Reply to reviewers' comments:

Quantifying the effect of aerosol on vertical velocity and effective terminal velocity in warm convective clouds

We would like to thank the reviewers for their insightful and helpful comments that helped us clarify and improve this work. Please find below a point-by-point reply to all of the reviewers' comments (in blue)

Reviewer 1:

This study investigated the aerosol effects on warm convective clouds via the interplay of updraft (w) and effective terminal velocity (eta) using both single cloud model and large eddy simulation (LES). The topic is very interesting and the authors provided detailed analysis on how aerosols affect the evolution of thermodynamic instability of cloud field using both characteristic vertical velocities.

<u>Answer:</u> We thank the reviewer for the important comments and we are happy that the reviewer found this work interesting.

General comments:

1. The simulated clouds from both cloud model and LES were growing at very humid environment, e.g., "the relative humidity in the cloudy layer was 90%" (L134). The authors found monotonically increased vertical velocity with enhanced aerosol loading, i.e., aerosol invigoration effect on warm convective clouds. As we know from previous studies, however, the aerosol indirect effect varied with different atmospheric conditions. For instance, if the atmosphere is not so humid or the relative humidity is lower than the current study, will the aerosol suppress effect be expected? If so, how will aerosol effects on both characteristic vertical velocities as well as thermodynamic properties change with varied relative humidity?

<u>Answer:</u> Thank you for this important comment. This question was in the focus of several of our recent studies. Indeed aerosol effect on clouds depends on the environmental conditions (like RH and instability) as was shown in previous studies

((Fan et al., 2009;Seifert and Beheng, 2006;Khain et al., 2008;Lee et al., 2008) and in additional studies that focused on warm convective clouds- (Dagan et al., 2015a;Dagan et al., 2015b;Sato et al., 2018)). This dependence on the thermodynamic conditions can be explained by a competition between core and margin dominated processes, in which core processes have an adiabatic nature whereas margin processes are controlled by mixing and entrainment. In warm convective clouds the fuel for invigoration relies on core-oriented processes, i.e. enhanced condensation in elevated aerosol concentration conditions that increase the updraft and transport the smaller droplets (that have smaller effective terminal velocity) higher in the atmosphere. While clouds suppression processes are mostly periphery processes, i.e. enhanced evaporation that fuels stronger downdrafts and mixing (in addition to the suppressive effect of the water loading). Core processes take place within the core volume while margin processes occur on the interface between cloud and the ambient air. Therefore, in relatively small clouds for which the surface area to volume ratio is relatively large, entrainment will be a dominant process. On a similar manner, since entrainment is controlled by RH gradients, in drier conditions the entrainment is expected to be stronger. Therefore, in lower RH conditions or under initial conditions that support shallower clouds (for example under lower inversion base height) margin processes are enhanced as the aerosol concentration increases and therefore cloud suppression is expected to take place above a turning point that corresponds to lower aerosol concentration (lower optimal aerosol concentration) (Dagan et al., 2015a;Dagan et al., 2015b).

The important point for this comment is that the turning point between invigoration and suppression (the optimal aerosol concentration), and the slopes of those opposite trends are different when examining different clouds' properties. Cloud's properties that are more "core-oriented" (see examples below) will be more positively affected by aerosols. While cloud's properties that are more "periphery-oriented" will be more negatively affected by aerosols (Dagan et al., 2015a;Dagan et al., 2017).

The mass weighted mean air vertical velocity (w) is a "core-oriented" property because of two reasons: 1) the strongest air vertical velocities are found in the cloud core, and 2) the averaging by mass gives more weight to the more massive core than to the more diluted periphery (which contain, on average, lower liquid water content). Hence, even under drier or more stable initial conditions, *w* analysis will reflect more the core invigoration effect and will show a turning point at high aerosol concentrations. This can be seen in Fig. 7 taken from Dagan et al. (2015a) (shown below) which presents the maximum over time of w as a function of aerosol concentration for nine different sets of initial conditions spreading a wide range of environmental conditions as expressed by various relative humidity values and cloudy layer depths. It demonstrates that the invigoration part of the trend is much more significant than the suppression part for w. This is true compared with the other clouds' properties such as the total surface rain yield which is affected by the entire cloud and hence by both the cloud's core and periphery. Please note that the results presented in the manuscript demonstrate this behavior: the turning point corresponds to high aerosol loading with less significant suppression trend compared to the invigoration part of the trend (Fig. 1 in the manuscript shows that the 10000CCN simulation has a bit lower w than the 500CCN but it is higher than in the 25CCN simulation).



