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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.

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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 comments:*

The manuscript summarizes a cloud mission referred to as CHASER, which would

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consist of three cameras (VIS/NIR/SWIR/MWIR/IR) flying in a 1400 LT polar orbit and viewing off-nadir into the backscattered solar direction. The multiple cameras work like MISR to determine stereoscopic cloud height but at much higher spatial resolution (50m) as well as cloud effective radius and phase. The mission was "inspired" by the CLAIM-3D concept of Martins et al. (2007, 2011), Zinner et al. (2008), etc. Apparently, a manuscript on the CHASER mission has also been submitted to BAMS (Renno et al., 2012, in review). Perhaps the authors have informed the editor as to how this AMT manuscript differs from the BAMS submission. If not, I recommend this be discussed.

AR: The BAMS article discusses the mission as a whole. This manuscript discusses the scientific basis. The BAMS paper is already referenced in this context and the BAMS editor is aware of both manuscripts.

RC: *The science goal of the mission is highly relevant and I commend the authors for taking on important science questions via this passive imager approach. The paper is generally well-written but I have several major concerns on the suitability of the presented material for a measurement/technique journal. Largely, these come down to: (a) the lack of detail provided on mission science and measurement requirements, coupled with (b) a lack of significantly new science technique descriptions and/or validation. While the manuscript probably does provide a "scientific basis" for the mission as stated in the title, the quantitative link between the science (algorithms) and mission are not strong. I consider the manuscript not acceptable in its current form. Major comments/questions*

AR: While the techniques for measuring temperature, precipitable water and cloud particle effective radius are not new, combining them in high resolution measurements and analyzing the data in the new described way described in this article constitutes a breakthrough. In particular, it provides the scientific basis for assessing drop number concentrations of convective clouds and to estimate the CCN in the cloudy boundary layer.

RC: *1. What clouds?*

From the introduction: "The uncertainty in aerosol cloud-mediated radiative forcing is composed of two large and highly uncertain opposite effects from shallow and deep clouds (Rosenfeld et al., 2012b). This underlines the importance of conducting global measurements of the aerosol effects on clouds." But based on the title, the emphasis of the CHASER mission is on convective clouds, and from the microphysical retrieval discussion, it is about cloud tops/sides that are still in the liquid phase. Does the mission address "shallow" clouds? If so, what does shallow mean in the practical sense? The references to cloud sensitivity in the literature are largely concerned about shallow marine BL clouds. Does the mission address ice phase cloud properties or just the onset of the ice phase?

AR: The retrieval of CCN is based on the lower portion of the convective clouds, below the height of onset of precipitation, as stated in the text. Answering the question of the reviewer with respect to the sensitivity of different kinds is the objective of the mission. The mission will also retrieve the development of ice in the growing convective clouds, and relate them to the other observed cloud and thermodynamic properties.

RC: *2. Mission Details*

The authors don't have to show us mission proposal-level details but further information is needed. The manuscript would be strengthened by a list of instrument requirements, and nominal data products with expected uncertainties and sampling (and supporting text). I leave it to the editor to provide guidance on expectations for AMT for this type of article. Suggestions follow:

AR: This study is focused at the science of how to combine various retrieved properties into the stated objective, and thus describes the scientific basis for the paper that does describe the mission. The mission and measurement technique is discussed in a BAMS article by Renno et al (2012).

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The following text was added to the introduction:

"This paper introduces a new concept for retrieving from space microphysical and dynamical properties of convective clouds ad reconstructs from that the cloud condensation nuclei (CCN), the vertical motions of the cloud tops, and the height at which rain and cloud glaciations initiate. This will allow disentangling the effects of aerosols (CCN and ice nuclei) and meteorology (cloud vertical motion, temperatures and depth) impacts on the properties of the observed cloud and precipitation properties. A satellite mission for measuring the cloud properties is described in Renno et al. (2012). The full characterization of the cloud-aerosol-precipitation interactions can be achieved when combined with precipitation properties observed by other satellites or ground based measurements. Here we provide the scientific basis for these kinds of measurements from a space, showing the feasibility of what has been considered impossible until now."

