Reply to the referees of "Competition between core and periphery-based processes in warm convective clouds – from invigoration to suppression"

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Before answering each and every point we would like to express our appreciation for the reviewers' dedication and efforts. We have done our best to answer all points in a detailed manner. The overall reply is rather long as it reflects our efforts to answer all of the questions and to make the paper clearer.

Trying to make this reply shorter we open it with a general part that can answer several of the reviewers' comments, following by a part of more specific answers, avoiding repetitions as much as possible.

General

On this ideal, theoretical study - Like in the case of other complex dynamical systems that are controlled by many processes and feedbacks we use a simplified model that contains only part of the processes in order to be able to start untying the complex interactions and understand which process is important when.

This study is all about the interplay between key processes and how this interplay is affected by key controlling parameters: aerosol loading, the inversion height and the RH outside the cloud that serves as the fuel for the entrainment.

As such it is an ideal, theoretical study that does not include the cloud field scale interactions as well as other factors that can add to the complexity such as wind shear. Moreover we are fully aware that the theoretical profiles are too smooth and that we may miss a thin mixed-phase layer in the case of the most developed clouds. Nevertheless, our model was tuned to include the key processes that enable to study the interplay between them. It shows that understanding the timing and competitions is critical on the way to the understanding of the overall effect. The ideas gained in this study should be later examined with more complex tools such as LES of a cloud field.

We clearly declare this study as theoretical and idealized at the end of the introduction: "*Here we used a single cloud model to study how changes in aerosol loading affect warm convective clouds at the process level, with a dependency on the environmental conditions. More specifically, we describe the evolution in time and the competition between key processes: condensation/evaporation, collision-coalescence, rain fallout, drag force and entrainment. A single cloud model might be quite simplistic in capturing the dynamic processes on the whole cloud scale and does not account for larger (cloud field) scales processes like self organization and effects of clouds on the environmental conditions with time (Lee et al., 2014; Seifert and Heus, 2013). However, the essential microphysical and dynamical processes affecting finer scales are well captured and are the focus of this study.*"

At the end of the summary part we discuss the need to further study synergism between the single-cloud scale processes described here to processes of in the field scale: "*There is a need to further study the synergism between the single-cloud scale processes (as described in this work) to the processes that act on the field scale. The overall aerosol effect on warm cloud fields would be a result of both types of processes.*"

On known processes - We are fully aware that some of the processes studied here such as the aerosol effect on condensation efficiency and on the delay in the onset of collection processes were defined and examined in the literature before. Here we study the interactions, competitions and synergism between them. In the paper we had to describe these processes as they are the building blocks of the interplay we study. Moreover, to show the strength of our model, this part in the paper provides a sanity check to show that the model can produce the expected (but far from being trivial) effects of aerosol on warm processes before we investigate the interactions and feedbacks between them. Throughout the revised manuscript we gave more references on previous studies that described some of the building blocks components that interact in this study. Examples appear in the answers below.

More specific points:

1) Missing definitions and the used notations. According to both of the reviewers' comments we added the revised text clear definitions of all the terms we use in the paper including core, periphery, invigoration and condensation efficiency. We uniformed the terminology used in the paper to be consistent. Details and examples of all the changes appear in the answers below.

2) Supplementary material was added to the paper for including some additional details on the methods and results without making the paper to long. So the interested reader will be able to find additional information on: (1) the aerosol size distributions used in the model simulations. (2) The maximal updrafts velocities in the different simulations as a function of aerosol loading. (3) Examples of the time evolution of the surface area to volume ratio (eta) for different clouds.

3) Additional graph describing the minimum of cloud's surface area to volume ratio (eta) as a function of aerosol loading in the simulation was added to the paper (as fig. 6). This graph gives further details about the insights this parameter provides.

4) The treatment of ice processes – as we stressed above we clearly declare this study as theoretical, idealized study that aims in understanding competition and synergism between in-cloud warm processes and their sensitivity to key environmental and microphysical properties. As such, we avoid dealing with cold processes and fields scale processes. As the size of the convective cloud matters to the effects we study, we want to explore the sensitivity of a wide range of clouds' sizes, from small to deep warm clouds. We are aware that our deepest profile (T1RH1) can theoretically allow the cloud to develop to the level of -10ºC that maybe can create a thin mix-phase layer. For the sake of clarity we have turned off all the cold processes in the model schemes and we did not consider them.

A clarification regarding this point was added to the revised methodology section: *"The idealized profiles enable examination of the aerosol effect on warm convective clouds under a large range of environmental conditions with minimum noise driven by local small scale perturbations in the temperature and humidity profiles that usually appear in real sounding data. In the deepest clouds cases the cloud's top temperature is around -10ºC; thus, there is a small likelihood that we neglect the formation of a thin mixed-phase layer. Because warm processes act as the initial and boundary conditions for mixed-phase processes in deep convective clouds, extending the examination of warm convective clouds to the boundary between warm to mix-phase clouds can improve the understanding of the effects of aerosol on deep convective clouds".*

5) The use of a weighted (by mass) average of the vertical velocity: in this paper we follow the vertical velocity trends because it is an important factor that controls the liquid droplets vertical displacement. As such we found that averaging it weighted by the liquid water mass represents best and in condensed way it's potential to affect the liquid water displacement. Moreover, we have seen that the maximum vertical velocity in the cloud (that is usually showed) can be sensitive to local fluctuations that do not necessarily represent the bulk cloud convection intensity whereas the averaged by mass velocity is more robust. Nevertheless, a figure presenting the maximum vertical velocity was added to the new supporting material (fig. S2) in order to give the reader this information as well. To make this point clearer we revised the text (in the results section): "*Figure 7 presents 3 clouds' properties for each simulation as a function of the aerosol concentration (each curve represents 10 simulations of specific profiles): (1) the maximum cloud top height per simulation (defined by the height level of 0.01 g/kg liquid water content, top panels), (2) the maximum (over the cloud's lifetime) of the mean cloud's updraft (middle panel). As vertical velocity serves as an important factor that controls the droplets vertical displacement, the average is weighted by the liquid water mass. The (non weighted) maximum vertical velocity (fig S2 in the supporting material) shows similar results but is more sensitive to local fluctuations of the velocity field".*

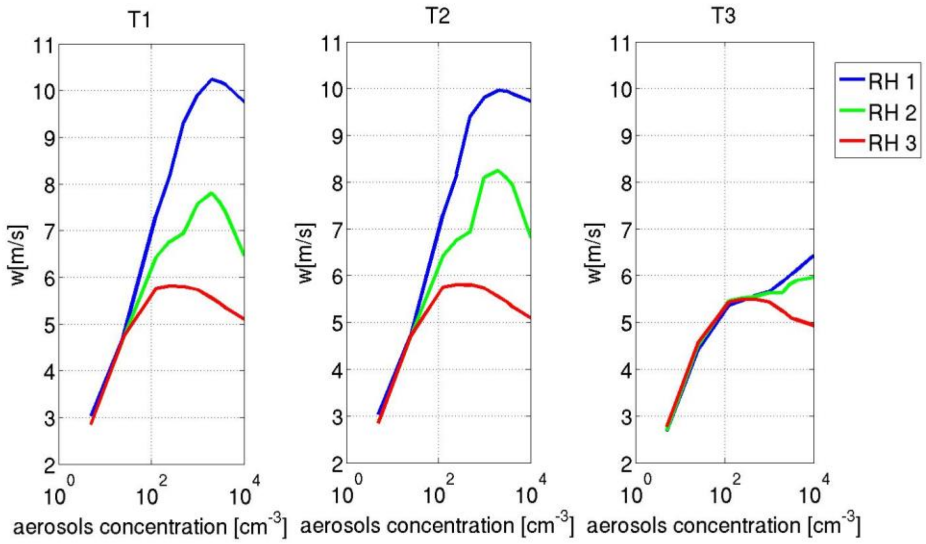

Figure 1 (S2 in the revised paper). cloud maximum vertical velocity as a function of the aerosol loading, for each simulated cloud as a function of the aerosol concentration used in the simulation. Each curve represents 10 simulations performed for an initialization profile (a total of 9 profiles).

A point-by-point replay to Reviewer 1

General comments

1) This is a basic study for idealized modeling simulations of aerosol effects on shallow cumulus clouds. Most of the findings in the paper (such as increased condensation with aerosol concentration due to larger surface area; delay of collision processes due to smaller droplet sizes, etc) have been well established and I do not think this study provides significant progress in this area. That say, I do not understand the motivation of the study.

Authors reply: Increase in condensation efficiency and delay of collision processes are indeed known and we provide references to show it (more so in the revised version). As explained above this work studies the synergism and competition between such key processes. We study what is the overall result of such processes acting together but with a different magnitude that depends on the location within the cloud and on the cloud's age. We show that location and timing of processes can make the whole difference in the overall results. Moreover, we show great sensitivity to key thermodynamic parameters and how they affect the cloud for different aerosol loadings. Finally the results of this study helps in bridging the gap between a long lasting discrepancies of observation and numerical modeling studies that showed contradicting results. Since modeling studies are biased to small warm clouds and observations to large, the change in the overall trend and the concept of optimal aerosol concentration per given thermodynamic conditions provides an explanation to the reason models suggest suppression and observations suggest invigoration.

