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We thank the reviewer for his/her comments that have improved the completeness and clarity of this manuscript. The comments by the reviewer are given below in black, our responses are marked in red and the corresponding changes to the manuscript are in *italics*.

Interactive comment on "Characterization of Transport Regimes and the Polar Dome during Arctic Spring and Summer using in-situ Aircraft Measurements" by Heiko Bozem et al.

Anonymous Referee #2

Received and published: 16 March 2019

This work makes use of the atmospheric tracers CO and CO2 measured on two NETCARE flight campaigns together with 10-day back trajectories to describe air mass transport into the high Arctic during spring and summer. The authors find distinct transition zones between the mid-latitudes and the polar dome for the two seasons based on tracer gradients. The tracer derived polar dome boundaries are subsequently applied to aerosol number concentration data. In addition, the authors explore different transport pathways of air masses into the Arctic using a previously published phasespace approach that relates the maximum change in potential and absolute temperature along the trajectory.

This manuscript is very comprehensive and represents a novel approach to localize the polar dome boundary and to characterize air mass transport into the Arctic. The work shall definitely be published with revisions as described below.

General remarks:

To give the findings more relevance for Arctic atmospheric research it would be of high interest, whether the derived polar dome boundaries are representative for other Arctic sectors and years as well? Or would each field campaign have to do their own analysis following this example? So a discussion on how far the results can be generalized is needed.

This study was intended to derive a tracer based diagnostic for the determination of the polar dome boundary. In a follow-up paper to this study we will discuss the application of the metrics to a comprehensive data set consisting of several field campaigns in the Arctic covering different seasons and different locations.
To demonstrate the general applicability of our campaign-based approach we analyzed two years of hourly ground based observations at the Zeppelin Mountain observatory (Ny Alesund, Spitsbergen) to show a more generalization of the tracer-based diagnostic (see Figs. R2 a and b). According to our campaign-based findings using the CO-CO_2 relationship the analysis of the ground-based data confirm the signatures and characteristics of both species inside the polar dome during the campaign. This potentially allows for a determination of the station location relative to the polar dome. Note, however, that ground based observations are in principle strongly affected by local sources and sinks. Depending on e.g. the strength of the boundary layer inversion these effects decouple the free troposphere above from these observations within the planetary boundary layer below.

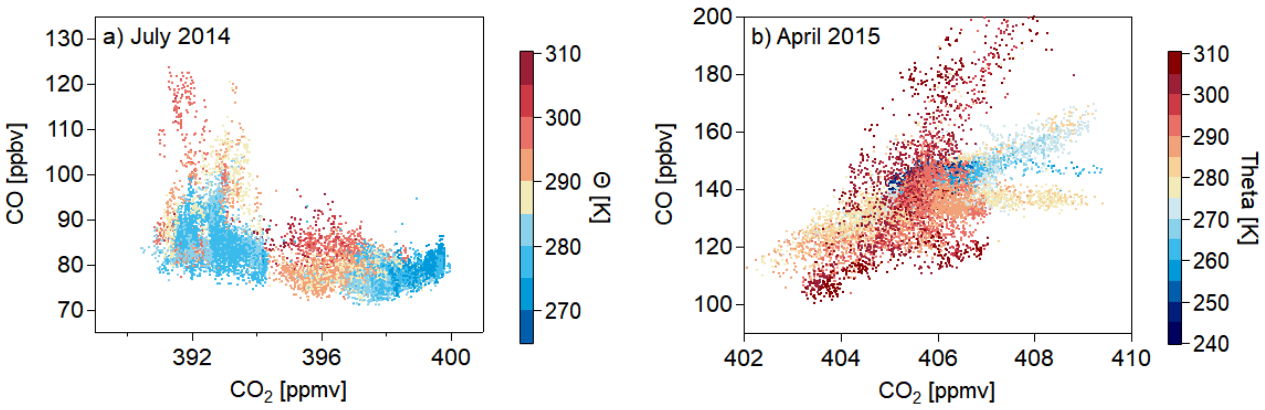

Figure R1 (a): Tracer-tracer scatter plot of all aircraft data points (background + pollution plumes) for July 2014. (b): Tracer-tracer scatter plot of all aircraft data points (background + pollution plumes) for April 2015. The color code denotes the potential temperature.

