Ms. No.: ACP-2022-256

A meteorological overview of the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) campaign over the southeast Atlantic during 2016-2018: Part 2 – daily and synoptic characteristics

by Ju-Mee Ryoo, Leonhard Pfister, Rei Ueyama, Paquita Zuidema, Robert Wood, Ian Chang, and Jens Redemann

Dear Editor, Dr. Yuan Wang,

Thank you so much for the review opportunity for acp-2022-256. We addressed the referees' concerns as shown below.

- ***Following the suggestion of Referee #1***, we addressed all the comments and suggestions by the reviewer. We also added the implication of this study and the possible future research topics based on the results in this paper in the summary and discussion section.
- ***Following the suggestion of Referee #2***, we made the statement clear that we are discussing the moisture transport from the continent in the free troposphere in the revised manuscript.

We hope we have addressed all the key comments and suggestions from the reviewers and incorporated them into the revised manuscript. Enclosed is a point-by-point response to each reviewer's comments.

Sincerely,

Ju-Mee Ryoo, Leonhard Pfister, Rei Ueyama, Paquita Zuidema, Robert Wood, Ian Chang, and Jens Redemann

Response to RC2 (Referee#1)

In this response letter, we repeat the reviewer's questions and answer them individually. Our response is marked in blue letters.

This study presents the detailed synoptic-scale meteorological conditions, on the daily and weekly scale, during the three deployment months of the ORACLES field campaign over the southeastern Atlantic. The key meteorological factors associated with the low-level cloud fraction are interpreted, with the goal of supporting the future process-orientated study on the aerosol-stratocumulus interactions. The results and analyses are solid and sound. Without major concerns, I do have minor comments and suggestions listed below, which should be considered and addressed, before the potential publication.

General Comment:

This study presents and describes the meteorological conditions thoroughly with multiple figures and tables and concludes with interesting results. However, with the plentiful recent observational studies of MBL stratocumulus and aerosol-cloud interactions over the southeast Atlantic published on the ACP special issue (https://acp.copernicus.org/articles/special_issue978.html), this paper will benefit from a discussion where the results are put into context of the previous studies (e.g., what is the implication of the unusual-to-climatology meteorological conditions presented here on the aerosol-cloud interactions; or certain discussions on how the future study would better disentangle the meteorological factors from the aerosol-induced cloud-adjustment based on these results). I will leave this to the author for consideration.

⇨ Thank you for the comments. In section 5 (Summary and discussion), we added the implication and a few future research directions shown below:

"*One implication of this paper is to enable us to expect when the direct or indirect aerosol radiative effect is dominant. For example, when the AEJ-S is elevated high around 4 km, the aerosol can also be elevated above the low cloud deck, which is well observed in September and October. In contrast, when the AEJ-S is less elevated (e.g., August), lower transport altitudes make it easier for the aerosol to be in contact with the cloudy boundary layer and mix into it, increasing the importance of the boundary layer aerosol indirect and semi-direct effects.*

While we examined several large-scale meteorological factors tied to aerosol transport and stratocumulus decks, the detailed investigation of the processes controlling stratocumulus decks, aerosol lifting, and transport is beyond the scope of this study. Future studies can focus on specific scientific questions such as 1) the roles of mid-latitude circulations on the aerosol transport and its boundary layer entrainment, 2) the impact of the continental mesoscale convective system (MCS) on the AEJ-S and the biomass burning (BB) aerosols, 3) further investigation of aerosol warming effect in the boundary layer by disentangling the meteorological factors from the aerosol-induced cloud-adjustment based on the model and airborne measurement, 4) the impact of the unusual-to-climatology meteorological conditions on low-cloud, aerosols, and their interactions at different time scale, 5) the influence of smoke-induced aerosol on cloud type and precipitation by adjusting large-scale environmental conditions, 6) the causal relationship among aerosols, low-cloud, and other meteorological factors over the different ocean basins and geography."

Minor Comments:

P5 L124. Fig. 1a is not showing the grid box clearly. Perhaps it would be better to reference Fig. 1b or 1c.

⇨ We fixed it.

P6 L133. Is there a reference for the threshold?