The new text added to the introduction*: "The sensitivity of deep convective clouds and precipitation to aerosol properties were shown to depend on the environmental conditions (Seifert and Beheng, 2006;Khain et al., 2008;Lee et al., 2008;Fan et al., 2009).*

Seifert and Beheng, (2006) studied the role of vertical wind shear and the convective available potential energy (CAPE) in modulating the clouds' maximum vertical velocity and the surface precipitation amount. For higher CAPE values and lower vertical wind shear conditions, higher aerosol loading resulted in clouds' invigoration. Low CAPE values and strong wind shear resulted in clouds suppression by aerosols. Fan et al., (2009) have shown that for deep convective clouds, under strong wind shear conditions the increase in evaporative cooling due to the increase in aerosol loading is larger than the change in condensational heating and so resulted in cloud suppression. Under weak wind shear and relatively clean conditions, the increase in condensational heating can be larger as aerosols loading increase, and lead to cloud invigoration. This trend continues up to an optimal aerosol concentration for which additional increase in aerosol loading can lead to cloud suppression".

We also added the revised summary clarification about the focus of this work on warm convective clouds:

"Optimal aerosol concentrations were discussed before in the context of precipitation susceptibility (Jiang et al, 2010) and sensitivity to wind shear conditions for deep convective clouds (Fan et al., 2009). In this work the focus is on warm convective clouds with a detailed description of the competition between all the processes involved under different environmental conditions."

2) Second, the methodology may have problems.

(a) The sharp changes as shown in Figure 1 in the dew point temperature may have a problem. Also, it does not look realistic at all.

(b) The RH of 95% and 90% is too high. This kind of condition is not a usual environment for forming convective clouds. 70%-80% of RH already represents very humid environment.

(c) Strong warm bubble initialization (3°C) and without ice processes: for clouds with an inversion layer, this kind of initialization is very unrealistic. Such a strong warm bubble initialization under an extremely high RH environment would lead to very strong convection leading to deep convective clouds. But the authors used an inversion layer to limit the cloud vertical development and also turned off the ice microphysical processes to force a warm cloud. In reality, it would not happen in this way (likely it would be deep convection with mixed-phase and ice phase processes). Radom perturbation would be recommended to do shallow cumulus clouds.

Authors reply: As we explained above, this study presents a theoretical sensitivity study of interplay between key processes on the cloud scale. As such, to make it as clear as possible we use idealized initialization profiles. To avoid the usage of a specific profile of a certain day and location we kept the profiles as general as possible with a subcloud mixed layer, a conditionally unstable and very humid cloudy layer and an overlaying inversion layer. Such profiles were characterized in accordance to the general features of tropical profiles (Garstang and Betts, 1974). We changed the profiles by controlling two factors: the height of the inversion layer (which has a strong effect on the cloud's thickness) and to demonstrate the competition between adiabatic processes and entrainment we changed the entrainment fuel (e.g. RH outside the cloud).

The usage of less realistic values of parameters is often done in modeling studies in order to separate the effects of different processes. Indeed RH levels of 95% in the cloudy layer may be considered as high values, but it practically enables strong reduction of the entrainment role. Therefore it enables an understanding of the balance between the adiabatic and the entrainment parts. Again it can be viewed as an extreme value used in a theoretical study.

We better stress this point in the revised methods section: "*The idealized profiles enable examination of the aerosol effect on warm convective clouds under a large range of environmental conditions (including very high RH values). It also minimizes the noise driven by local small scale perturbations in the temperature and humidity profiles that usually appear in real sounding data*".

And it is pointed out in the summary section as well: "*The dependency of N_{op} on the thermodynamic conditions was examined (over a wide range of environmental conditions including for example very humid environment that weakens the entrainment role).*"

As for the initialization of the convection: using an LES-like random perturbation would initiate many clouds in the domain and not only one cloud. This is suitable for a cloud field with a large statistics of clouds. In a single cloud model it is preferable to use a uniform perturbation for all runs in order to produce similar initial convection at the sub cloud layer for all the simulated clouds. Then, the differences between the clouds are not driven by the differences in the initiating bubble. The size of the bubble in our simulations is only one grid point so even though its magnitude is 3^{o}c its total energy is small.

3) Third, the paper is not clearly written. They created many phrases but they are not well defined and consistently used. See below:

From the title and throughout the paper, the authors use phrases like "core process", "periphery- based process", "margins' effect", and "margins' processes" but they were never clearly defined. In fact, they are only about condensation (they mean core process) and evaporation/entrainment processes (they mean margins' processes but at least three different terms were created for this) in this study. I do not understand why not sticking with physical terminologies in a scientific paper? Creating fancy terminologies may be good for general public which is not the purpose of ACP journal. It only creates confusions for scientists in this area. It is not necessary at all for this study since the involved processes are simple.

<u>Authors reply</u>: We agree with the reviewer that better definitions are required. Based on this comment the terminology in the paper was changed and clear definitions were implemented into the revised text. We unified phrases that represent the same thing to be identical along the whole paper – now we use only the terms core processes and periphery-based processes. We define them in a clear way in the results section of the revised version: "*Similarly, throughout this paper, the cloud core is defined as the part under supersaturation conditions, while the cloud periphery is the part under subsaturation (Wang et al., 2009). This definition determines the dominant processes in each of these regions in the cloud; the core is dominated by condensation and the periphery by evaporation and entrainment."*

- **Define cloud invigoration: looks like you meant enhanced condensed water here. However, for deep convective clouds, it refers to the enhanced convection or precipitation many times. To avoid confusion with cloud invigoration for deep convective clouds, I'd suggest using cloud mass enhancement/suppression instead of cloud invigoration/suppression.**

<u>Authors reply</u>: Cloud invigoration by aerosols is the outcome of series of feedbacks that are based on the coupling between microphysics and dynamics. Unlike the aerosol effect on the droplets size distribution that is more direct and easy to measure, invigoration can be manifested in several connected ways such as deeper clouds and/or cloud with larger water mass and/or stronger updrafts. Important part of what we show in this paper is that invigoration plays a role also in warm convective clouds. Following this and the above comments the most appropriate and direct measure for invigoration in a modeling study is indeed the total cloud mass.

We added a clear definition in the introduction: "*These microphysical processes were suggested to be coupled to dynamical ones and in the case of convective clouds to form the baseline for the invigoration effect in which high aerosol loading leads to larger and deeper clouds with larger water mass (Andreae et al., 2004; Koren et al., 2005; Rosenfeld et al., 2008; Tao et al., 2012; Fan et al., 2013). Surface rain, as the end result of all the cloud's feedbacks, was shown to be affected by changes in aerosol loading as well (Levin and Cotton, 2009; Khain, 2009; Koren et al., 2012).*

Unlike the straightforward physical basis of the Twomey effect, in which for a given amount of LWC, an increase in the aerosol loading increases the amount of cloud droplets and therefore reduces the droplets average size (and increases the cloud's reflectivity, Twomey, 1977). Invigoration is the outcome of a series of feedbacks that are all a result of the aerosol-imposed changes on the droplets initial size distribution (Altaratz et al, 2014). As such, the invigoration effect can be expressed in several different forms such as an increase in the cloud total mass, or an increase in the cloud's depth and area (Koren et al., 2005; Rosenfeld et al., 2008; Tao et al., 2012). In this work we use the cloud's total mass as the main measure for cloud invigoration."

- **You have at least three types of Nop: for cloud mass, for surface rain, and for cloud top height. It is currently written in a confusing way. Please be clear about it throughout the paper. Also, the existence of an optimal aerosol Concentration is not new. Although past studies may have not clearly pointed out that the optimal aerosol concentration increases as RH increases and clouds get deeper for shallow clouds, it is something that is easily inferred. Even if this is new, is it enough to make a paper in ACP? I will leave the question to the editor.**

Authors reply: Thank you for this comment. As elaborated in details above, N_{op} is not the only new topic of this paper. The essence is all about the interplay between processes which make this paper basic and important in our opinion. Specifically about N_{op}, that shown an optimal aerosol concentration and the way it depends on cloud size and environmental conditions for warm convective clouds. It helps bridge the gap between previous works that showed a variety of different results.
N_{op} is clearly defined as the optimal N with respect to the cloud liquid mass in the results section as: *"We defined here the optimal aerosol concentration (N_{op}) as the concentration that is associated with the simulated cloud that has the largest maximum total liquid water mass per profile."*
The aerosol concentrations that correspond to the maximal surface rain, mean vertical velocity and cloud top height are not marked as *(N_{op})* and they are compared to its value: *"For the three cloud features shown, the optimal concentration per atmospheric profile is at a slightly higher aerosol loading compared with the N_{op}*

value, which was defined as the optimum aerosol concentration for the maximum in the total mass."

4) Fourth, the study has a narrow literature survey. The papers cited on aerosol impacts on shallow clouds are mainly from one group. Many studies in the same area especially these that have the same findings are not cited. Recommend a thorough literature study and understand what has been done already. As stated above, the findings of this study are not new.

