Reply to short comment SC1

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The paper is well written and the results are very exciting. The enormous potential of the ICON model coupled with the state-of-the-art aerosol module ART is documented in a fascinating way. Nevertheless, I was thinking some comments from my side should be given and may improve the paper a bit. As a co-author of the papers of Mamouri et al., ACP, 2016, and Solomos et al., 2017, both dealing with this record dust storm in September 2015, and, in addition, as a lidar expert having a long-term cooperation with the lidar group at CUT, Limassol, I would like to recommend the following:

Below we provide our answers and changes made to the manuscript in response to your comments.

Q1) P1, L22: Please check the paper of Nisantzi et al., ACP, 2015, they report Saharan and Middle East lidar observations (2011-2014), perfomed in Cyprus, and provide statistical results. This article could be mentioned in the introduction.

A1) Thank you for your detailed comments and references to existing literature. Our focus is on the transport mechanisms during the September 2015 severe dust event. We did not find statistical results for frequency of dust transport sources or dust transport mechanisms in the mentioned paper beyond the list of dust cases they use for their analysis. They provide a detailed description of dust optical properties in dependence of source region, this is not the main focus of our study. However, as it is relevant to the optical properties section we have added a reference to the paper there with some surrounding discussion on the topic. Furthermore, we have extended our discussion of existing literature in the introduction, please see also N2.

N1) Sec. 2.1: The spatially invariant mineral composition of dust in ICON-ART means we assume similarity to Saharan dust everywhere. Studies have shown that mineral dust optical properties can depend on the source region (Petzold et al., 2009), which presents a great uncertainty for the radiative forcing as discussed in Myhre and Stordal (2001). For our region of interest, Nisantzi et al. (2015) find differences in the dust particle lidar ratios in a comparison of dust from the Middle East and the Sahara. Two problems prevent a more detailed description of the mineral dust optical properties for our study. First, there is a lack of observations of the refractive index for our dust source region and the variance within source regions can be considerable (Petzold et al., 2009). Second, to the best of our knowledge a dataset of the earth's crust mineralogical composition for our region is missing so far, making a more detailed availability of refractive indices futile. However, the influence of differences in the refractive indices is small compared to the influence of a varying size distribution (Myhre and Stordal, 2001) and this latter effect is represented in ICON-ART.

Q2) P2, L8-13: We need a short discussion on the existing literature for this September 2015 dust storm, i.e., a short discussion of Mamouri et al., ACP, 2016 and the companion paper of Solomos et al., ACP, 2017 (just finally published on 27 March). This is the normal 'way of life' in science, i.e., to discuss previous work, to discuss what is already known, and what will be the new points of the new article. I speculate that you (the authors) did not read the final version of the Mamouri et *al. paper with all the findings concerning mass loadings, dust height distributions, optical depths... Because there are so many useful observations and findings that corroborate your statements and findings..... The submitted ACPD version of Mamouri et al. is very different from the final one. By the way, in that paper, also the limits of MODIS concerning max AOT retrievals are discussed, and the quality of MODIS data at such high AOT conditions is discussed.*

A2) We have included a more detailed discussion of Mamouri et al. (2016) in the introduction and more references throughout the text, this was necessary indeed. In addition, we have included a comparison of ICON-ART with the Mamouri et al. (2016) lidar measurements, please see SC1 Q9 A9 N9. Furthermore, we have rewritten parts of the introduction in order to give a more detailed description of previous studies. We now also refer critically to Solomos et al. (2017) in multiple places, however, we believe Solomos et al. (2017) lacks crucial information necessary to understand this event. Please see RC1 Q1 A1 for further details on this.

N2) Sec. 1: In an analysis of measurements from Cyprus, Mamouri et al. (2016) also report dust surface concentrations close to 8000 μg m^{-3}, with maximum aerosol optical thickness (AOD) values above 5 retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS). Based on a climatological comparison of the observed AOD values Mamouri et al. (2016) classify the event as 'record-breaking'. They report an observed multi-layered dust plume structure, indicating a complex event evolution with multiple dust emission sequences.

