# Retrieval of effective dust diameter from satellite observations

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Abstract. Dust aerosol particle size plays a crucial role in determining dust cycle in the atmosphere and the extent of its impact on the other atmospheric parameters. The in-situ measurements of dust particle size are very costly, spatially sparse and time-consuming. This paper presents an algorithm to retrieve effective dust diameter using infrared band Brightness Temperature Difference (BTD) from SEVIRI (the Spinning Enhanced Visible and InfaRed Imager) on the Meteosat satellite. An empirical model was constructed that directly relates BTD of 8.7 and 12.0  $\mu$ m bands ( $\Delta T_{8-12}$ ) to dust effective diameter. Three case studies are used to test the model. The results showed consistency between the model and in-situ aircraft measurements. A severe dust storm over the Middle-East is presented to demonstrate the use of the model. This algorithm is

15 expected to contribute to filling the gap created by the discrepancies between the current size distributions retrieval techniques and aircraft measurements. Potential applications include enhancing the accuracy of atmospheric modelling and forecasting horizontal visibility as well as solar energy system performance over regions affected by dust storms.

## 1. Introduction

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- 20 Aerosols including dust have a significant impact on the climate through a range of complex mechanisms. In the short term, the effects of aerosol variability generate perturbations in atmospheric turbidity. Aerosols alter atmospheric turbidity by modifying the short-wave solar radiation and terrestrial long wave radiation through scattering and absorption. The amount of absorption and forward and backward scattering depends on the concentration, size distribution and chemical composition of aerosol particles. Despite continued research, the multiple dust aerosol effects are still poorly represented in climate
- 25 models which lead to substantial uncertainty (Ben-Ami *et al.*, 2010; Boucher *et al.*, 2013). One of the reasons for such uncertainty might be the scarcity of adequate and routine measurements of dust aerosol properties. Most of the particle size in-situ measurements in operation take place on the ground by sampling the precipitated dust aerosols (Afeti and Resch, 2000; Sunnu, Afeti and Resch, 2008). Ground measurements are not sufficient because aerosols have different and dynamic vertical distributions. Limited aircraft campaigns have been conducted to sample the aerosol particle size in the atmosphere (
- 30 e.g. Tanré et al. 2003; Müller et al. 2012; Ryder et al. 2013b; Ryder et al. 2013a).

The sparsity of in-situ dust sampling opened the door for remote sensing techniques to fill the gap. Nakajima et al. (1996) and Dubovik & King (2000) developed inversion algorithms for retrieval of the aerosol volume distribution  $\left(\frac{dV}{d\ln r}\right)$  from Sun and sky radiance ground measurements, such as AErosol RObotic NETwork (AERONET). From space, Atmospheric Infrared Sounder (AIRS) observations made at 9.4 µm are used to retrieve dust effective radius (Pierangelo et al. 2005).

5 Klüser et al. (2011) also used a Singular Vector Decomposition method on observed spectra from the Infrared Atmospheric Sounding Interferometer (IASI) to extract dust effective radius.

However, the current techniques do not satisfy the need for accurate dust particle size data. Discrepancies have been observed in retrieving the size distributions between the AERONET algorithm (Dubovik and King, 2000), the Sky Radiation 10 (SKYRAD) algorithm (Nakajima et al., 1996) and aircraft measurements (Estellés et al., 2012; Ryder et al., 2015). The comparison between in-situ sampling during Saharan Mineral Dust Experiment (SAMUM) 2006 and AERONET effective radii retrieval showed that the Sun photometer observations are smaller by a factor of approximately two compared with the in-situ observations (Müller *et al.*, 2012). The underestimation of the dust size distribution also appears to be a common pattern among the current satellite algorithms (Klüser et al., 2011; Pierangelo et al. 2005). The abundance of large dust 15 aerosol particles over desert surfaces might have a role in reducing the accuracy of the current sun-photometer and satellite techniques (Ryder et al. 2013b). Recently, signs of improvements have been demonstrated if a detailed analysis of particle shape and composition are considered in the retrieval models (Capelle et al., 2014; Legrand et al., 2014; Klüser et al., 2015, 2016). One problem that limits the advance in improving particle size retrieval is the noise introduced by the vague estimation of the many dependent variables. This study aims to avoid this problem by using the strong and dominate 20 exponential effect of the particle size on the value of 8.7 and 12.0  $\mu$ m Brightness Temperature Difference ( $\Delta T_{8-12}$ ). The empirical evidence for  $\Delta T_{8-12}$  and the dust particle size is presented and then used to develop a formula based mainly on observational data and a simplified conceptual model.

