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Atmospheric Measurement Techniques Discussions

AMTD
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Interactive Comment

Interactive comment on "The scientific basis for a satellite mission to retrieve CCN concentrations and their impacts on convective clouds" *by* D. Rosenfeld et al.

D. Rosenfeld et al.

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We thank the reviewer for the constructive comments, which helped to improve the manuscript considerably. The original Reviewer's Comments are reproduced in *Italics* under heading of ***RC***. The The Author Responses are under the headings of **AR**.

RC: General remarks Rosenfeld et al. propose a way to retrieve cloud condensation nuclei number concentrations for convective clouds consisting of liquid water from satellite observations – a very challenging and interesting objective. A plenty of assumptions are necessary to perform this retrieval. This paper is intended as the scientific basis for a new satellite mission. It is thus expected that the retrieval methods laid out in this article will serve to produce the scientific data from the satellite should it be built and operated. This has two implications, namely (1) that it is likely a very important article, and highly relevant to AMT, but also (2) that is has to be a study carried out very soundly. By this, I particularly expect a very thorough error analysis, which the study currently still is lacking.

AR: We agree with the reviewer that this article does not include detailed error analysis. The objective of our article is to describe the scientific basis for the retrieval. Error analysis of the various steps necessary for retrieving CCN is described in other articles, for example Zinner et al. (2008) study the accuracy of the retrieval of re when accounting for the 3-D effect. Calculating just this single entity was a major study that was published in a 16-pages long article in ACP. Many other aspects require similar studies for meeting the requirement of a very thorough error analysis. But the motivation for such analyses, which each has the capacity to be a full fledged study and ad published article(s) on its own, has to come from a higher vision that integrates them all towards an objective that they will fulfill. Our article is aimed at providing this high level framework. We added a new section on the error calculations and their propagation from data and simulations that are presently available to us. We plan to do a much more detailed error analysis of the entire retrieval process if our project is funded. This will be a major undertaking.

***RC:** In the Introduction section, the authors describe many postulated aerosol effects on clouds in a way that the uninformed reader could consider them as textbook knowledge. A more cautious language is necessary.*

AR: We revised the introduction. Additional support and qualifications were added to the statements. See the changes in the text of the response to the specific comments.

***RC:** It should also be clarified in the Introduction section that reliable measurements of*

CCN(S) are just one – albeit certainly very important – contribution to a better understanding of aerosol-cloud-interactions. One could characterize it as a necessary, but not sufficient condition to solve the aerosol-cloud uncertainty problem.

AR: We agree with the reviewer. CCN(S) is now described now as a necessary component for disentangling the effects of aerosols from those of the green house gases on the Earth energy budget.

RC: *The manuscript is written in a very good English language, and the choice of Figures is appropriate.*

Section 9 is superfluous, and controversial. It should be deleted from the manuscript.

AR: We respectfully disagree with the reviewer. We have added a whole section to explain the importance and relevance of the text in question. Please see the added section here. Section 9 is now titled: **"Using the retrieved CCN and cloud properties for disentangling thermodynamics from aerosol effects**".

It is divided into two sub sections.

A new sub section titled **"Measurements of thermodynamic parameters that affect clouds"**, followed by the old Section 9 as a second sub section that is now titled **"The entangled roles of aerosols and meteorology in controlling clouds"**.

The text of the new first sub section reads:

"Clouds are affected primarily by thermodynamical conditions, which determine to a large extent where and when they form, their updraft speeds and vertical extent. Aerosols modulate the cloud properties by affecting the cloud droplet sizes and ice nucleation process, and in turn the rate of conversion of cloud water to hydrometeors, glaciation, latent heat release and evaporation. This, in turn, affects the cloud dynamics and feeds back to the meteorology.