Figure 7. The cloud's maximum top height (top panels), the maximum over time of the mean vertical velocity weighted by the mass in each grid point (middle panels) and the total surface rain yield (bottom panels) as a function of the aerosol loading, for each simulated cloud as a function of the aerosol concentration. Each curve represents 10 simulations performed for an initialization profile (a total of 9 profiles). T1 represents a profile with an inversion layer located at 4 km, T2 at 3 km, and T3 at 2 km. RH1 represents a profile with 95% RH in the cloudy layer, RH2-90%, and RH3-80%. Taken from Dagan et al. (2015a).

To demonstrate that our simulations results are general we have conducted an additional set of simulations with drier initial conditions (RH=80% instead of 90%, as presented in the paper) and shallower cloudy layer (1 km instead of 3 km). This initial atmospheric profile is denoted as T3RH3 in Dagan et al. (2015a) and the results are presented in Fig. R1, below. In this shallower and drier cloudy layer the turning point between invigoration to suppression trend corresponds to lower aerosol concentration (Dagan et al., 2015a). However, even in this case (as in the case presented in the manuscript), the *w* of the two polluted clouds (500 cm⁻³ and 10000 cm⁻³) initially increase at the same rate while the clean cloud has lower *w*. The maximum *w* over time is higher for the most polluted cloud (10000 cm⁻³ - 2.16 m/s) compared to the cleanest cloud (25 cm⁻³ - 1.98 m/s) representing less significant role of the suppression part in the trend as compared to the invigoration part for *w*.

In this shallower and drier cloudy layer the aerosol concentration above which there is total rain suppression is lower than 500 cm⁻³ (see Fig. 7 above and Dagan et al. (2015b)). Thus, there is a sharp increase in $/\eta/$ (representing a significant amount of precipitation) only in the cleanest cloud (25 cm⁻³) for this initialization profile. However, during the growing stage of the clouds, $/\eta/$ demonstrates an increase in the droplet mobility also in this case. For example, after 40 min of simulation $\eta = -7.7 \cdot 10^{-4}$, $-8.2 \cdot 10^{-3}$ and $-5.3 \cdot 10^{-2}$ m/s for the simulations with the aerosol loading of 10000, 500 and 25, respectively.



Figure R1. (a) Mean vertical velocity (w), (b) mean effective terminal velocity (η), (c) mean vertical velocity plus effective terminal velocity, and (d) cloud center of gravity (COG) as a function of time for three different aerosol concentrations. This figure is the same as Fig. 1 in the manuscript but for initial atmospheric conditions representing shallower and drier cloudy layer.

In addition, please note that the SAM-LES results presented in this work are based on the BOMEX case study (Holland and Rasmusson, 1973;Siebesma et al., 2003) that describes less humid initial conditions (the RH in the cloudy layer decreases with height down to ~75%, with a mean over the cloudy layer of RH~84.5%) and shallower clouds (the cloudy layer depth is only ~1 km compared with ~3 km in the single cloud simulations). Hence, the single cloud simulations and the SAM-LES represent in a way two edges of the spectrum of initial conditions for warm convective clouds. Please also note that even under this less humid and shallower initial conditions the air vertical velocity increases with the aerosol concentration (Fig. 3 in the manuscript).

Regarding the evolution with time of the thermodynamic conditions (which is relevant for the cloud field simulations i.e. the LES). As the shift between precipitating to non-precipitating clouds occurs under different aerosol concentrations for different initial conditions (see Fig. 7 above) the transitions between consumption of the thermodynamic instability (under precipitating conditions) to increase in it (under non-precipitating conditions) is also initial conditions dependent. However, the trends under precipitating and non-precipitating conditions would be similar regardless of what the initial conditions are (only the aerosol concentration that marked the shift between them changes). An evidence for this claim can be seen in Fig. S2, in the supporting information of Dagan et al. (2016) (shown below). It presents the evolution with time of the mean virtual potential temperate vertical profile for precipitating (clean) and non-precipitating (polluted) conditions for three different large-scale forcing (LSF) conditions.

Under clean precipitating conditions, the cloudy layer (~550–1550 m) warms up with time, while the sub-cloudy layer cools down compared with the polluted non-precipitating simulations. The inversion layer (~1550–2000 m), in the polluted simulations cools down compared to the clean simulations regardless of the magnitude of the LSF.



Figure S2. Changes in the domain mean virtual potential temperature [K] profile as a function of time. Each subplot represents one simulation conducted under different aerosol loading conditions (50 and 2000 cm⁻³) and different large-scale forcing (LSF) conditions: the standard BOMEX LSF (panels a and b), no LSF (noLSF – panels c and d), and two times the standard BOMEX LSF (x2LSF – panels e and f). Taken from Dagan et al. (2016).

Following this comment, we have added clarifications to the revised manuscript:

"The results presented here were examined for a few different sets of initial conditions (different inversion-base heights and cloudy layer RH). Although for different initial atmospheric conditions the transition between aerosol invigoration to suppression occurs at different aerosol concentration (Dagan et al., 2015a), the conclusions were found to be general for different sets of initial conditions."

