Reply to anonymous referee RC1

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The Manuscript entitled "An analysis of the September 2015 severe dust event in the Eastern Mediterranean" describes in great detail the mechanisms of the dust storm episode using the ICON model coupled with a desert dust module (ART). The paper is very well written and I would recommend it to be published on ACP after the following comments have been addressed:

We would like to thank the referee for thoroughly reading our manuscript and providing meaningful questions. Below we provide our answers and changes made to the manuscript in response to your helpful comments.

Q1) Abstract, Line 3: The authors state that "...state-of-the-art dust transport models were unable to forecast the event. . .". I don't think this is accurate. For example the publication of Solomos et al. (2017) in ACP describes the same episode using another model. I think that the two manuscripts were submitted very close to each other and the authors were not aware of this, even though they give reference to this work when it was still in ACPD. Please correct this statement accordingly. This is present in other areas of the manuscript as well and should also be corrected.

A1) Thank you for this comment, we think it needs a detailed discussion and clarification. By using the term state-of-the-art dust transport models we referred to the global dust forecast models which provide continuous dust forecasts on an everyday basis. From our point of view ICON-ART, being a global dust forecast model, is comparable to these models with the added feature of allowing flexible grid refinements. The driver of our dust simulations is also a global ICON-ART dust forecast with 40 km grid spacing, which gives similar results to the other models when used without the local grid refinement. We have changed the text and now call them 'operational' in order to make our intended statement more clear. We have included references to the Solomos et al. (2017) publication and their modelling study, however, we would like to limit our references to the Solomos et al. (2017) publication in the main analysis section, as our results are not comparable or even contradict theirs to a great extent. We think that our results can provide a much more detailed and accurate description compared to Solomos et al. (2017), which is necessary to understand this event. We would like to highlight some important differences which are crucial in our opinion, but avoid doing so in our manuscript as it will take up too much space there.

1. Solomos et al. (2017) do not use a global dust forecast model and they do not use their model in normal forecast mode but assimilate additional radiosonde data. In addition, they tune their model and dust emission scheme without giving the specific settings ("RAMS–ICLAMS in this study is not used in forecasting mode, but rather as a tool for the a posteriori analysis and explanation of the event. This means that the configuration of several model parameters, such as the nested grid structure, convective parametrization schemes, and dust source strength, is

guided by the available observations.", Solomos et al. 2017). We do not assimilate any additional data or modify ICON-ART model physics for our simulation of the event, but use the same version as used for other studies.

2. They do not identify the synoptic situation as an active Red Sea trough situation which explains the highly unusual dust transport direction and is responsible for the unique character of the event due to its very early occurrence at the beginning of September.

3. Their highest resolution, convection permitting domain with 2 km grid spacing covers only the Turkey-Syria-Iran-Iraq border region (Fig. 1, Solomos et al. 2017), whereas our simulation covers the whole region at convection permitting resolution (please see the attachment to this reply, 1). Due to the large spatial extent of the meso-scale convective system, their domain is far too small to capture the full MCS development and its related flow structures (compare Fig. 6 in this manuscript). Because of this, they are unable to identify the different event stages and the individual, consecutive cold-pool outflows. Consequently they do not achieve a meaningful dust distribution, both in spatial coverage as well as magnitude, as a comparison with the satellite data provided in our work reveals. This results in them being unable to link the different dust plumes to the meteorological drivers correctly. They do not mention or investigate the transport direction of the main dust plumes (CPO2 and CPO3 in our work) towards the south-west across Syria, into Jordan and further onwards to the southern EM at all. We would like to describe some of the discrepancies which we found in more detail:

   - They present simulated peak AODs above 20 next to large areas of AODs in the range of 1-3 (Fig. 4, Fig. 5, Fig. 12, Solomos et al. 2017). An AOD above 20 as well as its spatial extent are highly unrealistic when compared to satellite observations. AODs below 1 are not identifiable from their color scale, further complicating the analysis as in reality large areas were covered by AODs of less than 1. They do not compare their spatial model results to spatially quantifiable observations (e.g. MODIS AOD, MODIS VIS). The SEVIRI images shown by them are highly distorted map projections and cannot be translated into any quantitative measure, therefore they lack the information necessary to decipher the event.

   - No bimodal maximum with AOD values greater 20 was observed in the dust plume structure around the heat low on 06 September 2015 above Syria and no ’closed cyclonic flow’ existed as is stated by them (Fig. 4c, Solomos et al. 2017, compare Fig. A1 in this manuscript as well as EUMETSAT animation of the event, the observed maximum was 2.78 with a drastically different horizontal structure). As this presents the beginning of their simulation this result is problematic.

   - Their simulated cold-pool spreads towards the north. As we show in this manuscript this is not the observed direction of travel (which is westward / south-westward) and the spatial cold-pool extent is far too small (compare Fig. 7b, Solomos et al. 2017). As cold-pools are the main drivers of the event, this finding is problematic.

   - No widespread areas of AOD values greater 15 were observed over eastern Syria at 00 UTC 07 September 2015. In addition, the location of clouds is misrepresented in their results (over Syria, Iraq and Turkey in Solomos et al.