RC: *2a. There are no instrument requirements other than Table 1 and brief text. Table 1 should include spatial resolution (abstract says 100m for re but Sect. 2, paragraph 2 only seems to mention 50 m). Is that pixel resolution for the center camera only or do the other cameras have higher spatial uncertainty to give identical FOV at cloud level?*

AR: The resolution is discussed in the text of the AMTD manuscript. Please find it in P1322 L1-14.

The statement that all channels of the MSI have a footprint of 100 m is included in the captions of Table 1.

RC: *Where did the spatial resolution come from for re retrieval requirements, i.e., reference for 1327, L7 (w.r.t. 1329, L24 – there is no Rosenfeld et al. 2004 in the reference list)?*

AR: Indeed the reference was missing, it is:

Rosenfeld D., E. Cattani, S. Melani, and V. Levizzani, 2004: Considerations on daylight

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operation of 1.6 μm vs 3.7 μm channel on NOAA and METOP Satellites. Bulletin of the American Meteorological Society. 85, 873-881.

***RC:** What are the cloud temperature retrieval requirements for the unspecified 3.7 μm r_e retrieval accuracy and RH requirements?*

AR: The following text was added:

9. Error calculations and their propagation

9.1 Retrieving errors in cloud drop effective radius

The sensitivity of the retrievals of re was tested by using the MODIS Airborn Simulator aircraft data near the southern tip of Florida on 28 July 2006, at a sensor zenith angle around 30° eastward of nadir, and solar zenith angle 35° westward of zenith. The surface footprint at this geometry was near 70 m.

An error of 1°K overestimate in brightness temperature of 3.7 μm incurs an error of 0.8 μm underestimate in r_e for r_e=14 μm. According to Table 1, an instrument measurement noise of NEDT of 0.2°K at the 3.7 μm channel would translate to added noise in r_e of 0.16 μm.

The error becomes larger at greater r_e and less at smaller r_e. An error of 1°K overestimate in brightness temperature of 10.7 μm brightness temperature incurs an error of 0.4 μm overestimate in r_e for re=14 μm. The error becomes slightly larger at smaller r_e. According to Table 1, an instrument measurement noise of NEDT of 0.1°K at the 10.7 μm channel would translate to added noise in r_e of 0.04 μm. An error of a factor of 1.1 overestimating the precipitable water above low cloud tops at 20°C over Florida during summer conditions incurs an error of about 0.6 μm underestimate in r_e for r_e=14 μm. The error increases slightly for larger r_e.

The accuracy of retrieval of water vapor above clouds by differential absorption near 0.9 μm was shown to be about 0.2 mm (Albert et al., 2001). The accuracy is expected to be much improved at the 1.2 μm waveband due to the greater absorption of vapor

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at that range.

According to Table 1. An overestimate error of 0.2 mm in the precipitable water incurs an underestimate error of about 0.5 in r_e for r_e=14 μm. The error decreases for smaller r_e.

The retrieval of r_e at 2.1 μm is free of errors incurred by temperature measurements and has 1/3 of the 3.7 μm error due to inaccuracies in precipitable water above cloud. While the retrieved errors of re of 2.2 μm are generally higher due to the smaller dependence on intervening vapor and the lack of need to separate the solar and thermal components of the radiation, the greater absorption at 3.7 μm (Mitchel, 2002) minimize the 3-dimensional effects in the convective cloud elements, thus improving the accuracy for small cloud elements and for small distances above cloud base. The solar reflectance of the same opaque cloud in the visible is calculated to be at 3.7 μm half of the 2.1 μm reflectance. In order for having negligible contribution from the underlying surface, the retrieved re at 3.7 μm of the smallest resolvable cloud depth of 100 m with r_e of 7 μm is negligibly affected from surface properties when its liquid water content exceeds 0.25 g m^{-3} (Rosenfeld et al., 2004). The required geometrical depth or water content of a cloud with similar r_e for having the same opacity at 2.1 μm is more than double. Therefore, an effort is made here to retrieve re in both wavelengths and use them in combination. The way by which they will be combined requires additional study.