⇨ This is the threshold we used in this study. The sensitivity of the strength of the heat low during the deployment to the precise choice of levels is minimal. We didn't use the specific thresholds in Ryoo et al. (2021), but the heat low (defined as 850–600 hPa geopotential height difference) over land (including the coast) typically starts 2920 m over the SE Atlantic Ocean and southwestern African continent during August-October.
In the Sahel region in the NH, the 700–925 hPa difference was used as the heat low by Knippertz et al., (2017). However, because the 925 hPa level is below the ground for much of our study region of interest, we chose a different, but similar quality to represent the heat low.

P6 L143. Please state the spatial resolution of the product.

⇨ We realized that we only stated the spatial resolution of the monthly mean cloud product (MODIS) in L147 (1° grid resolution). The spatial resolution is the same for VIIRS (1° longitude x 1° latitude grid). We stated it clearly in the revised manuscript.

P7 L189. Please define ER-2 and P-3 prior to the abbreviation.

⇨ We believe ER-2 aircraft is the abbreviation of Earth Resources 2. This is NASA's high-altitude airborne science aircraft (https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-046-DFRC.html#:~:text=The%20ER%2D2%20is%20a,65%2C000%20feet%20within%2020%20minutes).

⇨ P-3 aircraft is a former U.S. Navy patrol aircraft that has been extensively modified by NASA for use as an airborne science laboratory. P-3 is now NASA's aircraft designed for endurance and range and is capable of long-duration flights (https://airbornescience.nasa.gov/aircraft/P-3_Orion_-_WFF).

P10 L208. Do you mean Figs. 2(a, b)? Also, if you are trying to convey the strong association between AEJ-S, RH, and the heat low, why not overlay the wind contours on all Figs. 2abc for better illustration?

⇨ Yes, it is. Thank you for catching this. We changed it in the revised manuscript.

Regarding overlaying of AEJ-S, RH, and heat-low, we did not overplot them because we thought the plot would look so busy. However, following your suggestion, we overplotted the AEJ-S wind isotach (zonal wind of -7 m/s) on RH, BC, and the heat low, and it seemed to illustrate the relationships more clearly indeed. Thus, we overplotted the wind contour on Figs. 2 (a-c) (Figs. 7, 12 (a-c) as well) in the revised manuscript. Thank you again for your great suggestion. Below is the new Fig. 2 in the revised manuscript.