2017, compared to over Iraq, Iran in EUMETSAT observation. Compare Fig. 5a Solomos et al. 2017, and A2 in this manuscript, due to the distorted EUMETSAT picture this is disguised in their publication). They do not provide their modelled wind fields for the important event stage at 00 UTC 07 September (Fig. 5, Solomos et al. 2017). In addition, the structure of the dust plume apparent from CALIPSO is not visible in their model results. As this presents a crucial event stage, this finding is problematic.

- They neither provide an overview of the different cold-pool outflows contributing to the event nor do they decipher the timing of the cold-pools. They do not provide an analysis of the cold pool or dust plume structures during 07 September 2015, which is the main event day, nor do they provide a quantitative comparison on this day. The only plot they provide during 07 September 2015 is Fig. 10 (compare Fig. 6 in this manuscript). There, they compare a highly distorted (see direction of Eastern Mediterranean and position of Iraq), north-centred EUMETSAT image to a different Lambertian projection from RAMS which in addition does not display the AOD quantity shown before. In their analysis are lacking:

(a) An analysis of the dust plume structure with the marked features (compare Fig. 6 in this manuscript).

(b) A quantitative comparison of the spatial dust plume structure to MODIS VIS or AOD.

(c) Their modelled wind fields or a measure to identify the cold-pool outflow borders.

(d) A representation or comparison of the modelled MCS or cloud structure in general.

The above items are crucial for the understanding of this event. The comparison to CALIPSO in Fig. 10c and d further highlights the problems of their simulation. The maximum dust concentrations are achieved north of 36° N in Solomos et al. (2017), where in reality a clear local minimum was observed, this is both visible in the map display as well as the vertical cross-section (compare Fig. 6 and Fig. 7 in this manuscript).

- On 08 September the spatial dust plume distribution around Cyprus does not represent observations with AOD values above 10 next to large regions of 1 (Fig. 12 in Solomos et al. 2017). The Solomos et al. (2017) local minimum with AOD values of 1 to the east of Cyprus was actually where the maximum was observed (see A4 this manuscript). Furthermore, there is an increase to unrealistic AOD values above 10 towards Syria and Lebanon, which was also not observed. From the EUMETSAT animation, MODIS VIS and ICON-ART model results it is clear that the dust transport direction towards Cyprus was not from the south as stated twice in the publication but from the east. There is no discussion of this problematic model result given in the publication; on the contrary the simulation results are compared to measurements while saying that the model captures the situation correctly. A time series comparison between model and station measurements for the temporal evolution of e.g. PM10 is lacking, even though measurements are available to the authors in Cyprus (Mamouri et al., 2016).

4. Solomos et al. (2017) provide physical explanations of the mechanisms leading to the cold pool development which appear unrealistic. The temperature difference between rain droplets and ambient air is not known as dominant driver of cold-pool formation in literature (Knippertz et al., 2009; Marticorena, 2014) and it seems

unlikely that this could be the case as is also noted by one of their reviewers. What can strengthen cold-pool formation is the descent of frozen hydro-meteors into sub-saturated air masses (besides a deep, dry-adiabatic mixed layer, high rain water mixing ratios and small raindrop sizes), however, Solomos et al. (2017) do not investigate this. In addition, droplet- ambient air temperatures of -20°C exist in regions where no clouds were observed (e.g EM) ("A number of atmospheric parameters that determine the formation of the cold pool are shown in Fig. 7a–d. As seen in Fig. 7a, the iso-temperature line of -20 °C between rain droplets and ambient air temperature clearly defines the cold pool area.", Solomos et al. 2017).

In comparison, ICON-ART shows a much better agreement spatially, temporally and magnitude wise. It is able to reproduce all major structures observed by satellite in great detail. We do not think that our simulation results are the best possible result which can be achieved and we know that further improvements will be made in the future, especially with respect to the magnitude of dust emission and concentrations. However, our simulation captures important meteorological event stages and drivers leading to its unique character and structure which is proven by the extensive comparison with measurement data. By doing so, we are able to provide a detailed description of the event course, its stages and responsible drivers. Concluding from the points listed above, we do not think that Solomos et al. (2017) were able to achieve this and we would like to limit our references as we think that there is very little agreement between the studies. In order to make the reader aware of these discrepancies, we added several critical references to the work of Solomos et al. (2017). As before, we continue to refer to Solomos et al. (2017) for their coherent analysis of the Mesopotamia soil degradation over the past decade.

N1)

Sec. 1: Adding to the extraordinariness, state-of-the-art operational global dust transport models were unable to forecast the event as is also noted by Mamouri et al. (2016). In the simulations started at 12 UTC 07 September, none of the models is able to forecast a significant dust concentration in the EM region for 12 UTC 08 September (see All predictions provided through the World Meteorological Organizationdust forecast comparison's Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS, http://sds-was.aemet.es) . This is despite the fact that some of the models use data assimilation of satellite dust optical depth data. initialised at 12 UTC 07 September failed to simulate significant dust concentrations in the EM region for 12 UTC 08 September. The simulated values of the dust optical depth in the EM are between $0.1-0.4$ in the multi-model mean with a standard deviation of $0.1-0.2$. The forecast failure is highly problematic due to the severe impact of the event.

