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Interactive comment on "Retrieval of effective aerosol diameter from satellite observations" *by* Humaid Al Badi et al.

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We thank Reviewer# 3 for his comments. This reply is structured by introducing sections of the reviewer comments (in Italics) followed by a response. The page and line numbers of the updated version of the paper are used in the responses unless otherwise stated. The amended manuscript is attached in the supplement file.

(i) *The radiative transfer theory used here is far too simplistic. In reality, in the thermal infrared, one needs to consider both extinction (scattering and absorption) by, and emission from, the dust layer. Moreover, one has to consider emission from the sur-face and the underlying (and possibly overlying) atmosphere depen-*

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dent on the dust height (atmospheric temperature structure) and the wavelength considered if one is to correctly interpret the satellite signal.

(ii) *There seems to be no appreciation of the Beer-Lambert law, or alternatively the differential nature of extinction, as radiation passes through a medium. Just considering absorption and removal by scattering by the dust layer alone would lead to an exponential dependence of the final 'intensity' on optical depth, which is itself a function of the extinction cross section. Add in emission, plus scattering into the upward direction and you will obtain the full radiative transfer equation (usually expressed in radiance although conversion to irradiance is possible if done properly).*

In summary it should be noted that this reviewer is unconvinced that, even using the correct radiative transfer theory, and employing the simplifying assumptions that dust particles are spheres and have the same composition everywhere, there is enough independent information in a single BTD to extract size information. To do this I would suggest that at the very least, dust optical depth and height need to be known, and even then one would still have to account for the impact of confounding influences such as variable surface temperature, surface emissivity and water vapour content. It may be that there are 'regimes' of behaviour (e.g. dust plumes above a certain optical thickness) where size information can be extracted but I suggest the authors perform a much more comprehensive suite of (correct) radiative transfer calculations (explicitly simulating SEVIRI BTDs, including the relevant instrument characteristics) to look at whether what they are attempting to do is actually feasible. If they believe it is then they also need to come up with a much more convincing strategy for validating their results, including a traceable uncertainty analysis.

The authors agree with the reviewer on the complexity of the correlation between brightness temperature and various dust layer properties and ground emissivity. An

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acknowledgment of the complexity has been briefly introduced in the Introduction. Many studies tackled this problem through theoretical analysis but had limited success achieved to date in filling the gap between the observed and the modeled particle size. The reason, as the reviewer points out, is the high number of dependent variables that link the remotely sensed radiance and particle size in the radiative transfer theory. In addition, the high uncertainty in the in-situ estimation of these dependent variables which is an important source of the retrieval error (e.g. Merchant et al. 2006). The results of previous models seem to inherit the noise introduced by the vague estimation.

This paper approach tries to avoid this problem by exploiting the strong and dominate exponential effect of the particle size on the value of 8.7 and 12.0 μm Brightness Temperature Difference (ΔT_{8-12}). Here we try to present this empirical evidence then use it to build a formula based mainly on observations and simplified conceptual model. However, we agree that basic support for the conceptual model through mathematical analysis cannot be avoided. The amended manuscript has corrected the over-simplified radiative transfer theory. Section 2 and 3 are substantially changed towards more theoretical bases that support the use of the empirical model. In a single thermal SEVIRI band, the effect of dust diameter is potentially "diluted" and difficult to see. In this paper, we show empirically that the change in effective diameter has very strong influence on the Brightness Temperature Difference (BTD) of 8.7 and 12.0 μm (ΔT_{8-12}) over a surface of constant emissivity. In addition to the AbuDhabi case – (Figure 4), newly introduced Figures 5 & 6 add additional clarification to the exponential relation between ΔT_{8-12} and the effective dust diameter.

Action: more detailed mathematical description has been added to describe the basis that supports the model. Sections 2 and Section 3 have been rewritten. New Figures 5 and 6 have been introduced to explain the empirical evidence for the relationship between ΔT_{8-12} and effective diameter. More detailed description of the effect of surface emissivity, water vapour, and dust layer emissivity, height, non-sphericity has been included in section 3 and section 4.3 (Discussion of Results).

(iii) *The various relationships given near the start of section 3 are hence not correct. In fact, even if the earlier assumptions were ok I cannot see how they would logically follow. Why should the extinction efficiency be inversely proportional to the radiation incident on the dust layer? The former is an intrinsic property of the dust and is only dependent on the size distribution, shape of particles and composition. Similarly, brightness temperature is not directly proportional to the radiation incident on the dust. It is not even directly proportional to the intensity (as defined here) on the satellite radiometer but rather results from a non-linear conversion of the incident radiance using the Planck function.*

There is a typing mistake in that line. Instead of $Q_{ext}\ \alpha\ \frac{1}{I_0}$, it should be $Q_{ext}\ \alpha\ 1-\frac{I}{I_0}$ $(or\ \ Q_{ext}\ \alpha\ \frac{P_{removed}}{I_0})$ where I is the radiance received by satellite radiometer. The pretext and the context that follows the relationships fits this intention. However, the authors agree that there is over simplification in the wording of that paragraph which resulted from using the Rayleigh-Jeans law which is not appropriate in thermal infrared part of the spectrum.