Infrared window bands 12.0, 10.8 and 8.7 µm from SEVIRI (the Spinning Enhanced Visible and InfaRed Imager) on 25 Meteosat satellite are widely used to track dust plumes in operational meteorological applications. In 2003 the first METEOSAT Second Generation Satellite was launched carrying SEVIRI. It has an unprecedented temporal resolution of 15 minutes over the Sahara Desert and the West Asia regions where the primary dust sources in the world are located. SEVIRI has relatively wide spectral bands compared with polar orbiting satellite imagers. On the one hand, the relatively wide range of SEVIRI spectral bands makes the signal less sensitive to using approximation such as Mie theory approximation of 30 spherical shape compared to higher spectral resolution instruments (Rees and Rees, 2013; Klüser et al., 2015). On the other

hand, there are other 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.

The Dust Red, Green and Blue (Dust RGB) image composite corresponding to infrared window band combination of 12.0-10.8, 10.8-8.7 and 10.8 µm respectively, is one of the most used combinations to track dust clouds (Eumetsat-MSG, 2016). The Dust RGB composite uses the fact that the change of the band's brightness Temperature (T) is strongly correlated with the change in the scattering and absorption caused by dust variability in the atmosphere. That is, the dust aerosol variability

- 5 alters the radiance falling on the satellite radiometer from which T is calculated. The problem of retrieving dust particle size through analytical approach is complex because a dust layer alone has many variables which might affect a single band brightness temperature T even if the other variables such as surface temperature, surface emissivity, atmospheric water vapor and temperature, and viewing angle are known. A dust layer affects T mainly by Aerosol Optical Depth (AOD), dust particle size and shape and the dust aerosol emissivity which is in turn linked to dust chemical composition (e.g. Brindley et
- 10 al. 2012; Klüser et al. 2011). The uncertainty in the approximation of these many depended variables might be one reason to limit the advance in improving the accuracy of dust size retrieval through detailed analytical approach. The results of previous particle size models seem to inherit the noise introduced by the vague estimation of the dependent variables. In a single thermal SEVIRI band, the effect of dust diameter is potentially "diluted" and difficult to see while the case is different with  $\Delta T_{8-12}$  as it is presented later. This study aim to avoid the inherited noise of many dependent variables by exploiting
- 15 the strong and dominate exponential effect of the particle size on the value of  $\Delta T_{8-12}$ . Here the empirical evidence of this relation is presented and then use it to build a model based mainly on empirical data and a simplified conceptual model. To build the empirical model that link  $\Delta T_{8-12}$  with effective diameter (d), a full range of  $\Delta T_{8-12}$  versus d observations were needed. That is, observation from light to severe dust storms. For relatively light dust emission, the effective diameter sampled by Fennec aircraft campaign during June 2011 over West Africa (Ryder et al., 2013) was used with the corresponding  $\Delta T_{8-12}$ . For severe dust storms, the Mie extinction efficiency factor is used to estimate the effective diameter
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for  $\Delta Q_{ext} = 0$  which then used in building model.

#### 2. Estimating brightness temperatures that correspond to $\Delta Q_{ext} = 0$

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To assess how much a spherical dust particle scatters light, the extinction efficiency factor  $Q_{ext}$  needs to be introduced. Any particle of diameter d which intersects the radiation path will remove power from the incident radiation with intensity  $L_0$  by an amount  $P_{removed}$ 

$$P_{removed} = C_{ext} L_0 \tag{1}$$

where  $C_{ext}$  is the extinction cross section (Hahn, 2009).