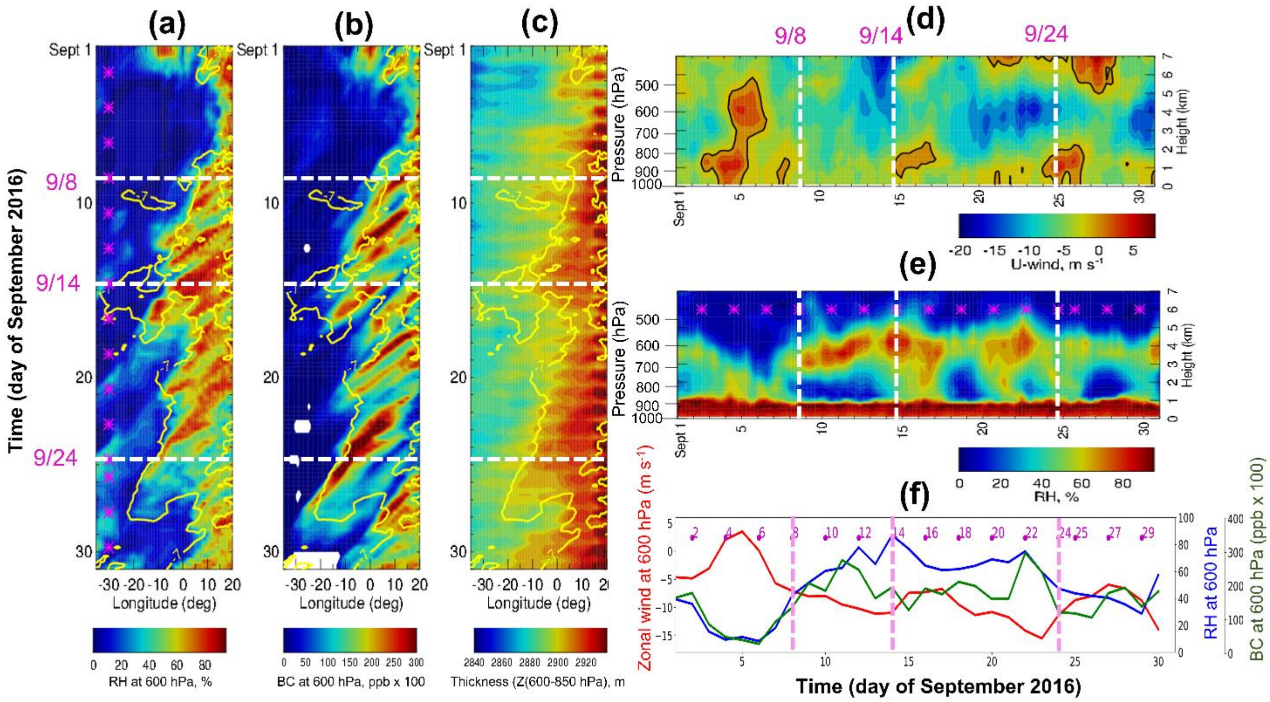

Figure 2*. Longitude-time cross-section of 6-hourly (a) 600 hPa RH (%), (b) 600 hPa BC (shading, ppb x 100), and (c) thickness (geopotential height difference (600-850 hPa); high values (> 2920 m) over a South African plateau represents the heat low, m) averaged over 8-10° S during September 2016. (a-c) are overlaid by 600 hPa zonal wind isotach (yellow line, -7 m s^{-1}). (d-e) Altitude-time cross-section of zonal wind and RH at 10° S, averaged over 0–10° E during September 2016. The black contour in (d) represents 0 value of zonal wind. (f) Daily time series of the 600 hPa zonal-wind (red line, m s^{-1}), 600 hPa RH (blue line, %), and 600 hPa BC (green line, ppb x 100) averaged over 8–10° S and 0–10° E. The dashed white lines indicate the flight days investigated further in this study, and the magenta asterisks (and numbers in f) represent the flight days during the September 2016 deployment. White areas in (b) represent the missing data values.*

P10 L211. Do you mean Figs. 2(a, b, f)?

⇨ Yes, Thanks for pointing that out.

P12 L227. '…flight days (Figs. 3a & 3b', and '…targeted flight on 24 September 2016 (Fig. 3c)'

⇨ Thanks for the suggestions. We changed it in the revised manuscript.

P12 L230. Please be consistent with the units and avoid using the non-SI unit.

⇨ We removed the values in kft unit.

P12 L239. Shouldn't it be Fig. 3h for 20160914?

⇨ You're correct. Thank you for pointing this out.

P14 L256. It should be either 'weakly' or 'insignificantly'.

⇨ That's right. We changed it into 'weakly' by removing the other.

P14 L259. I am a bit confused here. In Fig. 3jkl, the high concentrations of 600 hPa BC (region A) sit on the 600 hPa high wind-vector (by the previous definition, that would be the AEJ-S), while here states the BC did not reach the AEJ-S altitude. Please clarify the discrepancy between the messages shown in Fig. 3jkl and Fig. 4a.

- ⇨ Sorry for the confusion about this statement. The statement “the BC did not reach the AEJ-S altitude” refers to the BC aerosol in the boundary layer (typically in the layer < about 2-2.5 km over the ocean). We updated this sentence in the revised manuscript.

P14 L261. Sounds conflicting with the previous discussion that the subsidence facilitates the entrainment of the near-BL-top BC. Are you suggesting that the entrained BC have fully interacted with the cloud droplet?

- ⇨ On some occasions, subsidence was not strong enough to facilitate the entrainment of the BC (see the magenta arrows; Figures A1 and A2b showed the subsidence was weak (about 0-1 hPa day^{-1}; see Figure A1) in the vicinity of BC around 23 September 2016 in region A). And the BC from the continent below the AEJ-S level (~ 4 km in September) drifted westward by the easterly wind, getting into the marine boundary layer (Figure A2, and Fig. 4a in the manuscript).