Authors reply: Thank you for this comment. As we answered above the basic interplay between key processes and the change in trend as a function of the environmental conditions is the essence of the paper. Following this comment we redid a literature survey and to the best of our knowledge this study is basic, important and novel. Following this recommendation and to make the papers point clearer a detailed review of additional previous works was added to the introduction part of the revised paper. The additional studies that focused on warm clouds: *"Dey et al., (2011) showed that over the Indian Ocean cloud fraction increases with the increase in aerosol optical depth while changing from clean to slightly polluted conditions, and then followed by a decrease in cloud fraction for higher pollution levels. Those observations were explained by the semi direct effect (absorbing aerosols) that stabilizes the lower atmosphere. Costantino and Bréon, (2013) studied warm clouds over the south-eastern Atlantic and found higher cloud fraction for increased aerosol loading."*

And: *"Jiang et al., (2010) found a monotonic decrease in precipitation with the increase in aerosol loading. They demonstrated a non-monotonic change in the derivative of the surface rain rate with aerosol loading (determined as susceptibility) for clouds with higher maximal liquid water path. Seigel, (2014) showed that under polluted conditions cloud and cloud-core size decrease. The shrinking of the polluted clouds was explained by enhanced entrainment-driven evaporation at the cloud margins. He also showed that the clouds' core vertical velocity is higher under polluted conditions."*

As stated above, for completeness we have added more references on deep convective clouds (in the introduction): "*"The sensitivity of deep convective clouds and precipitation to aerosol properties were shown to depend on the environmental conditions (Seifert and Beheng, 2006;Khain et al., 2008;Lee et al., 2008;Fan et al., 2009).*

Seifert and Beheng, (2006) studied the role of vertical wind shear and the convective available potential energy (CAPE) in modulating the clouds' maximum vertical velocity and the surface precipitation amount. For higher CAPE values and lower vertical wind shear conditions, higher aerosol loading resulted in clouds' invigoration. Low CAPE values and strong wind shear resulted in clouds suppression by aerosols. Fan et al., (2009) have shown that for deep convective clouds, under strong wind shear conditions the increase in evaporative cooling due to the increase in aerosol loading is larger than the change in condensational heating and so resulted in cloud suppression. Under weak wind shear and relatively clean conditions, the increase in condensational heating can be larger as aerosols loading increase, and lead to cloud invigoration. This trend continues up to an optimal aerosol concentration for which additional increase in aerosol loading can lead to cloud suppression".

Specific comments

P23559:

5) Methodology: Is it a 2-D or 3-D model used for simulations? What is binary breakup?

Authors reply: The model used for the simulation is an axisymmetric model which is a 1.5-D model. A clarification about this point was added to the revised version: *"We used the Tel Aviv University axisymmetric (1.5-D) nonhydrostatic cloud model (TAU-CM) with a detailed treatment of cloud microphysics".*

Binary breakup is the process that describes the breakup of drops after collision, which was shown to be the significant process (compared to the spontaneous breakup) in governing the large drops size evolution (McTaggart-Cowan and List, 1975;Low and List, 1982). Those references were added to the revised version: *"The warm* *microphysical processes included are nucleation of CCN, condensation and evaporation, collision-coalescence, binary breakup (Low and List, 1982; McTaggart-Cowan and List, 1975), and sedimentation."*

P23560:

6) Provide a figure for size distributions of maritime and anthropogenic pollution.

<u>Authors reply</u>: Thank you for this comment. A figure presenting the background marine size distribution and two examples of polluted size distributions (1000 and 10000 cm^{-3}) was added to the supplementary material of the revised paper (shown below). The text that was added to the revised version of the paper: *"(a figure of the background maritime aerosol size distribution and two examples of polluted size distribution are given in the supplementary material, fig. S1)"*.

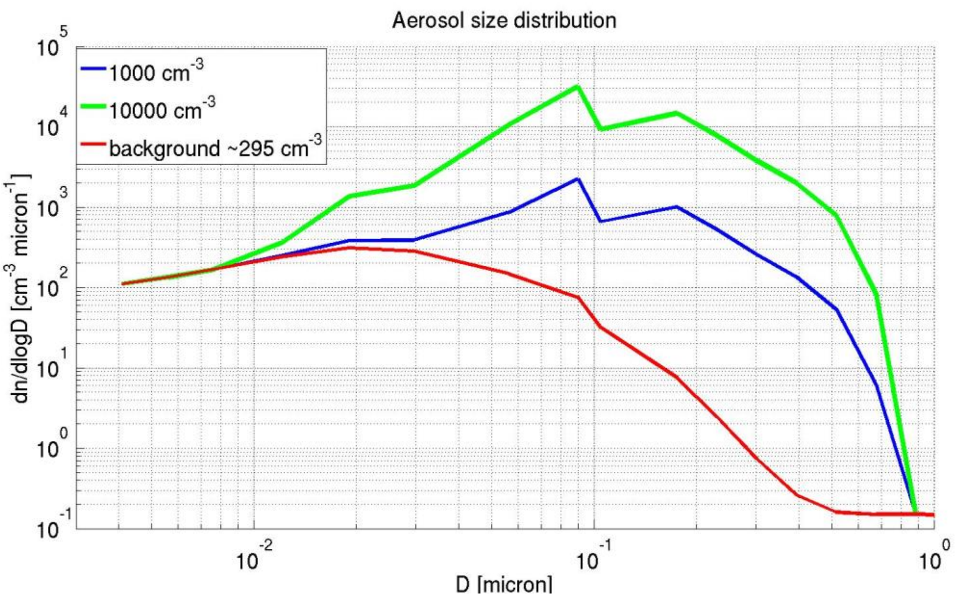

Figure 2 (S1 in the supplementary material). Maritime background (red curve) and two examples of polluted aerosol size distribution: 1000 cm^{-3} blue curve and 10000 cm^{-3} green curve.

P23561:

7) Line 8-10, very confusing sentence.

<u>Authors reply</u>: The sentence was changed in the revised version: *"In each of the curves (that represent 10 simulations done for different aerosol loading values, using one initialization profile) the maximum total cloud mass increases with the increase in aerosol loading until a maximum point. Additional increase in aerosol loading above this maximum value results in smaller maximal mass of the simulated clouds."*

P23562:

8) "Difference in the total condensed mass are due to increased efficiency of the condensation process and the delay in the collision-coalescence process, in the polluted cloud"– well established already. Need discussion of this.

<u>Authors reply</u>: Thank you for this comment. We are aware that this is well established. As explained above the essence of this work is timing and competition between key processes. More references of previous works that showed it before were added to the revised version: *"In agreement with previous studies (Khain et al., 2005; Reutter et al., 2009; Pinsky et al., 2013; Koren et al., 2014) difference in the total condensed mass are due to increased efficiency of the condensation process (consuming the supersaturation in shorter time) and the delay in the collision-coalescence process, in the polluted cloud".*

9) Last paragraph, about larger surface area leading to stronger condensation in the polluted clouds – well established.

<u>Authors reply</u>: Please see our long answers above. We are not attributing it to this study. We cite now previous studies that studied it: "*The condensation efficiency is determined by the droplets' surface area (Pinsky et al., 2013; Seiki and Nakajima, 2014)*".

10) Line 19-20: I did not see this significantly. Condensation growth stops at 70 min in all three cases. Also, why does condensation have negative value?
I think evaporation is included, then the Figure legend needs to be changed.

<u>Authors reply</u>: It is true that the condensational growth stops more or less at the same time in all three cases (at t~70min) but the collision-coalescence at the clean cloud becomes significant before the end of the condensational growth stage and so reduces the droplet surface area and the condensation efficiency. In order to make it clearer we added the revised version clarification about this point: *"In all of those clouds the condensational growth stage ends more or less at the same time (t=70 min) but in the clean cloud the collision-coalescence becomes significant earlier, before the end of the condensational growth stage and so reduces the droplet surface area and the condensation efficiency"*.

In the revised version the figure legend was change from "condensation" to "condensation-evaporation".

11) P23563: nothing new and main points are well established.

<u>Authors reply</u>: We hope that following this long reply and additional focusing of the paper it is clear that we are not attributing these points to this paper. This paper presents the chain of events and competition between processes in warm clouds as impacted by changes in aerosol loading and as a function of the environmental conditions. We need to describe all the processes and the link between them in order to create the base for the complete description of the reversal trend in clouds response to the change in aerosol loading.

Moreover, to show the strength of our model, it provides a sanity check that the model can produce the expected but far from being trivial effects of aerosol on warm processes before we integrate everything together. Based on this comment in order to refer better to previous works in this field we added more references to the revised text: *"The mean radius is larger and the size distribution is wider for the clean case so the droplets reach the critical size for collisions rapidly (Freud and Rosenfeld, 2012) and the collision-coalescence process becomes significant almost immediately after the condensation start (Khain et al., 2005). The early initiation of the collision-coalescence process acts as a positive feedback for this aerosol effect on the condensed mass and further reduces the droplets' surface area (fig. 4). The less effective condensation prevents the clean clouds from consuming more of the available supersaturation (Pinsky et al., 2013; Seiki and Nakajima, 2014). The condensation peaks at 56 min of simulation for the T1RH1_125 clean cloud (with*

2.4% mean supersaturation in the supersaturated region in the cloud), compared with 78 min (with 0.05% mean supersaturation) in the T1RH1_4000 case. On the same note, the early initiation of the collision-coalescence process in the clean cloud also drives an early start of the rainout from the cloud. The early rainout leads to mass transfer downward and therefore an increased drag force (that is proportional to the liquid water mass, Rogers and Yau, 1989) at the lower part of the cloud that further impedes the cloud's development (Khain et al., 2005)."

