Manuscript: EarthCARE Cloud Profiling Radar Observations of the Vertical Structure of Marine Stratocumulus Clouds – Point to point response to reviewer 1 comments

We are grateful to reviewers for their insightful comments, which have helped us improve the clarity and impact of our study. In the remainder of this document comments from the reviewer are in black and our responses are in red.

General Comments:

This paper presents some early performance characteristics of the EarthCARE cloud profiling radar with regard to detection of of hydrometeors in marine stratocumulus clouds. EarthCARE performance is shown to be a notable advance over CloudSat in respect to detection sensitivity and surface clutter suppression. Marginal improvements in the detection of precipitation (drizzle) are shown as well. The paper is timely - EarthCARE is new and a good reference specific reference relative to StCu is warranted. The presentation is generally of a high quality and the methods are appropriate. I only have a few minor comments listed below to be addressed.

We would like to thank the reviewer for the positive, general comments.

Specific comments:

Line 240: 2.5 km should be 1.7 km. See Tanelli et al. 2008, Table 1.

Corrected. I think you meant line 40 instead of 240.

Line 128: add 'the' before 'model'.

Added.

Subsection numbering is messed up. There are two 2.1 and two 2.3 sections but no 2.2!

Corrected.

Figure 4: I think you could probably make this figure more compelling. I think it would help to add both an EarthCARE and CloudSat example of a thin non-precipitating cloud with cloud top at or below 1 km. There are lots of examples where CloudSat has only one or two bin of reflectivity where EarthCARE might see significantly more detail. I think you envision your panel A as showing a marginal cloud but this is actually a fairly thick StCu.

Thanks for the suggestion. We added two additional examples to the supplement along with some descriptions to illustrate the potential differences observed by the two sensors for such clouds.

Line 220: note that this field campaign included coordinated under flights of EarthCARE here.

We added ", which included coordinated underflights of EarthCARE for validation purposes." after the 1st sentence of this paragraph.

Lines 240-247: This paragraph describes model results. Does it belong here? I would put this back in your section 2.3 (the one that discuss the model results.

We would like to thank the reviewer for his logical suggestion. The text and associated figure (Fig. 6 in the original manuscript) have been moved to section 2.3 (model results).

Lines 248 – 276. You might want to include a sentence or two before this discussion to describe why you are showing these results. I think you are trying to identify a multi-variable relationship with precipitation that goes beyond a simple reflectivity threshold. I also think your results show that this is hard to do and there is likely inherent uncertainty in cloud/precipitation identification. Maybe add a little discussion of that fact.

Completely agree. At the beginning of this part, we added "Ambiguities exist when it comes to partition cloud and drizzle with single-frequency radar reflectivities (e.g., Xu et al., 2019). The variability associated with microphysics, dynamics and the fact that reflectivity is dominated by the large drops in the radar volume all contribute. Therefore, using a threshold of Z_{MAX} for drizzle detection is subject to uncertainties. Combining model outputs and EarthCARE observations allows for some exploration of the possibility to identify a multi-variable relationship beyond a simple threshold of reflectivity."

Additional discussions are also added near Line 276 in the original manuscript – "The observed NH_{MAX} of cloud-only and light drizzling profiles is close to 0.5. We know from ground-based and airborne radar observations (Kollias et al., 2011; Remillard et al., 2013; Fan et al., 2018) that the NH_{MAX} of cloud-only and light drizzling profiles is usually near the cloud top. Thus, the PTR limits our ability to diagnose the absence of drizzle particles using the NH_{MAX} value. As the size and number concentration of drizzle particles in the profile increases, Z_{MAX} increases and NH_{MAX} decreases but the PRT has reduced the dynamic range of the NH_{MAX} compared to those from the model simulations without the PRT (Fig. 3). Further effort would be devoted to combining other observations that could afford additional constraints such as Doppler velocity and path integrated attenuation (PIA)."

Line 280: What CloudSat years. The MDS changed by about 6 dB over the course of the mission which would significantly influence the pdf's in figures 8 and 9.

We used CloudSat CPR observations collected in 2007 and 2008, during the early period of CloudSat in space, when the CPR sensitivity was high.

Figure 9: I'm confused about two aspects of this figure. The CS pdf's don't show detections smaller than about -26 dBZ (related to question above). There is no reason that EarthCARE

should detect more -15 dBZ clouds than cloudsat at altitudes above 750 m – but panels b and c show this. Why? Is it just that the time period sampled is different?