Sec. 1: However, to our knowledge a detailed analysis of the driving atmospheric systems and their interaction has not been published so far. Solomos et al. (2017) model the event at convection permitting resolution, however, the spatial extent of their convection permitting domain is chosen too small and does not cover the full MCS region. Consequently, their model fails to reproduce the observed CPO outflow structures and connected dust plumes correctly (see discussion in Sec. 3.2 and 3.3).

Sec. 3: The For the global grid, ICON-ART simulation results produces results comparable to those from other global models. However, due to its flexible nesting capability, it allows for convection permitting simulations for the finest resolution. As is shown in this section, ICON-ART is thereby able to resolve the meteorological drivers of the event in great detail. The results show that the dust event consists of multiple stages and is created by the interaction of different meteorological systems.

Sec. 3.2: Our analysis contrasts the simulation results by Solomos et al. (2017, their Fig. 4c), who model AOD values above 20 already before the onset of strong downward mixing of momentum. Furthermore, their modelled bimodal maximum dust distribution was not observed by satellites and no closed cyclonic flow around the heat flow appears to have existed.

Sec. 3.2: ~~(a~~ The above findings again contradict those of Solomos et al. (2017, their Fig. 7b), who in their model results find a northward travel direction of a small cold-pool structure. Based on the good agreement between ICON-ART and satellite observations this result is implausible. Furthermore, the intensity and spatial extent of their modelled CPO is much too small.

Sec. 3.3 When comparing our results to those of Solomos et al. (2017, their Fig. 10), again large differences become apparent, both in spatial dust plume structure as well as vertical dust distribution. The driving MCS and related CPOs and their clearly marked borders discussed above are not identifiable in their model results and they do not provide a detailed analysis of the flow structures.

Q2) Page 3, Line 20: The 3rd research question posed by the authors is "What are the meteorological drivers responsible for pick-up and long-range transport of mineral dust?". It is not clear of they mean in general or in cases such as the event described in the manuscript, because the dust-cycle mechanisms in general are well known and documented. Please rephrase

A2) We rephrased the sentences to be

N2) (3) What are the meteorological drivers responsible for pick-up and long-range transport of mineral dust during this event?

Q3) Page 4, Line 15: You state that ". . .the seamless modelling capabilities of ICON are of crucial importance because inconsistencies in tracer transport and tracer physics at the nest boundaries can be avoided. . .". Please remove the word "seamless". Also I cannot understand how these inconsistencies are avoided. Please expand.

A3) We removed the word seamless and rephrased the paragraph to explain in more detail which inconsistencies we are talking about.

N3) For the tracer transport simulations the ~~seamless~~ modelling capabilities of ICON are of crucial importance because the same physical parametrization packages can be used from a global to regional scale. Thereby, inconsistencies in tracer ~~transport and tracer physics at the nest boundaries~~ concentrations arising from differences in tracer advection and physical parametrizations between the driving model and the high-resolution model can be avoided~~, which is a major problem for other modelling systems~~.

Q4) Page 4, Line 22: What do you mean by sedimentation? Does it refer to the sandblasting mechanism for production or the deposition of particles?

A4) By Sedimentation we mean gravitational settling. We have modified it accordingly.

N4) The processes which affect mineral dust number and/or mass concentrations in ART are ~~sedimentation, dry deposition~~ gravitational settling (sedimentation), deposition due to turbulent diffusion and wet deposition due to washout.

Q5) Page 5, Line 9: It is important to see how the model defines the dust sources between the nests. Are they defined separately for each domain? If so how do you assure there are no continuity problems in the fields? Is this what you mean in Page 4, Line 15 (see comment 3)?

A5) We are using a physical parametrization for mineral dust emission which depends on different external datasets. As now stated above (see our answer to comment Q3, A3), this parametrization is the same for each domain. The horizontal grid on which the information from the external datasets is aggregated to varies from nest to nest which is accounted for by the tile approach we use. Additionally, the meteorological input parameters for the parametrizations (like friction velocity, soil moisture content) can show differences due to differences in the horizontal resolution. The different representation of for example convective systems at different resolutions can therefore also lead to different emission fluxes. As we have seen the best agreement of meteorological parameters at convection-permitting resolution, we decided to focus on these results and added a sentence stating so.

N5) In the following, a detailed analysis of the development stages and responsible atmospheric drivers, which lead to the severe dust event, is provided. We focus on the results from the convection permitting domain, as it yields remarkable improvements compared to the global domain.

Q6) Page 5, Line 17: You state the timestep for calling RRTM is 288 seconds. Please provide the timestep of the simulation as well.

A6) We moved this statement to the 'Model set-up' section and added the other model timesteps.

N6) In our setup for the finest resolution, the advection/fast physics time step is 18 seconds with a sub-stepping of the dynamics at 4.5 seconds. RRTM is called every 288 seconds for the finest resolution.