P23564:

12) Lines 17-19: please present updraft velocity in clouds. I do not understand the means of the weighted updraft velocity presented in Figure 6

Authors reply: Please see the detailed answer about this issue in the reply to the general comment no. 5 above. The weighted updraft velocity presented in figure 6 represents better in our opinion the cloud's convection strength. It measures the contribution of each grid point to the weighted updraft velocity according to its mass. The maximum vertical velocity can be affected by local fluctuations that don't necessarily represent well the whole cloud. A figure that presents the maximum vertical velocity during the cloud evolution was added to the supporting material (Fig. 1 in this document and Fig. S2 in the supporting material).

13) Line 26: how do you define cloud margins and core?

Authors reply: A definition was added to the revised results: "*Similarly, throughout this paper, the cloud core is defined as the part under supersaturation conditions, while the cloud periphery is the part under subsaturation (Wang et al., 2009). This definition determines the dominant processes in each of these regions in the cloud; the core is dominated by condensation and the periphery by evaporation and entrainment.*"

14) Figure 6:

Nothing is sensitive to RH when the inversion height is at 2 km, even for surface precipitation, which is hard to believe. This could be related to the problems that I pointed out for methodology. Need explanations how it is happening.

__Authors reply__: Thank you for the comment. In fact there is a significant effect on the shallower cloud subset but because we used the same scale for all the panels in this figure (representing clouds in different sizes) it is harder to recognize the differences between the results of the smaller clouds. Please see below a zoom-in on this part of the figure using different Y-axis scales from ones used for the fig in the paper to emphasize the differences between the clouds.

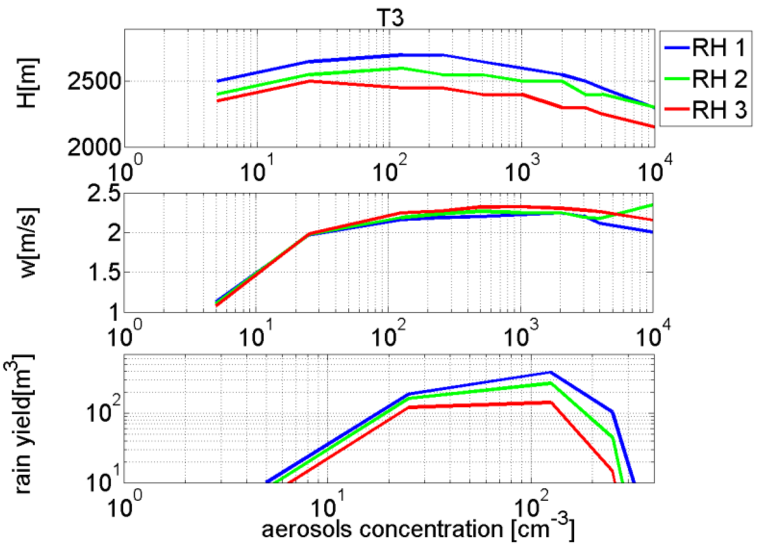

Figure 3: The cloud's maximum top height (top panel), the maximum over time of the mean vertical velocity weighted by the mass in each grid point (middle panel) and the total surface rain yield (bottom panel) as a function of the aerosol loading, for T3 profile (only) simulated clouds, as a function of the aerosol concentration.

When examining the numbers it demonstrates better the differences between these clouds (presented in figure 6 for profile T3). For example the total surface rain yield for the cloud that gave the maximum rain (125 cm^{-3}) was 384 m^3 for the case of RH=95% and 142 m^3 for the case of RH=80%. This means that increasing the RH by 15% results in almost 3 times more surface rain. For those two clouds the maximum top was 2700 m for T3RH95_125 cloud compared to 2450m for T3RH80_125 case. The differences between the small clouds (profile T3) that formed in different RH levels are smaller compared to the differences between the deeper clouds (profiles T1 or T2). This is also due to the fact that all of the small clouds crossed the inversion layer and their main evaporation (cloud tops) took place in a similar very dry environment (RH=30%).

In order to emphasize this point for the reader we added the revised text a clarification for the results (in the results section): *"Finally it should be noted that the differences between the cases of the small warm clouds (profile T3) are smaller (compared to the deeper clouds)and as expected, have low values of optimal aerosol concentrations. In all those small clouds their top is above the inversion and so most of the evaporation takes place in a similar very dry environment (RH=30%) and so* N_{op} *values were shown to be ~25* cm^{-3} *for the T3 cases (fig. 2). It suggests that under our current atmospheric conditions, apart from the extremely pristine places, the local aerosol concentrations are larger than the optimal value, locating the clouds already on the descending branch"*

15) About the vertical velocity (middle panels), what do you mean by "the maximum over time of the mean vertical velocity weighted by the mass in each grid point"? Why not plot the maximum vertical velocity directly from simulations?

Authors reply: Thanks for this comment. Indeed the description should be clearer. As discussed in the opening (general) part, since the updraft is used here as a measure for the water mass vertical displacement we are weighting the updraft average by the liquid water mass. Therefore more weight is given to grid-boxes with high LWC compared to low values. We changed the text to: "*the maximum (over the cloud's lifetime) of the mean cloud's updraft (middle panel). As vertical velocity serves as an important factor that controls the droplets vertical displacement, the average is weighted by the liquid water mass.*" For clarity additional figure presenting the maximal updraft was added to the supplementary material (Fig S2).

P23566:

16) Line 26-27: why weighted by the liquid water mass for updraft velocity? Need a figure for the physical vertical velocity (such as maximum vertical velocity) to get an idea about convective intensity of the clouds.

<u>Authors reply</u>: Please see our detailed reply above in answers number 5 and 12 about the mean weighted updraft velocity.

P23567:

17) In the first paragraph, the authors use phrases like "margins' effect" and "margins' processes" but they were never clearly defined. Please refer to my major comment on this.

<u>Authors reply</u>: Thank you for the comment. Based on this comment we improved the definitions in the revised text of all the used terms including core, margins, and their related processes: "*Throughout this paper, the cloud core is defined as the part under supersaturation conditions, while the cloud periphery is the part under subsaturation (Wang et al., 2009). This definition determines the dominant processes in each of these regions in the cloud; the core is dominated by condensation and the periphery by evaporation and entrainment.*"

Please see detailed answer no. 3 above.

18) Line 8-10, why should maximum total mass of the cloud is sensitive to cloud top height?

<u>Authors reply</u>: Thank you for this comment. The total mass of the cloud is sensitive to the periphery's processes and the cloud top height is less sensitive to those processes. We revised the sentence in order to make it clearer: "*The maximum total mass of the cloud is more sensitive to the cloud periphery- based processes. The cloud's maximum top height (which is located above the cloud's core)* is less *sensitive* to these processes."

19) Line 11-12: what are lighter margins? What is the declining branch? Please describe with physical terminologies.

<u>Authors reply</u>: This sentence was changed in the revised version in order to make it clear: *" Similarly, since the mean updraft is weighted by the liquid water mass and so* *less sensitive to aerosol effects on the lighter periphery (contain less liquid water mass), the declining branch (in the graphs in the middle panel in fig 7) that is controlled by the enhanced entrainment and evaporation at the clouds' periphery is less significant".*

20) Line 26-27: Collection efficiency should decrease with the droplet number concentration. But the total rain mass converted from the collisions of droplets may not be decreasing with the droplet number concentration.

Authors reply: Thank you for this comment. We believe there is some confusion with the used terminology. We agree with the reviewer that the collection in polluted clouds starts later compared to clean clouds. But after this process starts a drop that falls in a polluted cloud can collect many more smaller drops due to high collection efficiency (Altaratz et al., 2008). So the total collected mass over the cloud lifetime could be higher in polluted clouds. To make this point clear we changed the relevant part in the revised version:

"In clean clouds the collection process becomes significant early compared to polluted clouds but the total collected mass (integrated over the cloud lifetime) not necessarily decreases with the increase in aerosol loading. The collected mass increases with both the number concentration and the variance of the droplet size distribution. Thus aerosols would have a contradictory effect on the total collected mass. At low values of aerosol concentrations, as the aerosol loading increases, a few big lucky drops (Kostinski and Shaw, 2005) that initiate the rain can collect more small drops and consequently produce more rain yield and larger rain drops (Altaratz et al., 2008). The mean rain drop radius below cloud base can serve as an evidence for this process (see the results produced by the same model in the paper by Altaratz et al., 2008). For example in our results, for the profile T2RH2 the cloud forming in aerosol loading of 125 cm^{-3} has a maximum (over time) of mean radius below cloud base (at H=750m) of 0.77mm (at t=56 min) while the cloud with aerosol loading of 2000 cm^{-3} has a maximum mean radius at the same height of 1.21mm (at t=81 min).

This trend continues until the effect of the smaller variance of the droplet size distribution (with increasing aerosol loading) becomes more important and then there *are less lucky drops. The aerosol concentration that corresponds to the maximum total collection efficiency for a given profile is slightly higher then N_{op}".*

P23568:

21) Line 1-2: please verify if you see the same thing in your simulations.

