Reply to anonymous referee RC2

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We recommend the paper publication with some revision outlined below. Nice research in this article includes: 1. It identifies & describes clearly the role of a MCS and detailed developments of 3 cold pools (CPO1,2,3) as sources for this unique dust evolution in time & space. 2. It describes an advanced attempt to provide a better model to simulate this dust event that had no precedence 3. It applies measured data close to the source and in Israel which is far from the main plume origin 4. Though the model describes fairly well the main features of the event the authors are not afraid to mention some discrepancies that were found in the details of dust spreading and attempt to provide an explanation. 5. An important physical contribution here: The mineral dust radiation interaction has been implemented in ICON-ART which seems necessary in this event.

However, it is suggested to add some remarks to the paper. In the period of 6-8.9.2015 at least 3 events of dust raising and spreading were evident. The first resulted from a rotating thermal low and the rest from a long red sea through. In Israel, the dust entered as an elevated plume. Then it was mixed downward affected both by the topography and local diurnal cycle of the land sea interaction. This fact is marked in section 3 and 3. 4 and 3.4.1 but we feel that there is a tendency to describe a black and white picture according to the model findings and the features of ground measurements alone. We suggest some modifications:

> We would like to thank the referee for the comments related to the dust transport towards the southern EM. Below we provide our answers and changes made to the manuscript in response.

Q1) The authors seem to describe the dust penetration to Israel from east to west + a portion coming from the north through the Golan heights (in Sec. 3.4 lines 10 etc. and especially line 15 on). However, in Sede Boker (inland station) the AOT started rising from the 7th afternoon (Sede Boker Aronet). Therefore, we suggest that prior to line 28 (Sec. 3.4) the author will add a comment on the turbulent and complicated nature of the event and will explain that the following study described in 3.4.1 is an attempt to explain the discrepancies they found. They can quote the hour to hour SEVERI satellite showing the complicated patterns of the dust.

> A1) We have rewritten the paragraph discussing the complicated nature of the dust transport towards the EM and state so in the conclusions as well. In addition, we have added a comparison with the Limassol, Cyprus lidar following a suggestion by SC2 Q8 A8 N8 and cross-sections along the transport direction following RC1 Q12 A12 N12.

N1) From 10 UTC onwards on 07 September, the MCS starts to dissipate and is in the course advected east along with the mean flow conditions above 500 hPa. The dust transport to the Eastern Mediterranean is complex, the previously identified plumes are advected in different directions at different altitudes as visible in the SEVIRI RGB dust product animation (Kerkmann et al., 2015). This results in the multi-layered plume structure observed by Mamouri et al. (2016). The aged plume from CPO1 and HL is transported south-westward during the course of 07 September, consequently dust is detectable in Israel during 07 September already. The CPO3 airmass created during the night spreads south-west during daytime on 07 September. At all times it shows the characteristic features associated with CPOs such as an increase in surface wind speed, higher dew point temperatures and an arc cloud forming above the leading edge during the afternoon hours. The high surface wind speeds and turbulent mixing inside the CPO3s result in enormous dust emissions during daytime, consequently the dust is transported within the full boundary layer height up to 5 km ~~.~~ (Fig. A4, A5).

With nightfall on 07 September the CPO2 and CPO3 merge. As the merged CPO is still located in the western, downstream flank of the RST the air mass and dust contained within it are advected fast towards the south-west over the course of the night. The Dead Sea Rift Valley is passed by the dust mass after midnight on 08 September, with the dust plume interacting with the complex orography. 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. A4). 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 $\mu\mathrm{g\,m^{-3}}$ 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 $\mu\mathrm{g\,m^{-3}}$ at $0.75-1.5$ km height. ICON-ART shows the dust plume arrival past 21 UTC 07 September with concentrations up to 3000 $\mu\mathrm{g\,m^{-3}}$ at $0.5-2$ km height. During 08 September, dust concentrations increase up to 3500 $\mu\mathrm{g\,m^{-3}}$ and the plume thickness grows further, extending from 0.5 km up to 3 km height in the model.

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. Therefore, the transport into this region is analysed further in section 3.4.1 in order to investigate the differences found. Overall, a significant dust forecast improvement is achieved through convection permitting simulations with ICON-ART at 47 hour forecast time without data assimilation. During daytime on 08 September the dust plume is mostly stationary in the EM and influenced by the local circulation systems. In visible satellite pictures, the dust can be seen to remain in the EM at high concentrations over the course of the next four days. This period is not investigated as a part of this study as the scope of this work is the analysis of the generating mechanisms.