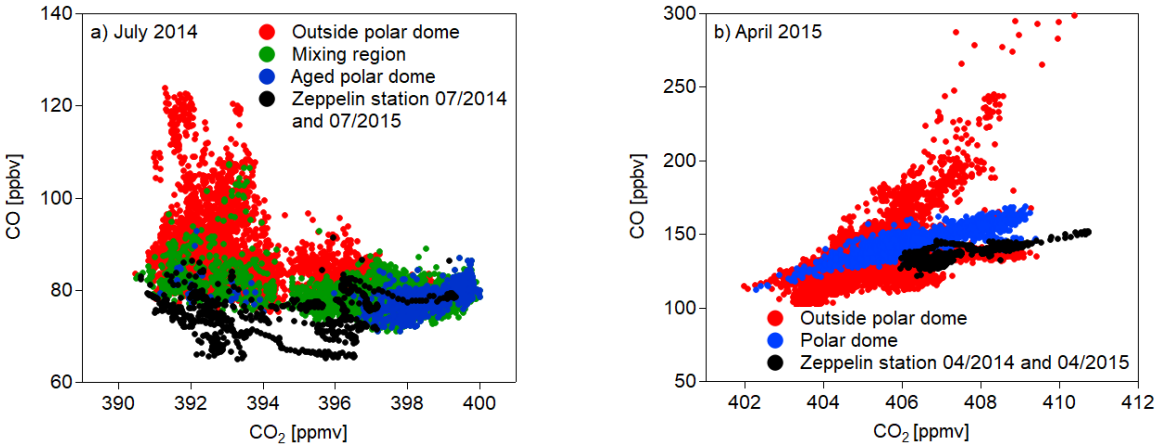

Figure R2 (a): Tracer-tracer scatter plot of all aircraft data points (background + pollution plumes) within the aged polar dome (blue), the mixing region (green) and outside the polar dome (red) for July 2014. (b): Tracer-tracer scatter plot of all aircraft data points (background + pollution plumes) within (blue) and outside (red) the polar dome for April 2015. To separate the different regions the tracer derived polar dome boundaries are used. Boundary values for each region are summarized in Tab. 2 in the paper. The black circles denote the ground based data from the Zeppelin mountain observatory (Ny Alesund, Spitzbergen) for the months July (a) and April (b) 2014 and 2015.

Note however, the good agreement at low potential temperatures particularly for the April 2015 case with exactly the same slope and similar absolute values at the station as deduced from the aircraft data as inside dome (see Figs R2a and b). Based on this analysis we conclude that the Zeppelin observatory was inside the polar dome for April 2014 and 2015 and most probably inside the polar dome with episodes outside the polar dome in July 2014 and 2015. The latter is indicated by the correlation following the characteristics of the mixing region (see Fig. R2a). However, potential temperatures were as low as those observed during the research flights (not shown).

There is no discussion on the uncertainties of the variables along the trajectory such as potential and absolute temperature. Particularly the vertical location of the polar dome boundary would be subject to the uncertainty. At least some discussion on how the ECMWF input data compares to the in-situ measurements should be added.

The figures below show a comparison of temperature based on in-situ data and temperature derived from the analysis data interpolated to the time and location of the measurement. Lagranto backward trajectories were initialised every 10s along the flight track based on GPS horizontal coordinates and pressure. Therefore, the variability of potential temperature is driven by the temperature difference between observation and analysis. To quantify this temperature difference, we analysed the temperature for July 2014 and April 2015. For the measurements in July 2014 the median difference between in-situ temperature data and analysis data is 0.31 °C (interquartile range: -0.71 - 1.72°C). For the April 2015 measurements, the respective median difference is 1.50°C (interquartile range: 0.69 - 2.14 °C). Thus, we conclude, that the local variability of the dome boundary is largely driven by the variability of tracer gradients and the uncertainty of transport history backward in time. The latter, however, we try to evaluate (at least qualitatively) by using median latitude and maximum potential temperature. Linking these to our trace gas observations should in turn resemble the latitudinal and vertical gradient and thus account for transport history.