<u>Authors reply</u>: Yes we do see it in our results, at low values of aerosol concentrations, as the aerosol loading increases, a few big lucky drops collect more small drops. The mean rain drop radius below cloud base can serve as an evidence for this process (see the results produced by the same model in the paper by (Altaratz et al., 2008)). For example in our results, for the profile T2RH2 the cloud forming in aerosol loading of 125 cm^{-3} has a maximum (over time) of mean radius below cloud base (at H=750m) of 0.77mm (at t=56 min) while the cloud with aerosol loading of 2000 cm^{-3} has a maximum mean radius at the same height of 1.21mm (at t=81 min). It was added into the paper's revised text (in the results section): " *The mean rain drop radius below cloud base can serve as an evidence for this process (see the results produced by the same model in the paper by Altaratz et al., 2008). For example in our results, for the profile T2RH2 the cloud forming in aerosol loading of 125 cm^{-3} has a maximum (over time) of mean radius below cloud base (at H=750m) of 0.77mm (at t=56 min) while the cloud with aerosol loading of 2000 cm^{-3} has a maximum mean radius at the same height of 1.21mm (at t=81 min).*"

Summary:

22) N_{op} in the model is sensitive to condensation and evaporation. Very low N_{op} for cloud mass (25 cm^{-3}) of shallow clouds with a inversion height of 2 km even at RH of 90% and 95% looks unreasonable. The model could simulate too strong evaporation. Or the methodology was not appropriate. This should be discussed.

<u>Authors reply</u>: We agree that this result looks intriguing but to the best of our understanding it is right. Indeed N_{op} is sensitive to the competition between evaporation to condensation specifically for the shallow clouds that their surface to volume ration is high. Specifically for the shallowest clods (profile T3, inversion at 2 km) most of the evaporation takes place above the inversion layer where the RH is only 30%. Those clouds tops penetrate the inversion and get into a dry similar layer.

This strong evaporation above the inversion leads to the low N_{op} of those clouds. A clarifying sentence about this issue was added to the revised paper: *" Finally it should be noted that the differences between the cases of the small warm clouds (profile T3) are smaller (compared to the deeper clouds) and as expected, have low values of optimal aerosol concentrations. In all those small clouds their top is above the inversion and so most of the evaporation takes place in a similar very dry environment (RH=30%) and so N_{op} values were shown to be ~25 cm^{-3} for the T3 cases (fig. 2). It suggests that under our current atmospheric conditions, apart from the extremely pristine places, the local aerosol concentrations are larger than the optimal value, locating the clouds already on the descending branch. Similarly, the clouds' top height, for the T3 cases, shows relatively low sensitivity to aerosol loading, with optimal concentrations of ~100 cm-3 (fig. 7)."*

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A point-by-point replay to Reviewer # 2

General comments

We are happy that the reviewer finds our paper interesting and valuable for this field of research. We followed all his recommendations and the revised paper is more detailed and clear.

1) The title of the manuscript refers to warm clouds, but also clouds are simulated which in principle allow for ice production. Although primary ice formation is typically not expected to be very efficient at temperatures higher than -10°C, it should be kept in mind that in this range the ice multiplication due to rime splintering can potentially increase the ice number concentration at these relatively warm temperatures. It would thus be useful to argue why the potential ice in the investigated clouds is negligible nevertheless, or otherwise in which direction the results of this study would be shifted in case that ice effects were not negligible. Furthermore, it should be explained why in addition to pure warm clouds, also profiles were used which result in cloud top temperatures of -10°C. Do these simulations add significant value to the results of this study in spite of the uncertainty that is introduced by neglecting the ice particles?

Authors reply: In this theoretical study we tried to "stretch" the dynamic range of the vertical development of the clouds as far as we could as long as we stay in the warm regime. We agree that we might miss a thin mixed-phase layer in the case of clouds that do reach the -10ºC level. For the sake of simplicity we chose to close the cold processes in the model schemes and to leave it as a theoretical study that reach the limit of warm cloud development. Please see more details in the opening part.

2) The authors describe their model to be axissymmetric and I think it should be discussed in more detail what this means for the simulated clouds. Does the symmetry only refer to the model grid, or also to the cloud appearance? Can we imagine a cylindrical domain, or a 2D-plain with axis symmetry? Since the mixing at cloud edges is a basic process that determines the results of this study,

what are the limitations of this approach and in which direction could the results shift if a full 3D large eddy simulations was used?

Authors reply: The cloud model used in this study is a single cloud axisymmetric model (1.5D). The basic equations of the model are described in (Tzivion et al., 1994) and (Reisin et al., 1996). The vertical and horizontal dynamics of the cloud are fully resolved with the restriction that the cloud has a rotational symmetry along the vertical axis. This implies no tilting and no wind shear.

A paragraph discussing the limitations of this approach in estimation of the entrainment strength was added to the results part in the revised version:

"Those results obtained using an axisymmetric model with a geometry that is only an idealization and simplification of a full 3D flow. This may affect the estimation of the entrainment strength and turbulence mixing as was discussed in details in (Benmoshe et al., 2012) (focusing on the comparison between 2D and 3D cloud models)."

Another sentence regarding the model was added to the methodology part: "*An axisymmetric grid describes movement in the vertical and radial directions. It is limited in its ability to describe the dynamics"*.

3) Drag force effects as a result of liquid mass accumulation are mentioned multiple times to explain an impeded cloud evolution and updraft strength. A more extensive discussion on the exact mechanisms (acceleration due to -gq_{liq}?) including references are needed. Also an estimation of the relative contribution compared to the entrainment effect of dry air into the cloud would be useful.

Authors reply: Thank you for this comment. The definition of the drag force is as you mentioned: the condensed water in a parcel of air exerts a downward force that is equal to its weight (Rogers and Yau, 1989) pg. 50 and is proportional to -gq_{liq}. A clearer definition and a reference were added to the revised version: *"The early rainout leads to mass transfer downward and therefore an increased drag force (that* *is proportional to the liquid water mass, Rogers and Yau, 1989) at the lower part of the cloud that further impedes the cloud's development (Khain et al., 2005)".*

The maximum values of the liquid water mass are presented in figure 2 and an example of its evolution in time as a function of aerosol loading is presented in figure 4 and they give some information about the magnitude of the total drag force in the clouds.

Regarding the relative contribution of different processes to the updraft velocity in the clouds. The graph below presents the cloud mean updraft, drag force and turbulent term of the vertical velocity equation. All of those parameters are calculated as cloud mean values, weighted by the liquid water mass at each grid point. They are presented as a function of time for four levels of aerosol loading for the same initialization profile (T2RH2). The drag force and turbulent terms are both terms in the vertical velocity equation and hence have units of acceleration. The vertical velocity equation:

(Tzivion et al., 1994): $\frac{\partial w}{\partial t} = F(w) - D(w) - \frac{\partial \pi}{\partial z} + g(\frac{\theta_v}{\theta_{v0}} - M_w)$

The first two terms on the right hand side are the turbulent and advection operators, respectively. The turbulent diffusion operator is defined as:

$$F(w) = \frac{1}{r}\frac{\partial}{\partial r}(\nu r \frac{\partial w}{\partial r}) + \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 \nu \frac{\partial w}{\partial z})$$

The turbulence term of the vertical velocity can serve as a measure of the entrainment strength because it indicates of the turbulent mixing between the cloud and its dry environment.

It can be seen from the figure that the turbulent mixing increases monotonically with the aerosol loading. The maximum in drag force increases with the aerosol loading until a certain level and then decreases, but by the end of the cloud evolution the most polluted cloud has the largest drag force. This is due to the delay in the collision-coalescence and rain processes in those clouds. In this case the magnitude of the negative effect of the drag force is larger than the turbulent mixing. A full understanding and quantification of aerosol effect on each of the terms in the vertical velocity equation is interesting and relevant. However it will force us to add a very detailed and long part to this paper and so we choose to leave it for future work.

