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Interactive comment on "Classification of Arctic, Mid-Latitude and Tropical Clouds in the Mixed-Phase Temperature Regime" *by* Anja Costa et al.

Anonymous Referee #2

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Review "Classification of Arctic, Mid-Latitude and Tropical Clouds in the Mixed-Phase Temperature Regime" by Anja Costa, Jessica Meyer, Armin Afchine, Anna Luebke, Gebhard Günther, James R. Dorsey, Martin W. Gallagher, André Ehrlich, Manfred Wendisch, Darrel Baumgardner, Heike Wex and Martina Krämer

In the manuscript "Classification of Arctic, Mid-Latitude and Tropical Clouds in the Mixed-Phase Temperature Regime" A. Costa et al. present a statistical classification of clouds in the mixed-phase temperature regime based on four extensive field campaigns in the Arctic, mid-latitudes and the tropics. The analysis is based on the measurement data from the cloud spectrometer NIXE-CAPS, which is the size distri-

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bution in a wide size range and asphericity of the particles. The latter can be used to conclude the phase of the particles. The dataset is unique to quantify the microphysical characteristics of the investigated clouds in the mixed-phase temperature regime.

The clouds are divided in four cloud types in this study: liquid clouds, mixed-phase clouds, glaciated mixed-phase clouds due to the Wegener-Bergeron-Findeisen (WBF) process and clouds with secondary ice formation. In the Arctic the investigated clouds were mostly liquid, probably due to the shortage of ice nuclei. In the mid-latitudes the glaciated clouds due to the WBF process are dominant. At warm temperatures (in the temperature regime of the Hallet-Mossop process) some clouds with secondary ice formation occurred. In the tropics also glaciated mixed-phase clouds due to the Wegener-Bergeron-Findeisen (WBF) process were dominant throughout the whole temperature range. Secondary ice formation occur at much colder temperatures compared to the mid-latitudes.

The resulting cloud classification is very nice and provides some insights into the microphysics of mixed-phase clouds. The paper is written in a clearly structured way.

General comments:

- The uncertainty of the measurements, campaign etc. is not discussed very detailed. How sensitive might the results be to the time period and location of the campaign, e.g. weather conditions? How representative are the measurement campaigns of the general conditions in the areas? And assuming that the time period and location of the campaign itself is representative, how representative are the sampling times during a campaign, e.g. 1.5 h sampling during the ACRIDICON-CHUVA? It would be nice to add some more critical thoughts about this and maybe also a uncertainty estimation.

- Some microphysical processes occurring in mixed-phase clouds are strongly temperature dependent (freezing, secondary ice formation, but also accretion etc.). This could be included a bit more in the discussion, e.g. page 9, line 16-20.

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- The mixture of naming the clouds Type 1 oder Type 2 clouds or referring to the microphysics, e.g. 'Coexistence' clouds, 'WBF/Large ice' clouds is sometimes not so easy to follow. You could consider to always add a number to the cloud types, 1a, 1b, 1c and 2 (together with the physical naming).

- In the paper there are two different units used for the temperature, sometimes °C and sometimes K. At some parts that makes reading something out of the plot etc. quite difficult, e.g. page 10 line 24 this is difficult to read out of the plot right away, or Fig. 11 where you also have a mixture of °C and K. I would recommend to uniformly do everything using one unit.

- The term cloud particle is very general, sometimes it would be more specific to use the term cloud hydrometeors (to exclude aerosol particles).

Specific comments:

- page 2, line 11: Please also add a primary source.

- page 2, line 16-17: You are only referring to immersion freezing here. It should be legitimated or explained why or rephrased in a more general way.

- page 2, line 24: Be more clear what do you mean by high relative humidities (S=1 is sufficient for immersion freezing).

- page 3, line 13: Hallett-Mossop could be briefly explained (at least rime splintering could be mentioned).

- page 3, line 13 and line 28: Frozen droplet shattering is another process which can produce secondary ice (Mason and Maybank, 1960, Leisner et al. 2014, Lawson et al. 2015).

- page 3, line 14/15: Why only via contact freezing? The WBF process also takes place more efficient if there are more ice crystals in the close surroundings of supercooled water droplets.

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- page 3, line 14/15: Contact freezing mostly refers to a collision of an aerosol particle with a supercooled droplet leading to freezing. In the case described the ice nucleus will be the ice crystal produced by secondary ice formation. An ice crystal is a perfect ice nucleus, but might be a bit confusing for some readers since ice nucleus is mostly associated with aerosol particles. Maybe it would be better to call it "collision freezing"?

- page 3, line 23: In case of sedimentation of ice particles it would not be a purely liquid cloud (or do the ice particles melt when falling into the cloud?).

- page 4, line 5: What is meant by active sensors? In-situ sensors?

- page 4, line 9: From which size on are they counted as ice particles?

- page 4, line 22: What is the lower threshold of the asphericity measurement of small particles?