There are detections with Zmax < -26 dBZ, though it is not apparent in the figure because we plotted the probability and the number of Zmax smaller than -26 dBZ is very small compared to the number with Zmax greater than -26 dBZ. For example, there are 1886 profiles that have Zmax < -26 dBZ relative to 332420 profiles with Zmax > -26 dBZ in the category of 750 < Hmax < 1000 m (Fig. 9c).

For the second question, we think it is likely mainly due to the different large-scale circulation, SSTs, and inversion strength during 2007-2008 and 2024-2025. The slightly weaker inversions and warmer than average SSTs in 2024-2025 tend to favor deeper boundary layer and more mixed stratocumulus-cumulus clouds that carry larger liquid water path, whereas the colder SSTs combined with strong inversions in 2007-2008 favor overcast Sc with overall less precipitation.

Line 320: So CS misses 20% of the EC precip detections at this height bin. Can you also add for reference what fraction of EC radar shots contain precip?

Yes, the fraction of EC and CS radar that contain precipitation with the height of Zmax in 3 different categories can be found in the caption of Fig. 9. We also added "The fraction of precipitating Sc observed by EC-CPR and CS-CPR is respectively 11.4% and 10.2%, summing the three height categories in Fig. 9. Overall CS-CPR misses the precipitation detection in Sc clouds by about 10.5%." to the manuscript.

Section 3.2: You should add a bit more analysis to this section. First it would be useful to include the total fraction of radar shots with a StCu hydrometeor detection in each of the two regions for both EarthCARE and CloudSat. Second I would add a plot that shows the vertical profile of the hydrometeor detection fraction from each sensor.

Sure. We added "The Sc cloud fraction (fraction of columns with a detection) as observed by EC-CPR and CS-CPR is approximately 40% (44.8% in SEP and 36.7% in SEA) and 20% (23.6% in SEP and 19.2% in SEA), respectively."

The suggested plot is added as the panel (c) in Fig. 8. It is done by summing the probability at each height bin in panel (a) and (b).

Referencing in the intro is a little thin. Here are some (not a comprehensive list) to add:

Thanks for pointing us to these important references. They are added along with some others.

Tanelli et al., "CloudSat's Cloud Profiling Radar After Two Years in Orbit: Performance, Calibration, and Processing," in IEEE Transactions on Geoscience and Remote Sensing, vol. 46, no. 11, pp. 3560-3573, Nov. 2008, doi: 10.1109/TGRS.2008.2002030

Wood, R., T. L. Kubar, and D. L. Hartmann, 2009: Understanding the Importance of Microphysics and Macrophysics for Warm Rain in Marine Low Clouds. Part II: Heuristic Models of Rain Formation. *J. Atmos. Sci.*, **66**, 2973–2990, https://doi.org/10.1175/2009JAS3072.1.

Wood, R., D. Leon, M. Lebsock, J. Snider, and A. D. Clarke (2012), Precipitation driving of droplet concentration variability in marine low clouds, *J. Geophys. Res.*, 117, D19210, doi:10.1029/2012JD018305.

L'Ecuyer, T. S., W. Berg, J. Haynes, M. Lebsock, and T. Takemura (2009), Global observations of aerosol impacts on precipitation occurrence in warm maritime clouds, *J. Geophys. Res.*, 114, D09211, doi:10.1029/2008JD011273.

Mülmenstädt, J., Salzmann, M., Kay, J.E. *et al.* An underestimated negative cloud feedback from cloud lifetime changes. *Nat. Clim. Chang.* **11**, 508–513 (2021). https://doi.org/10.1038/s41558-021-01038-1

Manuscript: EarthCARE Cloud Profiling Radar Observations of the Vertical Structure of Marine Stratocumulus Clouds – Point to point response to reviewer 2 comments

We are grateful to reviewers for their insightful comments, which have helped us improve the clarity and impact of our study. In the remainder of this document comments from the reviewer are in black and our responses are in red.

Overview:

In this manuscript, Xu and coauthors compare and contrast the first year of EarthCARE radar observations with those from CloudSat for stratocumulus over the Southeast Atlantic (SEA) and Southeast Pacific (SEP) Ocean. It is a nice paper, documenting and explaining key differences between the observing systems.

Recommendation: Accept minor revisions.