We also explain in the introduction the non-monotonic behavior and its dependency on the thermodynamic conditions:

"It has been recently shown (Dagan et al., 2015a;Dagan et al., 2015b;Dagan et al., 2017) that under given environmental conditions, warm convective clouds have an optimal aerosol concentration (N_{op}) with respect to their macrophysical properties (such as total mass and cloud top height) and total surface rain yield. For concentrations smaller than N_{op} , the cloud can be considered as aerosol-limited (Koren et al., 2014;Reutter et al., 2009), and an increase in the mean cloud properties with aerosol loading can be expected due to an increase in the condensation efficiency and droplet mobility (Koren et al., 2015;Dagan et al., 2015a;Dagan et al., 2017). Suppressive processes such as enhanced entrainment and water loading take over when the concentrations are higher than N_{op} and reverse the trend. It has also been shown that the value of N_{op} depends heavily on the environmental conditions (thermodynamic conditions that support deeper clouds would have a larger N_{op})."

The aerosol concentrations chosen for the single cloud simulations (Sec. 2.1 - 25, 500 and 10000 cm⁻³) represent conditions below, around and above the optimal aerosol concentration. This is explained in the revised manuscript:

"The background aerosol size distribution used here represents a clean maritime environment (Jaenicke, 1988). The aerosols are assumed to be composed of NaCl. The different aerosol concentrations (25, 500 and 10,000 cm⁻³, denoted hereafter as 25CCN, 500CCN and 10000CCN, respectively) and size distributions are identical to those used in Dagan et al. (2015a). To study the involved processes, we used a wide range of aerosol loading conditions, from extremely pristine to extremely polluted. These specified three aerosol concentrations represent conditions which are below, around and above the optimal aerosol concentration $(N_{_{op}})$."

Specific comments:

1. Fig. 4 show nicely the similar trend of COG velocity (VCOG) and the "authors defined-Angle" (A). The authors argued that the VCOG can be an indicator of thermodynamic instability and also of the aerosol effects on warm clouds. But for A, what can we learn from the evolution of it? Or does it have different function with VCOG? The amplitude of A seems depend on the relative amplitude of both velocities between the first and the last third part of simulation period, in other words, the order of peak time of both characteristic velocities for different aerosol scenarios. If w and (eta) peak earlier (at the first third stage in a clean run, for example) during the cloud lifetime, A might be around ~100 degree; whereas if they peak later (say at the last third part and may appear in polluted run), A might be around ~360 degree. I hope the authors give more information about how we can use the parameter A in the study of aerosol-cloud interactions.

Answer: Thank you for this comment. It helped us clarify this important issue. The angle *A* is relevant only for the cloud field simulations conducted with the SAM-LES model. In these simulations, many clouds at many different stages are present in the domain at any given time and *A* was calculated while averaging over each part of the simulations which covered many cloud's typical lifetime (4 hours and 40 minutes). Hence, *A* is not determined by the stage in the cloud lifetime in which $/\eta$ / or *w* peaks but rather it reflects the effect of the different evolution paths of the field's thermodynamic conditions (due to changes in the aerosol concentration) on the domain mean $/\eta$ / and *w*. If the thermodynamic instability decreases in time (as seen for the clean cases), both *w* and $/\eta$ / decrease in time and hence *A* is between 90° and 180°. While, if the thermodynamic instability increases in time (as seen for the polluted conditions) *A* is between 270° and 360° as both *w* and $/\eta$ / increase in time. This is explained in the manuscript:

"A between 90° and 180° (as shown for clean cases—Fig. 4b) represents a decrease in both w and $|\eta|$ and hence a decrease in the thermodynamic instability with time. A between 270° and 360°, on the other hand (as shown for the most polluted cases—Fig. 4b), represents an increase in both w and $|\eta|$ and hence an increase in the thermodynamic instability with time."

In the revised manuscript we emphasis that *A* reflects changes in the cloud fields' thermodynamic conditions rather than single cloud's processes.

"To quantify the evolution of the thermodynamic instability with time as a function of aerosol loading (on a cloud field scale), we looked at the time trends in the η vs. w phase space. We defined the angle 'A' as the angle between the time trend points on the η vs. w phase space per given aerosol loading (the line that connects the first and last thirds of the simulation and the x-axis on the η vs. w phase space —see schematic definition of A in Fig. 3b)."

Regarding the reviewer question about how can A be used in future works – any observational or modeling work that can follow the two characteristic vertical velocities over time, could estimate A and hence learn about the thermodynamic instability evolution with time. Following this comment, we have added the following part to the revised summary:

"We have defined the angle A, which represents the evolution of the thermodynamic conditions with time. A can serve as a compact measure of the thermodynamic instability evolution in future observational or numerical studies that quantify w and η ".

