Reply to the referees of "The relative dispersion of cloud droplets: its robustness with respect to key cloud properties"

E. Tas, A. Teller, O. Altaratz, D. Axisa, R. Bruintjes, Z. Levin and I. Koren*

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Dear Editor,

Attached please find the revised version of the manuscript (**acp-2014-227**), "The relative dispersion of cloud droplets: its robustness with respect to key cloud properties" by E. Tas, A. Teller, O. Altaratz, D. Axisa, R. Bruintjes, Z. Levin and I. Koren, for publication in Atmospheric Chemistry and Physics.

This paper presents a study of the relative dispersion of drops size distribution in continental warm convective clouds using flights measurements. The relative dispersion is a key factor used in various types of atmospheric models and yet the sensitivity of this factor to clouds' microphysical and thermodynamic properties and to environmental conditions is unknown and many studies reported on different results. We think our study can contribute to the essentially important knowledge about this factor.

We have included major revisions in the manuscript, based on the reviewers' comments, in order to present our study in a clearer and more complete way. We provide additional information and explanations about the methods used in this study regarding both the flights and the data analysis. Statistical information is presented in order to support our findings. We have also extended the discussion about our findings based on the available knowledge in the literature , in order to make the contribution of the paper clearer. The figures were revised significantly in order to present the results in a clear way and to include number of data points and error bars. Furthermore, we edited and revised the whole manuscript for English style and grammar.

We hope that the revised version will be found suitable for publication in the journal. We would also like to thank the two reviewers for their comments that helped us improve our paper and present a clearer and more complete study. We have addressed all of the reviewers’ comments. We open this response with a general part followed by point-by-point answers to each of the reviews' comments.

Sincerely,

Ilan Koren

<u>General</u>

In order to better describe the flights and analysis methods, to emphasize the main findings and their importance, a few changes and additions were done in the paper:

1) The methodology – detailed information was added to the revised version for better explaining the conducted flights and the method of analysis:

- We added information about the location of the 5 flights (in five clouds). Figure 1 includes a new map of the study area with the tracks of the five flights (see the figure at the end of this file).
- In addition the distances that the aircraft passed in each cloud's penetration are presented. It provides the reader a better idea about the horizontal dimensions of the measured clouds.
- The thermodynamic conditions that were measured near the base and top of the five clouds along the flights were added to table 1.
- Further details are given now about the method to determine the cloud's height and boundaries.
- Regarding the analyzed dataset, the number of analyzed data points were added to table 1 (total points per cloud) and to Fig. 3-5 and the error bars were marked as well, to give a better idea about the statistical significance of the results.

2) The quality and clarity of the figures were improved. All figures are provided at the end of this file with increased font size. The technical editor will be provided with figures in a resolution of 300 dpi.

3) The main findings from the supplementary section were implemented into the revised version of the paper.

4) The manuscript was sent for additional English proof and we have carefully improved writing style and grammar throughout the paper. We believe that the revised paper is much clearer and easy to follow.

Reply to comments by reviewer #1:

In the following part all the reviewer's comments (in italic font) are followed by our detailed answers:

1) "The paper discusses the variability of relative dispersion of cloud droplet distribution in convective clouds. Results are based on in-situ measurements performed in 2007-2008 during the Cloud and Aerosol Research in Istanbul (CARI) experiment. Five flights are analyzed. Data were collected during traverses of a research aircraft through a field of cumulus clouds. As can be inferred from Figure 1 the aircraft ascended from the cloud base to the cloud top over a horizontal distance over 100 km long. Clouds were 1000 to over 2000 m deep. We don't know where it is known from; obviously not from the in-situ measurements, because the aircraft didn't fly close to the cloud tops.
Relative dispersion is analyzed with respect to the location in cloud (with respect to the cloud base), mean concentration and Liquid water content."

Answer: Thank you for this comment. We would like to clarify a few points as it seems it was not clearly described in the original manuscript. The data presented in this study represents aircraft penetrations in five single clouds. Each case (TRK1 to TRK5) represents a single cloud that has been investigated uniquely.
For clarifying it in the revised manuscript we modified the opening sentence of the Results section (section 3): " Fig. 1c shows some differences between the clouds that were investigated on June 6th and 7th."
Figure 1 presents the flight profiles in these five single clouds. The horizontal distance that the airplane passed through each cloud penetration is only about 2 km. This information has been added into the revised text in section 2 (Measurements and instrumentation): "Each flight focused on one single cloud with penetrations at different altitudes (the aircraft ascended or descended at height steps of approximately 150 m). As can be inferred from Fig. 1c, the duration of each penetration was about 15–25 s, corresponding to horizontal flight distances of approximately 1–2 km (the aircraft speed was 70–90 m s^{-1} depending on the wind speed and direction). The

information about cloud top height presented in this paper is based on verification that no cloudy region was present above a specific height. This was done by visual inspection of the visibility around the aircraft, combined with the measured cloud droplet concentration and LWC above this height. Cloud top height was set as the highest altitude for which measured cloud droplet concentration and LWC were higher than 10 cm^{-3} and 0.01 g kg^{-1}, respectively, in agreement with the criteria of Deng et al. (2009) for the determination of a cloudy region."

2) "The technical quality of all figures is very bad. In all figures the vertical dimension, where the discussed parameter (relative dispersion) is presented is so small, that it makes impossible to see, understand and appreciate discussion of results. The vertical scale changes from one flight to the other making results shown very confusing"

Answer- Thank you for this comment. The technical quality of the figures was improved in the revised manuscript and the font sizes were enlarged. Concerning the vertical axes: except for Fig.2, all of the attached figures use a consistent vertical axis for all the investigated clouds. The vertical scale in Fig. 2 represents the height above the ground and the values are different from one cloud to the other. It turns out that if the same vertical scale is used for all the sub-figures it would make it difficult to follow the evolution of the droplet size distribution with height. Therefore, in Fig. 2 we chose to use different values for the vertical axis in each case but we added a note about it in the figure caption, in order to avoid confusion:" Note that the vertical axes are not uniform, accounting for the different cloud tops observed in the different flights."

3) "As can be inferred from Figure 1 the aircraft ascended from the cloud base to the cloud top over a horizontal distance over 100 km long. Clouds were 1000 to over 2000 m deep. We don't know where it is known from; obviously not from the in-situ measurements, because the aircraft didn't fly close to the cloud tops. Relative dispersion is analyzed with respect to the location in cloud (with respect to the cloud base), mean concentration and Liquid water content"

Answer - As mentioned above in the answer to the general comment each flight focused on one single cloud with penetrations in different altitudes (the aircraft ascended or descended at height steps of approximately 150 m). The horizontal flight distances were on the order of 1–2 km only in each altitude. It should be emphasized that the horizontal axis in Fig. 1B refers to the time, rather than to the horizontal distance the airplane travelled. In the revised manuscript (section 2) we added an explanation to clarify this point: "Each flight focused on one single cloud with penetrations at different altitudes (the aircraft ascended or descended at height steps of approximately 150 m). As can be inferred from Fig. 1c, the duration of each penetration was about 15–25 s, corresponding to horizontal flight distances of approximately 1–2 km (the aircraft speed was 70–90 m s^{-1} depending on the wind speed and direction). The information about cloud top height presented in this paper is based on verification that no cloudy region was present above a specific height. This was done by visual inspection of the visibility around the aircraft, combined with the measured cloud droplet concentration and LWC above this height."

This misconception may be attributed to the quality of Fig. 1, and hence, in agreement with the reviewer's comment we improved the quality of this figure.

4) "*As I stated at the beginning, authors use the notion of cloud depth (in the supplement) attributing the same cloud depth for the whole cloud field measured during a given flight. They should comment where they know this value from, and secondly why the attribute the same value for all clouds. This issue brings also a confusion while looking at Fig 2, where the vertical scale end for some flights at 'expected' cloud top (TR5, TR4, TR2), but not for two others.*"

Answer - As each flight focused on a single cloud, it allowed us to estimate cloud top height based on visual control of the visibility in the vicinity of the aircraft, and based on the measured LWC and droplets concentrations values in each case. This is the reason why the cloud tops differ from one flight to the other. As stated above we clarified this point in the revised manuscript.

