind of the ATTO". The SW part of the basin would include the states of Acre, Rondônia, and the southwest of Amazonas. However, Fig. 7 clearly shows that the region of interest ROI_{foot}, which defines the geographic extent of all subsequent maps (e.g., Fig. 10, 15 and 17), covers the NE and E states Roraima, Amapá, Pará as well as French Guiana and Surinam. The RENCA reserve is located in the center of the ROI_{foot}.

[R1.3] There appears to be a real disconnect between the authors' cavalier attitude that the trajectory results can be accepted intact with little question and the amount of detail presented in identifying the surface land-cover and fire presence categories. The authors assure the reader that: "*Trajectory models have been constantly improved, while gridded meteorological data became more sophisticated….*" However, please note that there are *still* only a few radiosonde stations to furnish the reanalysis with extremely important input *upwind* of the ATTO (see map below, along with the preferred trajectories identified in this manuscript). What's more, most of these stations are at the coast, and will not adequately represent the boundary layer inland. Granted, the wind is pretty steadily easterly, switching from NE to SE over the seasons, but the presence of large rivers means that local breeze circulations could significantly alter the trajectories in lower layers, precisely the ones that the authors want to emphasize.

[A1.3] We agree with the referee that the mentioned aspects require further clarification. Therefore, we added the following text section in p. 5, l. 27 to clarify that the limited number of radiosonde station bears uncertainties to be considered carefully:

> For the HYSPLIT BT analysis presented here it is important to note that the meteorological reanalysis, which serves as input for the trajectory model, relies on comparatively few radiosonde stations in the Amazon region. Moreover, several of the station upwind of the ATTO site are located at the coast and, therefore, likely will not adequately represent the boundary layer height in the basin. The associated uncertainties have to be considered carefully in the interpretation of the BT results.

Moreover, the potential influence of river-related local breeze circulations has been mentioned explicitly by adding the following statement in p. 13, l. 5:

> A potential major uncertainty to keep in mind is the influence of local breeze circulations at the large rivers in the region that could significantly alter BTs in lower atmospheric layers.

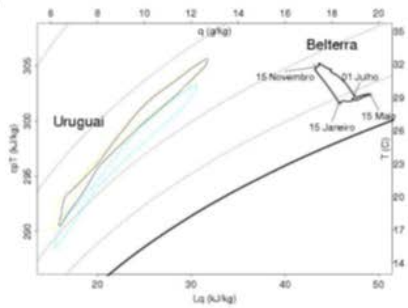
Despite the aforementioned uncertainties, however, we are quite convinced that the overall trends in the BT spatiotemporal variability (even with quite some detail) are an appropriate representation of the ATTO-relevant atmospheric circulation. This impression is supported by (partly surprisingly) good agreements between BT patterns and atmospheric measurements at ATTO. Some of these links between BTs and atmospheric composition can be found in several recently published papers (i.e., Moran-Zuloaga et al., 2018; Pöhlker et al., 2018; Saturno et al., 2018).

[R1.4] Unless I missed it, there are only two mentions of the 'boundary layer' is in this manuscript (line 30 page 12, and line 38, page 32, where this point is repeated), in the context of discussing the global Hadley Cell and the climatology of the trade winds feeding in moisture. A few references listed below indicate that identifying the HYSPLIT trajectories in this part of the world is not news anymore. This is an off-the-shelf effort. The authors are offering the readers this paper so it can be referenced in later work, but they owe the reader some more depth of understanding of the strengths *and weaknesses* of this approach. The 'residence time' that matters ought to be the duration *and location* of the presence of the virtual parcel when the airmass is in 'communication'—turbulent connection—with the surface, which I imagine to be during the presence of the midday convective boundary layer. When the authors mention HaPe Schmid's footprint work as a starting point, they don't carry over the idea that it is the turbulent mixing and subsequent diffusion that defines the 'tower footprint'.

[A1.4] See our response [A1.5].