2. The authors split the simulation period into 3 parts for the analysis of LES runs in Fig. 3a. Does the three parts stand for different stages of cloud evolution? And in Fig. 3b, "only clouds in the growing stage" were considered for the first and the last third part of simulation period. I am confused here. What should we expect for growing clouds at different part of simulation period?

<u>Answer:</u> Thank you. As noted in the previous point, the separation into 3 periods of simulation was done in order to illustrate the effects of changes in the thermodynamic

properties in time for the whole cloud field. Each period captures many clouds at different stages of evolution. It describes the evolution of the mean thermodynamic properties of the domain, which evolve on longer time scales than the typical cloud lifetime (Dagan et al., 2016). However as the reviewer pointed out, to learn more about the aerosol effect on the two characteristic vertical velocities we have used a cloud tracking algorithm (Heiblum et al., 2016a) to follow individual clouds in the domain and to determine the stage in their lifetime. In Fig. 3b we present the same analysis presented in Fig. 3a but only for the clouds that were identified as "growing stage" clouds (clouds with an ascending top). This method allows us to separate the clouds in the domain based on the stage in their evolution even though we used cloud field simulations with many clouds in the domain. This analysis was conducted throughout the entire simulations and hence can be divided to the different periods in the simulations in the same way that was done in Fig. 3a.

The part in the text in which we explain that the cloud field simulations include many clouds at different stages:

"In the single-cloud-scale analysis (section 3.1), we showed how the timing of the evolution of the two velocities dictates the aerosol effect. Here, having many clouds in the field in different stages of their lifetimes, we first analyzed the bulk properties of the two velocities."

The explanations in the text regarding the division of the simulations to three periods:

"To include the aerosol effect on the cloud-field thermodynamic properties, we divided the simulation period into three equal thirds (excluding the first 2 h, each third of a period covered 4 h and 40 min). The x and * markers in Fig. 3a represent the first third (2 h to 6 h 40 min into the simulation) and last third (11 h 20 min to 16 h into the simulation), respectively. During the first third, the slope of w vs. η was steeper than the mean over the entire simulation (slope of 0.92 with $R^2 = 0.96$); during the last third, it was more gradual (slope of 0.47 with $R^2 = 0.87$). The almost 1:1 relation between w and η in the first third of the simulation period suggests a comparable contribution in determining the aerosol effect on mean COG height. However, the relative contribution of η decreases as the simulation progresses, to about 1/3 during the last third of the simulation period (compared with 2/3 of w).

The decrease in the w vs. η slopes toward the end of the simulations is driven by the changes in the thermodynamic instability. The increase in instability under polluted conditions produces an increase in mean w (Dagan et al., 2016). Nevertheless, increased instability and deepening of the cloud layer are not sufficient to produce a significant amount of rain under the most polluted simulations and hence, there is no increase in the magnitude of η . An increase in w with no change in η is manifested as a horizontal shift to the right on the η vs. w phase space (red arrow in Fig. 3a). On the other hand, the decreased instability under clean conditions produces a decrease in both mean w and the rain amount (Dagan et al., 2017), and therefore in $|\eta|$ (blue arrow in Fig. 3a). The end result of the different changes in w and η under clean and polluted conditions is a decrease in the slope of η vs. w and therefore, a decrease in the relative contribution of η to the aerosol effect on the mean COG."

The explanation regarding the cloud tracking algorithm analysis:

"In Fig. 3a, the presented quantities are domain and time averages. Figure 1 showed that the relative contribution of w and η to the aerosol effect on COG height strongly depends on the stage of the cloud's evolution. The averaging in Fig. 3a mixes many clouds at different stages in their evolution and represents the effect on the mean COG in the domain. To further explore the relative contribution of the aerosol effect on w and η as a function of cloud-evolution stage, we used a cloud-tracking algorithm (Heiblum et al., 2016a). We identified the growing stage of the clouds as the stage for which the cloud top ascends. Figure 3b presents the η vs. w phase space only for clouds in their growing stage. Table 1 presents the slopes of the linear regression lines for the entire simulation time and for the different thirds of the simulation period."

3. Fig. 1c and 1d show that VCOG became negative after 65 min for clean run (blue curve), but COG height continues to increase until the end of the simulation. What is the reason for that, since negative VCOG seems denote the downward movement of center of gravity of cloud?

