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Atmospheric Measurement Techniques Discussions

Interactive comment on "Ground-based remote sensing scheme for monitoring aerosol–cloud interactions" *by* K. Sarna and H. W. J. Russchenberg

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We thank the reviewer for his thorough review. Our specific responses are detailed below.

Response to main review points

- *While legible and understandable, details of English usage require attention. In particular, hyphenation and word order are frequently deficient. A thorough revi-*

sion by someone fully proficient in English is required.

  - We would like to thank again the reviewer for a thorough review. We apologise for inconsistencies in the manuscript. The revised version of the manuscript was given much more attention to the proper use of English.

- *The organization of the manuscript is not ideal in many places - results, introduction and methods are frequently mixed.*

  - The organisation of the paper is improved in the revised manuscript.

- *Descriptions of instrumentation and methodology are incomplete in some places (see details)*

  - A more detailed description of the instruments used is presented in the revised manuscript.

- *It remains unclear whether correlation analysis, the central component of the methodology, was performed on normally distributed data. Tables 2 and 3 suggest a logarithmic transformation, but no mention of this is made in the text. Sample sizes are rather small (n in Table 2). Information on the statistical significance of the relationships (p values) is somewhat hidden and disjunct from the description of the correlation analysis.*

  - We performed a logarithmic transformation of both the effective radius and the Attenuated Backscatter Coefficient. Distribution of both variables approaches normal distribution. The logarithmic transformation of variables is clearly indicated in the revised version of the manuscript. It should be noted thought, that neither the Pearson Product Moment Correlation Coefficient or the linear regression assume the normality of the dependent variable, in our case ln(r_e), and independent variable (Montgomery, 2003), ln(ATB) in our study. In case of the linear regression, the distribution of

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errors is assumed to be normal.
However, the distribution of the data needs to be normal to perform the t test, used to test the statistical significance of the dataset. We agree with the referees comment that this should be stated explicitly in the manuscript. For that reason, in the revised version of the manuscript we address the issue. Further, we only perform the t test for the whole dataset for each day. Performing the test for every bin of Liquid Water Path (LWP) is more difficult, as the data set of each LWP bin is not always approaching a normal distribution.

- *In particular, it does not become clear to me on what basis previous and other approaches to quantifying aerosol-cloud interactions are discarded as not methodologically desirable.*

  – We would like to emphasize that in fact we do not discard previous and other approaches to quantifying aerosol-cloud interactions (ACI). They are a valuable contribution to understanding the ACI process. However, due to differences in methods used and in the different scales of data in between the studies, it is difficult to compare results from different studies with each other. ACI is a small, microphysical process that can be easily obscured by other cloud processes or changing meteorological conditions. We proposed in this paper a new method, that will enable comparison of ACI from different locations and meteorological conditions. The method we proposed is based on widely available instruments and on a standardised format of data. This will allow a direct comparison of ACI process at different locations, which is not the case with methods used until now (the data used in between different studies varies in the time and spatial resolution as well as in the instruments used to obtain that data). The new method we proposed is straightforward and hence can be easily applied, and possibly even automated, at cloud

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observatories. If this method was applied at several locations, and data from similar meteorological conditions were to be compared, it will provide a further understanding of ACI process and allow to better understand its drivers.

Response to detailed review points

- *Page 11954, line 10: "We show the Pearson...." - this seems like too much detail for an abstract. Please abstract.*
  - The abstract was abbreviated in the revised version of the manuscript
- *Page 11954-12: Can you find a positive way of saying this? I.e., we propose a new/improved way to represent aerosol-cloud interactions quantitatively.*
  - Sentence was changed to 'We propose a new method to represent aerosol-cloud interactions.' in the revised version of the manuscript.
- *Page 11954-16: low-level water clouds per se are not an uncertainty. Please specify what aspects about them are uncertain.*
  - The suggestion has been adopted. The sentence was revised to 'Low-level liquid water clouds and their interactions with aerosol are considered one of the main sources of uncertainties in climate change predictions.' in the revised version of the manuscript.
- Page 11954-16 and elsewhere: "water cloud" is ambiguous. Please use "liquid water cloud" instead.
  - The suggestion has been adopted throughout the revised manuscript.