The extinction efficiency factor  $Q_{ext}$  for a spherical particle  $Q_{ext}$  is given by Mie's solution for Maxwell's electromagnetism equations as

$$Q_{ext} = \frac{C_{ext}}{C_{geo}} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1)Re\{a_n(x,m,\Psi_n,\xi_n) + b_n(x,m,\Psi_n,\xi_n)\}$$
(2)

where x is called the size parameter and equals  $\frac{\pi d}{\lambda}$ ,  $C_{geo}$  is the geometrical cross section and equals  $\frac{\pi d^2}{4}$ , m is the refractive index,  $a_n(x, m, \Psi_n, \xi_n)$  and  $b_n(x, m, \Psi_n, \xi_n)$  are Mie scattering coefficients derived from solving Maxwell's equations, and  $\Psi$  and  $\xi$  are the Ricatti-Bessel functions (Hahn, 2009).

Eq(2) is solved numerically for any given x and m. The refractive index is wavelength and chemical composition dependent.

5 In this paper, the Di Biagio et al. (2014) estimation of the refractive index *m* has been used where,  $m_{8.7} = 1.10 + 0.20i$ ,  $m_{10.8} = 1.9 + 0.25i$ ,  $m_{12.0} = 1.75 + 0.40i$  are the values given for the 8.7, 10.8 and 12.0 µm respectively. These refractive index estimations were made in the laboratory for five dust samples collected during dust events originated from different Western Saharan and Sahelian areas (Di Biagio *et al.*, 2014). In this paper variation in chemical composition of dust particles from different sources has not been taken into account.



Figure 1: Extinction Efficiency Factor  $Q_{ext}$  at 8.7, 10.8 and 12.0  $\mu$ m wavelengths versus the particle diameter.

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MiePlot software (Laven, 2016) gives a choice to calculate 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  $\mu$ m] 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 distribution peaks between [10 to 60]  $\mu$ m in fresh, heavy dust events which is the focus of interest for this calculation. Figure 1 shows the calculated Mie extinction efficiency factor  $Q_{ext}$  for particle diameter from 1 to 50  $\mu$ m. As Figure 1 shows, Mie

theory predicts a significant change in the thermal infrared 12.0, 10.8 and 8.7  $\mu$ m extinction efficiency factor when the particle diameter lies between 1 and 20  $\mu$ m. This dust range covers the reported effective dust particle size range during the Fennec 2011 aircraft dust sampling campaign over West Africa which was between 2.3 to 19.4  $\mu$ m for several dust events (Ryder et al. 2013b).

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Since 
$$C_{ext} = \frac{P_{remove}}{L_0} = \frac{L_0 - L_r}{L_0} = 1 - \frac{L_r}{L_0}$$
, hence  

$$Q_{ext} = \frac{4}{\pi d^2} (1 - \frac{L_r}{L_0})$$
(3)

Where  $L_0$  is the surface radiance of a narrow spectral band,  $L_r$  is the radiance for the same narrow band received by a satellite radiometer, which is given by the integral of Plank's function for apparent brightness temperature T

$$\int_{\lambda_1}^{\lambda_2} L_{r\lambda} d\lambda = \frac{hc^3}{k\lambda^3 (e^{\frac{hc}{\lambda kT}} - 1)}$$
<sup>(4)</sup>

10 Following Widger Jr and Woodall, (1976); and Rees and Rees, (2013), for a finite range of wavelength

$$L_r = \pi \int_{\lambda_1}^{\lambda_2} L_\lambda d\lambda = \sigma T^4 (f(x_1) - f(x_2)) = \pi \int_{\lambda_1}^{\lambda_2} L_\lambda d\lambda = \sigma T^4 \Delta f$$
<sup>(5)</sup>