The dust plume remained detectable in the region over the course of the next seven days ~~(Alpert et al., 2016)~~ (Alpert et al., 2016; Mamouri et al., 2016). As discussed above, the propagation direction of the record dust storm into the Eastern Mediterranean from the east is very unusual and so is the duration of the event.

Sec. 1: A number of studies have shown that the inability to represent organized meso-scale convection and the related CPOs in models with parametrized convection can lead to a substantial underestimation of dust emissions ~~(Marsham et al., 2011; Heinold et al., 2013). However, CPOs~~ . Analysing simulations for summertime West Africa, Marsham et al. (2011) show that only convection permitting models are able to resolve an afternoon peak in a parameter termed uplift potential, which is closely related to dust emission. Heinold et al. (2013) model off-line dust emission and estimate the contribution of different meteorological systems using large-domain convection permitting simulations during a 40-day period also for summertime West Africa. Corroborating Marsham et al. (2011), they find that approximately 40% of dust emissions can be linked to CPOs, highlighting the need for convection permitting resolution modelling. In another in-depth study of CPOs, Pantillon et al. (2016) analyse year-long convection permitting simulations in the Sahara region. They conclude that in this region the contribution of convective CPOs to dust uplift potential is in the order of one fifth of the annual budget, with substantially higher proportions up to one third over the summer months. In summary, CPOs have been identified as important systems contributing to dust emission ~~(Knippertz et al., 2007; Marsham et al., 2011; Heinold et al., 2013)~~ (Knippertz et al., 2007; Marsham et al., 2011; Heinold et al., 2013; Pantillon et al., 2016) and their occurrence has been documented for all major dust source regions worldwide (Knippertz, 2014).

Sec. 1: Combining the above topics~~of dust and its interaction with CPOs and radiation~~, the influence of the radiative effect of dust contained in CPOs is investigated as a part of this study. The modification of the atmospheric radiation budget by CPOs ~~has been shown to be of importance by Redl et al. (2016). They investigate the influence of the radiative effect of moisture~~

~~contained in CPOs on boundary layer dynamics. However, a shortcoming of their study is the missing radiative effect of mineral dust, which is often emitted by CPOs in desert regions. This is also a shortcoming in the study of Heinold et al. (2013) who simulate dust emission due to CPOs but do not include the~~ can influence their evolution and lifetime. A first mechanism is intensively studied by Redl et al. (2016), showing that surface temperatures in CPOs can be higher than in the surrounding air masses at night. This counter-intuitive behaviour is due to increased cloud coverage inside the CPO and due to the dynamical breakup of the stable night-time inversion in the surface layers by increased turbulent mixing. The result is a downward transport of energy and reduced cooling of the surface, which in turn radiates this energy into space. The overall effect is a loss of energy from the lower boundary layer in the initial stages of cold-pool development. Redl et al. (2016) also investigate a second effect of higher humidity within the cold air-mass leading to increased downwelling longwave radiation in the order of 5 W m^{-2} and thereby warming of the lowest layer. They state that this effect becomes increasingly important in the later stages of CPO development after the dynamical effects diminish. The reduced stratification of the CPO in the lowest layers can result in increased vertical mixing, turbulence and drag, leading to a faster decay. A third effect, which is not included in the model of Redl et al. (2016), is the emission of mineral dust ~~radiative effect. Kalenderski and Stenchikov (2016)~~ due to the high wind speeds and its subsequent interaction with radiation. This is expected to reduce incoming shortwave radiation during daytime and increase downwelling atmospheric longwave radiation during night-time. Mineral dust can thereby feedback on boundary layer dynamics, which in turn can alter dust processes again (Heinold et al., 2008; Rémy et al., 2015). The missing radiative effect of mineral dust is also a limitation in the above discussed study of Heinold et al. (2013). However, Kalenderski and Stenchikov (2016) do not systematically investigate the mineral dust radiative feedback on the CPO structure.