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- Page 11954-22: In view of AR5 cited just above, the terminology presented here seems outdated. Please use the terms used there (“aerosol-cloud interactions” etc.)
  - The suggestion has been adopted throughout the revised manuscript.
- Page 11954-24: I do not consider this particular vertical order of aerosol and water layers to be part of the definition.
  - The sentence has been changed to: ’It is based on the close relation between the aerosol concentration and the cloud the droplet concentration.’.
- Page 11955-1: What do you mean by “impact of aerosol-cloud interactions”? Impact on what?
  - The suggestion has been adopted. The sentence has been changed to: ’An ample number of studies have been made in order to quantify the impact of aerosol concentrations on cloud microphysical properties.’.
- Page 11955-2: “some observational studies” - “some” seems a bit arbitrary. What criteria did you apply in choosing to present these particular papers?
  - The main point of this sentence, and paragraph, was to emphasize the broad spectrum of studies and method used to study aerosol-cloud interactions. Studies were chosen based on the methodology they used (in-situ observations, remote-sensing from ground-based instruments and satellite remote sensing) and the type of cloud they were focused on (low-level liquid water clouds). The spectrum of the studies in this areas is of course much broader, but the purpose of this work was not to give an overview of all the studies made about ACI, only to show how different the methods are. We wanted to emphasize that despite differences in methodology and scales the results

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obtained in all those different studies are often compared with each other. The validity of such a comparison is questionable.

- Page 11955-1 to 55-9: The compilation of studies presented here seems slightly unfocused: Why did you choose the present these particular studies? What is the significance/importance of each particular perspective for the study of aerosol-cloud interactions (ACI)?

  – This was explained in the response to the previous comment. The paragraph was rewritten in the revised version of the manuscript.

- Page 11955-10 to 55-12: I don't follow this line of reasoning. Why would the absence of a common quantitative basis in different studies cast fundamental doubt on the (qualitative!) presence of an aerosol effect? I disagree with this conclusion and do not see material in this paragraph to support it.

  – We do not negate the presence of the aerosol-cloud interactions as there is an ample amount of research confirming it's presence and the physical basis of those interactions are well understood. However, the magnitude of ACI and it's sensitivity to spatial averaging still remains uncertain. This sentence has been rewritten in the revised version of the manuscript.

- Page 11955-13: While I agree that this is a necessary and valuable study, the need does not become clear in the transition between the previous and this paragraph. Please clearly identify the need for research and justify the particular research setup taken.

  – The suggestion has been adopted. The paragraph was rewritten in the revised version of the manuscript.

- Page 11955-20: The meaning of 'spatial resolution' is unclear in the case of ground-based (point!) observations

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  - The suggestion has been adopted. 'Spatial resolution' was replaced with 'height resolution' throughout the revised manuscript.

- Page 11956-14: The meaning of γ needs to be explained directly above or below the equation
  - The suggestion has been adopted in the revised manuscript.
- Page 11956-18: sentence ending on "region": Please provide a reference.
  - The suggestion has been adopted in the revised manuscript.
- Page 11957-1: The first sentence is confusing and possibly affected by circular reasoning.
  - The sentence was rephrased in the revised version of the manuscript.
- Page 11957-7: If you choose to keep this equation, you may want to consider to exchange re and τd to more closely follow the reasoning in the text.
  - The suggestion has been adopted in the revised manuscript.
- Page 11957-12: reference for equation 4 missing
  - The reference was added in the revised manuscript.
- Page 11957-17: I find the use of r and τ in this equation slightly confusing. Maybe substitute them by c for 'c'loud property or similar?
  - Equation 5 was split into two separate equations in the revised version of the manuscript, as suggested by Referee #2.
- Page 11958-4: Please be more specific

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- This paragraph was rewritten in the revised version of the manuscript.

- Page 11958-8: What is meant by 'absorption optical thickness'?