Where  $\sigma$  is the Stefan–Boltzmann constant,  $x_i = \frac{hc}{\lambda_i kT}$ ,  $\Delta f = f(x_2) - f(x_1) = \frac{15}{\pi^4} \int_0^{x_2} \frac{x^3 dx}{e^{x_{-1}}} - \frac{15}{\pi^4} \int_0^{x_1} \frac{x^3 dx}{e^{x_{-1}}}$ 

Substitute the corresponding value of  $L_r$  in Eq (5) into Eq (3) for the two SEVIRI bands 10.8 [9.8 to 11.8µm], 12.0 [11.0 to 13.0] µm and solve for the difference of the extinction efficiency factor  $Q_{ext}$  we get,

$$Q_{ext10} - Q_{ext12} = \frac{4}{\pi d^2} \left( \frac{L_{r12}}{L_{012}} - \frac{L_{r10}}{L_{010}} \right) = \frac{4}{\pi d^2} \left( \frac{\sigma T_{12}^4 \Delta f_{12}}{\varepsilon_{12} \sigma T_s^4 \Delta f_{s12}} - \frac{\sigma T_{10}^4 \Delta f_{10}}{\varepsilon_{10} \sigma T_s^4 \Delta f_{s10}} \right)$$
(6)

Where  $T_s$  is the surface temperature and  $\varepsilon_{\lambda}$  is the spectral surface emissivity.

15 when  $Q_{ext8} - Q_{ext12} = 0$ 

$$\frac{\sigma T_{12}^4 \Delta f_{12}}{\varepsilon_{12} \sigma T_s^4 \Delta f_{s12}} = \frac{\sigma T_{10}^4 \Delta f_{10}}{\varepsilon_{10} \sigma T_s^4 \Delta f_{s10}} \rightarrow \frac{T_{12}^4 \Delta f_{12}}{\varepsilon_{12} \Delta f_{s12}} = \frac{T_{10}^4 \Delta f_{10}}{\varepsilon_{10} \Delta f_{s10}}$$

Which gives

$$\frac{T_{12}}{T_{10}} = \left(\frac{\varepsilon_{12}\Delta f_{10}\Delta f_{s12}}{\varepsilon_{10}\Delta f_{s10}\Delta f_{12}}\right)^{\frac{1}{4}}$$
(7)

The mean emissivity values of barren surfaces at 10.8µm and 12.0µm bands are 0.9478 and 0.9659 respectively (Trigo *et al.*, 2008). For a typical severe dust storm over the Middle East, the temperature of a dust cloud drops to 275

Kelvin while the surface temperature during the day is 300 Kelvin on average. Adopting the numerical solution for f(x) given by (Rees and Rees, 2013), under such conditions and for a thick dust layer, Eq (7) implies:

$$Q_{ext10} - Q_{ext12} = 0 \quad \rightarrow T_{12} = 0.991251 T_{10} \tag{8}$$

Obviously, more precise results can be obtained if localised emissivity data of  $\varepsilon_{10}$  and  $\varepsilon_{12}$  are used. 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 these two values,  $Q_{ext12} - Q_{ext10} > 0$ , and hence  $T_{12} - 0.991251 T_{10} < 0$ . Using the condition in Eq (8) with a real data of a dust storm, it is possible to find the values of  $T_{12}$ ,  $T_{10}$  and  $T_8$  which correspond to the effective diameter d 11.3µm and 18.0 µm for a severe dust storm. The values will be used to solve for the coefficients of a generalised model in section 3.

## 10 3. An empirical formula to link $\Delta T_{8-12}$ and effective diameter

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The measured Earth radiance at a satellite instrument has two components, a surface contribution, and an atmospheric contribution. The expression for of satellite remotely sensed spectral radiance  $L_{\lambda}$  can be simplified mathematically to the following form of the radiative transfer equation (Kerr *et al.*, 1992; Walton *et al.*, 1998; Dash *et al.*, 2002; Jin *et al.*, 2015):

$$L_{\lambda} = \varepsilon_{\lambda} t_{\lambda} B_{\lambda}(T_s) + (1 - t_{\lambda}) B_{\lambda}(T_a)$$
(9)