RC: *Table 1 could also include delta time requirements. Can the S/N or NEdT requirements realistically (cost) be achieved at the required spatial resolution? What are the radiometric/spectral calibration accuracy requirements and how can they be achieved? These requirements ultimately come from the data product retrieval requirements.*

AR: Table 1 specifies now the SNR and NEdT. The instrument is very practical and has been already designed by DLR. The instrument is expected to achieve the required SNR and NEdT. It will be fabricated and calibrated at DLR-Berlin for a cost of about $20 millions.

RC: *2b. Data products: includes phase and re (Table 1), stereo heights are implied elsewhere and of course derived quantities. Anything else?*

AR: Table 1 is devoted to showing only the channels of the MSI.

RC: *2c. Uncertainties include the propagation of derived Na from re (re retrieval errors including 3D biases, entrainment/mixing assumptions, the re to r_v relationship, etc.), uncertainty in phase determination, derived updraft errors (presumably a function of updraft speed, temperature->height errors, along-track wind component), etc.*

AR: There is no issue with phase determination with respect to warm clouds.

The following text was added for calculating the propagation error into the calculation of the CCN:

"9.2 Error propagation in the calculation of CCN(S, d)

Freud et al. (2011) have shown based on aircraft measurements of vertical profiles of r_e and N_d that the assumption of an extreme inhomogeneous mixing results in systematic overestimate bias of N_a by a factor of about 1.3, when the cloud environment is dry, with RH of about 50%. Taking into account the actual RH in the vicinity of the cloud may allow decreasing this bias and its uncertainty, as the difference between homogeneous and inhomogeneous mixing vanishes towards a saturated atmosphere. An error of a factor e in the retrieved r_e would be amplified by e^3 in the calculated N_d. This means that an overestimate error of 1 μm for a cloud with r_e=15 μm would propagate to a bias error in N_a of (16/15)3=1.21. When this uncertainty is added to a similar error of about 20% due to deviations from the assumed mixing model, the error in Na grows to a factor of 1.45. The concentration of CCN can be obtained if the maximum vapor supersaturation at cloud base height, S, is known. This, in turn, can be obtain from cloud base updraft speed, which can be retrieved from very high resolution (50 m) dual stereoscopic images at oblique view of 30 degrees off nadir for the center camera. The analysis with the benefit of knowledge that cloud base is flat over a well mixed bound-

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ary layer can yield vertical motions w_b near cloud base with an accuracy of 0.2 – 0.5 m s^{-1}. A bias error of 20% in w_b causes S to be biased by 12% in the same direction. A 45% bias error in N_a causes S to be biased by 14% in the opposite direction. This allows the retrieval of the CCN(S) with an accuracy of 25%. In order to obtain CCN(S, d), where d is the aerosol particle diameter, the hygroscopicity growth parameter of the aerosol κ must be known. 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: *2d. Sampling issues as a function of lat/long include the narrow swath (100 km) coupled with cloud fraction and the frequency of higher clouds obscuring the lower developing convective clouds of interest. How does sampling inform how long the operational phase of the mission should be to achieve science objectives?*

AR: In this paper we focus on the scientific basis for retrieving CCN. The important question presented here by the reviewer is beyond the scope of this paper. All that we can do is fly it for at least 1 year and obtain global statistics that will allow answering many questions, including this one.

RC: *2e. Given the science objectives, I'm curious why next generation active mea-*

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surements (cloud radar, lidar) are not a core part of the mission concept? Is it just a question of cost? Technology? Please elaborate.