General Comments:

1) Use of 1D model

I am unclear as regards how you generated the modeled points in Figures 6 and 7. Please describe this activity in sufficient detail that another researcher could reproduce your results. A variety of specific questions follow (lines 241-251).

More details are added. See our answers to your specific questions.

2) Data availability

Maybe I'm just missing it, but where can I get copies of the EC-CPR data (and other "inputs" to your analysis), as well as your derived-data. As regards the later, I would like to have access to the PTR function, at a minimum.

Data availability statement is added to the manuscript. The PTR function tabulated values are now available in the Supplement.

Specific Comments:

Line 10. Change "finer vertical and horizontal resolution" to "finer horizontal resolution and finer vertical sampling". (Afterall, the vertical oversampling and Point-Target-Response are major aspects of the paper).

Changed as suggested.

Line 16. I think the sentence, "CS-CPR is found to underestimate rainfall occurrence by up to ~20%" is misleading as this value applies only to the case where Zmax is located between 500 and 750 m above the surface. (See related comments and suggestions for lines 322). I suggest changing to 10% (so it encompasses all drizzle) or make clear the height-restriction.

Added "for Z_{MAX} located between 500 and 750 m above the surface" to make it clear that 20% underestimation is only for this height range.

Line 62. CloudSat minimum detectable signal varied significantly over the course of the mission being close to -30 dBZ at the start and ending near -25 dBZ. A cloud mask threshold of 20 is roughly equivalent to -28 dBZ in the first couple years of the mission. I am not sure this is documented anywhere in the peer-review literature, though I will do so in my next publication on this topic. As-is, I invite you to use a sentence along the lines of " … whereas CloudSat's MDS varied over the course of the mission being close to -30 dBZ in 2007 and ending near -25 dBZ in 2020 (personal communication, Roger Marchand).

The suggested sentence is added and thanks for providing this reference.

Line 63. Of course, 2.3 is just the along track factor. Perhaps clarify and add something about the field-of-view area (which must be what ~ 5 times smaller)?

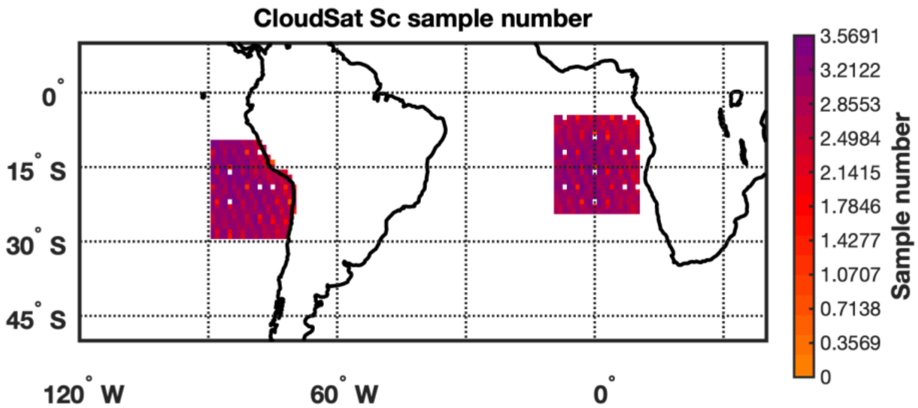
The field-of-view area is about a factor of 4 smaller. Also added in the manuscript.

Line 101. "Not reflectivity" is awkward. Perhaps "no measured reflectivities".