5) "*Clouds are heavily diluted. Although it is not so easy to see it from the color scale in Fig. 3 and 4 it is very likely that LWC very rarely rises up to 2 g/m^3 for those flights were the maximum adiabatic value goes up to 3,8 g/m^3. Division of cloud points into 'inner' and 'boundary' parts doesn't seem sound for me. The procedure doesn't provide a real division, because as I stated before all clouds are very diluted. A comment on inhomogeneous mixing as l. 20, p. 11161 is unjustified.*"

Answer – We agree with the reviewer that clouds are diluted but in our opinion it is possible to separate the inner parts from the boundaries of the clouds in the analyzed data. For separating the inner from the outer parts throughout all the analyses we used a threshold value of droplets concentration (Nc) >10 cm $^{-3}$ and LWC > 0.001 g cm^{-3} to define an in-cloud part (based on Deng et al. 2009). The cloud boundaries were defined as those data points that met the conditions of Nc > 10 cm^{-3} and LWC > 0.001 g cm^{-3}, while for one of their neighboring points this criterion is not fulfilled. Please notice that a sampling data point was regarded as an in-cloud only in case its neighboring sampling points (representing in total 2s or ~150 m) are all associated with Nc values larger than 10 cm^{-3} and LWC larger than 0.001 g cm^{-3}. So in our opinion these criteria are objective, consistent and robust for separating these two regimes.

Furthermore, our statement about inhomogeneous mixing is not meant to be conclusive and its purpose is to present a possible option: "The similar relative dispersion values when comparing Figs. 3 and 4 and the decrease in LWC and N_c suggest that a fraction of the droplets were totally evaporated due to mixing with the outside environmental air, but the shape of the droplet size distribution did not change. This <u>implies</u> that non-homogeneous entrainment mixing was the dominant process at the cloud boundaries, similar to the findings of Small et al. (2013)."

Regarding the values of LWC in figures 3 and 4, they are presented very clearly in parts B of those figures and not only by the color scale in panel A.

6) I don't understand the reason of submission of a supplement, that is discussed also in the main body of a paper. If the results are discussed in the paper *and references to supplement's figures are provided, this text should be merged to the main paper.*

Following this comment we incorporated two of the supplementary plots as well as the related discussion into the revised manuscript.

References

Deng, Z., Zhao, C., Zhang, Q., Haung, M., and Ma, X.: Statistical analysis of properties and 10 parameterization of effective radius of warm cloud in Beijing area, Atmos. Res., 93, 888–896, 2009.

<u>Reply to comments by reviewer #2:</u>

In the following part the reviewer's comments (in italic font) are followed by our response:

MAJOR COMMENTS:

1. It is unclear how they determine cloud height. This is an important quantity for their discussion and it is ambiguous how it is determined.

<u>Answer</u>:
The information about cloud top height presented in the paper is based on verification that no cloudy region is present above a certain height level. This was done by visual inspection of the visibility in the vicinity of the aircraft, combined with the measured cloud droplet concentration and liquid water content above this height. A clarification about this point was added to the paper (Measurements and instrumentation section): "Cloud top height was set as the highest altitude for which measured cloud droplet concentration and LWC were higher than 10 cm^{-3} and 0.01 g kg^{-1}, respectively, in agreement with the criteria of Deng et al. (2009) for the determination of a cloudy region."

2. They don't make a very strong case for why this new work is needed. They do not present a novel or unique way of assessing relative dispersion.

<u>Answer</u>:
The relative dispersion of cloud drops size distribution, which is the essence of this paper is a key factor used in various types of atmospheric models (from cloud resolving, CRM's, to global climate models, GCM's). The sensitivity of this factor to clouds' microphysical and thermodynamic properties and to environmental conditions is still unknown and many studies reported on different results. The flights data used in our analysis enables further investigation of the relative dispersion in warm continental convective clouds as a function of height above the cloud base and cloud properties. It is unique data in the sense that it enables a detailed investigation of warm continental convective clouds in high resolution.
For emphasizing the importance of this topic we included the following sentences in the Abstract and in the Discussion and summary sections. The contribution of this paper to the scientific knowledge in the field is now better highlighted and explained:

<u>Abstract</u>:

"The relative dispersion (ε), defined as the ratio between the standard deviation (σ) of the cloud droplet size distribution and cloud droplet average radius ($<r>$), is a key factor in regional and global models. ".

“ε is shown not to be correlated with cloud droplet concentration or liquid water content (LWC). However, ε variance is shown to be sensitive to droplet concentration and LWC, suggesting smaller variability of ε in the clouds' most adiabatic regions.

and

“A criterion for use of in-situ airborne measurement data for calculations of statistical moments (used in bulk microphysical schemes), based on the evaluation of ε, is suggested."

<u>Discussion and summary</u>:

“The present study uses airborne measurements to demonstrate that ε is not correlated with LWC, N_c or <r>, suggesting that ε is relatively invariant to changes in the cloud's microphysical properties. On the other hand, variance in ε was found to be correlated with LWC and N_c, suggesting that ε variance, rather than ε, does depend on the cloud's microphysical properties. This finding may pave the way for improving autoconversion and radiation parameterizations, which rely on ε values in CRMs and GCMs. However, further testing of the correlation of ε with these parameters under different ambient conditions and adiabatic and non-adiabatic cloud conditions is warranted.”.

3. They tend to generalize concepts without the necessary elaboration. Such as mentioning “microphysical processes” without describing what processes are relevant to their study.

<u>Answer</u>:
Thank you for this comment. In this research we study warm continental clouds and in the analysis we refer to the growing and mature stages in cloud's lifetime (when those clouds are usually measured during flights) when there are a few dominant microphysical processes. The major relevant microphysical processes in such clouds are diffusional growth, collision-coalescence of droplets and entrainment.

In the discussion part we explain it in details:
"Regarding all of the other clouds, based on the relatively small <r> values (see Fig. 2), the sparse population of large droplets (for all clouds except TRK3) and the relatively high aerosol loading, we assume that drop growth in all of the measured clouds was dominated by the condensation process. It is well known that growth by condensation leads to an increase in <r> but a decrease in the width of the size distribution (smaller σ (e.g. Rogers and Yau, 1989). However, the invariant nature of ε values in this and some other studies suggests that additional processes occur simultaneously with condensation. These additional processes act to increase σ such that the ratio of σ to <r> remains relatively constant. Such processes may include drop growth by collision–coalescence or the formation of new droplets by activation of cloud condensation nuclei (CCN) (increasing the number of the smaller droplets) or activation of giant CCN (which may increase the number of the larger drops). These scenarios act to broaden the droplet spectrum. In this study, we cannot determine

which of these processes is more significant. Moreover, the contribution of each of the two processes to maintaining a relatively constant range of ε may vary at different locations and stages of cloud evolution. Collection-based processes are more important higher in the cloud and at later stages in the cloud's evolution, while activation of new particles is more important near the cloud base and in the early stages of its development.". Our analysis (see Fig. 7) indicated that both ε values and variance tend to be smaller near the cloud base, suggesting that activation of new droplets dominantly contributed to maintain ε more confined.

4. It is unclear why they chose pre-frontal and post-frontal clouds. They do not elaborate on their reasoning for doing this. Why not use data from many more flights to establish a statistical grouping of clouds that can be sorted by cloud height and aerosol amount? The limited number of flights and the amount of data used is concerning. It is concerning that they only use two flights and 5 clouds since they are obviously not using high resolution data.

<u>Answer</u>:
In this study we use flight data collected in five warm continental clouds. In-situ data is always smaller compared to data acquired by other methods as it is more expensive and complicated to measure. This type of analysis of flights measurements is valuable as it serves to validate other observational datasets and numerical models. Here we focus on warm convective clouds, over land that developed in different levels of aerosol loading. Such data enables investigation of the relation of relative dispersion with the height above cloud base, the location within the cloud (cloud boundary vs. in-cloud measurements) and the thermodynamic conditions. As far as we know this type of detailed observation has not been shown in similar studies. The results are robust and it demonstrates the strength of such study.