Retrieving the CCN was described in the previous sections. In addition, the thermodynamic phase of the clouds can be retrieved by the method described by Martins et al. (2011), using the 2.1 and 2.3 μm wavebands. A number of parameters that are a manifestation of the cloud forcing can be measured by CHASER. Such parameters are:

a. The cloud vertical growth rate. This is a manifestation of the atmospheric instability and forcing. It can be obtained from the stereoscopic analysis of the MAI.

b. The sensible (Qh) and latent (Qe) surface heat fluxes. The magnitude and ratio between these fluxes (B= Qh / Qe) determine to a large extent the thermodynamic surface properties and cloud forcing. Over the ocean B is close to zero, whereas B is very large over land. B can be obtained from comparisons of the surface skin to surface air temperature, where the latter can be calculated using the dry adiabatic lapse rate extended from the cloud base to the surface. This can be retrieved because cloud base height, temperature and the surface temperature can all be retrieved by CHASER.

c. Vertical profile of the temperature and moisture. These properties can be retrieved from the vertical profiles of cloud surface temperature and the precipitable water above cloud elements at various heights.

d. Vertical profile of horizontal winds. This can be obtained from tracking with the MAI layer cloud elements, which can be confidently assumed not to grow vertically very fast, at various heights.

The essence of the difference between the land and ocean surface is the change in the sensible heat fluxes, relative humidity and respective cloud base height, and the resultant cloud base updrafts and organization, which in turn contribute to the difference between the maritime and continental clouds to an unknown extent. Having the measurements of both the aerosols and these thermodynamic properties, along with the relative humidity and cloud vertical motions aloft, will provide a dataset from which it will be possible to disentangle the effects of the aerosols from the other effects. The substantiation for this claim is provided in the next sub section, which shows the roles of both thermodynamic and aerosols in affecting clouds in a way that is difficult to separate."

RC: *Overall, I suggest the paper needs some substantial revisions before it can be published. Particularly, a thorough error assessment beyond the current "back-of envelope"- type of assessment is necessary. This in particular concerns also the algorithmic parts of the retrieval, and the validity of the assumptions. Specific questions for the error analysis An overall error assessment including the error propagation for each of the contributions to the overall retrieval error is necessary, and a special section on this is suggested. It has to consider the following points, in addition to what the study already provides:*

(i) Does the geometry allow for a unique detection of cloud base for each convective clouds?

AR: Viewing the cloud at an angle of 30 degrees from the zenith allows the cloud bases to be measured , unless they are tilted towards the satellite by an angle that approaches 30 degrees. The tilt angle can be identified by the multi-angle views.

RC: *Otherwise, how far apart do two clouds have to be in order to see the entire sides down to the cloud base? Is the retrieval biased by this?*

AR: This question can be answered by a simple geometrical calculation. One km deep clouds have to be at least 600 m apart for the retrieval to be possible. The cloud base and a piece of ground as its background, for a reference to the cloud base, needs to be observed.

The determination of the cloud base in the central view is assisted by the cloud temperature. The warmest cloudy pixels represent temperature just above cloud base. We must have cloud base height and temperature for making a retrieval.

RC: *(ii) The retrieval assumes that Na does not change above cloud base anymore. However, there are studies showing that this is not the case in convective clouds (e.g.*

Pinsky and Khain, Quart. J. Royal Meteorol. Soc, 2002). How important is this for the retrieval? Or can such cases be clearly separated from the ones for which the retrieval is valid?

AR: We do not assume that Na does not change above cloud base. We assume that variability in Na does not affect the deviation of re from the adiabatic re value substantially. The justification is given by Freud et al. (2011).

RC: *(iii) The retrieval relies on knowledge of the saturation water vapor mixing ratio, e.g., for the adiabatic liquid water mixing ratio in Eq. 1 (p 1328), for which the cloud-base value is necessary (and in addition the temperature profile within the cloud) and to correct for the homogeneous mixing. (a) how accurately is the temperature as a function of height retrieved? (b) what does this imply for the subsequent quantities?*

AR: It is sufficient to determine the cloud base temperature and pressure. The cloud base pressure is calculated based on the retrieved height, and has weak effect on the adiabatic water content (Freud et al, 2011). The cloud base temperature is retrieved to an accuracy of about 1 degree C. An inaccuracy of 1°C has very small impact on the adiabatic water in a cloud parcel. For example, an error of 1°C in cloud base temperature around 10°C incurs a same sign error of 3% in the adiabatic water at a height of 2 km above cloud base. Freud et al. (2011) have shown that the cloud vertical profile of r_e at the 100 m scale behaves as if the cloud is adiabatic. They also showed, based on a very large number of research flights at different parts of the world, that using these assumptions in clouds that heavily mix with dry ambient air can incur an overestimate of about 30% in the retrieved Na compared to the actual measured N_a. This overestimate can be addressed by additional algorithm development that will account for the ambient relative humidity, as retrieved based on the water vapor channel.