Q7) Page 5, Line 18: ". . .ART modifies the radiative transfer parameters of the climatological dust distribution. . .". What do you mean by "climatological"? Do you mean the dust distribution as described by the dust module? Please expand.

A7) Thank you, this section needed revision. Please see our answer to Q8.

N7) Please see N8).

Q8) The same confusion in Line 20: "The parameters returned by ART are the combined values from the local ART dust concentration plus the Tegen climatology". During the simulation dust concentration is calculated using both prognostic dust and climatological values?.

A8) What we tried to say is the following: We include only the mineral dust on-line radiative feedback in ART as a part of this study. The radiative effect of other aerosol species, such as sea salt or stratospheric aerosol, is non-negligible but not simulated on-line by ART as a part of this study. Therefore, for these aerosol species the constant climatological values from ICON are used. However, for different studies, ART is capable of simulating these species.

N8) Without ART, ICON uses a climatological distribution of aerosols (e.g. mineral dust, sea salt, stratospheric aerosol) to include their radiative effect. When using ART, any of these aerosol species can be calculated on-line and therefore its radiative effect can be included with much better accuracy. For aerosol species not simulated by ART the climatological values are still used and taken from ICON. Therefore, the ~~RRTM, ART modifies the~~ radiative transfer parameters ~~of the climatological dust distribution. Specifically, at every grid-point and for every level the~~ provided by ART to the RRTM are combined values from the local ART aerosol concentration plus the ICON climatology, which is used only for the aerosol species not simulated. For example, in our study we simulated mineral dust using ART, and therefore can include the on-line mineral dust radiative feedback. For the sea salt and stratospheric aerosol radiative effect, however, the climatological values from ICON are used.

The radiative transfers parameters needed consist of the optical depth, single scattering albedo and asymmetry parameter~~are calculated from~~ . In order to obtain the on-line mineral dust radiative feedback, the local radiative transfer parameters are calculated using the dust optical properties ~~as a function of the~~ and the local dust mass concentration at every grid-point and for every level as detailed in Stanelle et al. (2010). The ~~parameters returned by ART are the combined values from the local ART dust concentration plus the Tegen climatology, the latter being used only for aerosol species not simulated in ART~~radiative transfer parameters are calculated in ART and provided to the RRTM, where they feedback on the atmospheric state in ICON.

Q9) Page 6, Line 14: "Therefore, the median diameter of each mode is expected to decrease during transport". You mean that during the simulation the size of the particles changes? Please expand a little as this is very interesting.

A9) In ICON-ART, dust is described through collections of particles, the modes. For each mode the integral values of specific number and mass are the prognostic variables. The distribution of specific number and mass with particle size during transport is described using log-normal distributions for each mode with the diagnostic median diameter of the mass distribution and constant geometric standard deviation as parameters (Mode A, d = 1.5 μm, $\sigma = 1.7$; Mode B, d = 6.7 μm, $\sigma = 1.6$; Mode C, d = 14.2 μm, $\sigma = 1.5$). During transport, specific number and mass can change independently from each other, resulting in a median diameter change. In more detail: As the standard deviation is kept constant during transport the diagnosed median diameters of number $\overline{d}_{0,l}$ and mass concentration $\overline{d}_{3,l}$ are always directly related to each other through

$$\ln\overline{d}_{3,l} = \ln\overline{d}_{0,l} + 3 \cdot \ln^2\sigma_l.$$

The median diameter can be diagnosed from the prognostic variables using

$$\overline{d}_{0,l} = \sqrt[3]{\frac{\widehat{\Psi_{3,l}}}{\frac{\pi}{6}\rho_p exp(\frac{9}{2}\ln^2\sigma_l)\widehat{\Psi_{0,l}}}},$$

where ρ_p denotes the density of the mineral dust particles given as 2500 kg m^{-3} and the rest of the quantities is given as per our manuscript. The prognostic variables of specific number and mass mixing ratio can develop independently from each other as some parametrizations influence the distributions differently, e.g. the sedimentation velocities for number and mass distributions are different. This is why specific number concentration and mixing ratio are both prognostic variables in ART, leading to a change in median diameter during transport as at all times both distributions are linked through the above equation. For example, sedimentation of mineral dust is included through simulating a constantly downward directed vertical advection with a size- dependent sedimentation velocity. Because larger particles have a greater sedimentation velocity and therefore settle faster, the size distribution shifts towards smaller particles during transport. We included some changes as part of reply to SC1 Q4 A4, but did not include the above description as we think it is rather technical.

N9) The processes which affect mineral dust number and/or mass concentrations in ART are ~~sedimentation, dry deposition~~ gravitational settling (sedimentation), deposition due to turbulent diffusion and wet deposition due to washout.