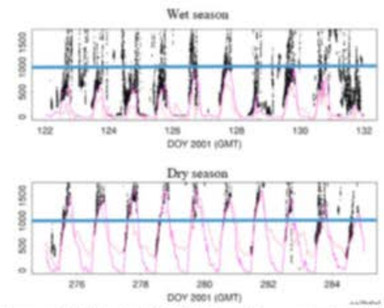
[R1.5] That 1000 m level (close to the ATTO highest level) is likely be in the CBL for some daylight hours during the eastern Amazon Basin dry season, but it will likely be in the cloud layer during the midday wet season CBL (see the illustrative plots below—data from the LBA km67 site near Santarém PA). That will turn out to precess over the course of the day for parcels tracked back from different arrival hours at the ATTO site, and would look like to a 'dashed line' of activity as the trajectory crosses into the continent. It shouldn't really the duration, total time the air is in motion. One should take into account the convective hours of connection upwind, and then the hours of convection at the ATTO to present to the bedazzled readers the 'hot spots' of potential upwind influence, no?

(a)



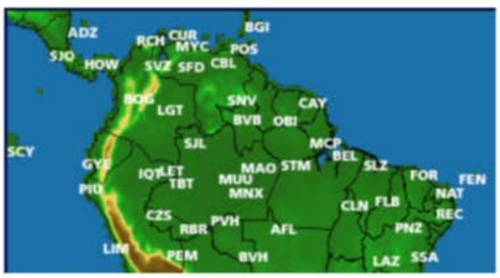
Surface seasonal changes of surface state on a T vs q phase plane.; LCL, km67. Gray lines show isolines of LCL. Mean conditions for Belterra (near Santarém) and an average of Uruguayan grassland sites

(b)



Cloud base and LCL, km67. Black points mark cloud base. Red and magenta lines are LCL at forest km67 and a nearby pasture km77 sites in LBA. Horizontal blue line at 1km altitude.

(c)



Radiosonde sites in northern South America.

(d)

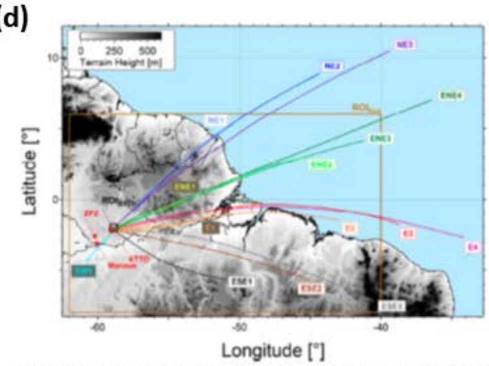


Figure 4. Map of northeast Amazon Basin with 15 clusters from systematic k-means back trajectory (BT)

Referee Figure R1.

[A1.5] We agree with referee that the relevance of the boundary layer for convective contact of the air masses with the ground deserves further and more systematic clarification. Accordingly, we recalculated a sequence of backward trajectory ensembles, taking the suggestion of the referee in his comments [R1.4] and [R1.5] into account. Specifically, we applied a sequence of (increasingly strict) filters to the BT ensembles to filter for (i) trajectory height, (ii) convective periods along the individual trajectories, and (iii) convective hours upon trajectory arrival at ATTO. The comparison of the results from the different filters shows some changes in the periphery of the footprint region, however, no fundamental impact on the shape for footprint's core region. The additional analysis as suggested by the referee has been implemented and clearly strengthens the manuscript. However, no major changes of the main aspects of the study became necessary since all derived footprints regions (filtered vs. unfiltered) have comparable geographic extents.