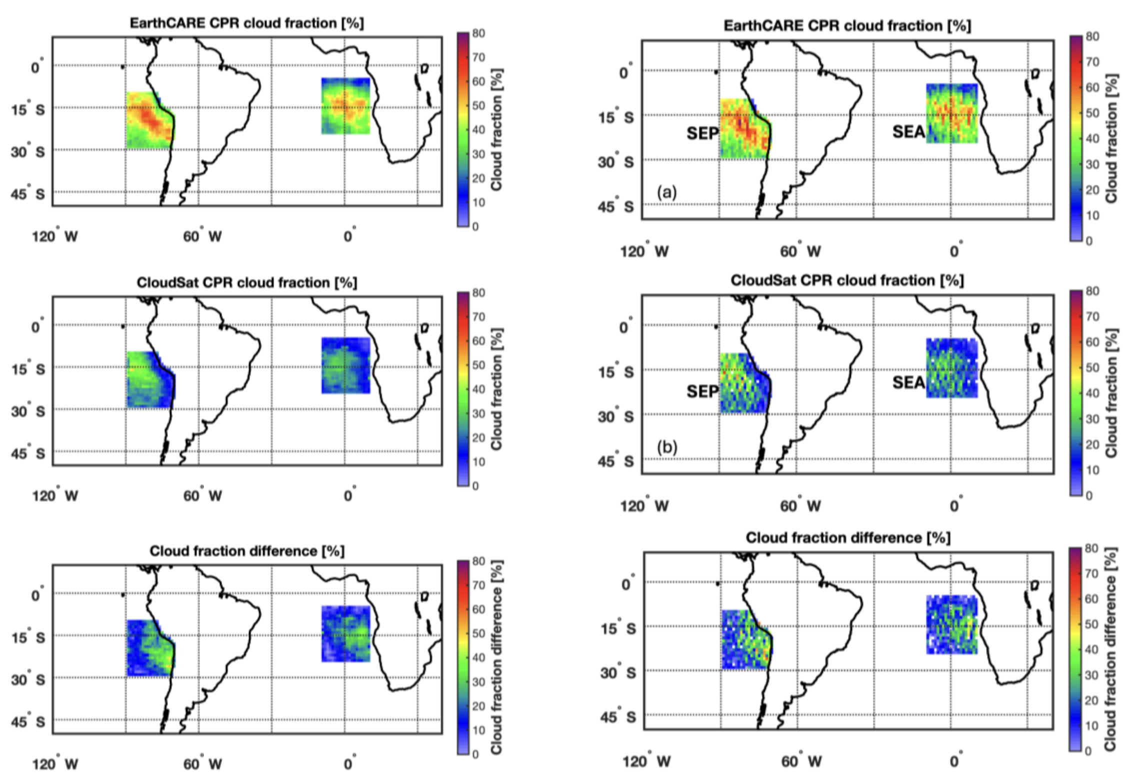
Corrected.

Line 116. I am a little surprised you were able to use a 1 x 1 degree grid with the CloudSat data. The fix-repeating orbit yields a ground-track spacing that is more than 1 degree between tracks at the equator. If you look at the number of CloudSat samples in each 1x1 degree bin, is there anywhere close to uniform coverage. In general, you might comment on the average number of orbits (transects) contributing to the data in each 1x1 degree grid to provide some sense for the sampling uncertainty in the cloud fractions shown here.

Yes, you are right. For CloudSat data we noticed some bins have low sample number using 1x1 degree bins. A 2D box smoothing was applied only in generating Fig. 1, so no impact on the analysis in the remainder of the manuscript (also added to the caption). The sample number on log base 10 scale in each 1x1 degree bin is shown below.



The following figure shows the spatial maps before (right column) and after (left column) the 2D box smoothing. The main message we attempt to convey is not affected by the smoothing. Note the range of color bar is 0-80% here, whereas the range of color bar in the Fig. 1 of the manuscript is 0-60%.



Line 120. “Dominance”?? Perhaps “… cloud fraction is lower consistent with well-known tendency of the extensive Sc cloud decks in this region gradually breaking …”

Edited as suggested.

Line 120. What about near the coast? Presumably the lower CTH is a problem for both sensors (but especially CloudSat) as one approaches the coast.

True. This is reflected in the lower cloud fraction detected by both sensors, though EarthCARE has some significant improvement in detecting coastal Sc (Fig. 1c). EarthCARE also provides a more accurate CTH near the coast. See more discussions added to the manuscript.

Line 122. Perhaps show (or put in a supplement) the mean "echo / cloud top height (CTH)" fields, rather than "not shown".

The mean radar-detected cloud top height is added as Figure S1 in the supplement. Some discussions are also added.

Line 147. Is the receiver linear over the full range (+35 to -30 dBZ)?

Yes, it is.

Line 161. What about drizzle, adiabaticity, sub-cloud RH? I think you should provide all the inputs needed for the 1D model (so that in principle another researcher could reproduce your results).

More details regarding drizzle, adiabaticity, sub-cloud RH are added to Section 2.1.

Line 166. Enhanced relative to what? I was confused when I initially read this sentence because I assumed enhanced was going to mean with PTR relative to without PTR. Perhaps rephrase, to "In general, larger LWP leads to larger cloud reflectivity (for the same Nd), and likewise smaller Nd leads to larger cloud reflectivity (for the same LWP). For Nd this is because ...".

Rephrased as advised.

