

ACP-2021-597: Convection-Aerosol Interactions in the United Arab Emirates: A Sensitivity Study

By Fonseca et al. (2021)

Reply to reviewer #1's comments:

This manuscript 'Convection-Aerosol Interactions in the United Arab Emirates: A Sensitivity Study' mainly investigate the impacts of aerosol loading and properties on the atmospheric circulation, convective activity, surface/air temperature, and local precipitation by Weather Research and Forecasting (model) in UAE on 14 August 2013. The authors carried out ten different scenarios for WRF simulations and compared the different results of circulation, radiative effect, convective, and rainfall.

In general, the paper presents in a logical way, but the English writing need to be greatly improved. Some interesting results of this manuscript will be helpful to understanding the interactions between the convection and aerosol. I therefore recommend publication of this paper in Atmospheric Chemistry and Physics after major revisions. My comments are listed as follows.

REPLY: The authors would like to thank the reviewer for his/her valuable comments/suggestions, which helped to improve the quality of the manuscript. Following his/her feedback, we have rephrased poorly written and potentially confusing sentences and put more emphasis on the main findings of the study. Below we address the reviewer's queries one by one, highlighting in the text where changes, if any, were made.

Major Comments:

1. Compared with the previous published papers, what are the main innovations of this manuscript? Please elucidate clearly in the context.

Many conclusions of this manuscript are consistent with the previous publications. For instance,

- **(Page 1, Abstract, lines 13-15)** 'The convection on 14 August 2013 was triggered by the low-level convergence of the circulation associated with the Arabian Heat Low (AHL) and the daytime sea-breeze circulation.' **This conclusion is the same as the previous publications in (Page 3, 1. Introduction, Lines 113-116.)** 'As discussed in Schwitalla et al. (2020) and Branch et al. (2020), it is normally triggered by the convergence of the low-level circulation associated with the Arabian Heat Low (AHL; Fonseca et al., 2021), the sea-breeze circulation from the Arabian Gulf and Sea of Oman, and the upslope flows on the mountains.'
- **(Page 6, 1. Introduction, Lines 123-124.)** 'Here, they are commonly triggered by the low-level convergence of the AHL and sea-breeze circulations (Steinhoff et al., 2018).'
- **(Page 2, Abstract, lines 31-32 and the Conclusions)** 'The surface downward and upward shortwave and upward longwave radiation fluxes are found to scale linearly with the aerosol loading,' **This conclusion is consistent with (Page 4, 1. Introduction, Lines 80-84.)** 'Liu et al. (2020) used the WRF model with Chemistry (WRF-Chem; Grell et al., 2005) to investigate the effects of biomass burning aerosol on radiation, clouds and precipitation in the Amazon basin. The authors found that ACI effects prevail at lower emission rates and low values of aerosol optical depth (AOD), while the ARI plays the largest role at high emission rates and high AODs.'

REPLY: We thank the reviewer for his/her comment.

The statements in the first two bullet points above are related to the triggering mechanisms of the convective event considered in this study. As noted in the Introduction (lines 112-134), there are two main types of summertime convective events in the United Arab Emirates: on the eastern side around the Al Hajar mountains, for which the cloud development is aided by the topographic circulation (Branch et al., 2020, Francis et al., 2020), and on the western side, where clouds typically arise from the low-level convergence between the Arabian Heat Low circulation (Fonseca et al., 2021) and the sea-breeze from the Arabian Gulf (Steinhoff et al., 2018). The 14 August 2013 event falls into the latter category, and therefore the triggering mechanism is expected to be consistent with that of previous studies of similar convective events. We would also like to stress that the sentences the reviewer refers to here are mostly in the Introduction, where a literature review is normally given, while in the remaining of the paper, and in particular in the Discussion and Conclusions section, the focus is on the novel results of the work.