  - Absorption optical thickness is the optical thickness due to the absorption, as opposed to the total optical thickness (most commonly referred to as optical thickness only) which is due to both absorption and scattering.

- Page 11958-12: As coagulation is defined as collision plus coalescence, the terms in this sentence are redundant.

  - The suggestion was adopted. Sentence was rephrased in the revised version of the manuscript.

- Page 11958-16: I don't understand this sentence. How can there be a (meaningful) cloud droplet concentration below the cloud base?

  - Sentence was rephrased in the revised version of the manuscript. The cloud droplet concentration should be measured close to the cloud base, but within the cloud. The aerosol concentration should be measured below the cloud.

- Page 11959-1: Unclear at this point: Are data sets tested for/transformed into normal distribution? Did you perform a log transformation? As normally distributed data are required for the application of the statistical methodology used, this has to be addressed explicitly?

  - The data used for the calculation of the correlation coefficients was transformed into a logarithm. Thus, the values we compared are the ln(ATB) - log normal of the Attenuated Backscatter Coefficient, and ln(r_e) - log normal of the effective radius. The distribution of both parameters, ln(r_e) and ln(ATB), approaches the normal distribution for the whole dataset on both days (by a whole dataset we mean the data points at the chosen height for both ATB

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and r_e in the time steps when all data selection criteria were met). It should be noted thought, that neither the Pearson Product Moment Correlation Coefficient or the linear regression assume the normality of the dependent variable, in our case ln(r_e), and independent variable (Montgomery et al, 2003), ln(ATB) in our study. In case of the linear regression, the distribution of errors is assumed to be normal.

However, the distribution of the data needs to be normal to perform the t test, used to test the statistical significance of the dataset. We agree with the referees comment that this should be stated explicitly in the manuscript. For that reason, in the revised version of the manuscript we address the issue. Further, we only perform the t test for the whole dataset for each day. Performing the test for every bin of Liquid Water Path (LWP) is more difficult, as the data set of each LWP bin is not always approaching a normal distribution.

The problem of statistical significance of each LWP bin is difficult to address, as the samples can be very small. After reviewing similar studies of the ACI done with the ground based remote-sensing we noted that the size of the LWP bins in which slopes are calculated is not always reported. In the studies that report it the sample size varies from 20 (Kim et al, 2008) to over 1000 (McComiskey et al, 2009), depending on the time over which the data was analysed and the size of the LWP bins. We agree that using small sample size is not meaningful and therefore we limited the amount of LWP bins in the revised version of the manuscript. We present only bins where number of samples is equal or greater than 20. It can be argued that the sample size should be even larger, however we must remember that one on the main assumptions of this and similar studies is the constant value of LWP. This means that we should strive to keep the size of the LWP bins as small as possible. In our study we chose to have LWP bins 10 g/m^2 wide.

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- Page 11959-11: How do you perform a t test for just one bin? The significance of what property do you test?
  - This issue was addressed on the previous comment.
- Page 11959-12: It seems that the remainder of this paragraph duplicates information already provided a few lines above.
  - The suggestion was adopted. Paragraph was rewritten in the revised version of the manuscript
- section 3.1: More detail is needed on the instrumentation used; e.g., what type radar, what frequency etc., ceilometer central wavelength, range, bin size, etc.
  - The suggestion was adopted. Detailed information about the instruments was provided in the revised version of the manuscript.
- Page 11959-22: What do you mean by 'time scale'?
  - We refer here to the time resolution of the measurements used for ACI calculations.
- Page 11959-23: What is the problem with 'specific measurement campaigns'?
  - Specific measurement campaigns are very useful for examining aerosol-cloud interactions. However, the purpose of our methodology is to have continuous measurements that will allow daily monitoring of ACI. This will allow to build a big data base of ACI in different meteorological conditions.
- Page 11959-25: why are 'multiple locations' necessary?
  - In order to have a better understanding of aerosol-cloud interactions studies it is necessary to compare the measurements over different locations and in

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different locations. Further, a ground-based monitoring of ACI over multiple locations will be an important tool into the validation of ACI observed with the satellite instruments.