Q3) P2, L31: This final sentence of the paragraph has to be 'updated' because there is this Solomos et al. (2017) paper..... or what do you mean with...a detailed analysis of the driving atmospheric system...has not been published so far....? A mentuoned, the final version of the Solomos paper is now published.

A3) We have adjusted our wording to take account of the Solomos et al. (2017) publication.

N3) ~~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 does not cover the full MCS region. Consequently, their model fails to reproduce the observed CPO outflow structures and connected dust plumes realistically (see discussion in Sec. 3.1 and 3.2).

Q4) P6, L10-11: just a short question: Why do you distinguish (always) sedimentation and dry deposition? I am not so familar with the terminology but to my opinion dry deposition includes gravitational settling. But maybe I am wrong.

A4) Dry deposition includes gravitational settling (sedimentation) and deposition due to turbulent diffusion. We corrected our wording to clarify, that we meant deposition due to turbulent diffusion.

N4) Sec. 2 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.

Sec. 2.1 Due to different processes such as ~~sedimentation and dry deposition~~ gravitational settling acting differently on the specific dust mass and number concentrations in ART, the diagnostic median diameter of each mode changes during transport (the standard deviation of each mode is kept constant).

Q5) Page 9, Figure 3 is very nice, but needs to be improved.... It is almost impossible to identify Turkey, Cyprus, Israel etc....

A5) We adapted the figure to include less information and better country outlines.

N5) Updated figure 3 included, please see also RC1 Q11 A11 N11.

Q6) Page 15, Figure 6, color scales are missing, but needed. The MODIS analysis stops when the observations indicate: AOD > 5.0 (as written in Mamouri et al, ACP, 2016). In the MODIS figure (Figure 6, bottom, left) all dust regions, where the surface (overthe dark Med sea for example) is not visible anymore, are regions with AOD of 5.0 and more. You may check the MODIS data basis (links are given in the Mamouri et al, 2016 paper). And this in contradictions with the MODIS results in Fig.6 ... Did you compute these AOD values (map), instead of taking the AOD values from official MODIS data sources? What does the map (Figure 6, bottom, right) show? We need a color scale. And what about the region just east of Cyprus. The AOD is obviously very high (bottom, left, because the dark Mediterranean Sea is no longer visible, the AOD was rather high, probably 5.0 or even more), but no values in the MODIS AOD map (bottom, right). Impossible, to my opinion! Something is wrong with these MODIS products. Please check!

A6) We have added the colourbars to the figure, although they are the same in every figure which is why we skipped them the first time and noted so in the description underneath. Thank you for noticing that by mistake we did not mark the regions where no MODIS data is available in a different colour than white (although we did say so in the text already: "Unfortunately, no measurements by MODIS are available over sea."). We changed this to grey in the new figures to make it clearly visible and further elaborated in the text. In addition we do not subtract 0.3 for the background aerosol concentration anymore to make it easier for the reader. As before, we continue to state that no data are available from MODIS AOD above the EM in an important section to the east of Cyprus. We do not think we are in a position to speculate why there is no data available in this region or how high the AOD might be. Luckily, we have enough data to compare ICON-ART to observations in the rest of the domain. Furthermore, we have included the maximum AOD values as measured by MODIS. On 07 September, the AOD is still well below the maximum value of 5 where MODIS stops working as you mention and we added a sentence noting the good agreement between MODIS and ICON-ART.