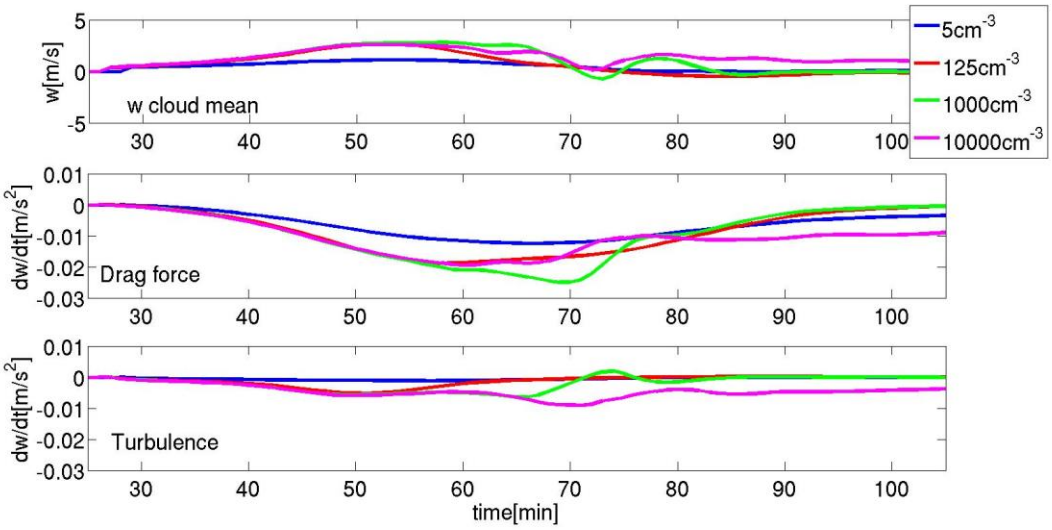

Figure 4: cloud mean vertical velocity and two terms of the vertical velocity equation: drag force and turbulent terms. All of those properties are calculated as cloud mean values weighted by the liquid water mass at each grid and are presented as a function of time for four levels of aerosol loading (5,125,1000,10000 cm^{-3}) for the same initialization profile (T2RH2)

4) Furthermore, the notation that is used throughout the study should be clearly defined. Some examples are:

- **condensation efficiency**
- **invigoration**
- **core, periphery**
- **core and periphery processes**

<u>Authors reply</u>: Thank you for this comment. As we wrote in the opening statement we made any possible effort to make the terminology clear and uniform in the revised paper. Specifically we added:

a) Results section - definition of core and margins*: "Throughout this paper, the cloud core is defined as the part under supersaturation conditions, while the cloud periphery is the part under subsaturation (Wang et al., 2009). This definition determines the dominant processes in each of these regions in the cloud; the core is dominated by condensation and the periphery by evaporation and entrainment ".*

In addition:

In the Introduction section*: "For example, for the T1RH1 profiles the mean horizontal winds averaged along the cloud margins (that were define according to RH=100%) were 0.26 m* s^{-1}*, 0.27 m* s^{-1}*, and 0.40 m* s^{-1} *for T1RH1_125, T1RH1_1000, and T1RH1_4000, respectively".*

b) Introduction section - definition of invigoration: *"These microphysical processes were suggested to be coupled to dynamical ones and in the case of convective clouds to form the baseline for the invigoration effect in which high aerosol loading leads to larger and deeper clouds with larger water mass (Andreae et al., 2004; Koren et al., 2005; Rosenfeld et al., 2008; Tao et al., 2012; Fan et al., 2013). Surface rain, as the end result of all the cloud's feedbacks, was shown to be affected by changes in aerosol loading as well (Levin and Cotton, 2009; Khain, 2009; Koren et al., 2012).*

Unlike the straightforward physical basis of the Twomey effect, in which for a given amount of LWC, an increase in the aerosol loading increases the amount of cloud droplets and therefore reduces the droplets average size (and increases the cloud's reflectivity, Twomey, 1977). Invigoration is the outcome of a series of feedbacks that are all a result of the aerosol-imposed changes on the droplets initial size distribution (Altaratz et al, 2014). As such, the invigoration effect can be expressed in several different forms such as an increase in the cloud total mass, or an increase in the cloud's depth and area (Koren et al., 2005; Rosenfeld et al., 2008; Tao et al., 2012). In this work we use the cloud's total mass as the main measure for cloud invigoration".

c) Introduction section - definition of condensation efficiency*: "For a given total liquid water mass (or volume), the total surface area of smaller droplets is larger and therefore, the condensation process is more efficient under the given supersaturation* *conditions (consuming the supersaturation in shorter time scale) (Pinsky et al., 2013; Seiki and Nakajima, 2014)".*

<u>Specific comments:</u>

p. 23556:

5) Lines 5: Suggest to mention the kind of model that is used, like single column/2D/3D/idealized or not?

<u>Authors reply</u>: Thank you for this comment. We added this information to the revised text: *"In this study, using an axisymmetric bin-microphysics cloud model, we propose a theoretical scheme that analyzes the evolution of key processes in warm clouds, under different aerosol loading and environmental conditions, to explain this contradiction".*

6) Line 9: Which framework is meant, the specific model framework that is used here?

<u>Authors reply</u>: the term framework refers to the theoretical scheme that is described in the previous sentence. In order to make this point clearer this part was changed in the abstract revised version: *"In this study, using an axisymmetric bin-microphysics cloud model, we propose a theoretical scheme that analyzes the evolution of key processes in warm clouds, under different aerosol loading and environmental conditions, to explain this contradiction.*

Such an analysis of the key processes reveals a robust reversal in the trend of the clouds' response to an increase in aerosol loading".

7) Line 23-24: Does the statement refer to cloud-resolving models, i.e. on a scale of single clouds, or also studies on scales larger than some kilometers?

Authors reply: this statement refers to cloud-resolving models mainly on the scale of a cloud field. The sentence was revised for clarity: *"On the other hand, modeling studies of cloud fields are biased in favor of small, mostly trade-like convective clouds, which are characterized by low Nop values (in the pristine range), and therefore cloud suppression is mostly reported as a response to an increase in aerosol loading."*

Later, along the paper examples are given for those kind of papers: *"Many of the numerical studies of warm convective clouds focused on trade-like cumulus clouds (Jiang et al., 2006; Xue and Feingold, 2006; Xue et al., 2008; Jiang et al., 2009; Koren et al., 2009; Jiang et al., 2010; Seigel, 2014) where the characteristic cloud size is around 1 km"*. All of those examples deal with LES simulations of cloud fields.

p. 23557:

8) Line 22: Variance should be described more exactly; otherwise I suggest "narrower size distribution".

Authors reply: we accept the reviewer suggestion and the revised text is changed accordingly: *"Polluted clouds initially have smaller and more numerous droplets, with narrower size distribution"*.

9) Line 24: Do you mean the change due to a different aerosol size distribution? Also, do you mean the interactions between droplets (not mentioned before in this paragraph), or between the processes (what exactly is meant in this case)?

Authors reply: Yes, we mean the change in drops size due to change in aerosol size distribution and we mean interactions between processes. In order to make this sentence clearer it was changed in the revised version: *"The change in the initial droplet size distribution (due to changes in the aerosol number concentration) affects key processes and the interactions between those processes"*.

p. 23558:

10) Line 1: What exactly or which regions of the cloud does the mixing refer to?

Authors reply: In this part we refer mainly to cloud periphery. This region in clouds is characterized by subsaturation conditions. The enhanced drops evaporation (due to larger surface area) increase the mixing of the cloud with it's environment due to the induced downdrafts. A clarification was added to this sentence: *"On the other hand, similarly, under subsaturation conditions (characteristic for cloud periphery), smaller droplets evaporate more efficiently and may enhance the mixing processes between the cloud and the drier surrounding air due to the evaporative cooling-induced downdrafts (Xue and Feingold, 2006; Jiang et al., 2006; Small et al., 2009)".*

11) Line 5: Again, I wonder if the change is that which is caused by different aerosol size distributions.

Authors reply: Yes, we refer to the change that is caused by different aerosol size distribution. A clarification was added to the revised introduction: *"The collision-coalescence and rain processes are impacted by the change in the droplets' size distribution (caused by the changes in the aerosol number concentration) as well."*

p. 23559:

12) Line 8: Suggest to explicitly name the key processes which are addressed in the analysis.

Authors reply: we accepted the reviewer suggestion and revised the introduction accordingly: *"More specifically, we describe the evolution in time and the competition between key processes: condensation/evaporation, collision-coalescence, rain fallout, drag force and entrainment."*

13) Lines 19: For a better readability and overview of the following text, please summarize the specifications of T*RH* notations in a table. Maybe the description of clean and polluted aerosol conditions could be contained in the caption.

<u>Authors reply</u>: we accepted this recommendation and a table was added to the text summarizing the notation and characteristics of the different initial atmospheric profiles.

Methodology section: *"Table 1 summarizes the characteristics of the initialization profiles."*

	T1	T2	T3
RH1	T1RH1: 6km, 95%	T2RH1: 4km, 95%	T3RH1: 2km, 95%
RH2	T1RH2: 6km, 90%	T2RH2: 4km, 90%	T3RH2: 2km, 90%
RH3	T1RH3: 6km, 80%	T2RH3: 4km, 80%	T3RH3: 2km, 80%

Table 1. A summery of the notations, inversion base height and RH levels in the cloudy layer for 9 different initial atmospheric profiles. For each profile 10 simulations were run with aerosol concentration of 5,25,125,250,500,1000,2000,3000,4000 and 10000

14) Line 20: In my opinion, "idealized" would be a more common notation than "theoretical" profile. More importantly, it is necessary to have references either for the idealized profiles that are used here, or measured data for comparison with typical moist tropical profiles.

<u>Authors reply</u>: We accepted the reviewer recommendation and changed the notation to "idealized" profile instead of "theoretical" profile along the whole paper. Garstang and Betts, (1974) have described a typical tropical atmospheric profile that includes a subcloud mixed layer, a small transition layer, a conditional unstable and very humid cloudy layer and overlaying inversion layer. Our idealized profiles are similar to this general characterization. This reference was added to the revised methodology section: *"To better understand the role of key environmental factors, we ran the model* *with 9 different initial conditions based on idealized atmospheric profiles that characterize a moist tropical environment (Garstang and Betts, 1974). Each of the profiles includes a well-mixed subcloud layer between 0 and ~1000 m, a conditionally unstable cloud layer between 1000 and 6000m (T1), 4000 m (T2), and 2000m (T3), and an overlying inversion layer".*

p. 23560:

15) Line 5: As described above, a more detailed justification concerning ice particles should be added.