Q10) Page 7 Line 29: ". . .which represents the soil moisture conditions in the region more realistically...". Do you have a reference or actual data to support that this method provides more realistic values? This is essential as soil moisture dictates *dust production. How can you be sure that the underestimation of the dust concentration by the model (as described in later chapters) is not attributed to false soil moisture?*

A10) No measurements are available to confirm this, our assumption was based on the observation that after a hot and dry summer no precipitation occurred previous to the event. Therefore, we decided to adjust the soil moisture to the surrounding conditions. By this, we reduce the correction applied to dust emission due to soil moisture to a minimum because we want to make sure it has little influence in order to exclude this as a possible reason for underestimation as you mention. However, other factors such as soil type and land cover information are certainly of great importance for dust emission and possibly misrepresented due to the lack of data in the region, this is discussed in the section 'Model setup'. We have adjusted the respective passage by excluding the words 'unrealistic' and 'more realistically' and rephrasing.

N10) The IFS initialization data for soil moisture was modified in a region along the Syrian-Iraqi border which showed ~~unrealistically~~ high soil moisture values and spatial ~~patterns~~ inhomogeneities without preceding rain or changes in soil properties. Therefore, in a region from 37.5°N – 41.5°N and 32.5°E – 35°E the soil moisture index in the four layers provided by the IFS is set to the average value of the region between 36.5°N – 38°N and 32°E – 34°E~~which represents the soil moisture conditions in the regionmore realistically~~. This is done in order to prevent a possible effect of soil moisture on dust emission in this region, where dust emission is likely to be under-estimated due to the recent changes in land use conditions (see Sec. 2). The region modified is an important dust source region and emission fluxes for mineral dust increased due to the reduction of the soil moisture content.

Q11) Page 9, Figure 3: I would like to see clearer plots, especially the national borders as to know exactly where they refer to. Maybe resizing them?

A11) We reduced the plot information content, there is no more display of geopotential height and surface pressure as this was not discussed in the text. Additionally national and continent borders are now thicker and the figure is resized.

N11) Included new figure 3.

Synoptic situation on 06 September at 18 UTC as simulated by ICON-ART for the global domain. Shown are ~~from top to bottom~~ the a 300 hPa, b) 600 hPa and c) 900 hPa level. ~~Colour coded on the left side is the relative topography as the geopotential height of the respective layer minus the geopotential height of the 1000 hPa layer.~~ Black lines denote the height of the respective pressure level in geopotential metres~~at 5 gpm intervals~~. ~~White lines show surface pressure in hPa. On the right side wind~~ Wind speed is colour coded and wind velocity is shown as vectors.

Q12) Section 3: Since this is a very detailed description of the event it would be very interesting to see a vertical cross-section of dust concentration and precipitation in the same plot, for different forecast hours. Like what you have in Figures A1-A4, but vertically.

A12) Thank you for this suggestion, we have included cross-sections for every point in time discussed in our work in the appendix. There are four new cross-sections which we have chosen, both the CALIPSO overpass tracks (Fig. A7) and two additional ones to provide insights into the east-west event structure and dust transport (Fig. A6). The first new cross-section runs from 35°N 32°E to 35°N 46°E along the 35°N circle of latitude, thereby providing insight into the east-west transport over Syria towards the northern EM. The second new cross-section runs from 32°N 34°E to 38°N 46°E along the main south-west dust plume travel direction (an extension of our previously existing Golan height cross-section), thereby providing insight into dust transport towards the southern EM. Besides the already discussed plume structure due to different meteorological drivers, the cross-sections reveal that during nighttime the cold-pool outflow is confined to a shallow layer of approximately 1 km close to the surface with wind speeds above 20 m s^{-1}. Dust concentrations are highest in the lowest hundred meters, due to a lack of turbulent mixing the dust plume does not cover the full cold-pool outflow depth. With sunrise wind speeds are reduced and the dust plume has a greater vertical depth as turbulent mixing increases.

N12) Sec. 3.2: In addition, there are four cross-sections through ICON-ART results along which the event evolution and vertical structure can be tracked for all points in time discussed in this paper. The first cross-section runs from 35°N 32°E to 35°N 46°E along the 35°N circle of latitude, thereby providing insight into the east-west transport over Syria towards the northern EM (Fig. A4, left). The second cross-section runs from 32°N 34°E to 38°N 46°E along the main south-westward dust plume travel direction, thereby providing insight into dust transport towards the southern EM (Fig. A4, right). The third and fourth cross-sections run along both the CALIPSO overpass tracks (Fig. A5).

Sec 3.2: The night-time spread of the CPO3 towards the west is crucial due to its subsequent interaction with the developing boundary layer mixing during daytime. ~~Dust pick-up in CPO2 and CPO3 is limited during the night but increases as soon as boundary layer mixing increases due to solar insolation. At 10 UTC 07 September all satellite platforms are available and an in-depth analysis is conducted~~During night-time the CPO is confined to a shallow layer of approximately 1 km close to the surface with wind speeds above 20 m s^{-1} (Fig. A4, A5). Due to the stable stratification the dust plume does not cover the full CPO depth and dust concentrations are highest in the lowest hundred meters. With sunrise downward mixing of momentum increases. This leads to an increase of dust emissions and a greater dust plume depth which subsequently extends throughout the full CPO.

Q13) Figures 6 and A1-A4. Please add labelbars to the plots (where applicable of course).