<u>Answer:</u> Thank you very much for this important comment. Indeed after 65 min of simulation, V_{COG} of the cloud simulated under aerosol concentration of 25 cm⁻³

becomes negative while it's COG height continues to increase. The V_{COG} represents the vertical velocity of the COG while, the COG is calculated based on the liquid water mass vertical distribution. There are processes, other than water mass movement, that affect the mass distribution in clouds. Specifically, condensation, evaporation and removal of mass to the surface by rain sedimentation change the vertical location of the COG in addition to the impact of the V_{COG}. For example, we can think of a case in which V_{COG} is negative but in parallel, there is a significant mass removal on the lower part of the atmosphere (by evaporation below cloud base and/or rain reaching the surface). In such case despite the negative velocity, recalculations of the COG at every time step may yield an increase in the COG height.

Following this comment, we have added clarifications regarding this point to the revised manuscript:

"We note that the vertical change in the COG height is determined by changes in the vertical distribution of water mass due to microphysical processes like condensation, evaporation and removal of mass by rain (in addition to movement according to V_{COG}). Hence, in some parts of the simulations the V_{COG} was not a perfect predictor of the COG evolution. This is especially true when rain and evaporation are strong i.e. toward the end of the clouds' lifetime".

4.L275: "and therefore delaying the increase in (eta) values early in the cloud's lifetime", I think (eta) should be |eta|. The value of (eta) is originally negative. I suggest the authors check the descriptions of |eta| and (eta) in the manuscript carefully.

<u>Answer:</u> Right! Thank you for catching this point. It was corrected here and checked along the whole paper as well:

"As shown for the cloud scale, one of the most notable aerosol effects can be viewed as delaying the onset of significant collection processes in the polluted clouds (Koren et al., 2015), and therefore delaying the increase in $|\eta|$ values early in the cloud's lifetime."

Reviewer 2:

The study is dedicated to analysis of general properties of a warm cumulus clouds on aerosol loading. The analysis is performed in the terms of Center of Gravity (COG) behavior. It is shown that aerosols induce cloud invigoration, and that the effects are maximum at the developing cloud stage. The paper is of interest. The approach to the analysis is original. The study is recommended to publication with minor revisions.

Answer: We thank the reviewer for the important comments and questions that helped us making this work clearer. We were happy that the paper was found to be interesting.

The comments and remarks are listed below.

1. Line 13. Which processes do you mean? Trends of which? Be more specific.

Answer: Thank you. In this paragraph, we meant to say that the aerosol effect on warm convective clouds was shown to be non-monotonic. Following this comment, we have changed this sentence to be clearer:

"Better representation of cloud–aerosol interactions is crucial for an improved understanding of natural and anthropogenic effects on climate. Recent studies have shown that the overall aerosol effect on warm convective clouds is non-monotonic. Here, we reduce the system's dimensions to its center of gravity (COG), enabling distillation and simplification of the overall trend and its temporal evolution."

2. line 75. Clarify, what is "clean precipitation conditions".

Answer: Thanks you. We have clarified it in the revised manuscript:

"A negative V_{COG} implies net transport of the liquid water from the cloudy layer to the sub-cloud layer. This holds true for clean (low aerosol concentration) precipitating cases (Dagan et al., 2016), in which the water that condenses in the cloudy layer sediments down to the sub-cloud layer where it partially evaporates."

3. line 94. Why does mixing increase? Seigel (2014) explains this effect by stronger evaporation of smaller droplets in polluted cases.

Answer: Indeed, a mechanism of evaporation-entrainment feedback that increases the mixing between the cloud and its environment was previously reported in studies of aerosol effects on warm clouds. It was shown that increased evaporation rate (of the smaller droplets) at cloud's margins enhances the rates of entrainment and mixing between the cloud and its environment under polluted conditions (Small et al., 2009;Jiang et al., 2006;Xue and Feingold, 2006;Seigel, 2014;Dagan et al., 2015a).

We added clarifications to the revised manuscript:

"Seigel (2014) showed an increase in w with increasing aerosol loading in the cloud core in numerical simulations of a warm convective cloud field. He also showed a decrease in cloud size under polluted conditions due to increased mixing between the clouds and their dry environment driven by stronger evaporation of smaller droplets in polluted cases."

4. line 99. Do you mean accumulated rain at the surface?

<u>Answer:</u> Yes. We added clarification to the revised manuscript:

"It has been recently shown (Dagan et al., 2015a;Dagan et al., 2015b;Dagan et al., 2017) that under given environmental conditions, warm convective clouds have an optimal aerosol concentration (N_{op}) with respect to their macrophysical properties (such as total mass and cloud top height) and total surface rain yield."

5. line 102. The sentence is not clear. What does a "correlation between aerosols and cloud properties" mean? Be more specific.