Regarding the characteristics of pre-frontal and post-frontal clouds. The thermodynamic conditions of temperature and pressure levels that were measured near the base and top of the five clouds along the flights were added to table 1. It can be noticed that the cloud base temperatures decreased a bit after the passage of the front but the differences are minor. The five clouds are similar in their depth (base around 950–1,250 m and tops between 2,350–3.550 m) in similar temperature levels (base around 10–16ºC and tops between ~5–(-2)ºC). It means that those five investigated clouds have similar properties and can be compared. The robust estimated values for ε demonstrate the similarity of those clouds.

We want to emphasize that we do use high resolution data. The sampling rate is 1 Hz and with an aircraft speed of 70–90 m s^{-1} the spatial resolution is 70 to 90 m. These resolutions both in time and space are considered as high resolution data regarding clouds measurements.

We add the following sentence in the Measurements and Instrumentation section: "A shallow frontal system passed over the area of Istanbul on the night of 6 Jun 2008, bringing some rain showers to the area. Figure 1a shows an image of the Eastern Mediterranean region, taken by the Moderate Resolution Imaging Spectroradiometer

(MODIS) sensor, on 7 Jun 2008, showing the area west of Istanbul after the passage of the front. The airborne measurements in five warm cumulus clouds were conducted before (clouds TRK1 and 2) and after (TRK3, 4 and 5) the passage of the front (see the flight tracks in Fig. 1b). There was a slight decrease in temperature after the passage of the front (this can be seen in the minor differences between the temperature levels of TRK1, 2 compared to those of TRK3, 4, 5 in Table 1). Such measurements provide a unique opportunity to study the relationships between relative dispersion (ε) and different cloud properties (e.g. height above the cloud base, LWC, N_c)."

5. It is unclear how the flights were conducted. Aerial views of the flight paths are never shown. Based on Figure 1B it needs to be assumed that they flew back and forth in single clouds an multiple levels, but they never explicitly say this.

Answer:
Thank you for this comment. The description of the flights was improved in the revised version. Following the reviewer recommendation we have modified figure 1 to include an additional map of the flight area with the tracks of the five flights in these five clouds (fig. 1a). Fig. 1c presents the flight height, the measured droplet concentration and temperature as function of time. The horizontal distance that the airplane passed through each cloud penetration is about 2 km. This information has been added into the revised text in section 2 (Measurements and instrumentation):
"Each flight focused on one single cloud with penetrations at different altitudes (the aircraft ascended or descended at height steps of approximately 150 m). As can be inferred from Fig. 1c, the duration of each penetration was about 15–25 s, corresponding to horizontal flight distances of approximately 1–2 km (the aircraft speed was 70–90 m s^{-1} depending on the wind speed and direction)."

6. They should include average meteorological parameters for each "cloud" in their table. They should have access to these data from the aircraft. This would allow a fair comparison between theses clouds rather than just saying they are pre- or post-frontal.

Answer:
Thank you for this good idea. Table 1 was modified to include thermodynamic data and in the new version it includes: number of data points, maximum and minimum temperature, maximum and minimum pressure, cloud base and (estimated) cloud top height.

Flight date/ Flight time (LT)	Abbr.	No. of data points (rounded)	Aerosol loading (cm^{-3}) (0.11–3 μm)	Min.-Max. Temp. (^{O}C)	Min.-Max. Height AGL (m)	Min.-Max. pressure (mb)
06.06.2008/ 12:00-12:36	TRK1	380	1,800	5.7–16	1,000–2,500	750–901
06.06.2008/ 12:54-13:24	TRK2	240	900	-2.1–15.4	1,200–3,550	655–882
07.06.2008/ 06:24-06:54	TRK3	1,040	700	-1.3–9.8	1,250–3,450	661–874
07.06.2008/ 13:18-13:45	TRK4	450	800	-1.4–13.6	950–3,550	660–907
07.06.2008/ 14:09-14:30	TRK5	110	1,000	5.7–13.9	1,000–2,350	767–905

Table 1. Airborne measurements which were used for the present study. The table indicates for each of the 5 airborne measurements used for the present study the flight date and the corresponding abbreviation used in this paper, number of data points, aerosol loading at the cloud base (see Sect. 3.2), minimum and maximum temperature, minimum and maximum pressure, cloud base and (estimated) cloud top height.

7. They need to provide evidence for the "regeneration of the air pollution layer." With the current wording it is just speculation that this is the case.

Answer:
Thank you for this comment. We deleted this sentence from the revised text as we could not support it in an adequate way.

8. Uncertainty, and an assessment of if their results are statistically significant in light of the few clouds/data points they have, in their measurements and results needs to be more thoroughly discussed. The lack of droplets over 20 um needs further discussion. How much will the results change if those droplets are included, the authors discussion of this is not thorough.

Answer:
We thank the reviewer for this comment as this issue deserves further discussion. The information about the number of analyzed data points were added in the revised version, both to table 1 (total points per cloud) and to Fig. 3-5 (total points per height or per LWC bin). 100's of measurement points were analyzed per cloud. Figures 3-5 present the 95% confidence interval for the calculated averages of the relative dispersion in order to give the reader information about the estimated error. The robust results of the analysis for those five different clouds demonstrate the statistical significance of our analysis. Although it is a small number of clouds the estimated relative dispersion for all of them give similar values. The following sentence was added in the results section:

“It should be noted that although the error bars in Fig. 4 are significantly larger than in Fig. 3, both figures demonstrate invariant values of ε as a function of vertical height above the cloud base and LWC."

Regarding the issue of lack of measurements of droplets larger than 20 μm. The case of TRK3 demonstrates a cloud where there are probably large drops that were not measured. In this case we see different behavior of ε compared to the other clouds. The ε values for the case of TRK3 tend to be smaller for higher LWC, higher up in the cloud. We expect those values to be similar to the values estimated for lower parts of the cloud. The reason for this difference is the lack of the big drops in the measured spectrum. In the case of droplets size distribution the tail of the distribution (representing the larger droplets) is known to be very important. In fact this is one of the main factors that contribute to the complexity of cloud physics. On one hand the tail of the distribution, counting the larger droplets, is likely to have relatively low numbers, and on the other hand these sparse large droplets control the non-linear part of the cloud processes.

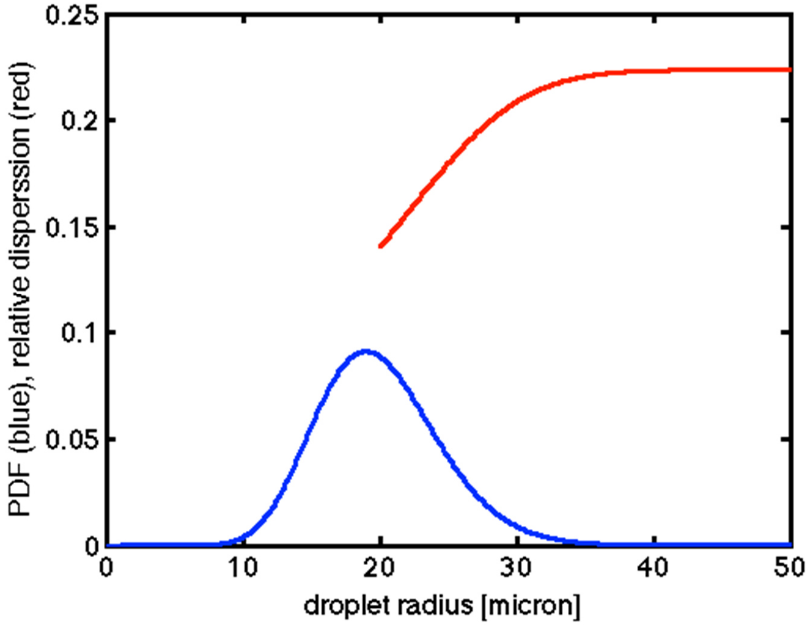
For distributions that have clear maxima (as opposed to uniform distribution for example), the relatively sparse tail of the large values (large droplets radii in our case) contributes strongly to the variance (or the standard deviation) compared to the average. Intuitively this can be explained by the fact that for clear maxima distribution most of the distribution members are concentrated near the maxima away form the tail and therefore trimming the tail will shift the mean toward smaller numbers relatively slowly while the variance depends on the square of the distance to the mean and therefore trimming it will reduce it faster. A formal proof for any distribution with a decaying tail is not trivial but we can easily demonstrate it for Gamma distribution. Assuming a Normalized Gamma distribution of the droplets radius (P):

$P(r) = \frac{b^{-a} r^{a-1}}{\Gamma(a)} e^{-\frac{r}{b}}$ where a is the shape parameter and so when a > 1 the distribution has a clear maxima and b is the scale parameter determining the sharpness of the decaying (exponential) tail.