Regarding the sentences in the third bullet point, Liu et al. (2020) did not reach the conclusion that the surface downward/upward shortwave and upward longwave radiation fluxes scale linearly with the aerosol loading. Instead, the authors focused on the aerosol-cloud and aerosol-radiation interaction effects on precipitation, which we also discuss in our study. As a result, that particular conclusion is novel and worth being reported in the Abstract.

Given the reviewer's comment, and in particular in the Discussion and Conclusions section, we have put greater emphasis on the novel findings of the study (lines 790-835) and now clearly highlight the take-home messages for potential future readers of this work (lines 837-853).

2. (**Page 11, 2.2 WRF Experiments and the whole context**): The authors implemented 10 different scenarios for WRF simulations based on two aerosol distributions (an idealized aerosol distribution profile and a climatological profile) and compared the different impacts of aerosol loading and optical properties on the atmospheric circulation, radiative effect, convective, and rainfall. The authors carried out a lot of simulations for sensitivity experiments and acquired many conclusions, **but it is not clear for the readers, which conclusion is important and which one is close to the observed results for this manuscript.**

For instance, (1) **Page 56, 5. Discussion and Conclusions, Lines 855-856**, 'The best agreement with that observed is obtained when the climatological values multiplied by a factor of 5, in line with the dustier atmosphere during this event'. (2) **Pages 57-58, Lines 879-882**, 'The downward and upward shortwave and the upward longwave radiation fluxes are found to decrease linearly as the as aerosol loading is increased, with a 10-fold increase in the amount of aerosols leading to a daily-averaged drop of the surface net shortwave flux of about 91 Wm^{-2} , and'. (3) **Page 58, Lines 887-889**, 'When 20% of the aerosols are replaced with more absorbing (carbonaceous) particles, the roughly 87 Wm^{-2} decrease in the surface net shortwave radiation flux...when the aerosol loading is augmented by a factor of 10'. (4) **Page 58, Lines 897-899**, 'The sensitivity to the maritime aerosol model, for which 20% of the rural aerosols are replaced by sea-salt and the larger particles removed, on the other hand, is much reduced.'

REPLY: We fully agree with the reviewer we have to emphasize the main findings of the study. As stated in the reply to his/her previous comment, we have now made it abundantly clear in the Discussion and Conclusions section our main findings and take-home messages for readers of this work (lines 790-853).

Regarding a comparison with the observational measurements, no simulation clearly outperformed another. In fact, Table S1 shows that, by and large, WRF's cold and dry biases are present in all model runs, and readers interested in running WRF over hyper arid regions need to be aware of this bias. Having said that, we are in a position to issue recommendations for users interested in running the WRF model for such

convective events in hyper-arid regions located next to major dust sources like the United Arab Emirates (UAE):

- When accounting for the observed aerosol loading, using a climatology-based distribution is preferable to an idealized distribution as it can improve the representation of deep convection, as evidenced by the increased precipitation generated by the model and the colder cloud tops, in particular when the aerosol-radiation interaction (ARI) effects are switched on. The vertical profiles of variables like temperature are also better simulated;
- Even in short-term (2-day) simulations, the fields in the interior of the WRF nests can be substantially different from those in the input (in this case reanalysis) dataset. Employing nudging in the outer nests (in this case in the first two model grids) is preferable to only applying it in the outer nest or not doing it altogether, as it helps to at least partially correct some of the WRF biases;
- It is vital to accurately represent the properties of the observed aerosols in the model, more so than the amount, provided the order of magnitude is in line with that observed. If the aerosols are more absorbing, the heating in the aerosol layer will peak closer to its top instead of in the bottom half, which has implications for the dynamics and convection in particular if the aerosol layer is deep and/or multiple layers are present.

We have stated this in the text (lines 837-853) and would like to thank the reviewer again for raising this issue.

Whether the changes of aerosol loading and optical properties in the WRF sensitivity simulations could reflect the true observations or not?