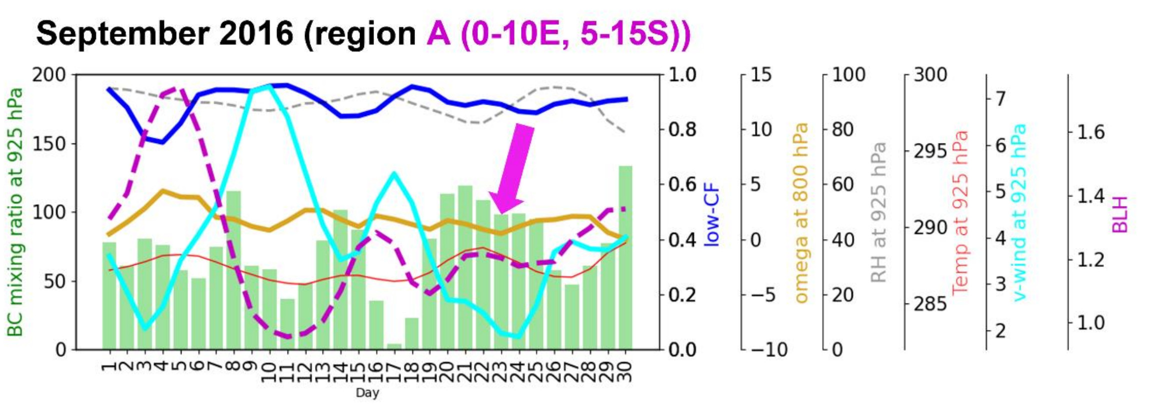

Figure A1. *Time series of daily-mean 925 hPa BC (green bar, ppb x 100), 800 hPa vertical velocity (omega, ω) (gold line, hPa day^{-1}), 925 hPa RH (dashed gray line, %), 925hPa temperature (solid red line, K), 925 hPa meridional wind (solid cyan line, m s^{-1}), BLH (dashed magenta line, km), and low-CF (blue line) over region B. Each color line represents the 3-day running mean.*

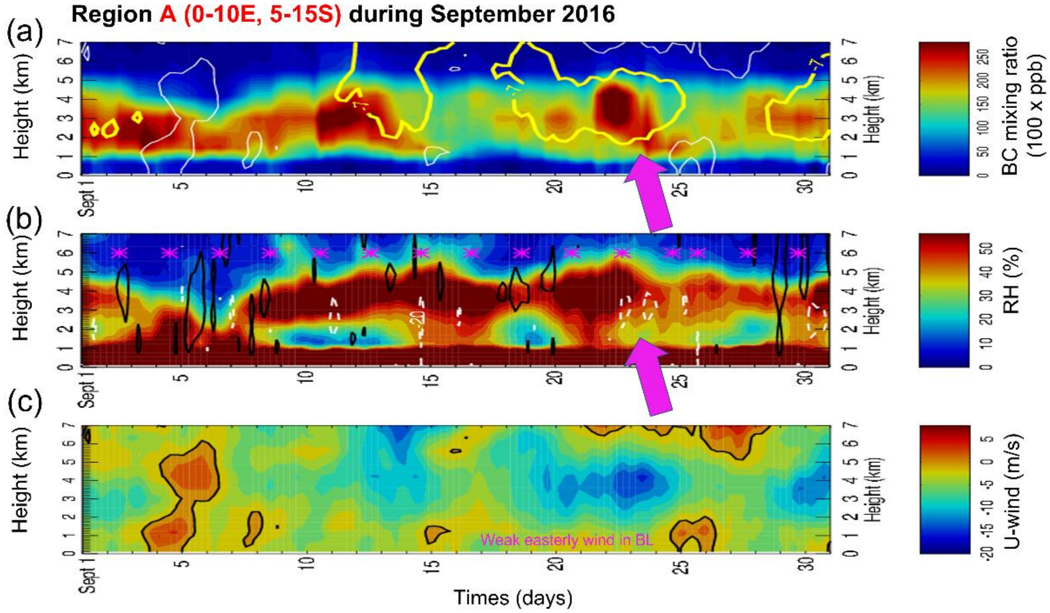

Figure A2. *Time-altitude cross-section of 6-hourly (a) BC (shading, ppb x 100) overlaid by 6-hourly zonal wind isotachs at -7 (thick yellow lines) and 0 m s^{-1} (thin white lines), (b) RH (shading, %) overlaid by 6-hourly vertical velocities of -20 and 50 hPa day^{-1} (dashed white and solid black lines respectively; positive values represent subsidence), and (c) zonal wind overlaid by 0 ms^{-1} (black contour) averaged over region A (0–10° E, 5–15° S) in September 2016. The asterisk in (b) represents the September 2016 flight days.*

P14 L265. If region A has similar features as B, why separate them? Some prior discussion on the particular interests (or importance) in choosing regions A and B might help readers interpret the elaborated analyses here.