RC: *(iv) Cloud-base vertical velocity retrievals rely on the identification and tracking over time of protuberances at cloud edges at cloud base plus the assumption that* *their vertical displacement is equal to the updraft speed relevant for aerosol activation at cloud base. The error assessment has to consider (a) the ability to identify such features by automated algorithms at the base of each convective cloud, (b) the ability to uniquely track these over the curse of 1 min,*

AR: Exact quantification of the accuracy of this measurement requires a major study in which high resolution simulated clouds will be tracked by a simulated sensor, and the data will be processed through an algorithm that will track the features. This is a major separate study, which will hopefully be motivated by the present publication In the mean time, it is sufficient to recognize the trivial case of tracking the vertical growth of isolated small clouds. Almost any image of a field of boundary layer clouds has several such clouds, where the tracking does not represent a challenge. Therefore, the success of the methodology does not depend critically on the ability of tracking small protuberances in convective clouds.

***RC:** and (c) the link between the retrieved vertical displacement and the relevant updraft velocity for cloud-base activation.*

AR: Aircraft measurements in cumulus congestus showed that the rising rate of cloud tops is roughly 50

***RC:** (v) The retrieval of CCN as a function of size is dependent on the assumed κ values. How accurate are these assumptions for an individual retrieval?*

AR: With state-of-the-art global atmospheric chemistry and transport models, the average deviation between predicted and measured kappa values and CCN concentrations can usually be kept below 30% (e.g., Pringle et al., 2010; Spracklen et al., 2011). An error of 30% in κ leads to an error of only 10% in the critical particle diameter of CCN activation (Kreidenweis et al., 2009; Pöschl et al., 2009), and the actual influence of kappa on cloud droplet number is even smaller because of compensation effects between updraft velocity, aerosol hygroscopicity and water vapor supersaturation (Reutter et al., 2009). Field measurement data confirm that the prediction of CCN concentration depends much more strongly on the variability of aerosol particle concentration and size than on the variability of kappa (e.g., Gunthe et al., 2009; Rose et al. 2010, 2011). The accuracy of individual CCN retrievals will depend on the accuracy of the available aerosol measurement and modeling data, and will thus vary for different regions and atmospheric conditions. In any case, kappa is expected to be one of the least uncertain and least critical aerosol parameters.

RC: *Specific remarks*

p1318

l3: The statement, if kept in the revised version, needs to be clarified: For climate sensitivity, it is more the cloud feedback, not the cloud-mediated forcing, which is the uncertainty. However, if the total forcing was known quantitatively, one could infer the climate sensitivity from the observed warming record.

AR: The cloud feedback pertains to the response of the clouds to global temperature change. Here we address the cloud aerosol-mediated radiative forcing, which is recognized by the IPCC as the greatest source of uncertainty in quantifying the global radiative forcing.

RC: *l4: It should be specified that these are some of the outstanding issues. To name a few others, more challenging ones, in this context: we should know about IN, anthropogenic fraction of the aerosol, . . .*

AR: To address this concern, the wording of the first 4 lines of the abstract was slightly changed to:

"The cloud -mediated **aerosol** radiative forcing is widely recognized as the main source of uncertainty in our knowledge of the anthropogenic climate forcing and in our understanding of climate sensitivity."

The bold word was added.

RC:

p1319

l10: This is just one of the reasons for the uncertainty, among others.

AR: The shallow and deep clouds, including the expansion of their anvils to cirrus and moistening the upper troposphere, pretty much encompass the range of clouds and the possible effects of aerosols on them. This statement is not limited to the CCN effects.