- page 4, line 25: It is not clear here what is meant by "1 Hz data".

- page 4, line 32: How many clouds were sampled within these 38.6 hours? That would be a valuable and interesting information, especially in terms of the occurrence statistic in the end.

- page 5, line 32: Why was the flying speed of HALO so high? Is that related to the aircraft itself or due to meteorological conditions?

- page 5, line 11-12: Is the concentration limitation at high aircraft speed a problem? What are typical concentrations? How many particles are missed? That would be an interesting information to add.

- page 7, line 13: What is the consequence of the possibility of near spherical ice crystals? Is that accounted for in the uncertainty estimate and how?

- page 7, line 26: What is expressed by the shadow intensity?

- page 7, line 32: Why is the smaller particle fraction measured by the CAS? Is that

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more sensitive in this size range compared to the CIP? How well do the number concentrations of both instruments overlap?

- page 8, line 8: Is the limitation to 300 particles per second reached often?

- page 8, line 11: What is an inter-arrival time correction? It would help the reader to understand the results if you add a one-sentence explanation here (it appears again in section 3.5.2).

- page 9, line 30: You could specify which lines the temperature groups refer to.

- page 9, line 32: This might be only true for the clouds where immersion freezing triggers the formation of ice crystals. That can be very different, especially for the convective tropical clouds, where ice crystals can sediment from colder regions of the cloud.

- page 10, line 4: The cloud particles are droplets or ice particles or both here?

- page 10, line 15: In DeMott et al. 2010 they do not limit the parameterization to 3 mum. The aerosol fraction estimated with NIXE-CAPS might therefore be underestimated (also because the lower threshold is at 0.6 mum instead of 0.5 mum). It would be nice if you could add some uncertainty estimation concerning this or some argumentation for your approach.

- page 10, line 15: The "aerosol data" used here are all particles in this size range so also all kind of hydrometeors? How good does that reflect the actual aerosol concentration? Are there some aerosol measurements for one of the four campaigns, where the approach could be evaluated against?

- page 10, line 19: How often is the maximum of N_INP reached and in which cases?

- page 10, line 33: "...formed around INP." might sound a bit miss leading, you could replace it by "...initial ice crystals have likely formed by immersion freezing" or "...and that the formation of the initial ice crystals has been likely initiated by INP immersed in

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the cloud droplet".

- page 11, line 1: Could that problem be solved with a size-dependent ice nucleation parameterization? That would be a very interesting aspect to look at (if not in this paper then maybe discuss this shortly here).

- page 12, line 22: Were the campaigns mostly located over open water or ice? That could explain missing marine ice nuclei. However, the freezing efficiency of these ice nuclei is rather low compared to other aerosol species. Thus even if present it could be that the clouds might not freeze at low temperatures. You could use the parameterization given in Wilson et al. 2015 and the estimated aerosol concentration to check for a few cases how high the freezing probability would be.

- page 12, line 30: Can you give a range of values for "very low updrafts".

- page 13, line 12: The WBF depends only on the presence of INP in "classic" stratocumulus mixed-phase cloud cases. In convective tropical clouds it could also be triggered by sedimenting ice from colder parts of the cloud.

- page 13, line 13: It is actually difficult to see a strong difference in Fig. 13 if it is plotted like this. In the current representation it looks actually like the quantities are higher in the Arctic?

- page 13, line 17: Is that already clearly proven that biological particles occur less frequently compared to mineral dust? That might be different in the Arctic or over the Southern Ocean.

- page 13, line 25: Do you have a hypothesis why secondary ice clouds appear more often in the mid-latitudes compared to the Arctic?

- page 14, line 5: You could add another sentence as an explanation why secondary ice is more likely to form in turbulent environments.

- page 14, line 9-11: From Fig. 12 I can not recognize anything mentioned in the text

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referring to the tropical vertical velocity, neither that they reach from -10 to -15 m s^-1, nor that velocities of 0.5 to 1 m s^-1 are reached in more than 10% of the cases, nor that the distribution if wider compared to the other cases. Maybe the plotting scale is wrong or the representation of the data inappropriate?

- page 14, line 15: It could point to biological INP, it could also point to strong sedimentation seeding the lower cloud levels.

- page 14, line 17: The focus of the DeMott et al. 2010 parameterization is not on dust. For the regions investigated all aerosol species are represented, which have an ice efficiency that leads to a frozen fraction larger than the detection limit of the instrument.

- page 16, line 3: Would it not be possible that these small ice crystals come from secondary ice formation as well?

- page 16, line 11: That (Wilson et al. 2015) might not be the best reference here- it would be better to cite ice nucleation field studies from the Arctic or the BACCHUS database, which was used in Wilson et al. 2015.

- page 16, line 22-25: It would be nice to have this aspect a bit more detailed, maybe adding the Pruppacher et al. estimates in Fig. 15 or have a separate figure for a comparison.