⇨ This is a good point. We separated the regions into A and B because the preliminary study showed that the relationship of low cloud with meteorological variables varies between the regions.

For example, subsidence in region B (0-10° E, 15-25° S) can be larger than that in region A (0-10° E, 5-15° S) because 15-25° S in the SE Atlantic is the region affected by local subsidence associated with St. Helena High as well as the large-scale subsidence associated with Hadley circulation. The latitudinal dependency of the low-tropospheric stability (LTS) and climatological difference in low-cloud (e.g., stratocumulus) fraction (Wood, 2012) was also a reason for the separation of the regions. The detailed correlations among low-cloud cover and meteorological variables are discussed in section 4 and Fig. 17 within the manuscript. We included this in the revised manuscript.

P16 L275-280. The skew-T charts in Fig. 5 (especially b & c) show much dryer layers (~900 – 700 hPa) sitting between the stratocumulus and the 600 hPa moisture layers, while the dry convection pushing up the moisture above 700 hPa, looks like the moisture (and BC?) advected aloft did not sufficiently propagate downward. How does it impact the BC entrainment discussion?
Is 600 hPa presented here the most typical BC transportation level? Did the aircraft pick up any signal of the BC vertical redistributing?

⇨ These are very insightful questions. We believe this would impact less BC entrainment into the boundary layer. Indeed, aircraft observation did not show much boundary layer aerosol in most of September.

Yes, In September and October, 600- 650 hPa (3.5-4.2 km) is the most typical BC transportation level along with the AEJ-S, supporting that BC is largely transported by the AEJ-S. These are all consistently shown in model and aircraft observation.

However, the maximum altitude of the AEJ-S is about 700 hPa (~ 3km) in August, slightly lower than the other months (September and October). This was also confirmed by the climatological mean (2000-2018) dataset, which was discussed in Ryoo et al. (2021).

We haven't checked the BC vertical redistribution in aircraft measurement in detail. But Pistone et al. (2021) showed that the elevated CO is transported at this level (600-650 hPa) with water vapor by AEJ-S in September 2016. Zhang and Zuidema (2021) also showed the BC in the boundary layer over Ascension Island, consistent with entrainment of BC when the smoke is situated lower in the free troposphere. When and where the free tropospheric aerosol first contacts the cloudy boundary layer is currently being explored further in another study.

P18 L313-314. Please be cautious about the causality implied here, perhaps adding a few references to support it.

⇨ We understand your concern. We added the reference to it and added the word "possibly". This may be the area where further research is needed.

P18 L320. Remove '…for this region'?

⇨ We removed that.

P18 L325. Do you have an associated analysis in (10° W–0, 5–15° S) to support the statement? It seems odd to bring up a non-aforementioned region when you are comparing regions A and B.

⇨ Yes, we have. We did see that "the LTS – low-CF relationships are weaker near the coast (e.g., 0–10° E, 5–15° S, region A) compared to further west (e.g., 10° W–0, 5–15° S) for all the deployment months." For example, the LTS – low-CF relationship in the west of region A (10° W-0, 5-15° S) and the west of region B (10° W-0, 15-25° S) is about 0.9 and 0.6, respectively (see Figure A3).

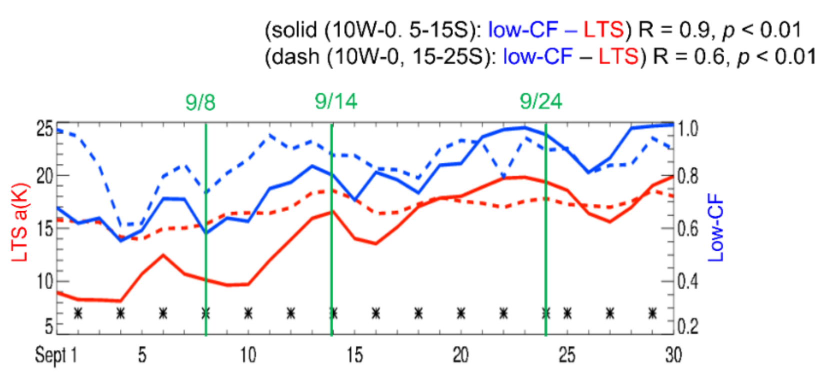

Figure A3. *Time series of daily mean low-CF (blue lines) and daily mean LTS (red lines, K) averaged over the west of region A (10° W–0, 5–15° S) and region B (10° W-–0, 15–25° S) during September 2016. All flight days (8, 14, and 24 September 2016) are marked by asterisks (gray vertical lines).*