Where  $L_{\lambda}$  is spectral radiance received by a satellite instrument,  $\varepsilon_{\lambda}$  is surface emissivity,  $t_{\lambda}$  is the transmittance of the 15 atmosphere,  $B_{\lambda}(T_s)$  Planks function for surface temperature  $T_s$ ,  $B_{\lambda}(T_a)$  Plank's function for the average temperature of the 15 atmosphere. This form of radiative transfer equation assumes no downward radiance and that atmospheric transmittance 16 variance results mainly from different absorption coefficients and forward scattering. 17 The transmittance  $t_{\lambda}$  is given by:

$$t_{\lambda} = e^{-\iint \pi n(r) Q_{ext}(r,\lambda)r^2 \, dr ds} = e^{-\int \pi \sigma_{ext}(d,\lambda)ds} = e^{-\tau_{\lambda}} \qquad (\text{Ackerman, 1997})$$
(10)

Where n(r) is the aerosol size distribution of radius r,  $Q_{ext}$  is the extinction efficiency factor,  $\sigma_{ext}$  is the extinction 20 coefficient, d, is the particle diameter,  $\tau_{\lambda}$  is the AOD.

Split window thermal infrared brightness temperature is commonly used to retrieve land surface temperature e.g. (Kerr *et al.*, 1992; Sobrino *et al.*, 1994; Dash *et al.*, 2002; Jin *et al.*, 2015). For SEVIRI band 8.7 µm and 12.0 µm Eq (9) can be given as:

$$L_8 = \varepsilon_8 t_8 B_8(T_s) + (1 - t_8) B_8(T_a)$$
(11)

$$L_{12} = \varepsilon_{12} t_{12} B_{12}(T_s) + (1 - t_{12}) B_{12}(T_a)$$
<sup>(12)</sup>

The split-window equation is formed by substituting expanding Plank's Function  $B_{\lambda}(T)$  and solving the two equations for  $T_s$ (e.g. Sobrino and Raissouni, 2000; Dash *et al.*, 2002):

$$T_s = T_8 + \beta_1 (T_8 - T_{12}) + E_1 \tag{13}$$

Where  $\beta_1$  accounts for the atmospheric transmittance  $\beta_1 = \frac{1-t_8}{t_8-t_{12}}$  and  $E_1$  accounts for the emissivity from different sources (e.g. Sobrino and Romaguera, 2004). It is also possible to form the following equation by solving Eq (11) and Eq (12) for  $T_s$  using 8.7 µm and 10.8 µm bands

$$T_s = T_8 + \beta_2 (T_8 - T_{10}) + E_2 \tag{14}$$

Subtracting Eq (14) from Eq (13) results in:

$$0 = \beta_1 (T_8 - T_{12}) - \beta_2 (T_8 - T_{10}) + E_1 - E_2$$

For a dry air mass or if significant dust aerosols exist, the difference of 12.0  $\mu$ m and 10.8  $\mu$ m brightness temperatures is small compared to a much bigger difference between 12.0  $\mu$ m and 8.7  $\mu$ m (Eumetsat-MSG, 2016). Thus, it is assumed here that  $(T_8 - T_{10}) = (T_8 - T_{12})$ , which leads to:

$$\Delta T_{8-12} = \frac{E_2 - E_1}{\beta_1 - \beta_2} \tag{15}$$

Eq (15) presents  $\Delta T_{8-12}$  as a function of the difference of the emissivity coefficients to the difference of the transmissivity coefficients. E2 and E1 represent mainly surface emissivity, water vapour (Sobrino and Romaguera, 2004) and dust in case 10 of high dust concentration. All the three bands have equally high water emissivity with small differences between them. Since a difference is taken  $(E_2 - E_1)$ , the net contribution of water vapour emissivity in  $\Delta T_{8-12}$  value is expected to be low and have a minor contribution. Brindley & Russell (2006) experiments with radiative transfer model and SEVIRI showed that BTD  $\Delta T_{8-10}$  and  $\Delta T_{12-10}$  variability rang with water vapour variability is less than 0.2 Kelvin which is very low variation given that the  $\Delta T_{8-10}$  can get up to 15 Kelvin (Eumetsat-MSG, 2016). The same is also expected from dust layer 15 emissivity because the difference in the dust aerosol emissivity between the two bands is also small when the particle size is between 0.1 to 37 µm (Takashima & Masuda, 1987). However, there is a significant difference in the ground emissivity between the bands; 12.0 and 8.7 µm. Most of the Earth's surface has a near blackbody 12.0 µm emissivity of 0.93 and higher. Sandy desert surfaces usually have a much lower 8.7 µm emissivity, typically around 0.65. Thus, this significant difference is expected exhibit itself in  $\Delta T_{8-12}$  value. In this paper, the Global Infrared Land Surface Emissivity Database has been used (Seemann et al., 2008). Figure 2 shows the emissivity of 8.3 µm with strong variability while 12.1 µm emissivity 20 in Figure 3 is more homogenous around a relatively high value.

It is clear that the dust layer brightness temperature decrease with height due to mainly decreasing ambient temperature, but the change of thermal infrared BTD with height is less obvious. Brindley & Russell (2006) and Merchant et al. (2006) used radiative transfer models to show that  $\Delta T_{8-10}$  changes with changing the dust layer height and AOD, extinction coefficient and absorption (Emissivity). Taking into account that AOD, extinction coefficient and emissivity are all a function of the particle size, the change in  $\Delta T_{8-10}$  convey information of the particle size too. Hence, the change in  $\Delta T_{8-10}$  value can be attributed partly as a change in particle size and it is misleading to conclude, based on these studies, that there will be a big impact on the accuracy of the effective particle retrieval using  $\Delta T_{8-12}$ .



Figure 2: Emissivity at 8.3 µm, processed using Global Infrared Land Surface Emissivity Database. The image shows strong variability over sandy desert surfaces compared to 12.1 µm emissivity in Figure 3



Figure 3: Emissivity at 12.1  $\mu$ m, processed using Global Infrared Land Surface Emissivity Database. The image shows more homogeneity compared to 8.3  $\mu$ m (Figure 2) around the relatively high value of 0.93.

In the following two subsections, empirical evidence is presented to show that for a dust cloud with effective diameter d:

- A. The effective diameter *d* is the dominating variable that determines the value of  $\Delta T_{8-12}$  in Eq (15)(12) for a dust layer over a surface of constant emissivity.
- B.  $\Delta T_{8-12}$  can be approximated by  $(E + \Delta \varepsilon)(\frac{A d^3}{(e^{\alpha d} 1)} C)$  where *A*,  $\alpha$ , *C* and *E* are coefficients,  $\Delta \varepsilon = \varepsilon_{12} \varepsilon_8$ ,  $\varepsilon_{\lambda}$  is the spectral surface emissivity.



Figure 4:  $\Delta T_{8-12}$  (left axis) and AERONET AOD (right axis) versus time from 1<sup>st</sup> to 7<sup>th</sup> of April 2015 over the city of Abu Dhabi (UAE). The dotted line is an interpolation of the actual. Limited correlation is observed between the two curves. SEVIRI Dust RGB animation shows that the first peak corresponds to relatively freshly emitted dust while the second corresponds to long transported dust with lower effective diameter expected.

# 3.1. The effective diameter d is the dominating variable of $\Delta T_{8-12}$

- 15 The effect of particle size in a single thermal band is potentially weak and seems to be "diluted" and difficult to see in the presence of the noise caused by the other variables such as Aerosol Optical Depth (AOD) which has a stronger correlation with the apparent brightness temperature of a single band. Previous attempts in using a single band to retrieve effective dust particle size from a single band had limited success (e.g. Pierangelo *et al.*, 2005). In this study, what is used in the model is the Brightness Temperature Difference (BTD) which, in contrary to a single band, strongly varies as a response to particle size change. A comparison plot of  $\Delta T_{8-12}$  BTD and AOD of a "fresh" severe dust storm and another event of long
- transported dust suggests a limited correlation between BTD and AOD. Figure 4 shows an example of AERONET AOD and SEVIRI  $\Delta T_{8-12}$  for six days over the city of Abu Dhabi which witnessed two successive dust events in that period. Dust

