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Interactive comment on "Remote sensing and modeling analysis of the extreme dust storm hitting Middle East and Eastern Mediterranean in September 2015" *by* Stavros Solomos et al.

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General comments This work is an interesting analysis of a dust storm that was generated over Iraq,Syria and Turkey and then produced a dust plume over the Eastern Mediterranean. The authors approach seems robust and the analysis of the meteorology leading to this dust event is in line with both literature and what I would expect from briefly looking into this particular case. It is generally well written and the figures show what the authors describe. I think more could be made of the conclusion that changes to land surface over relatively short timeframes can be very important for specific dust events (and presumably the overall dust load). Especially with respect to the known interannual variability of particular dust sources such as ephemeral lakes and fluvial

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Discussion paper

deposits from flooding.

[REPLY] We thank the reviewer for the thorough revision and comments. We agree with the importance of time-variant preferential dust sources due to changes in soil properties. The corresponding section has been extended in the revised manuscript and a new plot (Figure 3) has been added to comment on the land-use changes at the area of interest during the previous years. Replies to the specific comments follow below.

Specific comments

45-51 Description of cold pool/haboob production could be made clearer. e.g. “The responsible mechanism for haboob formation is the generation of a cold pool of ambient air due to evaporative cooling. The rain and ice condensates evaporate (or melt) as they fall through the warmer and unsaturated air and the absorption of latent heat from the phase changes leads in a vigor cooling of the surrounding air.

Haboobs are formed by the evaporation (and melting) of hydrometeors as they fall through warm, unsaturated air below the cloud base of convective clouds. The energy required for these phase changes (latent heat) generates cooled downdrafts. When the downdrafts hit the surface they spread out due to their enhanced density compared with the ambient air. When these The convective outflow boundaries are turbulent and gusty and when they travel over bare soil and desert areas they result in the generation of sediment can be lifted, creating a propagating dust wall.”

[REPLY] Done

66 Not all cited works relate to the Atlas mountains remove “as an aftermath of Atlas Mountains convective storms.”

[REPLY] Done

125-131 I think section 2.1.3 would benefit from a bit more detail. In particular the production and limitations of the SEVIRI RGB dust images. I

would like to direct the authors to the work of Banks & Brindley (2013) (http://dx.doi.org/10.1016/j.rse.2012.07.017) as an evaluation and description of the RGB SEVIRI dust images. Particularly the sensitivity to atmospheric moisture and dust height which is relevant to the interpretation of the SEVIRI dust images when dust is raised at different times and by different processes (recently lifted haboob dust less clearly distinguishable due to high atmospheric water vapour and high stability keeping dust close to the surface). This would be useful to add to the discussion in lines 225-227.

[REPLY] We have updated the corresponding section in the revised manuscript with a more detailed description of the product, and an extended discussion of its possible limitations.

143 I am not familiar with the RAMS model but I suspect the levels are terrain following close to the surface but relax to be smooth and parallel in the upper levels. A little more detail would be useful here.

[REPLY] The vertical coordinate system in RAMS is terrain following sigma-z and the grid stagger is Arakawa C. The first model level is at 50 m above ground and the levels stretch up to about 18 km. We have updated the relevant text accordingly.

157 and figure 1. I think it would be useful to mark on the locations of the radiosonde launch stations on to Figure 1b. Also the frequency of the launches.

[REPLY] Done.

160-162 Did you use any different data for initialisation as part of your sensitivity studies? Roberts et al.(2014) (doi:10.1002/2013JD020667) and Schepanski et al. (2015) doi:10.1002/qj.2453 both show that over West/North Africa the data used for initialisation has a much larger impact on the resultant simulations than other factors such as model resolution, boundary layer set-up or microphysical schemes.

[REPLY] Yes, but we found that our simulations are more sensitive to the location and

dimensions of the inner grids rather than to initial conditions. More specifically inclusion of the 2×2 domain was the key to obtain model results that are closer to the observations. It is true that the simulation of the specific event could be further improved, however for the purpose of our study we believe that with the combination of remote sensing and modeling data all the principal processes driving this episode are adequately explained.