- Page 11960-1: It does not follow from the previous lines that remote sensing instrumentation is required.
  - Ground based remote-sensing instruments are able to provide continuous measurements. The purpose of our methodology is to provide a monitoring tool for ACI with a fine temporal and spatial (height) resolution. This is possible only with remote-sensing instruments. This paragraph was rewritten in the final manuscript to explain the use of ground-based remote sensing better.
- Page 11960-6: What is a pixel in the context of this study?
  - Be a pixel we mean a specific height at a specific time step.
- Page 11960-6: How is this categorization performed? (scientific basis, method part of an existing product or performed by you?)
  - The categorisation is a specific product of Cloudnet dataset. The description of the classification is referred in the paper (Hogan et al, 2004).
- Page 11960-8: What do you mean by 'specific targets'?
  - Cloudnet categorisation divides data in to categories. Those categories are: liquid cloud droplets, precipitation, ice, insects, aerosols.
- Page 11960-13: peak of the Koehler curve = 'critical radius'
  - The suggestion was adopted in the revised version of the manuscript.

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- Section 3.2 does not belong into the 'Methodology' chapter.
  - Section 3.2 was moved to the theoretical part of the paper in the revised version of the manuscript.
- Page 11961-14: how are 'well-mixed conditions' determined?
  - Well-mixed conditions are defined as conditions when there is a single cloud layer on the top of the boundary layer, the cloud base is below 2000 m.
- Page 11961-15: What data are integrated?
  - In this sentence we refer to the Attenuated Backscatter Coefficient. This sentence was adjusted in the revised version of the manuscript.
- Page 11961-15: At what altitude is the 'level of complete overlap'?
  - In this stud the level of a complete overlap is at 170 m. This is equal to four height bins. Data below that height is not used.
- Page 11961-17: How did you determine a distance of 300 m?
  - We chose 300 m because distance closer to the cloud base is often considered to include a mix of cloud droplets, drizzle and haze. We want to avoid including a mix of cloud droplets in the data that is supposed to represent aerosol. Based on the literature study distance of 300 m seems to be the closest possible to the cloud.
- Page 11961-20: How did you find this?
  - We performed comparison of aerosol property (Integrated Attenuated Backscatter Coefficient) and cloud property (Effective Radius) at a set height below the cloud(for ATB) and in the cloud (for r_e) and then at the set distance

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from the cloud base (300 m below the cloud for ATB and 85 m up from the cloud base for the r_e). In the second case, when properties were compared at a set distance from the cloud the absolute values of Pearson Moment Correlation Coefficient were higher.

- Page 11961-20: What is the 'level of aerosol proxy'?
  - It is the height at which we compare Attenuated Backscatter Coefficient.
- Page 11961-20: Is there a quantification for this dependence?
  - We observed an increased value in the Pearson Moment Correlation Coefficient when data is compared based on the set distance from the cloud base instead of a set height.
- Page 11962-10: Do you actually perform the retrievals or do you use finished products? In the latter case, please cite the relevant publication(s) instead of presenting the details of the methodology.
  - We perform the retrievals based on the cited publication (Knist, 2014).
- Page 11963-1: robust in what respect?
  - Not affected strongly by the instrumental errors of the Liquid Water Path (LWP) and radar reflectivity factor.
- Page 11963-2: What kind of 'observational errors'?
  - By 'observationa errors' we mean the error of the remote-sensing instruments.
- Page 11963-2: What kind of 'algorithm assumptions'?

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- The fundamental assumptions used to retrieve the cloud properties from the observables are that (1) the droplet size distribution is approximated by a mono- modal gamma distribution, (2) the moments of the DSD are correlated among each other and (3) the droplet concentration and DSD shape parameter remain constant with height in each profile (Knist, 2014).

- Page 11963-8: Why did you chose 85 meters?

  - The distance of 85 m was chosen based on the difference between the detection of cloud base. As lidar is more sensitive to small liquid water droplets it is more suited to detect the cloud base height than cloud radar. However, the retrieval of the effective radius is based on the radar reflectivity. The sensitivity of radar to detecting cloud base is smaller and therefore there is a substantial difference between the height detected by lidar and by radar. In case of this setup this difference is 85 m, which corresponds to two height bins.