<u>Answer:</u> Thank you. Indeed, we have written this sentence in a condense form. Following this comment we have modified it:

"For concentrations smaller than N_{op} , the cloud can be considered as aerosol-limited (Koren et al., 2014; Reutter et al., 2009), and an increase in the mean cloud properties

with aerosol loading can be expected due to an increase in the condensation efficiency and droplet mobility (Koren et al., 2015; Dagan et al., 2015a; Dagan et al., 2017)."

6. Line 110. What do you mean presenting the references? How is the study by Grabowski et al., 2006 related to the COG behavior?

<u>Answer:</u> Thank you. This reference is indeed not needed and we have removed it from the revised version.

7. line 115. Can you comment the choice of the model? The axisymmetric model may have problem because rain mass (mass loading) is located in the cloud center substantially decreasing updrafts. Such configuration may decrease the generality of the conclusions, because even small wind shear may form a moment between updrafts caused by buoyancy and downdrafts caused by mass loading and other factors.

Answer: Thank you for this important comment. We agree that an axisymmetric model describes an idealized and simplified form of a full 3D flow. It cannot capture processes that deviate from symmetry on the cloud scale (such as wind shear). Moreover, such a model does not account for larger (cloud-field scale) processes. We use it as a conceptual model to inspect first order coupling between microphysical and dynamical processes in an ideal way. The essential microphysical processes affecting finer scales and the basic cloud dynamics are well captured in this model. Both as a "sanity check" and in order to explore feedbacks on the cloud field scale, the second part of this study is dedicated to analysis of a full bin-microphysics 3D LES cloud-field model that accounts for the larger scale processes and, as the Reviewer mentioned, wind shear that might affect the clouds' development. The fact that the two different models (focusing on different scales) show consistent results reassured us that the described conclusions are general and helped us to describe how processes that start in the small (in-cloud) scale are reflected and affect the larger scale.

Following this comment, we have added a discussion about the axisymmetric model limitations to the "Methodology" section in the revised manuscript:

"The axisymmetric model uses a geometry that is only a simplification and idealization of a full 3D flow and does not account, for example, for wind shear and processes acting on larger scales like clouds effect on the environmental conditions with time. For accounting for these processes, we used 3D cloud field scale simulations as well (see Sec. 2.2 below)."

The possible effect of wind shear is now also mentioned at the beginning of Sec. 3.2:

"Shifting our view from the single-cloud scale to the cloud-field scale adds another layer of complexity as clouds affect the way in which the whole field's thermodynamics evolve with time. Moreover, 3D simulations account for the effect of wind shear."

Moreover, in the revised summary we also mention this point:

"Similar to the single-cloud case, the cloud field (LES) results (that unlink the single clouds simulations, account for 3D processes such as wind shear) demonstrated an increase in w and decrease in the magnitude of η (less negative η) with aerosol loading, both yielding a higher COG."

8. line 119. Tzivion et al. refer the method they developed to as microphysical method of moments (MMM). The name "two-moment bin method" is somehow confusing, because alternative SBM method used in SAM calculates size distribution functions and the values of any moment of DSD in each bin.

Answer: Thanks. Following this comment this sentence was changed in the revised manuscript:

"The microphysical processes were formulated and solved using the method of moments (Tzivion et al., 1987)."

9. line 135. The sentence is not clear. Results certainly should depend on inversionbase heights, and RH in cloud layer. **Answer:** Thank you. This question was in the focus of several of our recent studies. Indeed aerosol effect on clouds depends on the environmental conditions like RH in the cloudy layer, wind shear and inversion height ((Fan et al., 2009;Seifert and Beheng, 2006;Khain et al., 2008;Lee et al., 2008). It was shown also in studies that focused on warm convective clouds- (Dagan et al., 2015a;Dagan et al., 2015b;Sato et al., 2018)).

It was shown that under drier conditions or under initial conditions that support shallower clouds (for example under lower inversion base height) the invigoration effect turns into suppression effect under lower aerosol concentration (Dagan et al., 2015a;Dagan et al., 2015b). However, in this sentence we were referring only to the results presented in this study.

To demonstrate that our simulations results are general we have conducted an additional set of simulations with drier initial conditions (RH=80% instead of 90%, as presented in the paper) and shallower cloudy layer (1 km instead of 3 km). This initial atmospheric profile is denoted as T3RH3 in Dagan et al. (2015a) and the results are presented in Fig. R1, below. In this shallower and drier cloudy layer the turning point between invigoration to suppression trend corresponds to lower aerosol concentration (Dagan et al., 2015a). However, even in this case (as in the case presented in the manuscript), the *w* of the two polluted clouds (500 cm⁻³ and 10000 cm⁻³) initially increase at the same rate while the clean cloud has lower *w*. The maximum *w* over time is higher for the most polluted cloud (10000 cm⁻³ - 2.16 m/s) compared to the cleanest cloud (25 cm⁻³ - 1.98 m/s) representing less significant role of the suppression part in the trend as compared to the invigoration part for *w*.