Specifically, section 2.5 has been edited with experimental details on the aforementioned analysis being implemented:

2.5 Definition of backward trajectory-based ATTO footprint region

The footprint concept has been introduced for atmospheric measurement sites to quantify the distribution and extent of biosphere-atmosphere exchange in their surroundings, which contributes to the variability of observed trace compound concentrations (Gloor et al., 2001). Schmid (2002) formally defined the footprint (sometimes also called airshed or effective upwind fetch) of a measurement as "the transfer function between the measured value and a set of forcings on the surfaceatmosphere interface" as a general description of various footprint modelling frameworks. Footprints have been mostly used in the context of long-term trace gas observations (e.g., greenhouse gases) (e.g., Thompson et al., 2009; Winderlich et al., 2010). The size of a footprint largely depends on the height of the measurement, and tall tower sites are known to cover large footprint regions, which makes them particularly valuable for representative regional monitoring (Gloor et al., 2001). The geographic distribution of a footprint is defined by the distribution of relevant sources and the predominant wind directions.

The modelling of specific footprints for the ATTO observations based on specific source-receptor relationships (i.e., for specific compounds and observational conditions) is beyond the scope of this work and will presumably be subject of dedicated future studies. Here, we use the term footprint in a more simplistic and general sense as the area on the South American continent that is covered by the air mass residence time maps, which are based on multiple years of 3-day HYSPLIT BTs. In order to discriminate our approach from footprint modelling attempts according to Schmid (2002), we use the term 'BT footprint' in this study. The choice of 3 days for this analysis is justified, for example, by a study by Lammel et al. (2003), reporting the characteristic formation times of secondary aerosols of about 48-72 h as well as the fact that coarse mode particles "were derived from emissions < 36 h back". With this approach, we aim to map the history of the air masses that were advected towards ATTO on the South American continent. Since primary aerosol and trace gas emissions mostly occur ground-based, only those BTs effectively pick up emissions that reach into the so called footprint layer, a "vertical layer adjacent to the ground in which surface emissions are present and assumed to affect passing air tracer particles" (e.g., Hüser et al., 2017). Accordingly, only those HYSPLIT BTs being transported at lower altitudes reach into the footprint layer and, thus, identify effective source regions. In order to analyze specific relationships between pollution sources and the receptor site (ATTO), assumptions on the vertical depth of the footprint layer and the BT mixing depth have to be taken into account.

The sensitivity of the geographic extent of the BT footprint region towards different BL heights and convective mixing inside the BL has been tested by applying dedicated filters on the BT data. We calculated different versions of the BT footprint region on the basis of multi-year BT ensembles with settings as specified in Table 1. Three types of filters were applied, which introduce increasingly strict conditions into the approach:

- **height filter**: The BT height is an output parameter of the HYSPLIT model. Height thresholds of 1500, 1000, and 500 m were defined as proxies for BL heights in the Amazon. Typical daytime BL heights at ATTO range from 1000 to 2000 m (Fisch et al., 2004). Accordingly, the thresholds at 1500 and 1000 m are realistic, whereas the threshold at 500 m is based on more extreme assumptions and, thus, primarily serves as a sensitivity test. The filter excludes all sections of the individual BTs from the analysis with heights exceeding the defined threshold. The remaining sections (with heights below the threshold) are assumed to be located within the convectively mixed BL.
- **convection filter *en route***: The sun flux along the BTs is a meteorological output parameter of the HYSPLIT model ranging from 0 to ~900 W m^{-2}. The sun flux of the BTs upon arrival (i.e., in the ATTO pixel) has been compared with local meteorological measurements and shows a reasonably good agreement. A sun flux threshold of 50 W m^{-2} has been chosen as a (rough) proxy for the onset and end of convective mixing along the individual BTs. The filter excludes all BT segments with a sun flux below the threshold from the analysis (i.e., the nighttime segments). The underlying assumption is that only the BT segments, which are in convective connection with the surface are relevant for the footprint analysis.
- **convection filter at ATTO**: Assuming that only BTs are relevant that arrive at ATTO during convective hours (i.e., excluding conditions with decoupled layers during nighttime), we further applied a filter that keeps only those BTs in the analysis when their sun flux upon arrival (i.e., in the ATTO pixel) exceeds a threshold of 50 W m^{-2}.