- Section 3.2.3 does not belong into the methodology chapter

  - Section 3.2.3 was moved to the theoretical part of the paper in the revised version of the manuscript.

- Page 11963-25: why?

  - We need to filter the data in order to only compare the profiles when all measurements requirements are met. We want to exclude data where: a double cloud layer is present(as this affect the validity of LWP); drizzle is present(we only want to observe non-precipitating clouds); cloud base is located above 2000 m. Those are the conditions under which we can observe aerosol-cloud interactions with this method.

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- Page 11964-5: How exactly do you define a 'changing aerosol background' quantitatively?
  - We define the 'changing aerosol background' in a matter of standard deviation of the integrated value of the attenuated backscatter. If the standard deviation is over 10% of the mean value we say that the aerosol background is changing.
- Page 11964-8: I don't agree that both need to vary - if only aerosol varies, but not cloud, an effect of 0 size would be observed. If only cloud varies but not aerosol, other factors are obviously present.
  - This is true, but we want to make sure that the other factors are not included in the calculation of the correlation coefficient or the slope of the regression line which we assume that represents the aerosol-cloud interactions.
- Page 11964-10: How do you define 'good quality data' quantitatively?
  - Cloudnet dataset contains a product, where the quality of the data in each pixel is evaluated, this accounts for the instrument errors.
- Page 11964-13: daily basis → one-day case studies?
  - Yes, we want to observe ACI with one-day case studies to see how the values of the slope of the correlation coefficient and the slope of the regression line (in the revised manuscript) change in different meteorological conditions.
- Page 11964-13: There can be transitions between meteorological conditions even within one day (and much smaller intervals of time)
  - We agree that transitions between meteorological conditions happen on a smaller scale than one day as well. However, this kind of changes we try

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to account for during the filtering of data. If a rapid change in conditions is detected, the data is excluded. The meteorological information we analyse include temperature, pressure and specific humidity.

- Page 11964-13: How are different meteorological conditions between days accounted for and how do they affect the validity of your findings?
  - Like we mentioned in the previous comment, we analyse include temperature, pressure and specific humidity. We compare data only if similar meteorological conditions are present. We identify similar meteorological conditions when the standard deviation of temperature, pressure and specific humidity is less than 10% of the mean value in the chosen profiles below the cloud.
- Page 11964-24: What do you mean by 'regimes'?
  - By regimes we mean general meteorological weather conditions.
- Page 11964-26: What do you mean by 'method presented here' - so many different aspects are addressed in the previous paragraphs that it is hard to tell for the reader what the core of your own methodology is.
  - This paragraph was rephrased in the revised version of the manuscript to underline the core of the methodology.
- Page 11965-2: Based on what criteria are the case studies chosen?
  - We chose study cases based on the criteria that we presented in Section 3.3 - Data selection criteria. For this paper we chose two cases from the same season, with similar cloud cover and meteorological conditions. In order to underline that many factors may influence aerosol-cloud interactions, we chose cases with different cloud base height and aerosol loading.

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- Page 11965-9: What are the channels/central wavelengths/frequencies of these instruments?
  - Vaisala CT25K operates at 905 nm, MWR is a two-channel microwave radiometer operating at 23 and 31.4 GHz and Cloud Radar (WACR) operates on W-band ARM (95 GHz). This information is summarised in a table in the revised version of the manuscript.
- Page 11965-11: How does the re-sampling affect the quality of the data?
  - Data is re-sampled to the time resolution of the instrument with the lowest sampling rate (MWR, time resolution 30s) and to the height resolution of the instrument with the lowest sampling vertical resolution (WACR - vertical resolution is 42.85 m). Data with a finer resolution is averaged in the bins. Details of the impact the re-sampling can be found in the Cloudnet data product documentation (Hogan et al, 2004).
- Page 11966-22: Correlation analysis assumes normally distributed data. Droplet effective radius, at least, tends to be log-normal rather than normal. This means that a correlation analysis on the non-transformed data set is not numerically permissible or physically meaningful. Accordingly, the analysis in the following paragraphs is of very limited validity.
  - We performed a logarithmic transformation of both the effective radius and the Attenuated Backscatter Coefficient. Distribution of both variables approaches normal distribution. The logarithmic transformation of variables is clearly indicated in the revised version of the manuscript.
- 67-19: If precipitation started after 15:00, why did you discard data between 14:00 and 15:00?