RGB animation revealed that the first peak of AOD corresponds to relatively freshly transported dust with large dust effective size, while the second peak mainly corresponds to long transported dust with smaller dust size. The different behaviour of  $\Delta T_{8-12}$  curve around the two AOD peaks clearly indicates different causes, which can be potentially explained by different effective dust diameters. It appears that  $\Delta T_{8-12}$  filters the strong correlation between AOD and *T* in each single band.

3.2. 
$$\Delta T_{8-12}$$
 approximation by  $(E + \Delta \varepsilon) (\frac{A d^3}{(e^{\alpha d} - 1)} - C)$ 

To get the full pattern of  $\Delta T_{8-12}$  variability against effective diameter it should be plotted for maximum variation range of d; that is, it needs to be applied for a severe dust storm. At the time of writing, there is no known available in-situ effective diameter d sampling for a severe dust storm. However, for a location which is about to be affected by a recently created severe dust storm, it is certain that d changes form low value to high value as time passes for that location. Hence, several plots have been created for  $\Delta T_{8-12}$  for locations ahead of a severe dust storm affecting the Arabian Peninsula on 1<sup>st</sup> to 3<sup>rd</sup> April 2016. Examples are presented in Figure 5 and Figure 6. In the vicinity of significant changes in dust concentration as a dust storm arrives at a point both  $\Delta T_{8-12}$  curves show the distinctive pattern of  $f(x) = \frac{ax^3}{(e^{bx}-1)} - C$  curve shown in Figure 7.

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Figure 5: The change of  $\Delta T_{8-12}$  versus time at a location 27.0 N and 47.8 E, Figure 17, which is approximately 300 km from the centre of the dust emission of a severe dust storm affecting the Arabian Peninsula.  $\Delta T_{8-12}$  increases exponentially when the storm starts influencing the atmosphere in the location. Similar in pattern to the curve in Figure 7.



Figure 6: The change of  $\Delta T_{8-12}$  versus time over central Qatar Peninsula.  $\Delta T_{8-12}$  increased exponentially when the dust storm, (Figure 17), starts affecting the location similar in pattern to the curve in Figure 7.





Actual values of ( $\Delta T_{8-12}$ , *d*) from four dust events were used to numerically calculate the coefficients *A*, *a*, *C* and *E*. Three of the dust cases were sampled by Fennec aircraft, Flights b602, b604, b605, b606 18-21 June 2011 (Ryder, *et al.*, 2013). As an example, Figure 9 shows the brightness temperature change of 8.7, 10.8 and 12.0 µm bands versus time of the 20<sup>th</sup> of June 2011 at the sampling experiment location 24.0N, 10.0W (Figure 8) by Fennec b604 flight on 20 June 2011. The reported mean *d* was around 6 µm. The fourth dust case was a severe dust storm which is utilized to guide the model at high *d* values. Figure 10 shows the brightness temperature of a severe dust case over Arabian Penisula at location 27.0N, 47.8E (detailed description is in Section 5). In this case, as explained in Section 2 (Figure 1), few points of ( $\Delta T_{8-12}$ , *d*) could be

estimated from the corresponding small pocket of  $\Delta T_{12-10}$  negative values formed between diameters 11.3 and 18.0 µm;

10 that is when  $\Delta Q_{ext10-12} = 0$ .



Figure 8: SEVIRI Dust RGB on 20th of June 2011 at 15:30 UTC; the head of the yellow triangle points to the location of Figure 9.



Figure 9: the brightness temperature of  $8.7,10.8, 12.0 \mu m$  bands (left axis) and effective diameter *d* (right axis) versus time of the 20<sup>th</sup> of June 2011 at 24.0N, 10.0W. The time of the satellite image in Figure 8 is shown.