REPLY: We thank the reviewer for raising this point. In Fig. 6c we compare the model-predicted aerosol optical depth (AOD) with that given by the MERRA-2 reanalysis dataset. This particular dataset explicitly accounts for aerosols and their interactions with the climate system, and is found to perform well in this region (Roshan et al., 2019; Ukhov et al., 2020). While we can get the correct order of magnitude when scaling the climatological aerosol loading by a factor of five, the diurnal trend in the reanalysis dataset is not simulated by the Weather Research and Forecasting (WRF) model. We speculate on why this may be the case (lines 504-518). Due to the extensive cloud cover on 14 August 2013 (Figs. 2a-c), AOD estimates from ground and satellite assets exhibit gaps and missing data and hence cannot be used to directly evaluate the WRF predictions. What is more, we do not have aircraft measurements of aerosol loading at different heights to assess the vertical distribution nor information regarding its optical properties. We understand this is a limitation of the study and have noted it in the text (lines 504-510). We believe a comprehensive assessment of the simulated aerosol loading and properties would require additional observational data that is not available for us. This has also been highlighted in the Discussion and Conclusions section (lines 858-863).

In this manuscript, the authors indicated that ‘The 14 August 201 was also a rather dusty day in the UAE, with Aerosol Optical Depths (AODs) in excess of two’, and **I suggest the authors should implement the sensitivity of the potential effects of dust aerosols’ loadings and optical properties on the circulation, convection, radiative forcing, and precipitation.**

REPLY: We thank the reviewer for his/her comment. This is precisely what we do in our study, and the 14 August 2013 event is selected as it features dusty and convective conditions in the country on a day for which observational data is available for model evaluation, as noted in lines 394-397. In this work, and

through sensitivity experiments with the Weather Research and Forecasting (WRF) model, we explore the changes in atmospheric circulation, convection, radiation and precipitation to different aerosol loadings and properties, considering both an idealized and scaled version of a climatological distribution of aerosols. Examples of this are listed below:

- *Circulation & Convection*: Figs. 6a-b for ERA-5 and the WRF-3 simulation; Fig. A1 for runs WRF-4 to 5; Figs. 9c-d for simulations WRF-5 and 9; and Figs. 10c-d for runs WRF-6 to 8;
- *Precipitation & Convection*: Fig. 8 and S2 for all WRF simulations;
- *Radiation*: Figs. 9a-b for simulations WRF-5, 6 and 9; Fig. 10a-b for simulations WRF-6 to 8.

Besides, we compare the WRF predictions with in-situ measurements at the location of 35 weather stations spread out over the UAE (Fig. 1c). We present the results for the diurnal cycle for runs WRF-1 to WRF-4 in Fig. 7, and for all simulations we give the skill scores for the full day in Table S1.

However, and as stressed by the reviewer's previous comments, we agree that in the previous version of the manuscript we have not clearly highlighted our findings in the text, which is a cause for confusion. In the revised version of the paper we have done so in the Discussion and Conclusions section (lines 790-853) and in the Abstract (lines 20-34).

3. In WRF simulations of this manuscript, how to consider the potential influences of environmental field (e.g. wind speed field, air humidity field), and vertical convection on the ARI, ACI, circulation, convection activity, and precipitation, etc?

REPLY: We thank the reviewer for his/her comment. In the Weather Research and Forecasting (WRF) model simulations conducted here, the aerosol-radiation interaction (ARI) and aerosol-cloud interaction (ACI) effects directly impact the environmental fields and vice-versa: i.e., they modulate the meteorological conditions where aerosols / clouds are present, and the modified atmospheric state influences the ARI and ACI. If the goal is to isolate the one-way interaction between the meteorological fields and the ARI/ACI effects, another modelling approach would have to be considered, such as the piggybacking framework (e.g. Grabowski, 2019). Such an analysis is beyond the scope of this study. We have stated this in the text (lines 871-875). As we highlight in the Introduction (lines 156-159), the goals of this work are twofold: (i) investigate the added value of incorporating aerosols on a dusty convective summertime event in a hyperarid region and account for their interactions with convection, and (ii) explore the sensitivity of the WRF model's response to changes in aerosol loading and properties. We believe this is achieved through the sensitivity experiments conducted in our study, with the results summarized in lines 790-835.