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- This was a typo. We considered only data before 15:00 UTC. This was corrected in the revised version of the manuscript.

- 67-26: Why is 30 chosen as the lower limit?
  - As we specified earlier in the manuscript, the error of the Microwave Radiometer is 30 g/m^{-2}, therefore we do not consider data where LWP is reported below 30 g/m^{-2}.

- 68-1: Why were these values excluded? What is the effect of excluding them?
  - The retrieval of the cloud droplet number concentration (N_d) overestimates the concentration of the droplets in cases when radar reflectivity factor is low (around -40 dBZ), to ensure that this error of the retrieval does not influence the calculated correlation coefficient and slope of the regression line we exclude values of N_d that are significantly higher than those reported in the in situ studies of the Stratocumul

- 69-13: New methodology should not be introduced in the last paragraph of the results chapter, but in the methodology chapter.
  - This paragraph was rewritten in the revised versions of the manuscript.

- 69-13: What is a “student’s p test”?
  - This was a typo. We referred to student’s t test

- 69-13: All p values should be given explicitly or in terms of significance level markers (e.g. asterisks) together with r in the corresponding tables and text passages.
  - The comment was adopted in the revised version of the manuscript.

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- 69-25: I think the data format is of little importance.
  - The specific dataset we use is significant as only Cloudnet dataset includes target categorisation which we use for data filtering. Cloudnet provides a uniform dataset at many different locations. The advantage of using data from Cloudnet is the possibility of applying the method directly.
- 70-8: What do you mean by “statistical significance of every bin sample”? What property of the bin is tested for significance? What significance level is chosen?
  - As we explained in the comment before, this was changed in the revised version of the manuscript. Only the whole dataset can be tested with the use of t test, as the data in separate bins only does not always follow normal distribution.
- 70-8: I missed this explanation. Since this is the summary, can you repeat it in a few words, please?
  - We refer here to the main assumption of the Twomey’s method that the cloud is homogeneous. The summary was rewritten in the revised version of the manuscript
- 70-10: “statistical parameters can be representative” - I don’t understand this statement. Can you try re-wording it, please?
  - This sentence was rephrased in the revised version of the manuscript.
- 70-14: I agree that meteorological variation is an important factor. However, how can you draw generally applicable conclusions from your study?
  - We agree that based on the two study cases we present we cannot draw a general conclusion. However, many previous studies report significant

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variations in the cloud properties based on the meteorological variations. If cloud properties on their own change due to meteorology it cannot be assumed that the interactions between aerosol and cloud properties remain the same in different conditions.

- 70-16: How do you define “very similar”? Can you make a suggestion on quantitative criteria?
  - As we mentioned before, we use mean value and standard deviation of the temperature, pressure and humidity to identify similar meteorological conditions. This specification was written explicitly in the revised version of the manuscript.
- 70-25: I don’t think you can make inferences like this from the analysis of just one single case.
  - We agree. This was rewritten in the revised version of the manuscript.
- 70-25: explain ’significant’ in this case, please, or replace by a different word or phrase.
  - The sentence was reworded in the revised version of the manuscript.
- 71-3: Widely available is relative: I think cloud radars are still fairly rare.
  - In recent years there was a significant development in the cloud radar systems. There are instruments that can be readily bought available on the market now.
- Figures 5 to 8: p values of the regression should be given for each panel. Where the p value is larger than a pre-defined threshold (e.g., 0.01) no regression line should be shown.

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– We addressed this comment in the discussion about the distribution of the data.

Response to technical remarks and suggestions

- All remarks and suggestions were adopted in the revised version of the manuscript.

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