Authors reply: Please see the three detailed answers to this issue: (1) in the general part in the beginning of this document, (2) in specific comment no. 4 in the general part and (3) answer no. 1 in the opening part to the reply to reviewer no. 2.

16) line 17: I missed the technical specifications like spatial and temporal resolution in the first paragraph of chapter 2. Therefore I suggest to shift this description, including the more detailed description and implications of the axissymmetric grid.

Authors reply: Based on this recommendation the technical specifications were shifted to the first paragraph of the methodology section. Some additional information regarding the implications of the axissymmetric grid was added as well: *"The model resolution was set to 50 m both in the vertical and horizontal directions, with a time step of 1 second. An axisymmetric grid describes movement in the vertical and radial directions. It is limited in its ability to describe the dynamics".*

As was described in the general part of this response**,** a paragraph discussing some of the limitations of this model regarding its ability to treat turbulent mixing was added to the revised version as well: "*Those results obtained using an axisymmetric model with a geometry that is only an idealization and simplification of a full 3D flow. This* *may affect the estimation of the entrainment strength and turbulence mixing as was discussed in details in (Benmoshe et al., 2012) (focusing on the comparison between 2D and 3D cloud models)".*

17) Line 19: To get a better overview, it would be helpful to have a summary of the clouds' vertical extent.

Authors reply: the clouds' vertical extent is presented as a part of the results section in the paper (and not in the methodology section). This property of clouds is a result of the initial atmospheric profile but also of all the relevant clouds processes. It is a major topic of this paper as the cloud depth is a well accepted measure for the aerosol effect. The depth of the cloudy layer (limited by the inversion base height) is presented in section 2. And in the results section, figure 6 (7 in the revised version) shows the maximum simulated cloud top height as a function of the initialization profile and the aerosol loading.

18) Line 25: Also here it is not clear to me which specific key processes are addressed. Please describe "magnitude" in more detail, for example, I can think of total maxima or in-cloud averages or domain averages.

Authors reply: in order to give more details about the analyzed processes we changed this sentence in the revised methodology section: *"To reduce the dimensionally of the results of our 90 simulations and to distill the essence of the interplay between processes, we focused on the magnitude and timing the key processes in the cloud's evolution like condensation/evaporation, collision-coalescence, rain fallout, drag force and entrainment"*. Regarding the use of the term "magnitude", a clear definition is given in the results section for each process that is presented. We chose not to give examples here since it refers to many different types of analysis presented in the results section.

p. 23561:

19) Line 4: For clarity, I suggest to describe it as a maximum with respect to the temporal evolution within a simulation. Furthermore, I wonder whether the time series of the total cloud mass has a similar shape among the simulations, i.e. only the magnitude varies, or whether the behavior is quite different among the 90 simulations. I see there is an example shown in Figure 4 for profile T1RH1 – are they representative for the rest of the simulations or can more pronounced differences be expected?

Authors reply: we agree with the reviewer and accepted his suggestion. The revised results section text: *"Figure 2 presents the maximum cloud total mass with respect to the temporal evolution of each cloud, as a function of the aerosol concentration used for the same simulation"*.

The 3 examples shown in figure 4 for the mass evolution of 3 clouds that developed in different aerosol loading represent well the effect of the aerosols on the total mass evolution. It can be noticed that the cleaner cloud had the smallest maximum mass. The most polluted cloud had very slow decrease in the total mass after the peak. This is a result of the postponement in the collision-coalescence and rain processes in polluted clouds. This is also indicative to the larger effect of the drag force in polluted clouds that is described in the paper. The middle cloud (1000 cm^{-3}) had the largest maximum mass and after the peak its decrease relatively fast because of the large amount of rain produced in this cloud (fig. 3).

p. 23562:

20) Line 11: I wonder how well-established the indicated relationship between condensation efficiency and droplet surface area is. In particular, how much do curvature effects of the smaller droplets on the saturation vapor pressure counteract the increased efficiency due to the larger surface area? Is it negligible, i.e. the surface area effect predominates, or what are the droplet sizes for which curvature becomes non-negligible? Are such sizes reached here?

Authors reply: to better establish the relationship between condensation efficiency and droplet surface area we added to this sentence a reference that deals with this issue: *"The condensation efficiency is determined by the droplets' surface area (Pinsky et al., 2013; Seiki and Nakajima, 2014) (fig. 4)*".

Activated droplets, by definition (Rogers and Yau, 1989), can grow spontaneously under supersaturation conditions. For example, under supersaturation conditions of 1% droplet with radius of 0.12μm will be in equilibrium (larger droplets will grow spontaneously). At the beginning of the cloud evolution (after 5 min) at the point of maximum liquid water content the mean radius of clouds T1RH1_125 and T1RH1_4000 are 7.4 and 2.3 μm respectively. Meaning, that even at relatively early stages of the cloud evolution and under polluted conditions, the mean droplet radius is order of magnitude larger than the equilibrium radius. The curvature effect is proportional to r^{-1} and so is smaller by an order of magnitude than in equilibrium.

p. 23563:

21) Line 5: Are there thresholds that define the start of these processes?

Authors reply: To define the starting point of the collision-coalescence one must use an arbitrary threshold. To avoid using a non-physical threshold we changed the discussion in the revised version to refer to the point when the collision-coalescence becomes significant and not to the starting point. Moreover, Freud and Rosenfeld, (2012) have shown that there is a critical size for the mean radius of the droplets (~13μm) that define the start of the collision-coalescence and rain processes. This reference was added to the revised version: *" The mean radius is larger and the size distribution is wider for the clean case so the droplets reach the critical size for collisions rapidly (Freud and Rosenfeld, 2012) and the collision-coalescence process becomes significant almost immediately after the condensation start (Khain et al., 2005)."*

p. 23564:

22) Line 23: delete ":"

Authors reply: Deleted in the revised version.

p. 23565:

23) Lines 4-7: It would be interesting to see the change of vertical velocities, for example in the same manner as in Figure 2, where maximum values are shown as function of aerosol concentrations. Is this possible with the existing model output?

Authors reply: A graph presenting the maximal vertical velocities as a function of aerosol concentrations were added to the supplementary material of the revised manuscript (fig. S2). It is shown in this document as a part of the reply to the reviewer # 1 comments (figure 1 in this document). Another graph that shows information on the vertical velocity is the middle panel of fig. 7 (fig 6 in the previous version) in the paper that presents the maximum over time of the mean vertical velocity (weighted by the mass in each grid point). Those 2 graphs present maximum values of vertical velocities as function of aerosol concentrations.

24) Lines 18-20: Is there a way to extract or estimate the relative contributions of the drag force effect and the entrainment effect to the suppression of the cloud development?

Authors reply: Please see detailed answer # 3 to reviewer no. 2 and the embedded figure (fig 4 in this document). It describes the evolution of the mean W (weighted by the mass), and two terms in the vertical velocity equation – the drag force and the turbulent term. Those two terms are calculated as cloud mean values weighted by the mass. The drag force is proportional to the liquid water mass in the cloud and the turbulence term in the vertical velocity represents the turbulent mixing of vertical momentum and so is indicative for the strength of the turbulent mixing between the cloud and the environment (entrainment). We can see that the turbulent mixing increases monotonically with the aerosol loading. The maximum in drag force increases with the aerosol loading until a certain level and then decreases but by the end of the cloud evolution the most polluted cloud had the largest drag force. This is due to the delay in the collision-coalescence and rain processes in those clouds.

25) Lines 20-27: As I see it, this is a repetition of what is already contained in the text above.

<u>Authors reply</u>: this paragraph was changed in the revised results section and part of it was deleted in order to avoid repetition: *"The competing effects discussed above show that, on the one hand, more aerosols result in enhanced condensation (higher efficiency and for a longer time), and with a stronger latent heat release, which leads to deeper clouds with a larger water mass. On the other hand, more aerosols induce mass accumulation that enhances drag forces and stronger entrainment-driven evaporation (suppression processes), which eventually leads to mass reduction and smaller clouds. This competition, poses the existence of an optimal value (N_{op}) with respect to the cloud mass, which dictates a change in the sign of the trend regarding the cloud mass response to an increase in aerosol loading (Figure 2)."*

p. 23566:

26) Paragraph 1: I suggest to clarify that the humidity outside of the cloud is addressed, instead of the "RH of the cloudy layer".

<u>Authors reply</u>: we agree with the reviewer and the text was changed according to his suggestion: "*The value of N_{op} strongly depends on the environmental conditions. As the inversion's base height increases (increasing the potential cloud depth and* *therefore reducing the cloud's surface-area-to-volume ratio) and/or the humidity outside of the cloud increases, the entrainment impact weakens and therefore, N_{op} increases".*

27) Line 27: What does a weighting of the mean updraft by the liquid water mean and what is the advantage of weighting compared to a non-weighted mean value? Does a parcel with 0.1g/kg liquid water content have a tenfold weight than a parcel with 0.01g/kg, such that the cloud core mean updraft is highlighted relative to the outer regions? Thus I wonder whether the cloud maximum updraft velocity would yield a very different picture. If not so, I think that this would be a measure that is easier to interpret for the reader. Otherwise, the idea behind the weighting needs to be described.