In this shallower and drier cloudy layer the aerosol concentration above which there is total rain suppression is lower than 500 cm⁻³ (see Fig. 7 above and Dagan et al. (2015b)). Thus, there is a sharp increase in $/\eta/$ (representing a significant amount of precipitation) only in the cleanest cloud (25 cm⁻³) for this initialization profile. However, during the growing stage of the clouds, $/\eta/$ demonstrates an increase in the droplet mobility also in this case. For example, after 40 min of simulation $\eta = -7.7 \cdot 10^{-4}$, $-8.2 \cdot 10^{-3}$ and $-5.3 \cdot 10^{-2}$ m/s for the simulations with the aerosol loading of 10000, 500 and 25, respectively.



Figure R1. (a) Mean vertical velocity (w), (b) mean effective terminal velocity (η), (c) mean vertical velocity plus effective terminal velocity, and (d) cloud center of gravity (COG) as a function of time for three different aerosol concentrations. This figure is the same as Fig. 1 in the manuscript but for initial atmospheric conditions representing shallower and drier cloudy layer.

In addition, please note that the SAM-LES results presented in this work are based on the BOMEX case study (Holland and Rasmusson, 1973;Siebesma et al., 2003) that describes less humid initial conditions (the RH in the cloudy layer decreases with height down to ~75%, with a mean over the cloudy layer of RH~84.5%) and shallower clouds (the cloudy layer depth is only ~1 km compared with ~3 km in the single cloud simulations). Hence, the single cloud simulations and the SAM-LES represent in a way two edges of the spectrum of initial conditions for warm convective clouds. Please also note that even under this less humid and shallower initial conditions the air vertical velocity increases with the aerosol concentration (Fig. 3 in the manuscript).

Following this comment, we added clarification to the revised manuscript:

"The results presented here were examined for a few different sets of initial conditions (different inversion-base heights and cloudy layer RH). Although for different initial atmospheric conditions the transition between aerosol invigoration to suppression occurs at different aerosol concentration (Dagan et al., 2015a), the conclusions were found to be general for different sets of initial conditions."

10. line 151. The title is not suitable, in my opinion. The simulations with a single cloud model discussed in section 2.1 is also LES. The authors, supposedly, want to stress that in SAM they simulate cloud

Answer: Thank you. Following this comment the title of this section was changed to:

"2.2 Cloud field simulations"

11. line 165. How were the mean values calculated? Over entire cloud?

Answer: The mean values are calculated over the entire cloud and they are weighted by the liquid water mass in each grid cell. This is done for consistency with the COG point of view:

This is explained in the Methodology section:

"To examine the effect of aerosols on the entire cloud, the properties presented in this work are cloud mean values weighted by the liquid water mass in each grid cell. Cloudy grid cells were defined as cells with liquid water content larger than 0.01 g/kg. The cloud's COG (Koren et al., 2009) was calculated as:

$$COG = \frac{\Sigma m_i z_i}{\Sigma m_i} \tag{1}$$

where m_i and z_i are the mass [kg] and height [m] of voxel i, respectively.

The n (*effective terminal velocity*) *was calculated according to Koren et al.* (2015):

$$\eta = \frac{\Sigma V t_j m_j n_j}{\Sigma m_j n_j} \tag{2}$$

where V_{t_j} , m_j and n_j are the terminal velocity [m/s], mass [kg] and concentration $[cm^{-3}]$ of droplets in bin *j*, respectively. This was calculated for all cloudy grid cells.

For being consistent with the COG point of view, the mean air vertical (w) was calculated as a mean weighted by the liquid mass:

$$w = \frac{\sum m_i w_i}{\sum m_i} \tag{3}$$

Following this comment, we added clarification and references to the relevant equations in the revised manuscript:

"Starting from the single-cloud scale, we first followed the entire cloud mean w (eq. 3), mean η (eq. 2), mean V_{COG} , and COG height (eq. 1) as a function of time for the three different levels of aerosol loading (25, 500, and 10,000 cm⁻³)."

12. line 196. Can you comment the potential effect of the fact that the model used is axisymmetric? The effect of wind shear should be very significant.

Answer: following the reviewer comment, we added a comment about the wind shear effect:

"Shifting our view from the single-cloud scale to the cloud-field scale adds another layer of complexity as clouds affect the way in which the whole field's thermodynamics evolve with time. Moreover, 3D simulations account for the effect of wind shear."

In addition, please see our answer to comment No. 7.

13. line 209. Please clarify what is "weighted by the liquid water mass". Please present expression used for the calculation.