N6) Sec. 3.2: The maximum AOD value observed by MODIS is 2.78, compared to a dust optical depth (DOD) of 2.41 modelled by ICON-ART in good spatial agreement. Differences in the AOD distribution from MODIS and DOD from ART over the EM are attributable to background aerosol (e.g. sea salt, black carbon), which is not represented in our simulation but measured by MODIS. It should be noted that MODIS can suffer from a systematic bias for AODs > 2.5, resulting in an AOD overestimation in the range from 0.5 - 1.5 as shown by Mamouri et al. (2016) through a comparison of MODIS and AERONET data in the region. 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. 3.3: There is good agreement in the maximum dust plume optical thickness, with MODIS AOD measurements giving an AOD of 3.71 and the simulation a DOD of 4.15, although again the possible overestimation by MODIS should be kept in mind (Mamouri et al., 2016). Modelled DOD is higher in ICON-ART when compared to MODIS AOD in the eastern part of CPO3 and lower in the western part of CPO3 (~~fig~~Fig. 5d)~~)~~. Unfortunately, no measurements by MODIS are available over ~~sea~~the northern Mediterranean Sea where a substantial amount of dust is apparent in the visible satellite image. For the eastern part of CPO3 the MODIS AOD measurements seem doubtful when comparing to the MODIS visible satellite image~~(although it is reduced by a value of 0.3 to account for other background aerosols measured by MODIS, the discrepancy is much larger than this)~~.

Sec. 3.4: Dust transport into the southern EM is not simulated with the correct magnitude by ICON-ART despite the overall dust plume structure being captured~~well.~~, even when accounting for the MODIS AOD retrieval bias (Mamouri et al., 2016). MODIS measures AOD values consistently between 2 – 4 over Israel, the Palestinian Territories and Jordan, and values above 5 over the southern EM. In this area, the contribution of the different plumes transported into the region along the Mediterranean coast from the north and across the Dead Sea Rift Valley from the north-east is especially complex due to the steep orography.

Q7) Figure 7 (right panel): CALIOP obs, 34-36 N,.... The CALIOP retrieval gets lost at these conditions, the algorithm fails and cannot handle such situations. The dust extinction coefficients exceeded already 500 Mm-1at 3 km height.... and must be about 2000 Mm-1 or more at heights below 2 km to match the MODIS scence (Figure 6,bottom, left , AOD certainly larger than 5).

A7) We agree (on page 16, line 10 in our discussion manuscript we say: "Altitudes below 2 km are marked as no signal regions in the CALIPSO feature mask due to the attenuation of the lidar signal (not shown).") As your statement agrees with this, we will keep it, thank you for supporting our point of view. As before, we continue to state that the MODIS AOD retrieval seems doubtful in the eastern part of CPO3 and therefore agree with your statement on MODIS as well. However, the measured AOD which is given by MODIS is only in the range of 1-2 (not above 5 as suggested in your comment). As this cannot explain the visible satellite picture, we keep our statement, thank you again for confirming (page 14, line 15: "For the eastern part of CPO3 the MODIS AOD measurements seem doubtful when comparing to the MODIS visible satellite image").

N7) Nothing changed.

Q8) Page 17: I personally would like to see comparisons of ICON-ART results for the Cyprus region, for the 7-10 September period. But I am sure that huge deviations from our findings (presented in Mamouri et al., 2016) would become visible.

A8) Our focus is on the onset of dust storm during 07 and 08 September. Unfortunately no direct observations are available to us for 08 September from Cyprus. Thank you for the suggestion to compare our results with the Mamouri et al. (2016) observations, we have added a comparison of ICON-ART to the lidar observations to our manuscript. Due to the strong dust concentration gradient in the region and in order to compare the same air mass as measured by the lidar, please note that we are comparing the measurements to a 2° eastward shifted position in the model as the dust plume shows an approximate 2° eastward deviation. This is also noted and explained extensively in the text now. Considering the complex situation and the long 47 hour forecast time without data assimilation we deem the mentioned offset of 2° and a 3 hour delay in dust plume arrival to be a very good representation of reality. The double layered plume structure is clearly visible without specifically tuning the model for these results or updating the soil and land-use datasets as was done in Solomos et al. (2017). In ICON-ART the dust plume reaches Cyprus from east, as is also confirmed by the EUMETSAT animation, not from south as stated by Solomos et al. (2017). Furthermore, the spatial agreement is much better around Cyprus (figure A4 and reply to RC1 Q1). The temporal evolution with a first, higher dust plume and a second lower, mightier and much denser dust plume is readily identifiable from model results (compare figure 4, Mamouri et al. 2016). An even more detailed discussion of this result would further increase the length of the manuscript and Cyprus is not our region of interest in this study, as we are interested in the complex dust transport towards the southern EM. If you have any further questions or would like to see more results please feel free to contact us directly.