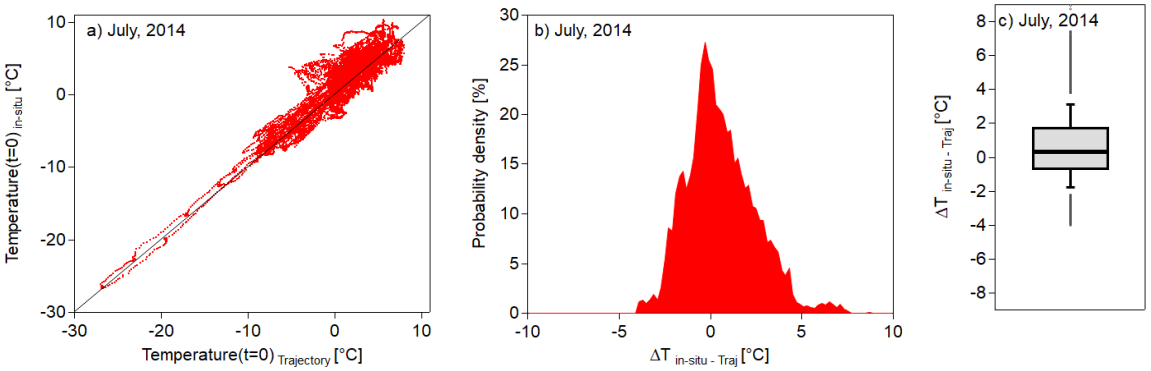

Figure R3: (a): Scatter plot of in-situ ambient temperature measured on the aircraft and temperature from the analysis data set at the time of the initialisation of the trajectories along the flight track for July 2014. (b): Probability density function of the difference between in-situ and analysis temperature data set. (c): Box and whisker plot for the difference between in-situ and analysis temperature data set.

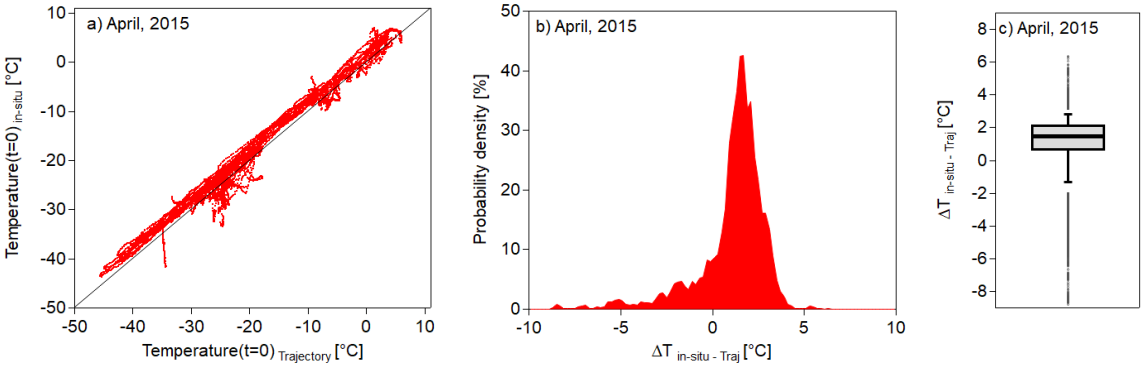

Figure R4: (a): Scatter plot of in-situ ambient temperature measured on the aircraft and temperature from the analysis data set at the time of the initialisation of the trajectories along the flight track for April 2015. (b): Probability density function of the difference between in-situ and analysis temperature data set. (c): Box and whisker plot for the difference between in-situ and analysis temperature data set.

We added the following to paragraph 3.3:

As a measure for the uncertainty of the temperature along the trajectory we calculated the median difference between temperatures measured in-situ on the aircraft and the corresponding temperatures interpolated to the initialisation point of the trajectory along the flight track based on analysis data. For the measurements in July 2014 the median is 0.31 °C (interquartile range: -0.71 - 1.72°C). For the April 2015 measurements, the respective median difference is 1.50°C (interquartile range: 0.69 - 2.14 °C)

The application of the polar dome boundary to aerosol data is intriguing and it would be very interesting to know how other aerosol properties relate to the boundary. Adding such information to the manuscript would make it even longer than it already is. I would recommend exploring whether a "part 2" manuscript on aerosols could make sense. The manuscript is partly repetitive and the abstract reads almost like an introduction. Both the abstract and the whole manuscript should be shortened. There are some recommendations in the attached PDF.
We thank the reviewer for this point and refer to a later comment.