Authors reply: Please see answer no. 5 in the general part that opens this document. A graph presenting the maximal vertical velocities as a function of aerosol concentrations was added to the supplementary material of the revised manuscript (fig. S2). We think that the cloud mean vertical velocity, weighted by the mass, is more appropriate to describe the convection intensity of the clouds. In order to make this point clearer we revised the text (results section): "*(2) the maximum (over the cloud's lifetime) of the mean cloud's updraft (middle panel). As vertical velocity serves as an important factor that controls the droplets vertical displacement, the average is weighted by the liquid water mass. The (non weighted) maximum vertical velocity (fig S2 in the supporting material) shows similar results but is more sensitive to local fluctuations of the velocity field".*

28) p. 23567:
Lines 3-8: I have difficulties to get the essence of these two sentences, which seem to compare the relative contributions of core and periphery processes. Please rephrase.

<u>Authors reply</u>: Thank you for this comment. This part was changed in the revised results section*:* ″ The aerosol concentration that gives the peak of the cloud features that are controlled by the cloud′s core processes, like cloud top height (less affected by entrainment) corresponds to larger aerosol loading values compared to features that are more sensitive to periphery-based processes (like total cloud mass). Eventually, since all the processes are coupled, the enhancement in the periphery's effects results in a weakening of the core-based processes as well. The maximum total mass of the cloud is more sensitive to the cloud periphery-based processes. The cloud′s maximum top height (which is located above the cloud′s core) is less sensitive to these processes.″

Figures:

29) Figure 2: Since eta is described as a parameter to estimate the relative importance of cloud core and periphery processes, it might be helpful (if not, why?) to have a plot that explicitly compares eta against the resulting cloud mass as shown in Figure 2, for example. However I wonder about the variability of eta with time, so can we gain further insight from the proposed comparison, if not so, why? I could think of three more panels which show the aerosol-dependent eta value corresponding to the maximum (wrt. time) cloud mass situation. It is left to the authors to extend their figure or not, but a short discussion should be added to the analysis.

<u>Authors reply</u>: Thank you for this good idea. Eta is the ratio of the cloud's surface area to volume. It changes as a function of cloud size. Its main dependence is on the initialization profile but also on aerosol loading. Due to that we chose to add the revised paper a figure (see below – fig 5 in this document) describing the minimal value of eta, during the cloud lifetime, for each of the simulated clouds, as a function of aerosol loading. It shows that eta has a non-monotonic response to aerosol loading which is opposite to the effect of aerosol on the total mass. For each initialization profile the cloud that corresponded to the maximum mass had more or less the smallest eta.

The text that was added to the results section of the revised paper for describing this figure: *"The minimal value of η during the lifetime of each cloud for all the different simulations (fig 6) shows a non-monotonic response to aerosol loading which is opposite to the effect of aerosol on the total mass. For each initialization profile the cloud that corresponds to the maximum mass has the smallest η. Moreover, the difference in η between the different initialization profiles is also shown. As the inversion base height becomes higher or the RH outside of the cloud increases the value of η generally decreases. The larger the value of η, stronger periphery-based (suppression) processes can be expected."*

We also added the supplementary material of the revised paper a figure of the evolution of eta with time (fig. 6 in this document, fig. S3 in the supplementary material). It represents eta evolution for three clouds that developed under the same aerosol loading (4000 cm^{-3}) but in different initial atmospheric profiles (T1RH1- blue, T2RH2 - green and T3RH3 - red). It demonstrates that as the inversion base height and the RH in the cloudy layer decrease the value of η increases.

The text that was added to the revised paper for discussing the new figure: "*Figure S3 in the supplementary martials presents the time evolution of η for three clouds that developed under the same aerosol loading (4000 cm-3) but different initial atmospheric profile (T1RH1 (blue), T2RH2 (green) and T3RH3 (red)). Once again we see that as the inversion base height and the RH in the cloudy layer decrease the value of η increases.* ".

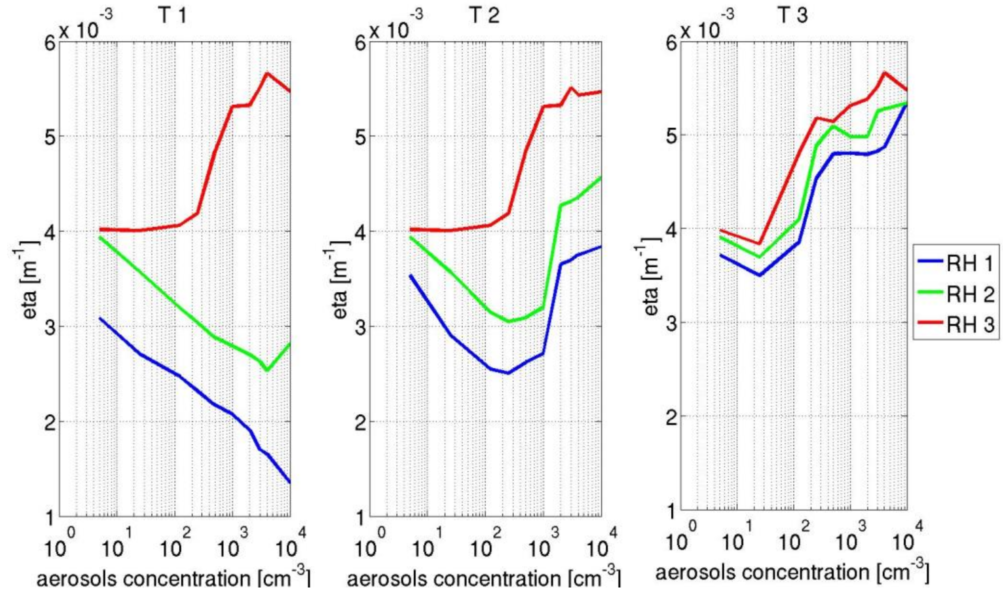

Figure ***5 (fig. 6 in the revised paper). minimal values of the surface area to volume ratio (eta) for each simulated cloud as a function of the aerosol concentration. T1 represents a profile with an inversion layer located at 6 km, T2 at 4 km, and T3 at 2 km. RH1 represents a profile with 95% RH in the cloudy layer, RH2-90%, and RH3-80%. Each curve represents 10 simulations performed for an initialization profile (a total of 9 profiles).***

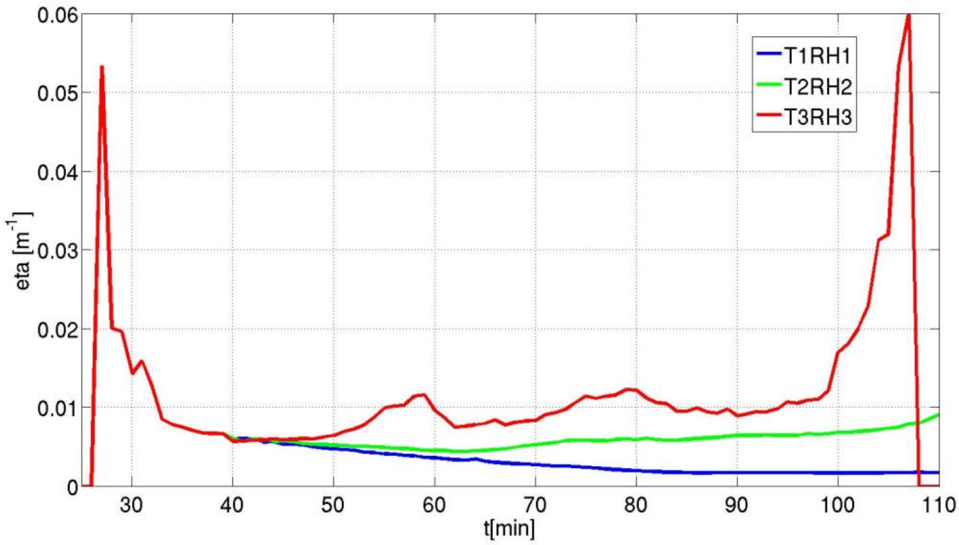

Figure 6 (fig. S3 in the supplementary material).The evolution in time of the surface area to volume ratio (η) of three clouds that developed under the same aerosol loading conditions (4000 cm^{-3}) but in different initial atmospheric profile T1RH1 (blue), T2RH2 (green) and T3RH3 (red).

30) Figure 4: Here I strongly recommend to show eta as a function of time for the three examples shown in Figure 4. How are minima and maxima of the time dependent eta and cloud mass correlated and is there a systematic shift between the simulations? Maybe a fourth panel could be added, showing the three eta time series that result from the existing panels.

Authors reply: Eta as a function of time is presented for 3 clouds in the supplementary material of the revised paper, as described in details in the previous answer (no. 29). Please notice that figure 4 in the paper presents the total droplet surface area and not the cloud surface area that is used for the calculation of eta. In order to prevent confusion between those two surface areas we added the time evolution of eta in a different figure. Eta changes between different profiles, and it was suggested to serve as a measure of the strength of the core versus periphery processes for a specific profile.

References:

Garstang, M., and Betts, A. K.: A review of the tropical boundary layer and cumulus convection: Structure, parameterization, and modeling, Bulletin of the American Meteorological Society, 55, 1195-1205, 1974.