196-197 You mention the combination of cold air aloft and low level warming leading to a thermal low. I think it would be better to discuss and even show the 1000-700 hPa thickness and either mean sea level pressure or 925 hpa geopotential height to identify the formation of a thermal low.

[REPLY] Figure 3 is replaced by Figures 4b,c in the revised manuscript. Figure 4b shows the 1000-700 hPa thickness and Figure4c the 925 geopotential height, wind vectors and dust AOD. The corresponding section has been revised in the manuscript.

238-243 I don't agree with this conclusion borne from Figure 7b that the temperature depression between the rain drops and the ambient air is the "crucial parameter". This is only a single factor that is likely to lead to high evaporation rates and therefore a strong cold pool. Arguably more important is the sub-saturation and depth of the below-cloud air. If below-cloud air is close to saturation and is shallow then regardless of the raindrop-ambient air temperature depression a strong cold pool will not be formed e.g. the patches over Turkey and Syria with similar values but no cold pool. The quantity of water held as hydrometeors is also important. Please amend to make it clear that the situation is more complex.

[REPLY] This is a good point and we agree with the reviewer on the importance of condensate mixing ratio and unsaturated air below the cloud base. The corresponding section has been extended in the revised manuscript, Figure 7a has been revised with the addition of relative humidity and two additional cross-section plots (Figures 7c,d in revised manuscript) have been added to indicate the severity of the particular convec-

tive storm. The cross section over the storm reveals the separate updraft-downdraft regions and a rainfall curtain extending from 4-5 km down to the surface. The cloud top is at 12 Km and the generation of a haboob is evident below the non-precipitating parts of the cloud.

251-252 “This latency between satellite and modeled haboob fronts is an indication that the convective downdrafts were in fact stronger.” Or could this also be attributed to a triggering delay due to the imperfect modelling of the boundary layer or the stability/moisture profile making conditions for triggering less favourable than in reality. Regardless of cold pool strength these factors could produce later triggering of convection and a latency in the storm progression compared with satellite imagery.

[REPLY] We have rephrased this sentence accordingly: “The latency between satellite and modeled haboob fronts is possibly attributed to a slower propagating modeled haboob or to a triggering delay of convection in the model due to the imperfect representation of boundary layer properties and atmospheric stability.”

316-321 It looks like these are thermally driven downslope/upslope winds caused by preferential cooling/heating of the land surface compared to the surrounding sea.

[REPLY] We agree and an extra sentence has been added in the revised text: “Differential heating between the land and water bodies and between flat terrain and mountain slopes results in the development of local wind flows (downslope / upslope winds).”

327-329 There are many factors that could (and likely are) responsible. I think you should include a few more of them here e.g. fall speeds, limitations due to dust emission size bins, transport effects due to imperfect modelling etc.

[REPLY] This sentence is rephrased in the revised manuscript: “(e.g. more intense downward mixing, increased emissions from the sources, limitations due to emission size bins, inaccurate deposition rates etc.).”

Technical corrections I feel that that work would have benefitted from being proof read

by someone who is a native English speaker. There are occasions when slight errors disrupt the flow of the text. I have highlighted errors that I have seen below.

[REPLY] We appreciate the thorough language review and we have corrected the text accordingly.

For example. 42-43 “These systems are well known by local populations at in desert and arid areas worldwide due to their devastating impact in on human health” [REPLY] Done.

64 “A variety of studies on haboobs has have been performed worldwide.” [REPLY] Done.

Make sure acronyms are always defined where they first appear in the text. For example. 55 “SAMUM 1 & 2” is not defined. SAharan Mineral dUst experiMent. [REPLY] Done.

56 “MODIS” [REPLY] Done.

105 “CALIOP” CALIPSO is defined but not CALIOP [REPLY] Done.

Use “led” not “lead” throughout e.g. 66 and 89. [REPLY] Done.

Wherever UTC time is used it would be useful for interpretation to include local time (LT) in brackets afterwards.

[REPLY] The experimental domain is quite extended and includes several time zones. We prefer to use UTC throughout the text for consistency.

Be consistent with use of AOD or AOT, they are interchangeable.

[REPLY] Done (AOT is used throughout the revised text).