Specific comments:

p. 7, l. 15: What is meant by "The stability of the instrument. . ."? Is this the accuracy? I wonder whether none of the instruments has been described before and whether such an extensive description here is necessary?
The instrument is regularly calibrated during the flights to check for longer term drifts. We use these drifts as a measure for the reproducibility, which we term stability. Note that post processing accounts for these slow drifts assuming a linear drift between the calibrations. Accuracy is further affected by the uncertainty of the calibration standards. For clarification, we added the following sentence:

"Stability is a measure for reproducibility and based on the mean drift between two subsequent calibrations which were performed during flights".

The instrument and measurement principle of the Aerolaser ultra-fast carbon monoxide (CO) monitor model AL 5002 were described extensively in for example two papers by Gerbig et al. (1999) and Scharffe et al. (2013). The Licor LI-7200 closed CO_2/H_2O analyzer from LI-COR Biosciences GmbH, modified for airborne use, was only briefly described in earlier studies in the Arctic in the framework of the NETCARE project. We follow the suggestion of the reviewer and shorten the description of the carbon monoxide monitor only leaving the specification of uncertainties for this study. We kept the more extensive description of the CO_2 monitor since it is the first time of a more comprehensive description of the current setup.

p. 8, l. 19: What is a "very stable stratification" compared to a stable stratification? Is the ECMWF data the analysis or re-analysis data?
The term "stable stratification" is appropriate and the text is changed accordingly. ECMWF data is operational analysis data.

Figure 6: The scales can be enlarged in both panels: 200 for a) and 415 for b). This way, more details would be visible. The legends will find place somewhere else… What is the purpose of the figure except discussing the seasonal cycle? If a direct comparison of the NETCARE data with the stations is the goal, there should be zooms for the short periods of time. Currently, one cannot see much because the symbols are so large and cover everything. Why is Mace Head chosen as a reference?
The purpose of the figure is to show both the seasonal cycle of both species CO and CO_2 in the Arctic as well as in the mid-latitudes and to illustrate the latitudinal gradient between the Arctic stations and mid-latitude stations. For figure clarity, only Mace Head is shown representing a mid-latitude station. It was chosen because it is a GAW station with CO and CO_2 data available at the respective

time period and Mace Head is furthermore located at one of the entry routes of mid-latitude air masses that frequently enter the Arctic. The comparison between ground based observations and airborne data is not the prime purpose of the figure. Therefore, we show a more extended time period and not only a zoom on the period of the measurement campaign. Figures 6 (a) and (b) were modified for figure clarity and are now Figs 4 (a) and (b) after restructuring the manuscript.

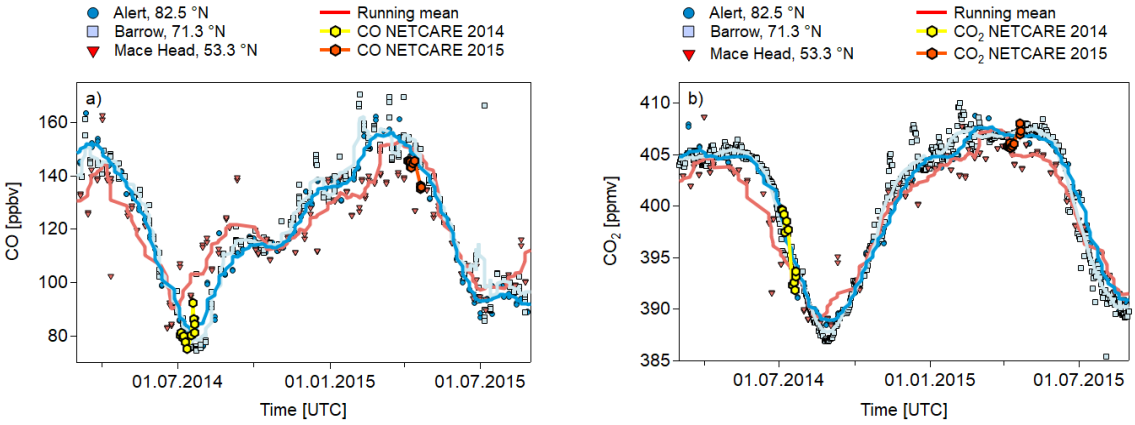

Figure 4. CO (a) and CO_2 (b) seasonal cycle based on NOAA ground based measurements in Alert (Canada), Barrow (Alaska) and Mace Head (Ireland) for the years 2014 and 2015. Running means are shown for the respective station data (symbols). Mean aircraft data for altitudes < 200 m for individual flights are overlaid. Error bars (yellow and orange shading) for the aircraft data are too small to be visible. NETCARE 2014 data are in yellow and NETCARE 2015 data are in orange.