Line 180. This is true. But it might also be worth noting that when drizzle is present Zmax is located below cloud base, and one should NOT interpret the altitude where Zmax occurs (Hmax) as the location of cloud base. Nor is Hmax necessarily the location where precipitation or total water content is largest.

These are very good points. They are added.

Line 180. I am not sure I think the algorithm would be "straight forward" = "uncomplicated and easy to do or understand". In particular, if one doesn't know the cloud thickness, adiabatic factor, RH. But if this is your opinion, so be it.

Sure, there are factors and unknowns that can complicate this retrieval, but what we meant is that it is easier compared to retrieving from profiles confounded by the PTR. We changed it to "location of the Z_{MAX} (H_{MAX}) and the morphology of the radar reflectivity profile could add critical information for the detection of drizzle particles in the radar reflectivity profiles of low-level stratiform clouds (Fig. 3a vs. c)."

Line 196. Perhaps change "ground-based observations" to "radar observations with high vertical resolution (short pulse)"

Changed.

Line 221. I presume the ER-2 was flying near 20 km, such that the sensitivity at the cloud level will be around -24 dBZ, yes? While it would be "OK" to just give the altitude of the aircraft, I think better to give the sensitivity for the clouds shown (rather than for an arbitrary 10 km distance).

We agree with the reviewer's comment: The following change has been done to the revised manuscript: "Considering the ER-2 flying altitude (approximately 20 km) the effective sensitivity of the CRS is -25 dBZ at the altitude of the marine stratocumulus clouds.

Line 221. How close (in space/time) are the ground tracks shown here? Clearly, they can't be too far off.

The track and time match are shown below. The x-axis is the same as in Fig. 5(a) of the original manuscript. We also added "The RMS of ground track match was 429 meters, and the relative time was -7 to 5 minutes." to the manuscript.

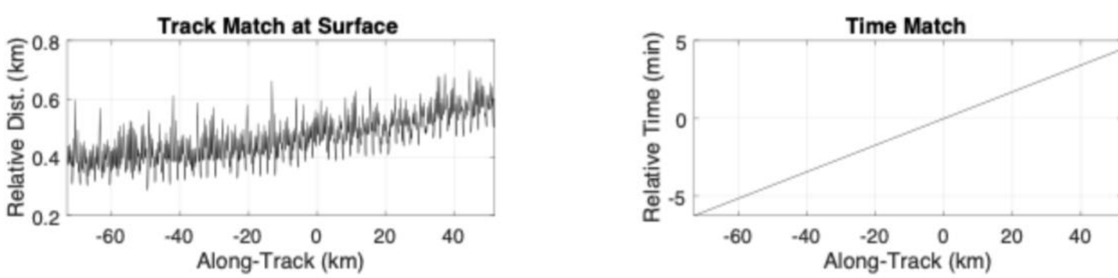


Figure 5. Caption is incomplete.

Descriptions for panel (c) and (d) are added.

**Lines 241-251.

A) What is "all"? I presume this relates to the ranges of Nd and LWP specified near lines 130 & 160.

“all” is the profiles we produced by combining different inputs of Nd, LWP, autoconversion schemes (5 options), liquid water content profiles (2 options), and embryo drizzle size (60 or 80 microns). Yes, some more detailed descriptions are in section 2.1.

B) Similar to comment for line 161, What about drizzle, adiabaticity, sub-cloud RH? The earlier description of the model also suggests five parameterizations for autoconversion or accretion. Is the model being “fit” to observed profiles or found via some “nearest profile in the library of curves”? If yes, which parameters are fit and which are fixed? I’m guessing that LWP and Nd are nearest values in the table (without interpolation). Broadly, please provide a more detailed (and nominally mathematical) description of what has been done here (see general comment #1).

Additional information about about drizzle, adiabaticity, sub-cloud RH, DSD assumptions, and accretion is added to Section 2.1. No, we do not fit the model to observed profiles or find some nearest profile in the library. All the points shown in Fig. 6 of the original manuscript (now Fig. 4) are completely from model and no observations are used. We forward simulate the reflectivity profiles from model microphysics, as shown in Fig. 3. Then the hydrometeor layer thickness is determined using the depth of simulated reflectivity profile where reflectivity is > -35 dBZ. The part below 500 m is not included in the hydrometeor thickness on the y axis in Fig. 6 of the original manuscript to consider the impact of clutter.