A13) We added labelbars below the plot valid for all plots as ART DOD and MODIS AOD use the same colours.

N13) Included labelbars.

Q14) Section 3.4.1: I would like to see a comparison for Dust Optical Depth from more stations in the computational domain. Is this possible? Maybe using AERONET data? If there is no additional data available then add a sentence in the text stating that.

A14) We have included the AERONET station in Sede Boker, Israel for comparison in Fig. 8 (see also RC2, Q2 A2 N2, Q4 A4 N4). Unfortunately, this is the only station which measured in the region on 07 and 08 September. Due to technical problems (personal communication) Rehovot, Israel only became active again on 09 September, a day which is not part of our analysis as it would greatly inflate the length of the paper. As a side effect (following our reply to RC 2, Q4 A4 N4 which deals with the whole section) we have also replaced the PM10 measurements for Ashdod in the plot and show the ones for Beer-Sheva, which is close to Sede Boker, instead.

N14) Sec. 3.4.1: ~~The large difference~~ A comparison of modelled DOD and AERONET AOD measurements shows a similar development of the optical depth for 07 September, although with an offset of 0.3. The offset is explainable by AERONET measuring the optical depth due to all aerosol species, whereas we only display DOD from ICON-ART, as well as a possible underestimation of dust background concentration in the model. Nevertheless, the main signal appears to be shaped by mineral dust processes captured by ICON-ART. The maximum modelled DOD for Sede Boker is 1.0 on 08 September, compared to 4.1 measured by AERONET. The AERONET values appear realistic, as they are in good agreement with MODIS AOD measurements in the region. Thus, ICON-ART shows an underestimation of DOD by a factor of four.

Q15) The authors show that the ICON-ART underestimated dust concentrations and give a very thorough explanation as to why this happens. However how can you be sure that this substantial difference is not caused by something simpler like wrong description of the strength of the dust source areas (maybe in reality the areas are more active than described in the model) or, as I stated above, bad definition of the soil moisture? Have you tried some sensitivity runs based on these?

A15) This is a good point. Our focus was not on simulating the event correctly with respect to dust magnitude in every detail, but first to understand the event and its meteorological drivers, their course and timing. We have not conducted sensitivity runs, as we think that a deeper analysis of different model settings and tuning parameters would be beyond the scope of this manuscript and increase its size further. From our point of view, important parameters which should be analysed in the future are the soil conditions in the dust source region. As stated above, we hope that we limited the influence of soil moisture to a minimum. We would like to emphasize, that the emission of dust in connection with the hydraulic jump should be seen as an additional and interesting feature. We agree, one reason for the underestimation of dust concentrations in ICON-ART is probably connected to the description of soil properties in the active dust source areas in the Mesopotamia region. However, in this part ICON-ART does a fairly good job when compared to satellite observations, and the main differences on the order of one magnitude only become apparent after the dust plume transects the Dead Sea Rift Valley. Therefore, we assume that the emission of mineral dust in connection with the hydraulic jump does play an important role indeed. However, it is certainly below the 90 % by which ICON-ART underestimates dust concentrations in some parts of the southern EM and we have added statements in our manuscript referring to the importance of soil conditions.

N15) Sec. 3.4: Summarizing, the existence of super-critical flow conditions in the region with connected hydraulic jumps is assumed to cause widespread and strong dust emissions on the eastern side of the Dead Sea Rift Valley. This ~~explains~~ contributes to the exceptional amount of dust in the southern part of the EM on 08 September. ICON-ART captures the special flow phenomena, albeit not with the correct magnitude and timing. The lack of a sufficiently developed super-critical flow and resulting high near-surface wind speeds prevents dust emission in Jordan and Israel in the model. ~~Consequently,~~

In combination with already underestimated dust emissions due to the recent land cover changes and soil degradation in the Mesopotamia region (see Sec. 2 and 3.2), this provides an explanation why dust transport into the southern EM is underestimated by an order of magnitude. Nevertheless, ICON-ART provides ~~us with~~ a detailed understanding of previously unknown processes contributing to the historic dust event which makes these findings worthwhile to report.

Conclusions: As the meteorological drivers are captured in detail, it is expected that the remaining underestimation of dust concentration is attributable to an out-of-date description of soil properties in the region due to the on-going conflict.

For the transport to the southern EM, a hydraulic jump is demonstrated to be of ~~crucial importance~~ importance for dust emission in addition to the advection of the dense dust plumes into the region. It is captured by ICON-ART, albeit with reduced intensity compared to observations. ~~Consequently dust~~ Due to the out-of-date soil conditions in the Mesopotamia dust source region and an underdeveloped hydraulic jump phenomena, dust transport into the ~~region is underestimated in the order of one magnitude , with DODs~~ southern EM is underestimated by one order of magnitude by ICON-ART. Modelled DODs are in the range of $0.5 - 1.5$ over Israel and PM10 concentrations reach up to 600 μg m^{-3} in Jerusalem. Nevertheless, the characteristic dust transport features are captured. The arrival of the main dust plume during the night of 08 September is simulated ~~in~~ at 1 km height and subsequent downward mixing increases surface dust concentrations. ~~Again, ICON-ART results are one order of magnitude better than those from other models.~~

Q16) Page 28, Line 21: "...this study presents the first successful simulation of the September 2015 severe dust event. . .". See point (1) in my review.