In theory the distribution is defined on the whole real positive domain $r \in (0, \infty)$ and then the distribution moments are well defined: the mean $\bar{r} = ab$, the variance $v = ab^2$ and therefore the relative dispersion $\varepsilon = \frac{1}{\sqrt{a}}$.

To demonstrate the effect of tail trimming on the distribution we calculate a theoretical droplet distribution with 20 μm mean radius and standard deviation of ~5 μm (figure below, blue curve). Then we gradually trim the tail from the large end and calculated the relative dispersion by-definition. The trimming effect on the relative dispersion (ε) is shown on the figure (in red). Note that when the tail is not occupied (for the very large droplets) ε does not change much and stay around its theoretical value of $\frac{1}{\sqrt{20}} = 0.22$. When the tail trimming reaches sizes that are significantly represented in the distribution, a clear reduction in the values of ε is shown.

We note that in the case of gamma distribution, the reduction in the ε values will continue even when trimming the distribution over the peak. This is not generally true for other distributions.



The related text in Sect. 4 provides an explanation for the special case TRK3 where the presence of droplet larger than 25 μm at the high regions of the cloud (that is evident from Fig. 2) cannot be detected by the measuring instruments. We added a clarifying sentence in this paragraph: " Clearly, ε estimations deviate when the tail of the size distribution exceeds 25 μm in radius, i.e., the estimated variance will be smaller than the real one (see TRK3 in Fig. 2) and as a consequence, the ε values as well (see TRK3 in Figs. 3 and 4). "

9. It would be helpful for them to include the number of data points in each cloud pass in Figure 1B and Figures 3-5.

Answer:
The number of data points was added to Figs. 3-5 and Table 1 in the revised manuscript.

10. Flight speed needs to be mentioned so we can accurately assess that 2 sec = 140 m of cloud.

Answer:
Thank you for this suggestion, the missing data was added to the revised text. We added the following sentence at the opening of the Result section:

"As can be inferred from Fig. 1c, the duration of each penetration was about 15–25 s, corresponding to horizontal flight distances of approximately 1–2 km (the aircraft speed was 70–90 m s^{-1} depending on the wind speed and direction). "

11. A discussion of entrainment and mixing at cloud top and cloud edges is necessary (see Small et al 2013, Tellus)

Answer:
Thank you for this comment. A detailed discussion about this topic was added to the revised paper. We added the following statement in the results section:

"The similar relative dispersion values when comparing Figs. 3 and 4 and the decrease in LWC and N_c suggest that a fraction of the droplets were totally evaporated due to mixing with the outside environmental air, but the shape of the droplet size distribution did not change. This implies that non-homogeneous entrainment mixing was the dominant process at the cloud boundaries, similar to the findings of Small et al. (2013)".

SPECIFIC FIGURE COMMENTS

12) Figure 1) This figure is poorly formatted. Flight tracks should be included over the MODIS image to show where the flights took place. Highlighting locations like the Black Sea and Istanbul are useless to the study. Where were the flights made? In part B of this figure the altitude axes are too short to be able to clearly tell the differences between cloud penetrations. Making these panels larger and including grid lines will help make this figure easier to understand. In the caption it states that the measurements were carried out from June 6-8, though in the manuscript (line 12) it says June 6-7.

Answer:
We adopted the reviewer's recommendation and Fig. 1 was significantly changed (see the figure at the end of this file) as follows:

1. The flight tracks were added in the upper panel of Fig. 1. MODIS image covers large area in the Eastern Mediterranean Sea and in our opinion it is a good way for showing the high cloud fraction in the measuring area. Therefore we added a zoom in of the map of East Turkey to show the tracks of the five research flights.
2. We extended the y-axis range in the graphs of the bottom panel (in fig. 1) and changed the location of the sub-figures (from 3 rows to 2 rows)
3. We added grid lines in the bottom panel
4. We corrected the figure caption

13) Figure 2) The vertical axes in these panels needs to be larger. It is almost impossible to see the green line that represents the standard deviation.

Answer:

The figure was modified to have a larger vertical axis. The data is presented in a better way now. Please see the revised figure at the end of this file.

14) Figures 3-5) these figures constitute the bulk of the results section and are incomprehensible. It is impossible to see the difference in colors of the dots (for LWC, Nc) due to the extremely short y-axes on every panel. It is also almost impossible to read the axes labels. These figures need to be completed re-done in order for them to be useful to the reader. With the figures in the current format this paper cannot be published.

<u>Answer</u>:
Figs. 3–5 were modified in the revised version and they are much clearer now.

1. The average values of ε are now clearly shown on the graphs with colors representing the LWC in Figs 3a and 4a and the droplet concentration in Figs. 3b and 4b
2. The error bars represent the 95% confidence interval for the calculated averages of the relative dispersion
3. The gray points show the raw data of ε.

SPECIFIC TABLE COMMENT
15) Table 1) Include key meteorological parameters from the atmosphere around each cloud. For example, the range of temperature from cloud base to top, the range of humidity etc.

<u>Answer</u>:
We added thermodynamic data to table 1 (see above in answer no. 6) including the temperature levels at clouds' base and top and the corresponding pressure levels. We could not add humidity data since it was not measured properly on those flights.

MINOR COMMENTS: ABSTRACT
16) Line 12: Clarify the "clear criterion" and what you are referring to when you state "statistical moments' calculations.

<u>Answer</u>:
Thank you for this comment. The revised sentence:
" A criterion for use of in-situ airborne measurement data for calculations of statistical moments (used in bulk microphysical schemes), based on the evaluation of ε, is suggested."

1. *INTRODUCTION (page 11154)*

17) Line 16: "droplets" should be "droplet"
Line 19: "drops" should be drop
Line 21: Are you talking about cloud dynamics or atmospheric dynamics, be clear.

Line 22: List or describe what "different microphysical processes" you are talking about Line 22: Are you talking about the terminal velocities of the rain drops or the cloud drops?
Line 18-24: The wording/English writing in this section needs to be revised and improved.

Answer:
Lines 16 and 19 - All corrections were included in the revised manuscript.

Line 21 – " the dynamics" was replaced by " the cloud's dynamics".

Line 22 – "the falling drops" was replaced by: "the falling raindrops".

Line 18-24: This part was rewritten in the revised version:
"Higher in the cloud, at later stages of the cloud's development, additional processes, such as collision–coalescence, raindrop sedimentation, entrainment and mixing, further modify the drops' size distribution. On the other hand, the droplet size distribution determines the timing and magnitude of microphysical processes, which affect the cloud's dynamics through determination of terminal velocities, drag of the falling raindrops, and the release of latent heat."

1. *INTRODUCTION (page 11155)*

18) Line 1-25: The wording/English writing in this entire section needs to be revised and improved.
Specific comments below.
Line 2: "like for" is awkward, change this.
Line 5: "It is done in" is awkward, change this.
Line 16: "strartiform" should be "stratiform"
Line 20: What type of aerosol loading was the Lu et al and Berg et al papers made under?
Line 23: It is random to mention that the Nc was higher than 50 cm^{-3}, why do you include this?
Line 24: You state "similar results were reported" which previous paper that you mentioned are you referring to?
.
Answer:
- Lines 1-25: the English was improved in this section (as was done along the whole paper).