<u>Answer:</u> Thank you for this comment that helped us clarify this point. Following this comment, we added an expression explaining the calculation to the revised Methodology section:

"For being consistent with the COG point of view, the mean air vertical (w) was calculated as a mean weighted by the liquid mass:

$$w = \frac{\sum m_i w_i}{\sum m_i} \tag{3}$$

We also added reference to this equation in the revised text:

"Figure 3 presents the domain's mean w (in both space and time, weighted by the liquid water mass to be consistent with the COG view – see eq. 3 above) vs. the domain mean η ."

In addition, please see our answer to comment No. 11.

14. lines 213-214. Saleeby et al. and Seigel use RAMS bulk parameterization scheme. Do you suppose that this scheme describes increase in the latent heat release by the increase in aerosol loading?

<u>Answer:</u> Many bulk microphysical schemes use "saturation adjustment" approximation (which is not used in bin microphysical schemes). Under this approximation all available supersaturation is instantly condensed into liquid water and saturation is maintained. Hence, it does not account for the time needed for consumption of the available supersaturation and therefore it represents the upper limit of latent heat release (Heiblum et al., 2016b). The inaccuracy caused by this approximation is larger for clean conditions (Heiblum et al., 2016b).

However, the bulk microphysical scheme (in the RAMS) used in Seigel (2014) and Saleeby et al. (2015) do not relay on "saturation adjustment"; citing from Seigel (2014) describing the scheme:

"Once hydrometeors are present, an efficient, noniterative method of computing fully interactive vapor and heat diffusion between hydrometeors and air is used that includes a supersaturation computation and does not require a saturation adjustment (Walko et al. 2000)."

Hence, it is indeed expected that the increase in the air vertical velocity with the aerosol concentration shown in Seigel (2014) and Saleeby et al. (2015) would be because of the increase in latent heat release.

The explanation provided in Saleeby et al. (2015):

"Over most of the vertical profile there are increases in both domain wide (Fig. 9a) and in-cloud (Fig. 9b) updraft strength with an increase in [CCN]. Within this warm-rain cloud system there is a thermo-dynamic feedback linking cloud microphysics and vertical velocity whereby condensation growth of cloud droplets (Fig. 7a) releases latent heat, which increases buoyant forcing of the updrafts. In turn, vertical motion lifts an air parcel, which saturates, and allows for further condensation and latent heating. Once an initial updraft forms, the more numerous cloud droplets within polluted conditions allows for more efficient vapor consumption and condensation and further invigoration."

We note that in Seigel (2014) the increase in the air vertical velocity with aerosol loading was also explained by the narrowing of the polluted clouds (which is caused by enhanced evaporation rates of the smaller droplets). These narrower clouds must have stronger air vertical velocity to maintain almost constant convective mass flux.

In this sentence, we acknowledge that the trend of increase in air vertical velocity with aerosol loading (in warm convective clouds) was reported before, even if it was explain by different reasons (in the case of Seigel (2014)).

To make this point clearer we added clarification to the revised manuscript:

"In agreement with previous studies (Saleeby et al., 2015; Seigel, 2014), an increase in aerosol loading yielded an increase in w. In our simulations, this increase is driven by larger latent heat contribution to the cloud's buoyancy due to the increased condensation efficiency (Dagan et al., 2015a; Dagan et al., 2017; Koren et al., 2014; Pinsky et al., 2013; Seiki and Nakajima, 2014) and thermodynamic instability (Dagan et al., 2016; Dagan et al., 2017)." 15. Conclusion section. It would be important to add a discussion about the applicability of the results to evaluation of aerosol effects on radiative cloud properties, on precipitation amounts, etc.

Answer: Thank you. We agree that such addition is needed. Following this comment we added a short discussion about the connection of the results presented in this manuscript and the aerosol effect on the water and radiation budgets.

"Better process-level understanding of aerosol effect on cloud and rain properties in the case of warm convective clouds is essential for improving our understanding of the climate system. In this study, our aim was to better understand and quantify the aerosol effect on the air vertical velocity and droplet terminal velocity. Both characteristic vertical velocities quantities modulate the distribution of water along the atmospheric column, and hence affect the radiation (Koren et al., 2010) and heat balance (Khain et al., 2005). The findings presented here for the single cloud and cloud field scales could be used in future works to better represent cloud-aerosol interactions in coarser resolution models (like climate models) as it provides a compact way to represent aerosol effect on the liquid water vertical mass flux and clouds effect on the thermodynamic conditions."

Moreover, we also added discussion about how can the defined angle from this study '*A*' be used in future works. Specifically, any observational or modeling work that can follow the two characteristic vertical velocities over time, could estimate *A* and hence learn about the thermodynamic instability evolution with time.

"We have defined the angle A, which represents the evolution of the thermodynamic conditions with time. A can serve as a compact measure of the thermodynamic instability evolution in future observational or numerical studies that quantify w and η ".

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