Based on these differently filtered BT ensembles defined in Table 1, corresponding footprints were calculated statistically as outlined below. The original one hour trajectory points were interpolated to minute-wise steps and then counted within a 0.1° by 0.1° grid according to Sect. 2.2. Within the distribution of pixel values, which represent air mass residence times, contour lines for the upper 1 %, the upper 5 %, the upper 10 %, the upper 25 % and the median level were calculated. The continental part of the area, which includes the 25 % of highest air mass residence time levels, has been defined as ATTO BT footprint region. The different BT footprints based on the filtered BT ensembles as specified in Table 1 are shown in Fig. S5. With the same statistical approach, the BT cluster footprints of the 15 clusters from the *k*-means clustering have been defined. For certain aspects of the geographic analysis in Sect. 3.3, land cover properties have been weighted by the air mass residence time (see Sect. 2.7). In these case, we refer to the ‘weighted BT footprint’. In order to create GIS maps, which includes the most relevant regions, we define a rectangular region of interest (ROI) that includes the ATTO-site BT footprint region (ROI_{foot}: 62°W, 40° W, 8° S, 6° N; see also Sect. 2.8).

Table 1, which specifies details of the filters applied to the trajectories, has been added to the main text:

Table 1. Filters applied to multi-year BT ensemble. Height filter crops segments along individual BTs if values exceed height threshold (e.g., height of 1000 m; named “H1000”). Convection filter *en route* crops segments along individual BTs if sun flux values are below threshold (named “Cer”). Convection filter at ATTO removed entire BTs from analysis if sun flux upon arrival (i.e., in the ATTO pixel) is below threshold (named “Catto”).

filters	**height filter [m]**	**convection filter *en route* [W m^{-2}]**	**convection filter at ATTO [W m^{-2}]**
No Filter	none	none	none
H1500	>1500	none	none
H1000	>1000	none	none
H0500	>500	none	none
H1500_Cer	>1500	<50	none
H1000_Cer	>1000	<50	none
H0500_Cer	>500	<50	none
H1500_Cer_Catto	>1500	<50	<50
H1000_Cer_Catto	>1000	<50	<50
H0500_Cer_Catto	>500	<50	<50

Moreover, a new figure has been added as Fig. S5 to the supplement file, which compares the resulting ATTO footprints based on the differently filtered trajectory ensembles:

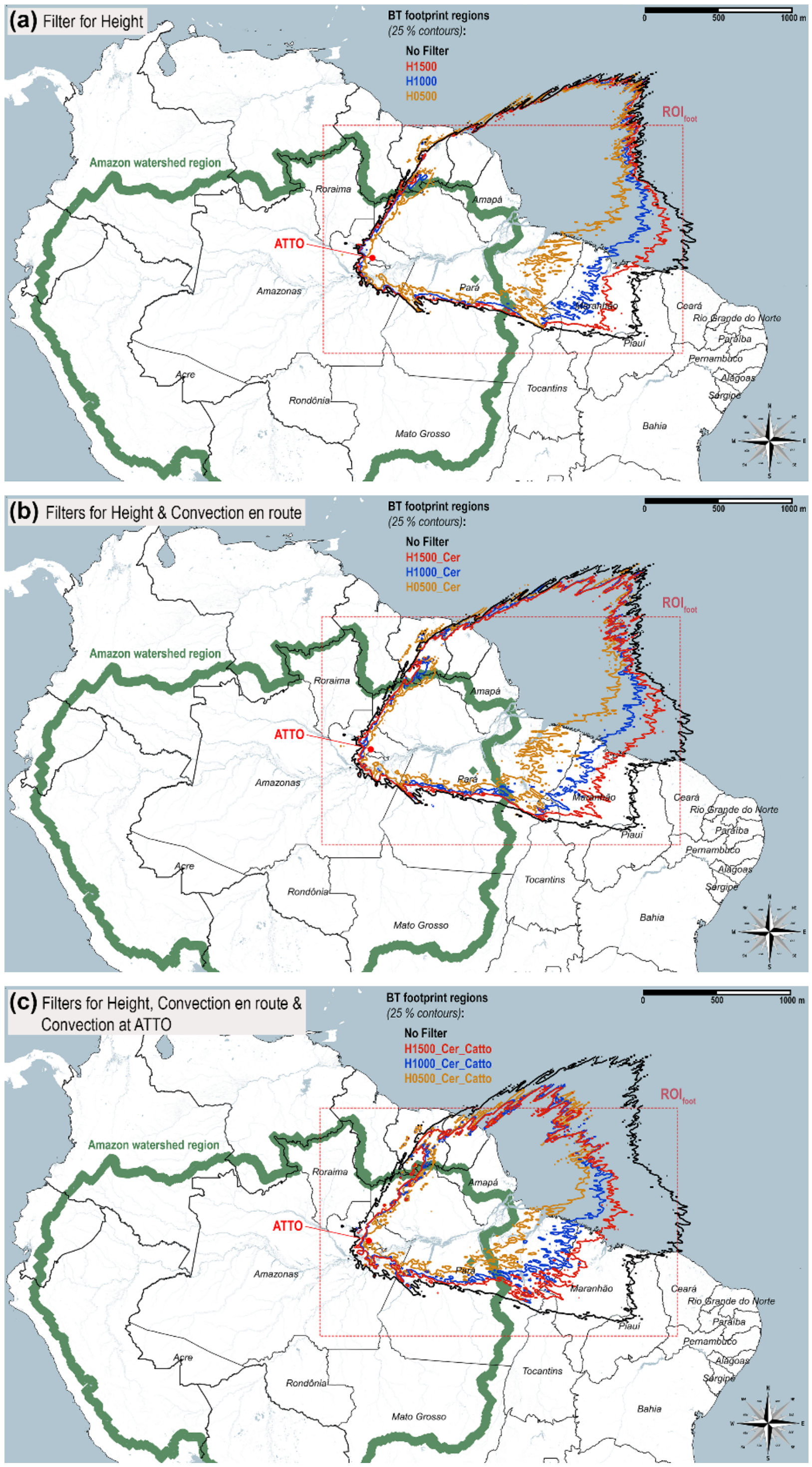


Figure S5. Versions of ATTO BT footprint region based on differently filtered BT ensembles as specified in Table 1 and discussed in Sect. 2.5 and 3.3.

In the main text (p.17, l. 16) the following text block has been added:

> The footprint shown in Fig. 7 (the base case) takes the entire BT ensemble into account. In order to assess to what the extent the individual BTs were in convective contact with the ground via the BL, we applied a sequence of filters to the base case BT ensemble (see Sect. 2.5). We found that the filtering does not substantially alter the geographic extent of the footprint's easterly core regions, whereas certain variations in the outer parts of the 25 % contour lines were observed (Fig. S5). With respect to the scope of this study, this indicates that the base case BT footprint is well suited to identify regions and land cover types that are of particular relevance for the ATTO research.

References:

Moran-Zuloaga, D., Ditas, F., Walter, D., Saturno, J., Brito, J., Carbone, S., Chi, X., Hrabě de Angelis, I., Baars, H., Godoi, R. H. M., Heese, B., Holanda, B. A., Lavrič, J. V., Martin, S. T., Ming, J., Pöhlker, M. L., Ruckteschler, N., Su, H., Wang, Y., Wang, Q., Wang, Z., Weber, B., Wolff, S., Artaxo, P., Pöschl, U., Andreae, M. O., and Pöhlker, C.: Long-term study on coarse mode aerosols in the Amazon rain forest with the frequent intrusion of Saharan dust plumes, Atmos. Chem. Phys., 18, 10055-10088, 10.5194/acp-18-10055-2018, 2018.

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