N8) Sec. 3.4: A comparison of simulated ~~dust optical depth~~ DOD with satellite observations for 11 UTC 08 September shows that the model represents the observed dust plume structure in the northern part of the EM (Fig. A6). The highest dust concentrations are present between Cyprus and Syria, although the dust plume has advanced approximately 2° further west in observations, reaching Cyprus. This shift can be explained by the northward deviation and less intense channelling of the CPO3 as well as the long forecast time. ICON-ART DOD values are one order of magnitude higher ~~than other~~ and show better spatial agreement than other global dust forecast simulation results in the northern part of the EM (see Sec. 1 ~~and fig. A6). However, dust transport across the Dead Sea Rift Valley~~). Taking into account the 2° longitudinal offset in ICON-ART, the vertical structure of the dust plume arrival represents observations by Mamouri et al. (2016) (Fig. A7). A first, elevated plume extending from $2-4$ km with concentrations up to 1000 μg m^{-3} is noticeable during 07 September in both lidar measurements and model results. Mamouri et al. (2016) observe the arrival of the main dust plume past 19 UTC 07 September with concentrations up to 2000 μg m^{-3} at $0.75-1.5$ km height. ICON-ART shows the dust plume arrival past 21 UTC 07 September with concentrations up to 3000 μg m^{-3} at $0.5-2$ km height. During 08 September, dust concentrations increase up to 3500 μg m^{-3} and the plume thickness grows further, extending from 0.5 km up to 3 km height in the model.

Conclusions: The transport to the northern part of the EM and Cyprus is modelled with DOD values above 2 and in good spatial agreement with satellite observations ~~.~~ at a 2° longitudinal offset towards the east. A comparison with lidar observations in Cyprus (Mamouri et al., 2016) shows very good agreement in vertical dust distribution.

Q9) Page 19, Figure 8: Please check the Weizmann Institute AERONET station (a bit east of Tel Aviv) for 9 September (This station measured AOD of 2.4-2.7). What did you find for 9 September for Israel? On 8 September, the dust load was even higher, but there are no AERONET observations, because of too high AOD, which the AERONET algorithm misinterpreted as clouds, I am speculating. That means, the modeled Jerusalem DOD values are much too low (by a factor 4...).

A9) Our focus is on the onset of the dust storm during 06-08 September in order to investigate the previously not known generating meteorological drivers. Therefore, we did not simulate 09 September. Including 09 September would add further length to the study as dust deposition processes would have to be analysed in detail. This is beyond the scope of this work but promising and interesting for the future, especially in comparison with ceilometer observations in the region. As a reply to RC1 Q14 A14 we have added the AERONET station in Sede Boker, which measured on all days, to the results. We state multiple times that our simulations results for transport into the southern EM are not too low by a factor of 4 but on the order of one magnitude (e.g. page 18 line 9, page 19 line 3, page 24 line 12, page 29 line 6 in the discussion manuscript) due to the complex dust transport and emission processes taking place which we refer to and investigate in detail. We continue to do so, however, for Sede Boker the deviation is actually ’only’ by a factor of 4.

N9) Please see RC1 Q14 A14 N14 and RC2 Q2 A2 N2.

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