However, the west of regions A and B are not the flight regions. Thus, we will remove this sentence in the revised manuscript to avoid confusion. Instead, we further discuss this relationship of low-level cloud fraction with the meteorological variables over the west of flight regions (region A and B) in section 4 and Fig. 17.

P23 L372. Besides the coordination with the CLARIFY, is there any other particular reason for choosing the flight 20170818? As it did not reach to A or B regions and did not show the AEJ-S or LLJ-related meteorological conditions along the flight track.

- ⇨ We chose the 18 August 2017 event because of two reasons:
    - First, the AEJ-S doesn't kick in until about 2 days after this day, on 20 August 2017. The late emergence of the AEJ-S can explain the dryness of August 2017 compared to the climatological mean (Ryoo et al., 2021).
    - Second, the entrainment of the BC aerosol into the boundary layer was found in airborne measurements (Fig. S9, Zhang and Zuidema, 2021) and ERA 5 data on Ascension Island. Ascension Island was the flight region for the 18 August 2017 flight.

P29 L452. Any possible explanation for the switch-signed correlation between the low-CF and BLH?

- ⇨ Regarding the correlation between the low-CF and BLH, not only was the sign changed, but also the statistical significance was changed. The correlation is insignificant at the 95% confidence level in August 2017. We think this is due to the disruption of the mid-latitude frontal system and its impacts on the LTS, BLH, low cloud cover, and even the cloud regime changes by aerosol (Diamond et al., 2022).

  Indeed, when the mid-latitude frontal system (20-21 August 2017) is developed northward, the correlation between low-CF and LTS gets lower. A similar interpretation can also be applied to the low-CF – LTS and low-CF – BLH relationship in October 2018.

P41 L620. Wouldn't the stronger subsidence associate with higher LTS, and hence higher low-CF?

- ⇨ As we discussed in the manuscript, the subsidence – low-CF relationship does not always have the same sign. Subsidence is typically negatively correlated with low-CF during the deployment months, except for south of 15° S near the coast in October (Fig. 17) at a daily time scale.

  Furthermore, subsidence can be not only influenced by meteorology but only altered by aerosols (i.e., shortwave absorption can lead it a relative self-lofting that counteracts the subsidence). We also think the other factors, such as AEJ-S, and LLJ as well as the time scale of the analysis (e.g., daily, synoptic, or monthly time scale) can be associated with this difference (Adebiyi and Zuidema, 2018). This can be a topic of further study.

Figures

Figure 3j. What are the A and B boxes?

- ⇨ Sorry about this mistake. The magenta box (in Figs. (3, 8, and 13)j) refers to region A (0-10° E, 5-15° S) and the yellow box refers to region B (0-10° E, 15-25° S). We included this description in the revised manuscript. We also added the reasoning behind separating these two regions in the revised manuscript.

Figure 4d. The black solid line is rather gray. Perhaps change to the black color or change the thickness of the line.

⇨ We changed the line color into the "red solid line" for all Figures 4d, 9d, and 14d.

Figure 6a. The A and B boxes are not matching the lat-long descriptions.

⇨ We are sorry for the misplacement. That was fixed in the revised manuscript.

Figure S3d. What is the meaning of the shaded area?

⇨ It just means the density of the data points. It can also be interpreted as the 2-D pdf (probability density function) plot.

Joint PDFs (e.g., in Fig. 6, 11, 16; S3, S5, S7). 'Pearson's r'.

⇨ The 'pearsonr=… and p=…' is computed from Python's statistics package, and the annotation was written from the package. Thus, we noted: "The pearsonr in (h) refers to Pearson's correlation coefficient with its statistical significance (*p-value*)." in the figure captions.

Reference

Adebiyi, A. A., and Zuidema, P.: Low Cloud Cover Sensitivity to Biomass-Burning Aerosols and Meteorology over the Southeast Atlantic. J. Climate, 31, 4329-4346, doi: 10.1175/JCLI-D-17-0406.1, 2018.