Line 2: The revised sentence:
"Both σ and <r> are key variables used in various parameterization schemes, such as reflectivity of clouds (Hansen and Travis, 1974; Slingo, 1989; Liu and Daum, 2000a, b; Daum and Liu, 2003) and autoconversion processes (e.g., Liu et al., 2005, 2006a; Hsieh et al., 2009). However, instead of using both σ and <r>, their ratio (i.e. the relative dispersion, ε) is often used. This is done in atmospheric models that span a wide scale from cloud resolution (CRMs) to global climate models (GCMs)."

Line 5: The revised sentence:
"However, instead of using both σ and <r>, their ratio (i.e. the relative dispersion, ε) is often used. This is done in atmospheric models that span a wide scale from cloud resolution (CRMs) to global climate models (GCMs)."

Line 16: strartiform" was replaced by: "stratiform.

Line 20: We've added information about aerosol conditions in both studies:
"Lu et al. (2008) and Berg et al. (2011) analyzed airborne measurements of shallow cumuli under various levels of anthropogenic pollution and found an average ε of around 0.3. In Berg et al. (2012), the pollution levels were assessed using CO concentrations (up to 170 ppbv) and in Lu et al. (2008), the highest accumulation mode aerosol concentration was 1,650 cm^{-3}" .

Line 23: It is clearer in the revised version that the convergence of ε is gradual: "Zhao et al. (2006) analyzed data collected in 135 flights in different environments and found that ε values tend to converge to a range of ~ 0.4 to 0.5 for droplet concentrations (N_c) higher than 50 cm^{-3}."

Line 24: The sentence was modified in order to make it clear that our intention is to compare the Deng et al and Zhao et al studies:
"Deng et al. (2009) also indicated similar convergence of ε with N_c.".

1. INTRODUCTION (page 11156)
19) Line 13: "more" should be removed Line 13: "due to that" is awkward, change this

<u>Answer</u>:
Line 13: The sentence was modified: "They suggested that continental clouds have smaller <r> and therefore, larger *ε*".

1. INTRODUCTION (page 11157)
20) Line 1-2: "relationship of the droplet concentration" should be "relationship between Nc"
Line 4: "Nc" should be "Nc" in italics and with a subscript "c"
Line 6: "affect" should be "affects"
Line 7: "for positive Nc-" should be "for a positive Nc-" with Nc in italics and with a subscript "c"
Line 9: ": : : and the surface precipitation" should be ": : :the surface precipitation"
Line 13: You did not previously introduce the abbreviation for cumulus (Cu). You need to do that first.
Line 16: "a most" should be "the most"
Line 27: ": : :and the relation between" should be ": : : and the relationship between"

Answer:
Lines 1-2: The revised sentence: “relationship between N_c”.

Line 4: “N_c” appears in the revised manuscript in italics and with a subscript "c".

Line 6: “affect” was replaced by “affects”.

Line 7: The sentence was changed to: “They concluded that the N_c–ε relationship (positive or negative change of ε with N_c) influences.”

Line 9: The sentence was changed to:
“Xie et al. (2013) suggested that for a positive N_c–ε relationship, the large-sized rain drops at high aerosol concentrations enhance the efficiency of the surface precipitation.”

Line 13: We removed the abbreviation “Cu” throughout the whole paper.

Line 16: “a most” was removed. The sentence was changed to: “Their results indicated that ε has a narrow range around ~0.25–0.35 during the mature stage of the cloud's lifetime (defined as the stage when the total water mass is around its maximum with only minor changes).”

Line 27: “and the relation between” was removed. The sentence was changed to:” In this study, we use detailed airborne measurements carried out near Istanbul, Turkey in June 2008, to explore ε in non-precipitating continental convective clouds under various conditions of aerosol loading”

21) 2. MEASUREMENTS AND INSTRUMENTATION (page 11158)
Line 4: “(CARI) was” should be “(CARI) project was”
Line 4-5: Avoid using the same work twice: “aimed at studying” and “as a feasibility study”
Line 13: Why did you choose the pre- and post- “frontal-passage” data. You need to justify this choice to frame your study and why it is different and contributes to the body of work relating to relative dispersion.
Line 15: “The upper panel of Fig. 1” should simply be “Figure 1a”
Line 20: Table1 needs to be expanded to include more information
Line 26: Was there no instrumentation on board to determine if there were ice crystals? A CIP perhaps?

Answer:
Line 4: “(CARI) was” was replaced by “(CARI) project was”.

Line 4-5: “The 2007–2008 Cloud and Aerosol Research in Istanbul (CARI) project was aimed at exploring cloud and precipitation characteristics as a feasibility study for cloud-seeding operations in the area of Istanbul (Teller et al., 2008). "

Line 13: This issue was addressed in details in the response to question 4 in the Major Comments above.

Line 15: Done

Line 20: Done

Line 26: This information was added into the text: “Cloud imaging probe (CIP) measurements carried out onboard the aircraft showed that the clouds did not contain ice hydrometeors”

22) 3. RESULTS (page 11160)
Line 3-4: you are speculating about the regeneration of the air pollution layer. You need to show evidence that this is the case
Line 28-29: English wording needs to be improved. This sentence is difficult to follow.

<u>Answer</u>:
Lines 3-4: This was addressed by our response to point #8 of the major revisions.

Lines 28-29: The sentence was revised: ”As can be seen in Fig. 2, the changes in σ and $<r>$ as a function of height above the cloud base (see the red and yellow lines in the figure) were similar for all clouds except cloud TRK3.”.

23) 3. RESULTS (page 11161)
Line 2: What do you mean by “are constrained within the cloud”
Line 3: “relation” should be relationship”
Line 15: “boundaries” could be replaced by “edges”
Line 10-17: English wording needs to be improved. This section is difficult to follow.
Line 18: You mention the “total number of data points” but these values can’t be seen in any figure, table or in the text. Include them in Table 1 or on the figures.
Line 24: “likely an artifact” – what do you mean by artifact, describe what you are referencing.

<u>Answer</u>:
Line 2: The sentence was revised for clarity: “This observation suggests that, except for TRK3, the relative dispersion value ($\varepsilon = \sigma/<r>$) is not sensitive to the vertical height above the cloud base. The reason for the exception in case TRK3 is discussed in Sect. 4”

Line 3: “relation” was replaced by "relationship”.

Line 15: We prefer to keep using "boundaries” in order to be consistent with other places for which this term is being used in the text.

Lines 10-17: This section was edited for clarity:
"The black lines in both figure panels represent the average values of ε, obtained for each of the 10 different bins, and sorted in the figure according to height (Fig. 3a) or

LWC (Fig. 3b). The error bars represent the 95% confidence interval for the mean ε. While it is clear that on average for each flight, the droplet concentration increases with LWC (see colors of the average ε points), the average relative dispersion falls into a narrow range and does not depend on LWC. Figure 4 is similar to Fig. 3, but is based only on measurements in the cloud boundaries where LWC and N_c are below the threshold values of 0.01 g kg^{-1} and 10 cm^{-3}, respectively. Figures 3 and 4 demonstrate that for both the inner cloud and its boundaries, the droplet concentration increases with LWC, while the average relative dispersion remains almost constant. ".

Line 18: The number of data points used in the analysis was added in Table 1 and figures 3-5 and 7.

Line 24: The sentence was modified in the revised manuscript:"It can also be noted that the trend for the TRK3 case is different. A clear decrease in ε is observed near the top of the cloud associated with higher LWC values. This issue will be further discussed in Section 4".

24) 4. DISCUSSION and SUMMARY (page 11162)
Line 25: You mention that the variance decreases significantly. What statistical test did you conduct to determine this?

<u>Answer</u>:
Line 25: Thank you for this comment. The reader is now referred to Fig.6 which demonstrates the decrease in ε variance with the increase in LWC and N_c. Statistically, fig. 6 demonstrates the convergence of ε with LWC and $N_{c.}$ by presenting the standard deviation of ε.