In Fig. 7, the 2D histogram in the background is purely from real EarthCARE observations. Again the hydrometeor layer is calculated based on radar echoes. The overplotted triangles and dots in gray, red, yellow and blue are independently from the 1D model.

C). Is the layer thickness is being used as an “input” in the retrieval? If yes, what do you do when the layer base reaches 500 m (and you can no longer determine the layer thickness)? More broadly, how is “ground clutter considered”?

No, layer thickness is not an input. The “hydrometeor layer thickness” in Fig. 6 (now Fig. 4) and 7 is the thickness where reflectivity is >= -35 dBZ. For observations, bins that are flagged as contaminated by ground clutter are not used. For model cases, the calculation of thickness is based on forward simulated reflectivites after applying the EarthCARE PTR, as exemplified in Fig. 3d. The part of reflectivity profiles below 500 m is omitted in the calculation to take into account the impact of clutter that real observations would encounter.

D) For the example shown in Figure 5, how well does this “retrieval” of the layer thickness compare with ER2 CRS?

Thank you for the suggestion. It compares quite well actually.

Line 255. I think you meant to write “… can capture ONLY … "? Perhaps the larger point that needs to be expressed here is that a 1D model can't fully represent the range of observed reflectivity profiles?

True. Large eddy simulations would provide a better agreement with observations in terms of capturing the natural variability, though the 1D model here is sufficient for our purpose to illustrate the impact of PTR and the sensitivity to LWP and Nd.

Figure 7(b). This figure does not get much discussion and I am not clear why you have opted to include such. (Perhaps explain to readers why this is of value).

We prefer to keep Figure 7b. From the ground-up, the location of the Zmax within a stratocumulus cloud layer is a great indicator of the presence and strength of the drizzle radar echoes: If the Zmax is near the cloud top, then there is no drizzle or is present at small concentrations and sizes that it does not affect the total radar reflectivity (cloud+drizzle). If the Zmax is lower in the cloud layer (often near the cloud base), this is an indication that drizzle is present. Unfortunately, the PTR of the 500-m long CPR pulse does not allow us to make such inferences about the presence of drizzle from the EarthCARE CPR observations. The following text has been added in the revised manuscript to justify the presence of Fig. 7b.:

"The observed NH_{MAX} of cloud-only and light drizzling profiles is close to 0.5. We know from ground-based and airborne radar observations (Kollias et al., 2011; Remillard et al., 2013; Fan et al., 2018) that the NH_{MAX} of cloud-only and light drizzling profiles is usually near the cloud top. Thus, the PTR limits our ability to diagnose the absence of drizzle particles using the NH_{MAX} value. As the size and number concentration of drizzle particles in the profile increases, Z_{MAX} increases and NH_{MAX} decreases but the PRT has reduced the dynamic range of the NH_{MAX} compared to those from the model simulations without the PRT (Fig. 3). Further effort would be devoted to combining other observations that could afford additional constraints such as Doppler velocity and path integrated attenuation (PIA)."

Line 280. I know this is just a pet peeve on my part and the term CFAD is in common usage, but I prefer (and recommend) using "reflectivity-height histogram." Are the data or the plot actually "contoured" in any way?

Changed to "reflectivity-height histogram". No, it is not contoured here.

Line 285. The "cloud fraction is … 40% or 20%". Is this the "volume fraction" in CFAD or the fraction of columns with a detection (which is of course NOT calculated from the CFADs). Please clarify.

This is the fraction of columns with a detection. Clarification is also added to the manuscript.

Figure 8. What is the bin spacing used here? (Perhaps put in the caption).

The vertical bin spacing is 30 m. The same interpolation to the 30-m bins was applied to both datasets. Also added to the caption.

Figure 9. It seems odd to give the cloud fraction (which I take to mean fraction of columns with a radar detection for any Zmax) in percent, but the drizzling fraction NOT in percent. Suggest give drizzle fraction in percent.

Changed as suggested.

Line 318. While resolution/sampling is a factor, the peak in the CS-CPR near -30 dBZ is likely due more to noise. That is, noise sometimes increases reflectivity, and resolution volumes with a signal that is just below the nominal noise floor sometimes experience an increased in total power are therefore more likely to identified as containing clouds. The uncertainty in the reflectivity factor for a detection at the noise floor is essentially 100%. As the EC-CPR data show there IS a large volume with clouds just below the ability of CloudSat to detect AND so a large volume where the noise can lead to detections with noise-enhanced reflectivity factors (leading to a bump).