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Response to RC1 (Referee #2)

In this response letter, we repeat the reviewer's questions and answer them individually. Our response is marked in blue letters.

This is a detailed study involving black carbon aerosol interactions with clouds in the tropical Southern Atlantic ocean off the coast of west Africa. The study is exhaustive in that it addresses aircraft measurements and meteorology to explain the seasonality of aerosol and moisture transport and their relation to cloud fraction. Though the dataset is small (2016-2017), the study uses reanalysis climatology data to point out any climate anomalies during this period which is a good idea.

I have concerns over the constant supposition that the African continent can be a moisture "source". It is not correct to assume this even though the study shows moisture transport (via elevated relative humidity values) advecting off of the continent due to moist deep convection. It may be more correct to say something to the effect that 'parcels with elevated relative humidity, possibly due to evaporation of raindrops from the moist deep convection, are being transported along with the smoke/black carbon'. The study seems to imply some kind of "green ocean" or "brown ocean" effect going on, but does not explicitly say it. It is confusing to imply that a continent can be a source of moisture that rivals the neighboring marine region. This needs to be cleared up as it may take away from the general merits of the study.

Further comments/suggestions are in the enclosed PDF.

⇨ Thank you for your valuable comments. We do respect your comments on this.

Your statement, 'parcels with elevated relative humidity, possibly due to evaporation of raindrops from the moist deep convection, are being transported along with the smoke/black carbon'., sounds reasonable.

However, we are concerned that this statement may miss our key finding in this paper - not only moist convection but also dry convection can produce moist plumes over the land, transporting them to the ocean with aerosols. And ORACLES campaign measurement does have not only "black carbon aerosol" but also other aerosols along with gases (CO, water vapor etc).

Regarding your concern about the moisture source, as we responded to the reviewer's comment earlier, the convection over land can be a source of moisture in the free troposphere (typically 2 km above the ocean, and 2-6 km above the land). We think you may consider the moisture source in the boundary layer.

Indeed, the ocean is the major moisture source region, but this moisture remains in the boundary layer because the strong inversion cap prevents upper movement. Over the southeast (SE) Atlantic, free-tropospheric moisture can be laterally transported from the continent, although previous studies do not definitely establish whether the moisture source stems from dry or moist convection. The free troposphere would otherwise be very dry over the ocean over the southeastern Atlantic, because of the large-scale subsidence. For example, the corresponding free troposphere over the SE Pacific, where the Andes mountains prevent the westward transport of moisture from the Amazon, has above-cloud water vapor paths of only one-two mm (Zuidema et al., 2012). Above-cloud water vapor over the SE Atlantic is about twice as large as that over the SE Pacific (Pistone et al., 2021). We made this statement clear in the introduction in the revised manuscript.

The altitude of the convection reaches around 600-700 hPa (about 3 - 4.2 km with moist (dry) convection during October to the north of 5° S (south of 5° S)). This moisture is transported by the mid-tropospheric southern African easterly jet (AEJ-S) at that level, as shown in time-longitude plots within the manuscript (Figs. 2, 7, 12(a-c)). The transport of elevated moisture from land to the ocean along with CO and aerosols was well documented in the literature (Pistone et al., 2021).

Specific Comments (in the supplementary document)

Line 75-76: may be better to say 'mean low-level cloud fraction'

- ⇨ We changed it.

Line 238: southward?

- ⇨ We think northward is correct because of a mid-latitude cyclonic circulation with its center at 30-40°S. This circulation is expanding "northward" to the North Pole.

Line 452: This looks like a conflicting statement. Instead of "high" consider 'elevated', 'increased', or 'higher low-level CF values', or something that would make more sense.

- ⇨ Thank you for the comments. We will change it into a more appropriate word, such as 'increased'.

Line 458: changes => patterns

- ⇨ Changed.

Line 691: advection => advected

- ⇨ Changed.

Reference

Zuidema, P., Leon, D., Pazmany, A., and Cadeddu, M.: Aircraft millimeter-wave passive sensing of cloud liquid water and water vapor during VOCALS-REx, Atmos. Chem. Phys., 12, 355–369, https://doi.org/10.5194/acp-12-355-2012, 2012.

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