25) 4. DISCUSSION and SUMMARY (page 11163)
Line 1-5: English wording needs to be improved. This section is difficult to follow.
Line 10: "NC" should be "Nc" in italics and with a subscript "c"
L:ine 18-20: Why do you bring up the second indirect effect here? You don't really discuss it anywhere else. It seems out of place and like you're trying to fill up space.
Line 22: "values right" should be "values correctly"
Line 10-25: English wording needs to be improved. This section is difficult to follow.

<u>Answer</u>:
Lines 1-5 - The related section was edited for clarity and English style: The following sentence was added:
"Overall, the mean ε values vary in the range of 0.24 to 0.37. This is in agreement with previous studies which indicated that ε tends to be bounded in a similar narrow range in warm cumuli (Pandithurai et al., 2012; Berg et al., 2011), stratus clouds (Peng et al., 2007) and stratocumulus clouds (Pawlowska et al., 2006).

Line 10: “N_C” appears now in italics and with a subscript "c" (N_c).This notation is now used along the entire text

Lines 18-20: Thank you for this comment. The related section was edited, and we hope it is clear now why the second indirect effect is mentioned:

"However, Tas et al. (2012) also showed, using detailed microphysical model, that ε tends to be more scattered during the non-mature cloud development stages and for entrainment zones in the cloud, which are also associated with low LWC and N_c values. Above the threshold levels of N_c and LWC, ε showed fast convergence to average values. Deng et al. (2009) and Zhao et al. (2006) also indicated convergence of ε to a narrow range (0.4–0.5) with increasing N_c associated with higher pollution levels. Tas et al. (2012) showed that ε fits into a narrow range for the core of a cumulus cloud in its mature stage, and for high LWC. In the present study, we also observed convergence of ε with aerosol loading, which might be related to an increase in N_c, LWC, or both. Note that an increase in aerosol loading can lead to extension of the mature stage, as a result of the second indirect effect (Albrecht et al., 1989). Therefore, the convergence of ε due to either an increase in aerosol loading or an extension of the mature stage might be related to the same basic mechanism.”

Line 22: “values right” was replaced by “values correctly”.

Line 10-25: The related section was edited for clarity and English style.

26) 4. DISCUSSION and SUMMARY (page 11165)
Line 1: “analyze airplane” is awkward. Reword this sentence.

Answer:
Line 1: "“analyze airplane” was removed.

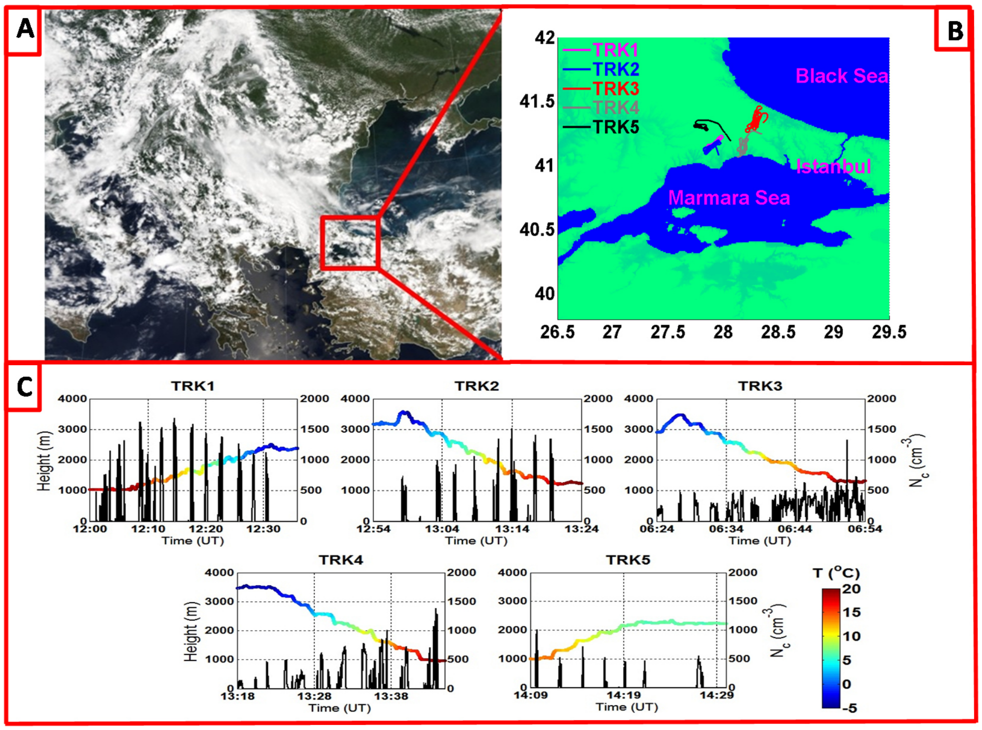


Fig. 1. (a) MODIS image of the Eastern Mediterranean region on 7 Jun 2008. (b) The tracks of the five flights. (c) A summary of flight profiles and cloud droplet concentration in airborne measurements carried out on 6–7 Jun 2008 around Istanbul, Turkey. Black line shows the droplet concentration and colored line shows the height above ground and the temperature.

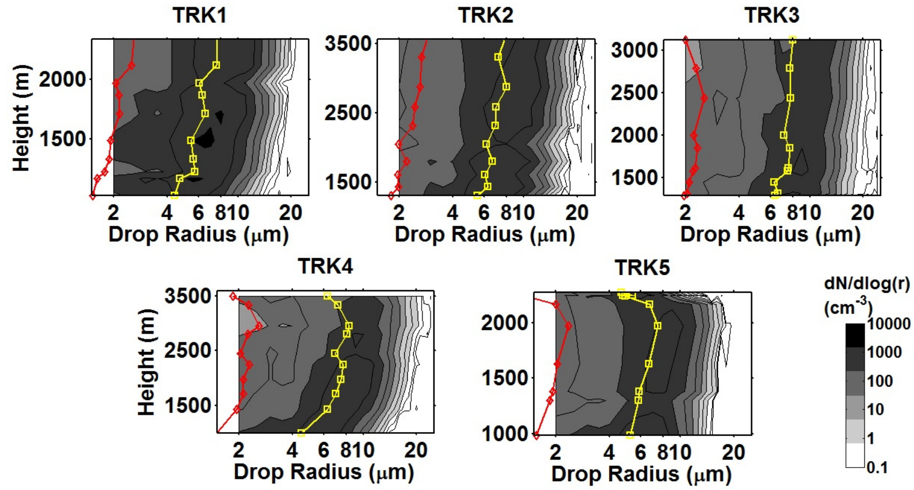


Fig. 2. Cloud droplet size distribution as a function of height above the ground. The contours show the distribution (dN/dlog(r)). The yellow and red lines represent the average and standard deviation of the radius over the entire measurements, respectively. For the purpose of constructing the lines of the average radius and the standard deviation, we divided the measurements into 10 height bins and for each bin the average was calculated. Note that the vertical axes are not uniform, accounting for the different cloud tops observed in the different flights.