A16) We have rephrased our wording.

N16) ~~To our knowledge, this study presents the first sucessful~~ This study presents a successful simulation of the September 2015 severe dust event at convection permitting resolution.

Q17) Page 29, Line 10: ". . .ICON-ART results are one order of magnitude better than those from other models. . .". This statement is rather odd since you do not present the capabilities of other models in the manuscript to support this. Of course this does not reduce the very good performance of your model in any way.

A17) We again referred to the global dust forecast models which provide continuous dust forecasts on an everyday basis and have altered the sentence in this sense (their results are available from the World Meteorological Organization dust forecast comparison (http://sds-was.aemet.es), see Q1, A1). On a side note, ICON-ART is also one order of magnitude closer to the observations and has the correct spatial distribution compared to Solomos et al. (2017), which overestimate the observed dust optical depth (AOD above 25 instead of the observed value of 2 above Syria on 06 September) and is unable to represent the spatial distribution (aforementioned two peak distribution around heat low).

N17) Sec. 1: Adding to the extraordinariness, ~~state-of-the-art~~ operational global dust transport models were unable to forecast the event as ~~is~~ also noted by Mamouri et al. (2016). ~~In the simulations started at 12 UTC 07 September, none of the models is able to forecast a significant dust concentration in the EM region for 12 UTC 08 September (see~~ All predictions provided through the World Meteorological Organization~~dust forecast comparison~~'s Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS, http://sds-was.aemet.es) ~~. This is despite the fact that some of the models use data assimilation of satellite dust optical depth data.~~ initialised at 12 UTC 07 September failed to simulate significant dust concentrations in the EM region for 12 UTC 08 September. The simulated values of the dust optical depth in the EM are between $0.1 - 0.4$ in the multi-model mean with a standard deviation of $0.1 - 0.2$. The forecast failure is highly problematic due to the severe impact of the event.

Conclusions: As the meteorological drivers are captured in detail, it is expected that the remaining underestimation of dust concentration is attributable to an out-of-date description of soil properties in the region due to the on-going conflict.

Q18) Finally, as far as I can tell, the model does not support the indirect effect of dust particles (cloud and precipitation). Does this affect the performance in this particular case? If the model was able to simulate dust acting as CCN would the results be any better? Just add a small paragraph expanding on this.

A18) For the cloud micro-physical processes a the two-moment cloud scheme is used (Seifert and Beheng, 2006). The two-moment scheme utilizes a parametrization developed by Seifert and Beheng (2001) which predicts number and mass concentrations for six different hydro-meteor species. These are cloud droplets, rain drops, cloud ice, snow, graupel and hail. For this parametrization an extension was developed by Rieger (2016), which includes the aerosol effect on cloud formation through using the current, local aerosol mass and number concentrations from ART. It is based on parametrizations published by Phillips et al. (2013) for the heterogeneous ice nucleation spectrum and by Barahona and Nenes (2009) for the cirrus regime with competition between homo- and heterogeneous freezing. The parametrization is not used in this study, as the inclusion of aerosol - cloud microphysics interaction creates a new set of research questions and the focus in this study is on the mineral dust radiation interaction. The combined effects of the mineral dust radiation and cloud microphysics interaction are investigated and quantified in a separate publication for a different event (Rieger et al., 2017). As a side note, trials have been conducted for this study as well, the results did not show any marked differences with a clear sign and therefore were stopped again in order to focus on the mineral dust radiation interaction. The most visible result of including the aerosol - cloud microphysics interaction is a change in the structure of the meso-scale convective system with altered rainfall positions. However, much larger differences results from usage of 1-moment versus 2-moment cloud microphysics scheme. Nevertheless, for further investigations the inclusion of aerosol - cloud microphysics interactions would be interesting.

N18) Sec. 2.2: For the cloud micro-physical processes a the two-moment cloud scheme is used (Seifert and Beheng, 2006), as this was found to lead to more realistic features of the meso-scale organized convection. The two-moment scheme utilizes a parametrization developed by Seifert and Beheng (2001) which predicts number and mass concentrations for six different hydro-meteor species. These are cloud droplets, rain drops, cloud ice, snow, graupel and hail. For this parametrization an extension was developed by Rieger (2016), which includes the aerosol effect on cloud formation through using the current, local aerosol mass and number concentrations from ART. The aerosol - cloud microphysics interaction is not included in this study as it creates a new set of research questions and the focus in this study is on the mineral dust radiation interaction. The combined effects of the mineral dust radiation interaction and its impact on cloud microphysics are investigated and quantified in a separate publication for a different event (Rieger et al., 2017).

C) Please note the additional changes which we have included in the paper as part of our improvements, most of them concern the English phrasing of sentences, figure labelling or units. More substantial ones are listed below.