RC: *The references Rosenfeld et al. (2012a) and Rosenfeld et al. (2012b) should be referred to in the opposite order.*

AR: We revised the article as suggested by the reviewer.

RC: *l18: The role of ice nuclei has to be mentioned here, too.*

AR: We mention ice nuclei in the revised article.

RC: *l23: This is a simplification. Entrainment-mixing may also enhance N_d, by enhancing N_a above cloud base, in certain conditions (e.g. Fridlind et al., Science 2004)*

AR: The text was revised as follows:

"The mixing with ambient air reduces N_a to N_d, as long as no new drops are nucleated. Such new nucleation can occur well above cloud base when cloud drops are depleted by conversion into precipitation and the supersaturation increases (Pinsky and Khain, 2002). This is rarely an issue in non-precipitating boundary layer clouds."

RC: *p1320*

l2: This is so far just a hypothesis, opposing effects have been postulated as well. l4: Rain forms eventually only if the thermodynamic conditions are appropriate.

AR: The text was revised to:

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"The dynamic response to the rain suppression lengthens the life-time and increases the cloud cover when suppressing precipitation in clouds, at least in the case of shallow heavily drizzling marine stratocumulus (Albrecht, 1989; Rosenfeld et al., 2006; Lebsock et al., 2008; Wang et al., 2011; Goren and Rosenfeld, 2012). In contrast, adding CCN to non precipitating clouds can enhance their evaporation and mixing with the ambient air due to the decrease in cloud drop size (e.g., Wood, 2007; Jiang et al., 2009; Chen et al. 2011)."

RC: *l5: Invigoration can occur only in certain situations. The hypothesis is formulated for clouds with liquid-water at the base, which reaches the freezing level.*

l6: This statement is based on hypotheses and should be reformulated with more caution.

AR: The text was revised to read:

"In deep convective clouds rain forms eventually, but the aerosol-induced delay in its formation to greater heights was shown to cause in some conditions cloud invigoration and additional electrification (Andreae et al., 2004; Rosenfeld et al., 2008, Yuan et al., 2011; Fan et al.,2012). The invigoration was shown to occur mainly for situations with weak wind shear and for clouds with warm base, in which there is large vertical distance between cloud base and the freezing level (Fan et al., 2009; Li et al., 2011). The aerosol-induced vertical growth and the consequent expansion of the anvils into cirrus was observed (Koren et al., 2010) and simulated (Fan et al., 2012) to inflict large positive radiative forcing, in contrast to the strong negative forcing that is caused by the aerosol effect on shallow clouds, at least in heavily drizzling marine stratocumulus (e.g., Albrecht, 1989)."

RC: *l15: The Rosenfeld and Bell (2011) study relies on statistics only and should not be taken as unequivocal evidence here.*

AR: This mechanism is supported by a recently published model simulations by Fan

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et al. (2012), which was motivated by the study of Rosenfeld and Bell (2011). The reference was added to the revised text.

RC: *l23: greenhouse in one word*

AR: We corrected the text.

RC: *p1321*

l1: quantities

AR: We corrected the text.

RC: *l6: Also simply because aerosols are currently usually not observed at all in cloudy skies (in some cases above the clouds, though).*

AR: The following text was added to the revised manuscript:

"Furthermore, aerosols in the cloudy boundary layers are often obscured by the clouds, so that there is no way to measure them directly regardless of these issues with the accuracy. This obviously occurs at the conditions where the importance for measuring them s greatest, because they interact with the clouds that obscure or distort their satellite view."

RC: *l15: Unfortunately, not just random, but also systematic errors such as the swelling or cloud contamination problems.*

AR: The text as amended as follows:

"As a result, the practice of relating retrieved cloud to retrieved aerosol properties is plagued by large errors in both parameters, which may cause both random errors and systematic biases."

RC: *P1323*

l5: velocities

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AR: Corrected.

RC: *l21: why extensive? Is a concentration not rather an intensive quantity?*

AR: In section 3 we show that the number of activated aerosols at cloud base, N_a, is a fundamental property that determines to a large extent the microstructure of the cloud as a whole.