- Figure 1: The homogeneous freezing and ice multiplication cloud should be at the same location on the x-axis- both are fully glaciated.

- Figure 1: Coexistence is not really a path, it is clear from the x-axis that in this region there is coexistence. Maybe the different RHw areas could be colored in the background to also account for this aspect?

- Figure 1: Why is there an arrow pointing from Coexistence to homogeneous freezing clouds?

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- Figure 1: Is there a reason for the WBF process to be located at -17°C?

- Figure 1: Especially in convective clouds instead of initial freezing there could be an interaction between the homogeneous freezing and the mpc cloud by sedimentation of ice crystals and thus a seeding of lower cloud regions.

- Figure 1: The different cloud types could be added in colors to the sketch.

- Figure 2: Where in the figure is (approx.) 235 K? Add a line to the corresponding altitude.

- Figure 2: Where exactly does the text < 235 K all ice refer to? Should not the drop growth curve then end at 235 K?

- Figure 4: What is the blue line in the plots?

- Figure 5: What does the color coding in the uppe panel stand for? dN/dlogDp?

- Figure 5: The labels of the color bar are too small.

- Figure 7 and 8: The second line is not at 20 mum.

- Figure 7 and 8: The lower panel is not explained in the caption or text. What is shown here? What does that show in addition to the size distributions? Do the stripes correspond to different diameters?

- Figure 9: The number of INP plotted nearly follows the constant aerosol concentration lines- does that only look like it or is the concentration not so variable with height/temperature?

- Figure 9: The color coding could be mentioned in the caption.

- Figure 9: Why is the temperature range limited here compared to Fig. 13?

- Figure 11: The Arctic campaigns look rather different compared to the other locations- why is that? Maybe also discuss that in the text with a reference to this figure.

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- Figure 11: Why are there so few data points for the VERDI campaign?

- Figure 12: Why is the vertical velocity distribution from RACEPAC not added?

- Figure 13: Is the limitation of the data points in the Arctic case due to flight altitude?

- Figure 14: Is there not also a difference due to different flight altitudes?

- Table 1: Particles can not be glaciated, wording needs to be adapted.

- Table 2: What is the difference between a "Stratocumulus" and a "Stratocumulus in mixed-phase T regime"? Is there a certain temperature threshold (even below 0°C) assumed (row 5-7)? The cloud in row 1 is also likely to be "Stratocumulus in mixed-phase T regime"? Or why is it a "Warm cloud"?

- Table 4: Remove 11.05. and 13.05. or are the measurements done at these days used within this paper?

- Table 5: Remove 21.09., 27.09. and 30.09. or are the measurements used within this paper?

Small remarks,typos:

- page 1 line 3: Space missing between number and unit (to be consistent with the rest of the paper).

- page 1, line 7: Replace associated with by : .

- page 1, line 13: You might also want to specify the temperature range for the tropics.

- page 1, line 15: The second "to" is too much.

- page 2, line 21: Delete "nature of" (it is not the nature of the properties...).

- page 2, line 31: "with modification" is redundant (already written "adapted from").

- page 3, line 29: Verb missing.

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- page 4, line 16/17: The clouds after the WBF process could eventually be named as 'glaciated clouds' (also this can be a bit ambiguous) or 'WBF glaciated clouds'. Or maybe it would be good to introduce the names here that are later on used, i.e. page 11 and 12.

- page 4, line 22: Add "(cloud spectrometer)".

- page 4, line 18-21: Sentence is too long and difficult to read.

- page 6 line 8: It would be nice to add a reference where NIXE-CAS-DPOL and NIXE-CIPg are explained later on in the text.

- page 6, line 13: One bracket too much.

- page 8, line 5: What does the "With these" refer to?

- page 9, line 10: One bracket too much.

- page 11, line 21: Shift this sentence to the beginning of this section.

- page 12, line 27: "reflected" instead of "reflect".

- page 12, line 24: The reference Augustin-Bauditz et al., 2014 does not fit in the context.

- page 13, line 10: Delete "and".

- page 13, line 22: replace the "-" with something equivalent, it could look like -253 K.

- page 13, line 22: There is a ":" too much.

- page 14, line 27: Switch bracket and "clouds".

- page 14, line 34: "darkblue" instead of "blue".

- page 15, line 27: "On the contrary" does not make sense since the statement is further supported?

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- Caption Fig. 1: . missing at the end.

- Caption Fig. 2: Add "z" after altitude.

- Caption Fig. 2: Remove the bracket WBF..., that is not written in the figure.

- Figure 4: There are some black dots around the axis labels at the right panel of the figure.

- Figure 6: Delete the 1 in the unit-brackets.

- Figure 7 and 8: The blue line is not thick and not so easy to differentiate from the others.

- Figure 13: RACEPAC is mentioned in the caption but not in the title of the figure.

- Figure 15: The fonts are quite small.

- Table 5: To be consistent remove "profiling".

- Table 5: Write out "Cb".

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