Action: A more detailed mathematical description using Plank's function has been presented in section 2 to justify the use of $\Delta Q_{ext} = 0$ with ΔT_{12-10} in estimating special cases of effective diameter d .

(iv) *As noted above, aerosol optical properties are related to composition, shape, and size distribution. The use of Mie theory as given implicitly assumes that the particles are spherical which is rather unlikely for dust. Moreover, the authors simply use one set of refractive indices yet compare a number of different cases,*

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including African and Arabian dust events. One might anticipate significantly different compositions dependent on source. While the assumption of sphericity is likely to be less severe in the IR than the visible, at the very least some sort of sensitivity analysis should be performed to assess the impact of uncertainty in the dust composition on the resulting BTDs.

The authors acknowledge that the variation of dust particle shape and chemical composition leads to a variation of the refractive index with a subsequent contribution to the total error. However, estimation of the error from non-sphericity and variation in chemical composition is a complex task and out the scope of this study. This is partly because it is still difficult to implement the available methods to quantify the effect of non-sphericity in estimating the extinction coefficient at a global scale. However, based on the performance of the other techniques that estimate the effective dust particle size, the method proposed within the paper is still potentially very useful for many applications with its current outcome.

Action: More detailed discussion about the limitation of the model including non-sphericity has been added in Section 4.3(Discussion of results), Page18.

(v) *As written, it is difficult to see whether the authors have any concept of the effect of a size distribution. Their Mie calculations appear to have been carried out for single particles (although I am not sure of this as the 'ringing' that one might expect to see in this case is absent). In reality, these responses will be weighted by the fraction of particles within each size bin, which will vary from dust event to dust event (and even during an individual dust event). Hence, when looking at real signals, the shapes in figure 1 will effectively be distorted differently for different distributions of particles such that fitting one empirical model is unlikely to be representative.*

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MiePlot software (Laven, 2016) gives a choice to calculate a Mie solution for a range of particle size distributions. Here the particle sizes are assumed to be lognormally distributed in the range of [0.02 to 60 μm] although it is acknowledged that real distribution could be different. The selection of this range is based on the Ryder et al. (2013a, 2013b) report of volume distributions peaks between [10 to 60] m in fresh, heavy dust events which is the focus of interest for this calculation.

Action: This clarification has been added in section 2, Page4

(vi) *Similarly, have the authors taken the spectral width of the SEVIRI channels into account? It is not clear from what has been written. Since the filters are quite wide they will also affect the size of the signal seen and its variability. The viewing angle of the satellite will also affect the signals seen due to differential absorption through the atmosphere.*

The authors acknowledge that SEVIRI has wide spectral bands. On the one hand, the relatively wide range of SEVIRI spectral bands makes the signal less sensitive to using a Mie theory approximation of spherical shape compared with higher spectral resolution instruments onboard polar orbiting satellites. In addition, the authors acknowledge the effect of large view angle in the use of SEVIRI. On the other hand, there are advantages for operational use of SEVIRI in having a high temporal resolution product for dust particle size even if the there is a potential sacrifice in accuracy. Future study will involve testing the algorithm with higher spectral bands from VIIRS.

Action: An acknowledgement has been added in Page2 line 27.

(vii) *In the derivation of their model the authors appear to make the assumption that* *the dust plume emissivity is the same as the surface emissivity (at least this is how it reads to this reviewer). This is not valid as, even if the composition is the same, the lofted particles are likely to be smaller and less densely packed than those at the surface.*

The authors acknowledge the difference in the emissivity between the ground and dust layer. However, it is found that using $\in_{8.7}^{2}$ gives more accuracy in the empirical model. The formula has been changed in the amended transcript to obtain better results, but it still shows the distinctive exponential pattern as described by Figures 5, 6 and 7.

Action: The model has been amended in the current version of the manuscript because it was found that by using the emissivity difference with other changes in the equation gave more accurate results.

(viii) *It is totally unclear where the 'measurements' at 15 micron used to fit the model have come from.*

Figure 1 shows two distinctive occasions when $Q_{ext10} - Q_{ext12} = 0$ for a dust layer. They correspond to effective diameter d of 11.3 μm and 18.0 μm. In between the two values, 11.3μm and 18.0 μm, $Q_{ext12} - Q_{ext10} > 0$, and hence, as shown in section 2, $T_{12} - 0.991251\, T_{10} < 0$. The lowest value of $Q_{ext12} - Q_{ext10}$ is around 15 microns. The process was to look for a severe dust storm case where this condition is valid and take the corresponding ΔT_{8-12} at the same point of time and space.

Action: Further clarification has been added in section 2 to explain how to estimate d from the corresponding brightness temperature when $Q_{ext12} - Q_{ext10} = 0$ in a severe dust case.

(ix) *In any case, using two clustered points to perform a curve fit such as that shown in figure 7 is, in my opinion, very bad science. I could fit any line I wanted through those points.*

The graph is a numerical solution for the coefficient of a known formula and a known line pattern which is already identified. It was not fitted from scratch. Excel solver was used to establishing the coefficients. The algorithm is based on searching for coefficients that correspond to a minimum square deviation from the model of the 12 sample points used in the solution. Using a known formula gives less freedom to fit an arbitrary line and still have a unique pattern. However, we agree that with more observations the model will become more precise.

Action: Two additional dust cases were added to the graph (Figure 11)