RC: *p1325*

l19: in the tropical atmosphere

AR: We corrected the text.

RC: *p1326*

l3: the study by Painemal and Zuidema (J. Geophys. Res. 2011) shows that the retrieval works well at least in some cases

AR: Thanks for pointing this out. The following text was added:

"The retrieval of Nd worked well in several cases of extreme homogeneous marine stratocumulus, where these assumptions are closest to reality (Painemal and Zuidema, 2011)."

RC: *l4: larger*

AR: We corrected the text.

RC: *l20: does*

AR: We corrected the text.

RC: *p1327*

l17: on the other hand, retrievals at 3.7 μm will be representative really of the cloud sides, not cores

AR: Measurements do not show any evidence that clouds have larger adiabatic fraction and re at their core. See for example Figure 4.

RC: *l1328*

l1: the relative humidity necessary for the assessment is the RH really in the vicinity of the clouds. However, RH is highly variable spatially, and it is highly questionable to which accuracy it can be retrieved. An error analysis is necessary here in which the measurement error for the water vapor mixing ratio from the vertical change in precipitable water as function of height from the absorption, and the measurement error for the temperature and subsequently saturation water vapor mixing ratio are taken into account.

AR: Here again doing such study is a major undertaking, which we hope that the publication of this article will motivate. The following text was added:

"The accuracy of this method has not yet been determined, but it is expected to be much more accurate than the alternatives of forecast/reanalysis or derived by satellite inversion techniques (e.g., Singh and Bhatia, 2006 and the references therein), because in this method the clouds serve as reflectors at known heights within the range of interest. Furthermore, the ability to calculate many vertical profiles for the same cloud around its sunny side allows quantifying the local gradients and inhomogeneity of the moisture field."

RC: *p1329*

l8: however, temperature has to be known with extreme accuracy, since the saturation water vapor mixing ratio depends exponentially on temperature.

AR: The vertical profile of the temperature is obtained from the cloud top temperatures at the reflecting reference points.

RC: *p1331*

l3: The assumption that the rate of vertical displacement of a protuberance is equal to the updraft speed at cloud base is crucial for the retrieval and needs corroboration. (i) how reliable is the assumption that a protuberance moves at the in-cloud updraft speed? (ii) to which degree is the updraft speed at the cloud edge representative for the average updraft speed for the entire cloud base? (iii) how valid is the assumption that at each clouds' base a protuberance is identifiable by an automated algorithm, and (iv) how valid is the assumption that it maintains its unique shape over the time of 1 min?

AR: Exact quantification of the accuracy of such ability requires a major study in which high resolution simulated clouds will be tracked by a simulated sensor, and the data will be processed through an algorithm that will track the features. This is a major separate study, which will hopefully be motivated by the present publication In the mean time, it is sufficient to recognize the trivial case of tracking the vertical growth of isolated small clouds. Almost any image of a field of boundary layer clouds has several such clouds, where the tracking does not represent a challenge. Therefore, the success of the methodology does not depend critically on the ability of tracking small protuberances in convective clouds.

Aircraft measurements in cumulus congestus showed that the rising rate of cloud tops is roughly 50% of the peak updraft within the cloud several hundred m below the tops. (Blyth et al., 2005). Little is known presently on this question, but it is reasonable to expect a clear positive relation in clouds that grow due to surface heating of the boundary layer. We hope that such a study will also be motivated by our publication.

***RC:** p1333*

l21: This is a quite misleading statement. Table 2 in the cited paper (Pringle et al., 2010) shows an agreement to within ±0.05 only in 4 cases, in another 6 cases, the model value is within the observed range or up to 0.05 outside this range. More importantly, these are monthly mean values, whereas the algorithm would need accuracy for *individual cases.*

AR: See the response to point (v) of the general comments.

RC: *p1334*

l4: Period is missing.

AR: We corrected the text.

RC: *p1354*

Please write Kappa consistently as a Greek letter.

AR: We corrected the text.

AR: REFERENCES

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