AR: Cloudsat and Calipso cannot inherently retrieve cloud drop effective radius and hence cannot address the CCN. A lidar is ineffective at obtaining CCN directly, especially in the cloudy boundary layer. The only part where radar could be helpful is in relating cloud drop effective radius to precipitation. TRMM has been excellent for that, and unfortunately the design of the GPM was crippled by excluding a high resolution vis/IR imager. Adding a radar to the mission would be obviously much desirable, but not absolutely necessary, because at many places surface radar measurements can be crossed with the satellite observations.

***RC:** 2f. What aircraft validation work do the authors feel should be done to support the mission, or be done before the mission moves to the development phase? Please discuss. I'm skeptical as to how such a mission would proceed without an aircraft simulator and intensive validation campaigns.*

AR: The estimates of accuracy should be refined based on simulations and validation against actual aircraft campaign that simulates the satellite measurements and provides in situ validation of the cloud and CCN properties.

Much can be achieved based on the MODIS Aircraft Simulator, which was used here already for assessing some of the errors involved in retrieving r_e.

***RC:** 3. With respect to comment 3, the larger question then remains as to whether the mission objectives have been achieved ("disentangling the effects of aerosol and [thermo/dynamics]", "a new concept to overcome these two challenges", "feasibility of what has been considered impossible until now", "significant advancement", etc.). It is not clear how these lofty objectives can be met with the mission. Given the fact that retrieval uncertainty requirements are not provided or mapped to science questions, there isn't much to go on with which to evaluate the likelihood of achieving mission success.*

AR: The following text was added to the beginning of Section 9 (now Section 10):

"Clouds are affected primarily by meteorological conditions, which determine to a large extent where and to a where clouds will form, their updraft speeds and vertical extent. Aerosols modulate the cloud properties by affecting the cloud drop sizes and ice nucleation process, and in turn the rate of conversion of cloud water to hydrometeor, 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 meteorological forcing can be also observed 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 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 growing vertically very fast, at various heights."

RC: *4. Much of the science of the manuscript reads as a review paper for the works of the authors. While the authors have made important contributions to cloud-aerosol interactions, surely there are more groups active in the field than references in some sections of the text would suggest. This is prevalent in certain parts (not all) of the manuscript and I don't think it requires elaboration. However one example that caught my attention was on p. 1320, L4, Rosenfeld et al. (2006) w.r.t. Sc cloud lifetime. This reference, put alongside the well-known Albrecht reference, refers to a "hypothesis" whereas there have been a number of detailed quantitative LES modeling and observational studies that have demonstrated the various sensitivities/complexities of Sc cloud-top entrainment for cloud evolution and lifetime.*

AR: A large number of references were added, as evident in the list of references at the ending of this Author Response.

The text reads now:

"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: *Other comments:*

5. Abstract refers to "the proposed satellite mission". For context, has the mission in fact been formally proposed to an agency?

AR: Yes. The status will be updated in the revised paper.

RC: *6. 1321, L17: I see the point, but rather simplistic. Depends on length of time*

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record relative to prescribed noise. Aerosol and cloud retrieval errors are not likely to be random as a function of cloud fraction.

AR: In such case a false correlation would be obtained, which is even worse.

RC: *L21: or might also be explained by hidden (non-retrieved) parameters.*

AR: This is true, but cannot be acted upon.

RC: *7. 1322, L8: According to Table 1, MAI has more than "visible" cameras.*

AR: The MAI is not shown in Table 1.

RC: *8. 1324, L5. The statement that "clouds mix nearly inhomogeneously" based on the 1989 reference is a key assumption in the use of r_e measurements near cloud boundaries as being representative for a Na derivation (the other assumption is the relationship between r_v and r_e). The authors then go on to show examples in Fig. 2-4 without providing a reference in the text. Perhaps the data are from Freud and Rosenfeld (2012) which is somewhat ambiguously cited in Fig. 2. Once again, the authors only cite their own work. As an alternate example, Burnet and Brenguier (JAS, 2007) looked at both convective and Sc clouds and, by my read, concluded that the entrainment situation is more complicated: "In summary, the three case studies presented here confirm that droplet spectra sampled in diluted cloud volumes show features intermediate between the two extreme scenarios [homogeneous vs. inhomogeneous]. This study also suggests that part of the inhomogeneous-like features observed in real clouds with single particle counters may be due to an artifact of the measurement technique, which also implies that the spatial heterogeneities of the droplet distribution in most of the mixed cloud volumes have scales smaller than 10 m. The examination of the buoyancy of the mixed parcels reveals that dynamical sorting could also play a role in the selection of the mixing scenarios."*