C1) We changed the title to be:

~~An analysis~~ Revealing the meteorological drivers of the September 2015 severe dust event in the Eastern Mediterranean

C2) The dust sources are located in northeastern Africa, not northwestern Africa as stated before:

As a result, the most important remote dust source regions for the EM are situated in north-western northeastern Africa and the southern Arabian peninsula (Ganor, 1991; Kubilay et al., 2000).

C3) We retracted a statement in the introduction, as it is valid above oceans which is not the case in our study:

~~This is despite the fact that some of the models use data assimilation of satellite dust optical depth data.~~

C4) We have added a sentence on the need for further research on the radiative effects in CPOs in Sec. 3.5:

A more intense and faster spreading CPO can have multiple reasons and further research is necessary in order to quantify the different contributions

C5) Added statement in the conclusions referring to questions posted in the beginning, in addition changed question heading to be non-bold:

Summarizing, we are able to answer the research questions presented in the beginning as follows

C6) We have added a statement on the outlook and overarching implications of this study to the conclusions:

In conclusion, this comprehensive case study has demonstrated the need to explicitly represent deep moist convection in dust storm forecasting. While Pantillon et al. (2016) propose a simple parametrisation to represent the climatological effects of haboobs in coarser resolution models, the forecasting of severe events like the one investigated here can hardly be successful without explicit convection. Given the substantial impact of the event and the potential benefit of an early warning, forecasting centres around the world should consider running higher-resolution dust forecasts for the most vulnerable regions. More research is also needed into the multi-scale interactions between Red Sea troughs, heat lows and convection. Moreover, the role of hydraulic jumps for dust emission and transport in the Dead Sea valley appears an interesting subject for further study, which would greatly benefit from a denser observational network.

1 Figures

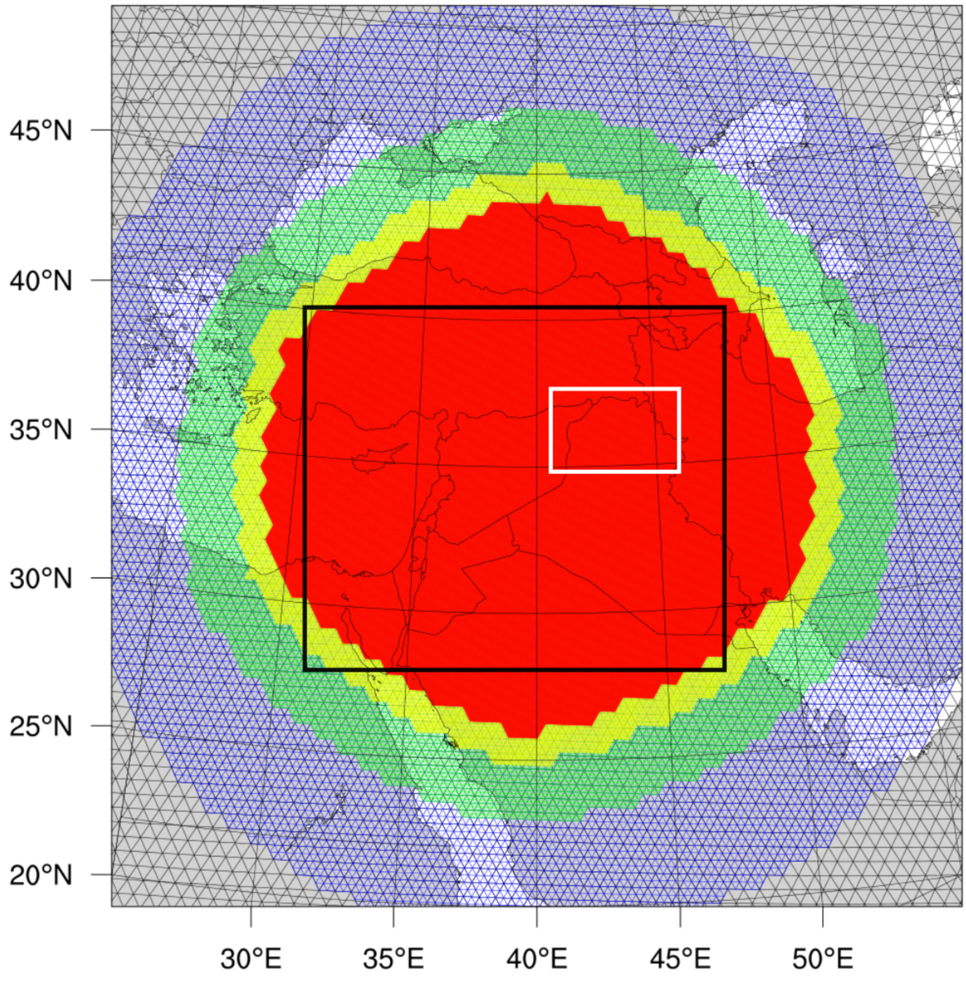

Figure 1. Model domain comparison. Marked in red is the ICON-ART convection permitting domain and as a black frame the section used for our analysis plots. The white frame shows the extent of the RAMS convection permitting model domain used by Solomos et al. (2017).

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