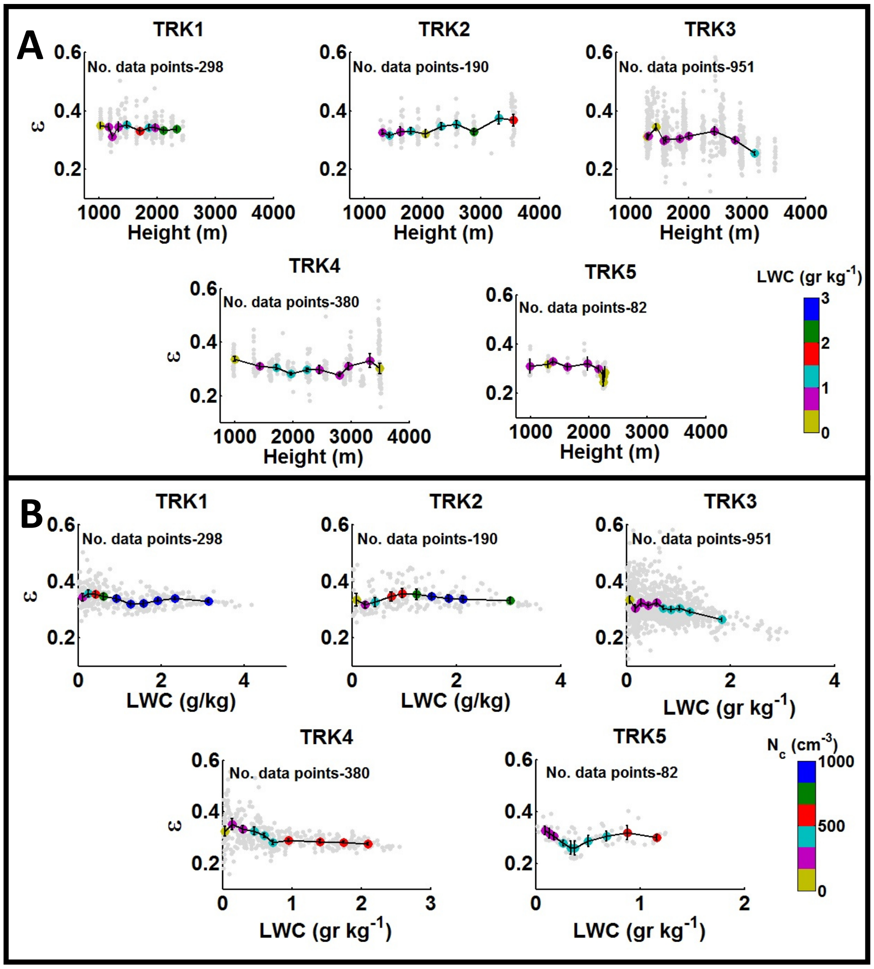


Fig. 3. (a) Relative dispersion (ε) vs. height above the ground with colors representing the liquid water content (LWC) and (b) ε vs. LWC with colors representing the droplet concentration for the inner cloud data points. Error bars represent standard error of the average ε for each height level (in a) and LWC (in b) with a confidence level of 95%.

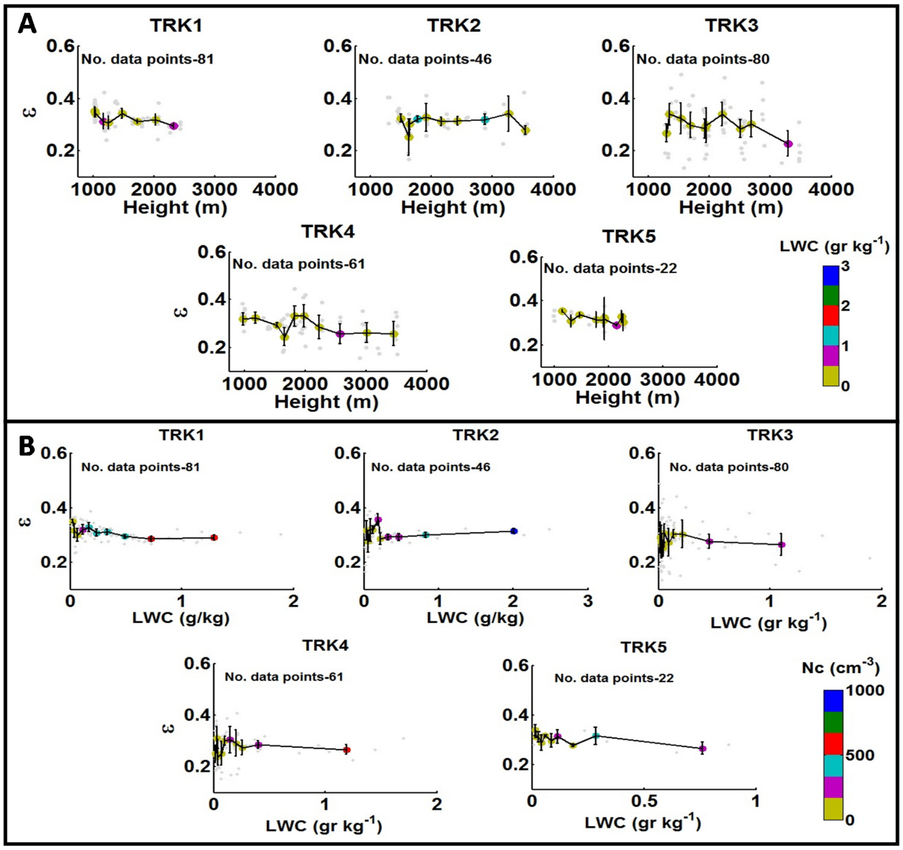


Fig. 4. (a) Relative dispersion (ε) vs. height above the ground with colors representing the liquid water content (LWC) and (b) ε vs. LWC with colors representing the droplet concentration for the cloud boundary data points. Error

bars represent the standard error of the average ε for each height level (in a) and LWC (in b) with a confidence level of 95%.

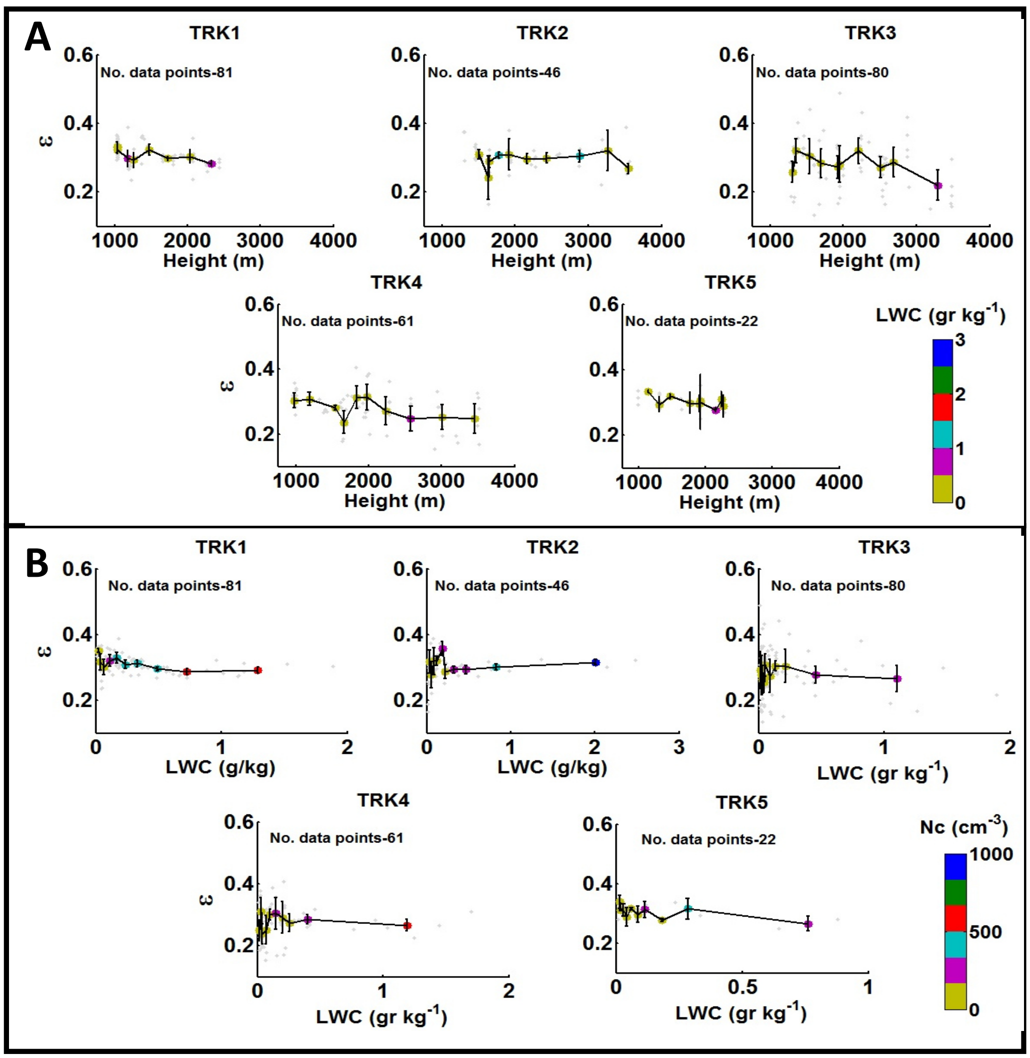


Fig. 5. Relative dispersion vs. average radius for (a) the inner cloud data, and (b) the cloud boundaries. Error bars represent the standard error of the average ε *for each <r> level with a confidence level of 95%.*