53 “Moreover, haboobs are usually generated over remote ...” 58 “It is also worth to mentioning...” 71 “synergy” I don’t really like this term here. I’m not sure the effect is greater than the sum of the individual parts. If you are talking about specific positive

feedbacks then be specific. If not you can just remove “and synergy” 114 “km analysis and vertical resolution...” 144 “dust production emission scheme” 187-188 “the combination between of two distinct meteorological features in the greater area:” 202 “extended bare soil areas in Syria (Figure 2).” 213 “As seen in Figure 4, shows the convergence...” 221 “(plume_2) also was detected...” 223 “the approach approaching of the...” 233-234 “circulation and as is shown in Figure 6b. it It is characterized...” 234 “Somalia” 259 “Figures 8 9 and 9 10” 272 “bellow” 281 “observations again suffers again from total...” 296 “Libanon Lebanon” 367 “regarding the forecast skills of the atmospheric...” 368 “such extreme episodes are very seldom, they still...” 370 “atmosphere are nowadays now often adequately...”

[REPLY] All spelling and grammar corrections are applied to the revised manuscript.

374 “systems for dust episodes in West Africa.”

[REPLY] We have rephrased the sentence : “Moreover, a recent study by Pope et al. (2016) at the area of Sahel/southern Sahara suggests that unresolved haboobs during the summer monsoon may be responsible for up to 30% of the total atmospheric dust and such considerations raise questions on the current status of early warning systems for dust episodes.”

375 “the complexity of these events makes their forecast forecasting them very ...”

[REPLY] Done

Figures

Figure 1a Change the scale used here. I don’t understand why you would only use the lowest third of the values specified on a colourbar. Label countries (at least Syria, Turkey and Iraq) for ease of interpretation.

[REPLY] Done (Figure 4a in revised manuscript).

Figure1b Include location of radiosondes that are assimilated. Their influence is obvi-

ously limited to a certain distance and time from the launch so knowing their position and frequency is important.

[REPLY] Done (Figure 1 in revised manuscript).

Figures 3, 5, 8, 9 & 10. Where possible SEVIRI RGB images should be cropped closer to the model domain they are compared with, either this or show more of the region and draw the domain box on top of the satellite imagery (Figure 5 was especially difficult to interpret) as the different panels are zoomed in different amounts and the model domains are rotated compared with the satellite imagery.

[REPLY] As the reviewer also states the different projection between satellite and model images makes their intercomparison somehow tricky. We revised the aforementioned figures including indication of the model domain over the corresponding satellite images whenever possible.

Figure 4. I think that it would be better for interpretation if the style and parameters plotted were changed slightly. Currently topography over 900 m is shaded. In reality we don't need this detail. You also discuss convergence but do not calculate or show it and interpreting convergence from wind vectors is very difficult. I suggest that you keep the vectors and the red contours for cloud (maybe make the contour lines thicker), but change the topography contours to a single blue or green contour at 1000 m. Then use colour filled contours (or greyscale) to show convergence. This can be as simple as a centred finite difference approach to show where the important convergence zones are.

[REPLY] We have revisited this plot based on the reviewer's suggestions. Indeed no convergence zones are found. Moreover, the near surface wind field does not contribute to the transport of dust which occurs at levels above 1 km along with the convective outflow from the mountains of Turkey. Figure 4 is removed from the revised manuscript.

Figure 6b Mark on location of domain shown in 6a.

[REPLY] Done

Figure 7 As discussed in Specific comments I do not agree that the rain droplet to air temperature difference is the crucial parameter in the formation of the cold pool shown. Change 7a to be of colour contours of boundary layer sub-saturation or dew-point depression and have line contours of the rain droplet –air temperature difference overlaid on top. This would show where the sub-saturation was strongest as well as where the temperature difference is greatest and where there are hydrometeors present.

[REPLY] Figure 7a has been revised following the reviewer's recommendations and two cross-section plots (Figures 7c,d) have been added to illustrate the severity of the convective storm and the generation of a density current haboob.

Figures 9 and 10 should have an additional panel added that shows the model dust load marked with the cross section (equivalent to 9a and 10a). This would help with interpretation, especially given the delay in triggering of convection discussed in the paper.

[REPLY] Done

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/acp-2016-1006/acp-2016-1006-AC1-supplement.pdf

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