4. The English written of this whole manuscript need to be greatly improved.

REPLY: We agree with the reviewer. In the revised version of the article we have rephrased poorly written and potentially confusing sentences, such as those in lines 24-27, 424-430, 579-583, 655-657, 752-754 and 787-788.

Minor comments:

1. **Page 3, lines 58-60:** ‘Dust has been shown to have an important impact on the climate system, in particular on the atmosphere (e.g. Min et al., 2014; Liu et al., 2019; Francis et al., 2020), ocean (e.g. Evan et al., 2012) and cryosphere (e.g. Francis et al., 2018) dynamics.’

⇒ Please delete all the ‘e.g.’ in the cited literatures, and modify the other places in the context.

REPLY: We thank the reviewer for his/her comment and have updated the text accordingly.

2. When talking about the direct and semi-direct radiative effects of aerosols, the authors could cite other references.

[1] Li Z., Y. Wang, J. Guo, et al. 2019: East Asian study of tropospheric aerosols and their impact on regional clouds, precipitation, and climate (EAST-AIR(CPC)). *Journal of Geophysical Research: Atmospheres*. 124 (23), 13026-13054. DOI: 10.1029/2019JD030758.

[2] Wang W., J. Huang, P. Minnis, et al. 2010: Dusty cloud properties and radiative forcing over dust source and downwind regions derived from A-Train data during the Pacific Dust Experiment. *Journal of Geophysical Research: Atmospheres*. 115 . DOI:10.1029/2010JD014109.

REPLY: We thank the reviewer for his/her suggestion. We now cite the referred studies in the text (line 45).

REFERENCES:

Branch, P., Behrendt, A., Gong, Z., Schwitalla, T. and Wulfmeyer, V. (2020) Convection Initiation over the Eastern Arabian Peninsula. *Meteorologische Zeitschrift*, 29, 67-77. <https://doi.org/10.1127/metz/2019/0997>.

Fonseca, R., Francis, D., Nelli, N. and Thota, M. (2021) Climatology of the heat low and intertropical discontinuity in the Arabian Peninsula. *International Journal of Climatology*, 1-26. <https://doi.org/10.1002/joc.7291>.

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Grabowski, W. W. (2019) Separating physics impacts from natural variability using piggybacking technique. *Advances in Geosciences*, 49, 105-111. <https://doi.org/10.5194/adgeo-49-105-2019>.

Liu, L., Cheng, Y., Wang, S., Wei, C., Pohlker, M. L., Pohlker, C., Artaxo, P., Shrivastava, M., Andreae, M. O., Poschl, U. and Su, H. (2020) Impact of biomass burning aerosols on radiation, clouds, and precipitation over the Amazon: relative importance of aerosol–cloud and aerosol–radiation interactions. *Atmospheric Chemistry and Physics*, 20, 13283-13301. <https://doi.org/10.5194/acp-20-13283-2020>.

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Steinhoff, D. F., Brientjes, R., Hacker, J., Keller, T., Williams, C., Jensen, T., Al Mandous, A. and Al Yazeedi, O. A. (2018) Influences of the Monsoon Trough and Arabian Heat Low on Summer Rainfall over the United Arab Emirates. *Monthly Weather Review*, 146(5), 1383-1403. <https://doi.org/10.1175/MWR-D-17-0296.1>.

Ukhov, A., Mostamandi, S., da Silva, A., Flemming, J., Alshehri, Y., Schevchenko, I. and Stenchikov, G.: Assessment of natural and anthropogenic aerosol air pollution in the Middle East using MERRA-2, CAMS data assimilation products, and high-resolution WRF-Chem model simulations. *Atmospheric Chemistry and Physics*, 20, 9281-9310. <https://doi.org/10.5194/acp-20-9281-2020>, 2020.