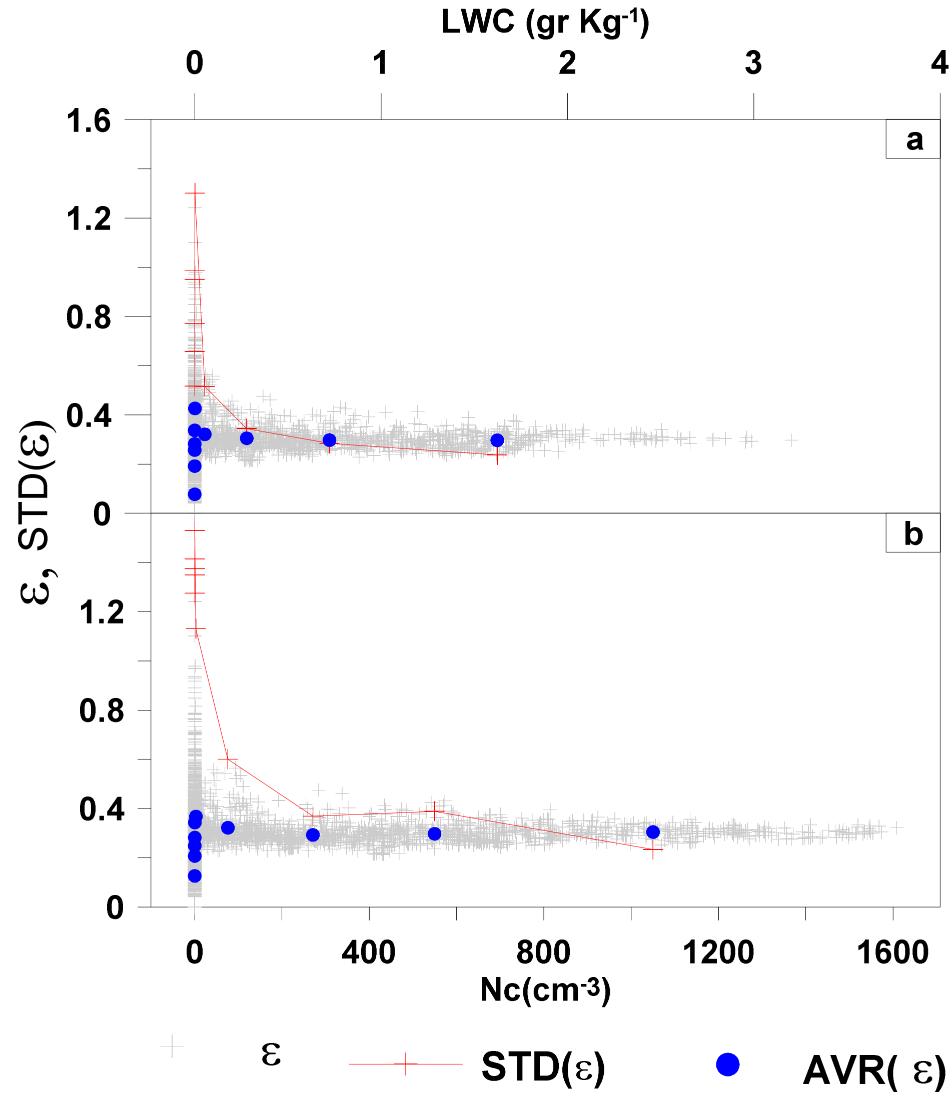


Fig. 6. Relative dispersion and its variance as a function of cloud liquid water content (LWC) and droplet number. Relative dispersion (ε), relative dispersion average (AVR(ε)) and relative dispersion variance (STD(ε)) are presented vs. LWC

(a) and Nc (b). AVR(ε) and (STD(ε)) are presented as the average values of 10 number-based size bins.

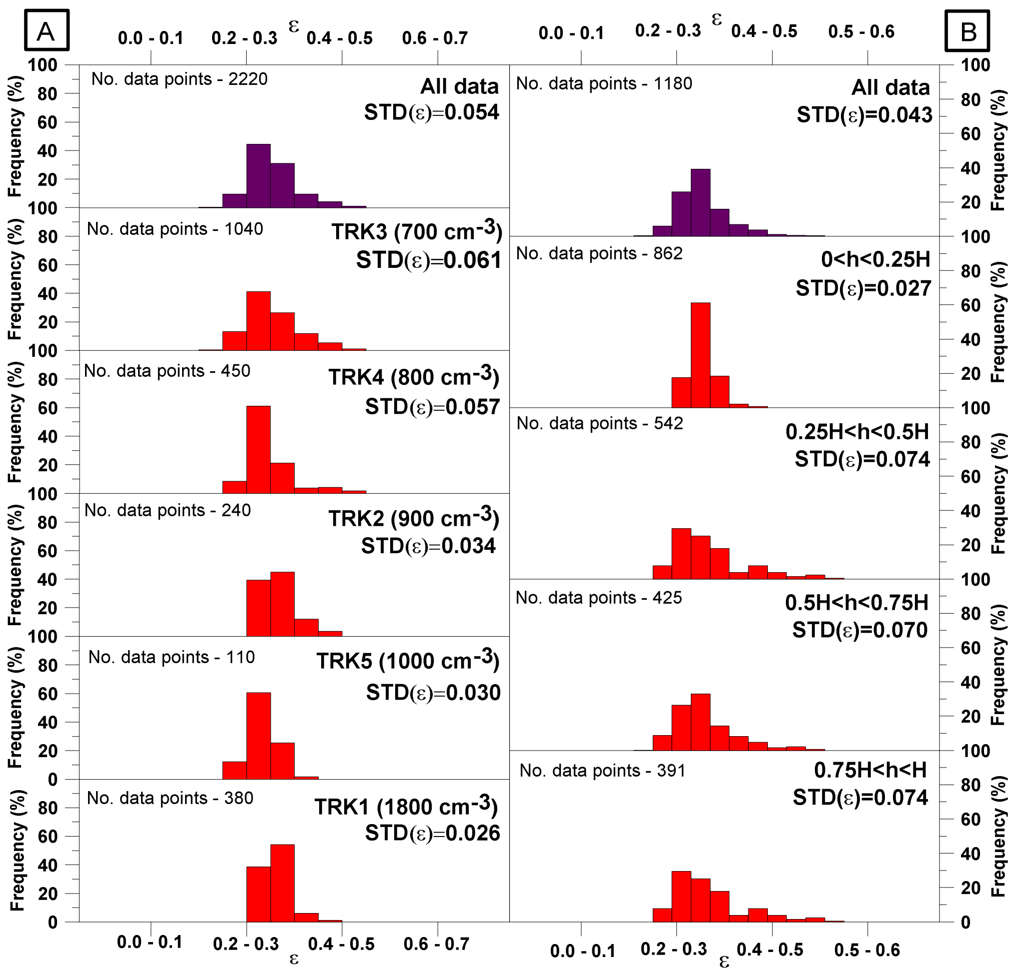


Figure 7. (a) Histograms of ε for different aerosol loadings. The average aerosol loading for each flight (calculated at cloud base height) is presented. All histograms are based only on measured data associated with N_c > 10 cm^{-3}. (b) Histogram of ε for different height ranges above the cloud base (indicated individually for each histogram by "h" range of the total cloud depth, "H"), excluding data collected

during flight TRK3. All histograms are based only on measured data associated with $N_c > 10$ cm^{-3}. The top panel (All data) is based on data collected during all flights. Data collected during flight TRK3 were not used for any of the histograms.