Figure 8 b: Why does the potential temperature increase below which CO maximum concentrations occur with decreasing latitude? Some explanation is needed.

The measurements at lower latitudes were all performed from Inuvik. At that time generally higher temperatures were observed in Inuvik compared to the Arctic at similar altitude levels. Furthermore, the CO maxima in the two respective regions have different causes. In the Arctic lower troposphere high CO values are observed at low potential temperatures inside the polar dome as remnants of the wintertime maximum of CO due to the weak photochemical activity. In contrast enhanced CO values at lower latitudes are mainly caused by recent emissions (1-2 weeks old) potentially transported from Asian source regions into the measurement region by long-range transport. Since potential temperature at the surface increases in general with decreasing latitude (due to increasing temperature, see Fig. 5 in the paper) the CO maxima originating from lower latitudes affect higher isentropes. In addition, warm conveyor belt (WCB) type transport may have occurred leading to diabatic transport of CO to even higher altitudes and higher potential temperatures

p. 28, l. 6-18: This paragraph is a result and should be moved to the results section instead of being added to the discussions.

The paragraph on aerosol was located in the discussion section since it was intended to illustrate the relation of our empirically derived dome boundary when investigating e.g. aerosol processes. We followed the reviewer's suggestion and moved the paragraph to the results section and revised the whole paragraph including figures.

p. 28, l. 10-13: How can you infer that secondary aerosol formation is responsible for the concentration difference in the blue area? Based on the information provided, those particles are either between 5 and 20 nm or > 100 nm. For the first option, I find it difficult to believe that there is evidence to relate the increase in 5 to 20 nm particles to secondary aerosol formation based on the AMS and ALABAMA measurements in Willis et al. (2017). These instruments do not cover the

relevant size range. If the second option is true, the information on SOA contributing to particle growth to form CCN does not make sense, because particles are already in the CCN size range, even for low supersaturations. What is the explanation for the difference between panel a and b? And what is the relevance for CCN? Please revise the statement.

We thank the reviewer for this point and revised the paragraph in the revised manuscript. We just want to show the relevance of our empirical dome boundary for other applications using aerosol formation as an example. The specific analysis and discussion of aerosol processes is beyond the scope of this paper. We modified the paragraph as follows:

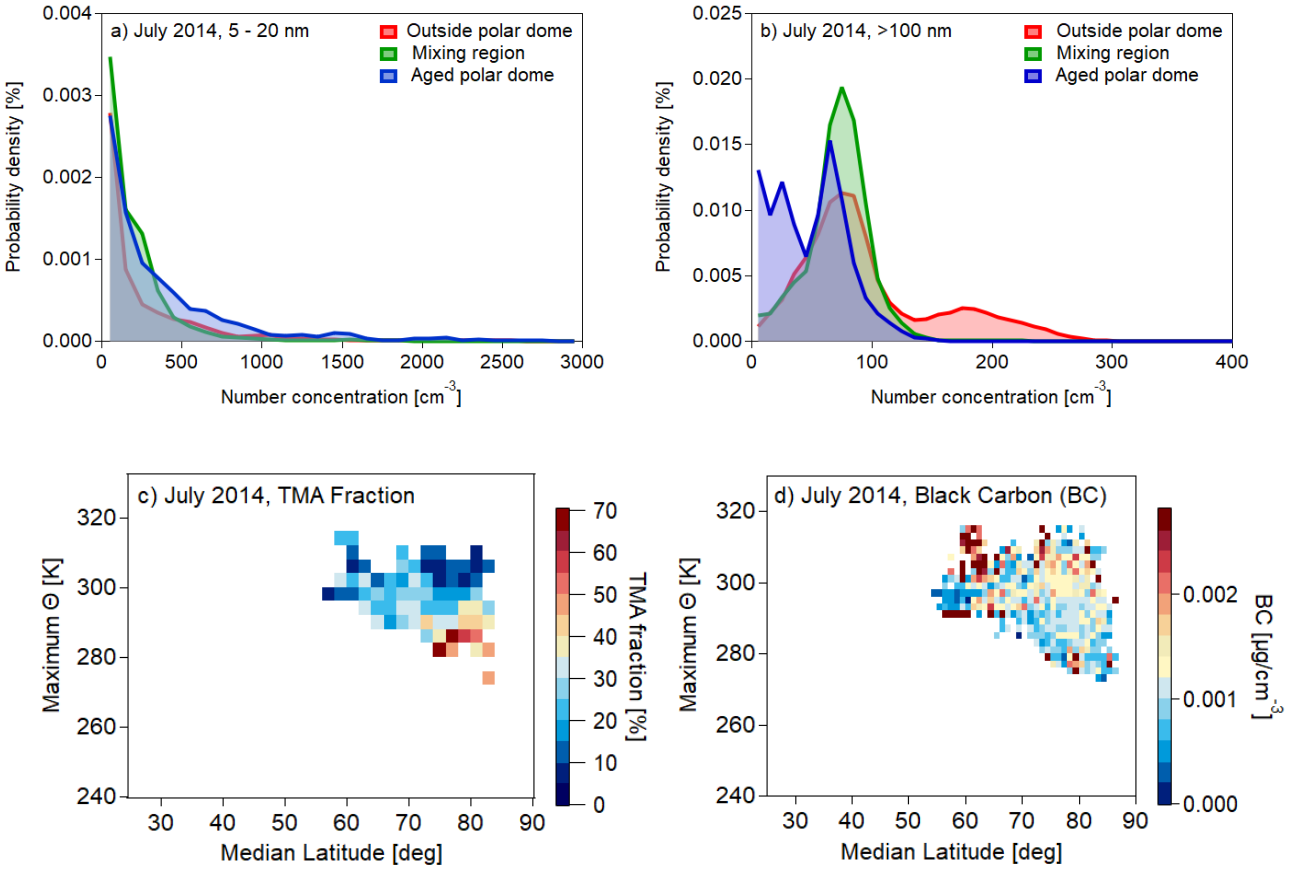

Figure 15: Normalized probability density functions for particles with diameters between 5 and 20 nm (a) and larger than 100 nm for July 2014 (b). The colour code represents the three different regions identified during the polar dome analysis. Panel (c) shows the distribution of the fraction of particles containing trimethylamine (TMA) with respect to the total amount of particles measured by single particle mass spectrometry (Köllner et al., 2017) in the maximum potential temperature and median latitude coordinate system. Note that for the reason of particle spectra statistics the resolution of median latitude and maximum potential temperature interval is reduced compared to the refractory black carbon distribution (BC) shown in panel (d). The enhancement in BC within the polar dome is most probably due to fresh local pollution.

Having defined the polar dome based on trace gas gradients now allows for a more detailed study on aerosol associated with the different air masses. Efficient wet removal and less efficient transport from lower latitudes lead to generally low aerosol concentrations (Stohl, 2006; Engvall et al., 2008), especially within the Arctic lower troposphere during summer. This is consistent with results in Fig. 15a and b. Observations of elevated levels of accumulation mode particles ($N_{>100}$) can be associated

with regions outside the polar dome and subsequent transport to the measurement region. In parallel, regions within the polar dome were characterized by $N_{>100}$ smaller than 100 cm^{-3}. In contrary, number concentrations of ultrafine particles (N_{5-20}) showed occasionally larger values within the polar dome compared to outside (Fig. 15a), indicating the formation of ultrafine particles occurred within the polar dome region (Burkart et al., 2017). Exemplary for aerosol composition, particulate trimethylamine (measured by single particle mass spectrometry) can be associated with sources within the polar dome (Fig. 15c), consistent with results in Köllner et al. (2017) and Willis et al. (2017). In contrast, the abundance of refractory black carbon can be linked to pollution sources outside the polar dome and subsequent transport to the measurement region (Fig. 15d; Schulz et al., 2019). To conclude, the method introduced in this study is a useful tool to combine Arctic aerosol observations with transport processes and sources within and outside the polar dome region.

Figure 15: The way the aerosol results are presented with the colored boxes makes it difficult to see the shading.
Figure 15 is replaced (see new figures above) to demonstrate the applicability of our empirical dome boundary to other constituents or processes using the aerosol formation just as an example.

Technical comments:

Please the comments in the attached PDF manuscript.

Please also note the supplement to this comment:

We thank the reviewer for the technical comments, which were implemented!

Acknowledgement:

All atmospheric data from Zeppelin are publicly available in the EBAS database (http: //ebas.nilu.no) and we thank Cathrine Lund Myhre and NILU - Norwegian Institute for Air Research for making the CO and CO_2 observations from Zeppelin available.