Thanks very much for the explanations. We added that noise can be a likely factor.

Line 322. While it is true that 20% are missing in this category, this category represents less than 1/3 of the drizzle. I think it would be better to note both 20% for the lowest altitude category and a value for the total loss. That is, perhaps add "… (3% to 2.4%); and overall CS-CPR misses ~10.5% of all drizzling Sc relative to EC-CPR (11.4% to 10.2%) ." (The later numbers come from summing the three categories).

Sure. We added "The fraction of precipitating Sc observed by EC-CPR and CS-CPR is respectively 11.4% and 10.2%, summing the three height categories in Fig. 9. Overall CS-CPR misses the precipitation detection in Sc clouds by about 10.5%.".

Line 325. Perhaps "similar" rather than "same".

Changed.

Line 356. This is an excellent point, and perhaps add "… and the Zmax does not necessarily maximize where the precipitation is most abundant."

Suggested text is added.

Manuscript: EarthCARE Cloud Profiling Radar Observations of the Vertical Structure of Marine Stratocumulus Clouds – Point to point response to reviewer 3 comments

We are grateful to reviewers for their insightful comments, which have helped us improve the clarity and impact of our study. In the remainder of this document comments from the reviewer are in black and our responses are in red.

This paper examines the new EarthCare cloud profiling radar (EC-CPR) compared with the earlier generation CloudSat CPR in marine stratocumulus regions of the Southest Atlantic and Southeast Pacific. Additionally, the use of a steady state cloud and drizzle model is used to examine how the EC-CPR observed clouds compare with theory. Comparisons to measurements collected by the ER2 are also used. I find the paper to be very well done and informative. I especially found the discussion of the PTR to be illuminating. I suggest the paper be published after minor revisions.

I think the authors should consider a minor reorganization of the paper by putting all the cloudsat comparisons in the earlier portion of the results section and comparisons with the cloud model and new results from EarthCare later. Specifically, I was surprised to find section 3.2 where it was since the cloudsat comparisons were all earlier in the paper.

We put Section 3.2 at the very end is because we'd like to use the model simulations in the earlier sections to illustrate the impact of point target response on the shape of reflectivity profiles and the location of Zmax and resultant impact on drizzle detection. The comparison of cloud fraction is presented at the beginning is because it is not affected by the vertical structure of the radar reflectivity profiles.

My only significant criticism is that the authors need to examine, at least briefly, the cloud controlling dynamics of the two periods 2023-4 and 2007-8. Given the well-documented changes in global low cloud cover over the past decade, it may well be that the clouds in the SEP and SEA regions have real differences between the periods examined. Furthermore, since both observing systems include lidars, a comparison of cloud occurrence including the lidars in the two regions would provide information on these issues as well.

This is a very good point. We added discussions about how the differences regarding large-scale circulation, SSTs and inversion strength in 2023-4 and 2007-8 could impact the cloud fraction and drizzle amount qualitatively. We will incorporate lidar observations in our future work.

Despite the weak La Nina forcing together with the abnormally warm SSTs in 2024-5 are inclined to cause modest decrease of Sc cloud fraction in the more offshore regions, EarthCARE detects overall higher cloud fraction due to its enhanced capability. In terms of drizzle, the slightly weaker inversions and warmer than average SSTs in 2024-5 tend to favor deeper boundary layer and more mixed stratocumulus-cumulus clouds that carry larger liquid water path more ready to rain, whereas the colder SSTs combined with strong inversions in 2007-2008 favor overcast Sc with overall less precipitation.

Minor comments:

- Figure 1: should note in caption and figure titles that cloudsat CPR is for a different period - 2007/8.

Data period of CloudSat CPR is added to the caption.

- Line 119: should acknowledge and cite the lidar-radar cloud product of CloudSat.

References for CloudSat and CALIPSO data are added.

- Figure 4: This figure needs to be displayed in latitude longitude coordinates instead of km along track. Because the tendency of the casual viewer is to compare cloudsat with EC, the panel titles should clear show the dates that the data were collected.

Date, longitude and latitude are added on each panel to avoid the potential confusion that EarthCARE and CloudSat observation are collocated. We prefer to keep the x axis as it is to better illustrate the different sampling resolution of the two sensors.

- Figure 5: Need to include latitude and longitude information in the figures and/or the caption.

Latitude and longitude information is added to the caption.