AR: The following text was added:

"Burnet and Brenguier (2007), based on aircraft measurements of at a sample rate of

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10 Hz, which provides a 10-m resolution in cloud, reported a state that is more intermediate between the two extreme mixing states, whereas Paluch and Baumgardner (1989) and Freud et al. (2011) used a sample rate of 1 Hz, or a scale of 100 path length in clouds. According to Lehmann et al (2009) mixing is expected to become more homogeneous at smaller scales. This apparent disagreement can be resolved when realizing that mixing goes to the homogeneous at the very small scales. Taking it to the limit, at the scale of the single drop the mixing by definition is homogeneous, as the drop must evaporate gradually and not vanish all of a sudden when exposed to dry air. But the satellite views the clouds at the 100 m scale, which is similar to the aircraft measurement scale at 1 Hz being about 100 m flight path. Therefore, the 100 m scale is the relevant one for the application to CHASER."

RC: *9. Section 4: Thermo/dynamic environment doesn't also control the onset of warm rain?*

AR: The thermodynamic environment determines where and when the clouds occur, but the CCN and updrafts control their microstructure and precipitation forming processes.

RC: *10. 1326, L17: A strong and important statement. References (or do they come later)?*

AR: References added.

RC: *11. 1327, L16: Inherently? Perhaps, but have the authors done a thorough error analysis that includes cloud temperature retrieval accuracy, round-trip atmospheric path absorption correction to the cloud element (at 3.7 and in IR channels), solar spectral irradiance at 3.7 μm,*

AR: Yes, we have done all these calculations, and reported the error analysis in what is now new Section 9, tittled "Error calculations and their propagation", as shown in a response to a previous comment above.

RC: *L25: Column water vapor from a 1130 nm channel is said to give RH near the cloud edge assuming enough measurements in the "cluster". Doesn't internal cloud scattering in that vapor band cause issues (refer to text regarding 1.6 and 2.1 μm)? This is what solar reflectance based A-band and water vapor retrievals of path absorption/cloud height have to deal with.*

AR: This is also addressed in the new Section 9.

RC: *12. 1330, L23: Don't understand how reducing spatial resolution to 50m reduces MISR-like derived height errors by an equivalent factor of 5. There are other MISR error sources besides FOV. What about the along-track wind component?*

AR: This component can be obtained by tracking cloud segments that are known to be at fixed height, such as convective cloud base, or features of layer cloud patches.

RC: *13. 1331, L3: Is this assumption validated in the literature?*

AR: This assumption is based on the mass continuity when cloud surface is close to cloud base.

RC: *14. 1332, L13: "Current" (this statement is new)? Certainly the κ factor includes the molecular information that goes back to Kohler theory (van't Hoff factor, molecular weights, etc.).*

AR: True, except for very large particles where the wetting effect is dominant. We do use the κ factor.

RC: *15. Section 9: I understand this text is trying to get at some of the important science questions of particular interest to the authors that might be answered in part with CHASER observations. But the review text doesn't make it obvious to me how well CHASER can resolve the issues, especially w.r.t. ice cloud and lightening since MAI imagery can't see through cirrus and ice cloud layers to allow correlations with water cloud Na, w_b. Presumably, statistical studies can peel back some layers of the entanglement, but the 1400 LT orbit will sample land and ocean at different parts of the*

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diurnal evolution.

AR: CHASER is planned to look at the side of the clouds. Therefore, strong vertical development will still allow chaser to document the clouds.

Section 9 (now 10) is rewritten to be tied more closely with the CHASER measurements.

AR: REFERENCES

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