Due to the problems in simulating dust transport towards the southern EM with the correct magnitude, the next section investigates the timing and structure of the dust plume and CPO arrival in Israel in reality and simulation. ~~This reveals the~~

~~interaction of the dust plume with the orography in the region in the form of super-critical flow conditions and connected, subsequent hydraulic jumps.~~

Conclusions: The aged plume from CPO1 and the HL is transported westward and south-westward along the EM coast, leading to a first arrival of dust in the region.

Q2) It is suggested to add the Sede boker Aeronet AOT finding and relate it to the Model AOD and add these results to Fig 8 in 3.4.1

A2) We have added the Sede Boker AERONET AOD to the figure. As it can be expected, this shows the same problems as are visible in the PM10 measurements already, with an underestimation of dust by a factor of 4. On 07 September the course of the AERONET AOD is replicated by ICON-ART, however with an offset of 0.3. This can be explained by other aerosols besides mineral dust (sea salt, carbon) which are measured by AERONET but not included in our ICON-ART simulation for this study. As a consequence of showing Sede Boker and your justified criticism of our Ashdod discussion, we also changed the PM10 measurements from Ashdod to Beer-Sheva, as this is in closer proximity to Sede Boker and therefore comparable, please see Q4+A4.

N2) Please see N4 for changes.

Q3) It is suggested that the PM10 graph will be given in a logarithmic scale. This will show that part of the dust will be found on the 7th too.

A3) We are now giving the graph with a logarithmic scale. As you expected, the development of the dust concentrations is now observable for 07 September already. We have extended the discussion to contain this behaviour. The features discussed in the text remain the same and we have adjusted the discussion to create a less "black-and-white description", see next question.

N3) Please see N4 for changes.

Q4) The authors tend to explain Ashdod low measurements (fig 8) as a result of sea breeze penetration that brings in clean air. As can be seen from the measurements of the Tera and Aqua and the PM10 measurements of other sea stations the sea was full of dust. There were numerous differences between station to station in Israel even in short ranges a few km apart. So taking only 3 stations for verification cannot reveal the whole picture in such ac complicated event though they seem to fit with the model logic. Therefore, we suggest that fig 8 will be given as a description to the event complexity without a black-and-white description.

A4) We agree that the dust distribution on 08 September was complex in the southern EM and that it cannot be adequately captured by a comparison with three stations alone. However, by displaying the chosen stations we tried to describe features which were not only visible in these stations but also the surrounding ones with similar characteristics (Northern Israel low land, Jerusalem mountain ridge, coastal which is now switched to arid). As a side-effect of showing Sede Boker AERONET values we now also display Beer-Sheva PM10 measurements. Your comments on the Ashdod measurements are correct, and we have retracted our statements. Of course, a more sophisticated comparison and statistical analysis is needed in the future, but in order to do so the dust emission and transport characteristics into the region need to be improved first. We believe, that in this context more research regarding dust processes is needed in the region (see also our new concluding remarks, RC2 C6). We now mention the complexity of the dust distribution and that the comparison is not complete using three stations alone as you suggested. Also, we tried to reduce the black-and-white description by wording our statements more carefully.

N4) Sec. 3.4.1:

In this section the simulated dust concentrations are compared to measurements from three stations in Israel. The selected stations are Afula, Jerusalem (Bar Ilan) and ~~Ashdod (Nir Galim)as they~~ Beer-Sheva for PM10 measurements, as well as Sede Boker AERONET for AOD comparison (see Fig. 9c for a map of the station locations).

The stations all show individual dust concentration characteristics during the event~~(see fig. 9 c) for a map of the station locations).~~

~~The modelled~~ , and the discussed features are present at other stations with similar characteristics as well. Beer-Sheva is chosen for its close proximity to Sede Boker at 45 km distance, in a similar arid desert environment. Clearly four stations are not enough for a complete validation of the complex dust distribution in the region. The comparison shown here is meant to highlight differences between model and reality as well as to investigate dust transport features.

Due to its northern location the modelled main dust plume reaches Afula first ~~, this is also where~~ at 00 UTC 08 September. Here, the highest values of DOD up to 1.5 are ~~achieved because of the previously discussed transport through the Golan Heights (first row in fig~~modelled (upper row in Fig. 8). A few hours later, Jerusalem shows an increase and its peak optical depth. ~~DOD increases even later in Ashdod~~ Even later, DOD increases in Sede Boker due to its location ~~in the south-west~~to the south of Israel, but the DOD values reach higher levels than in Jerusalem. Possibly, this is due to the lower altitude of the station as well as due to local dust emission.

~~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.

When comparing PM10 measurements, a larger difference between model results and observations on the order of one magnitude becomes apparent. The large differences in absolute values of modelled and measured PM10 concentrations (second and third row in ~~fig~~Fig. 8) ~~is caused by the~~ are probably linked to the underestimation of dust transport in connection with CPO2, possibly due to an out-of-date description of soil properties in Mesopotamia (see Sec. 2 and Sec. 3.3). Furthermore, there is an inadequately modelled interaction of the dust plume with the complex orography of the Dead Sea Rift Valley as the next section shows.

Despite the large difference in absolute values, ~~the~~ some insight into dust transport processes can be ~~studied~~ gained by comparing the course of the measured and modelled PM10 concentrations. ~~Although the~~ The DOD in Afula reaches highest values during the night ~~already, peak concentrations at 57 m surface elevation are only~~ from 07 to 08 September, and PM10 measurements show a corresponding increase up to 985 μg m^{-3}, which is missed by ICON-ART. A second, higher peak in concentrations with values up to 3422 μg m^{-3} is measured after noon on 08 September in Afula at 57 m surface elevation. This is ~~due to arrival of the dust plume in 1 km height. Consequently, the~~ linked to the onset of turbulent mixing ~~is~~ needed to transport the ~~high dust concentrations~~ highest dust concentrations from 1 km dust plume height towards the surface. The ~~discussed processes are modelled sufficiently~~ downward mixing of dust leading to the second, higher maximum is captured by ICON-ART, as ~~it shows a very~~ the results show a similar shape of the PM10 concentrations curve compared to the measurements with a peak at 12 UTC at 532 μg m^{-3}.

Highest overall PM10 concentrations are measured by the Jerusalem station ~~. It shows~~ with 5607 μg m^{-3}. The main peak is the earliest and most pronounced peak of all stations at 08 UTC 08 September. This is also the case in ICON-ART, although with a shorter peak duration and at 615 μg m^{-3}, one order of magnitude too low. The earlier and higher peak concentrations in Jerusalem are to due to the elevated location of the measurement station at 770 m, which is almost inside the dust plume. For this reason, PM10 concentrations are also more correlated with the shape of the DOD curve at this station. A secondary peak after sunset is visible in the measurements and model results. ~~This peak can be explained by the formation of a stable nocturnal boundary layer, in which the dust from higher altitudes settles to the ground.~~

~~The station in Ashdod measures the lowest~~ PM10 ~~concentrations at nearly all times, despite showing the highest values of modelled DOD past noon. This is due to the early onset of the Mediterranean Sea breeze at the shore which brings in cleaner air compared to the other stations. The reason for the cleaner nature is the less turbulent character of the marine boundary layer compared to the boundary layer over land. Consequently, it mixes less dust to the surface, a feature which is captured well by~~ measurements in Beer-Sheva show a first, pronounced peak during 07 September already, despite low values of AOD in Sede Boker. The first maximum is captured in magnitude and temporal duration by ICON-ART and can be linked to local dust emission. No measurements are available during the night, but on 08 September Beer-Sheva measured a maximum dust concentration of 2155 μg m^{-3}, compared to 512 μg m^{-3} modelled by ICON-ART. The underestimation by a factor of four between model and measurement is consistent with the AERONET measurements in Sede Boker.

ICON-ART fails to reproduce the measured low values of global radiation because for the radiative impact the absolute values of the dust concentration are of importance. The differences visible in the DOD above the stations manifest themselves in differences between the modelled amount of global radiation at the stations.

Q5) Fig. 1, caption, add time of satellite pictures.

A5) This was missing indeed.

N5) MODIS VIS satellite images of the EM region, from left to right ~~for~~ at 08.15 UTC 06 September, 10.35 UTC 07 September and 11.18 UTC 08 September 2015 (NASA Worldview, 2016).

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.

References

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