Figure 10: The change of the brightness Temperature (T) of 8.7, 10.8, 12.0 µm SEVIRI bands versus time of the 1<sup>st</sup> & 2<sup>nd</sup> of April 2015 at the location (27.0 N, 47.8 E) which is affected by a dust cloud (Figure 17).

To solve for the  $\frac{\Delta T_{8-12}}{(E+\Delta\varepsilon)} = (\frac{A d^3}{(e^{\alpha d}-1)} - C)$  model coefficients, Excel solver (Fylstra *et al.*, 1998; Harris, 1998) was used with the values of *d* and the corresponding  $\Delta T_{8-12}$  from the four dust cases described above. The technique was based on converging the solutions of the points towards a minimum sum of square deviation. The result was A = 0.087,  $\alpha = 0.12$ , C = 57.8 and E = 0.04. Figure 11 shows a plot of the model  $\frac{\Delta T_{8-12}}{(E+\Delta\varepsilon)}$  versus the effective diameter *d* with the actual points used to calculate the coefficients *A*,  $\alpha$ , *C* and *E*. For convince, a Look Up Table (LUT) was created for given *d* and the corresponding ratio of  $\frac{\Delta T_{8-12}}{(E+\Delta\varepsilon)}$ .



Figure 11: A plot of the model of  $\frac{\Delta T_{8-12}}{(E+\Delta \varepsilon)} = \frac{A d^3}{(e^{\alpha d}-1)} - C$  versus effective diameter *d* with the actual points from four dust cases used to calculate the coefficients by Excel Solver.

## 4. Testing the algorithm

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Three cases over West Africa (Figure 12) are presented here to test the algorithm. The sampling in the three cases was carried out by Fennec aircraft campaign during June 2011 over West Africa (Ryder *et al.*, 2013). In all cases, the location of

15 brightness temperature curves was chosen to be as close as possible to the middle of the sampling area and where there was minimum cloud presence at the time of sampling. The time slots with cloud contamination have been removed.

#### 4.1. Case 1: Mali; 17-18 June 2011:

The dust was sampled by Fennec flight number b600, 17 June 2011 10:00 to 11:15 UTC during the emission phase of the dust event (Ryder *et al.*, 2013). There was another sampling mission (Fennec 601) on the same day between 17:15 to 18:15
UTC. The reported mean *d* from Fennec sampling was around 12.3 µm. Figure 13 shows the calculated *d* using the model and the BT of 8.7, 10.8 and 12.0 µm bands versus time at 21.2N, 5.6W. The 8.7 µm ground emissivity in the location is 0.712 using the Global Infrared Land Surface Emissivity Database (Seemann *et al.*, 2008). The average *d* calculated using the model during the time of sampling was found to be 11.4 µm. This value is expected to be less than the one reported by Fennec sampling for a "recent uplift" dust event. In the recent uplift stage, incoherent structure of the dust cloud is at maximum, where large particles of dust are present in lower levels and fine dust in the higher level. Another good reason that might contribute to the underestimation is the Fennec aircraft sampling method. The sampling was limited to altitudes beneath 2400m above the ground level while SEVIRI measures the radiation coming from the upper part of the dust cloud which might have smaller dust size at higher altitudes



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Figure 12: Map of the locations (green triangles) of the three test cases (USGS, NOAA base map 2016).



Figure 13: The brightness temperature of 8.7,10.8, 12.0  $\mu$ m bands (left axis) and diameter *d* (right axis) versus time of the 17<sup>th</sup> to 18<sup>th</sup> of June 2011 at 21.2N, 5.6W.



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Figure 14: the brightness temperature of 8.7,10.8, 12.0  $\mu$ m bands (left axis) and diameter *d* (right axis) versus time of the 25<sup>th</sup> of June 2011 at 25.8N, 7.4W.



Figure 15: the brightness temperature of 8.7,10.8, 12.0  $\mu$ m bands (left axis) and diameter *d* (right axis) versus time of the 25<sup>th</sup> of June 2011 at 23.7N, 10.3W.

#### 4.1. Case 2: Mauritania; 25 June 2011:

The second case is another "recent uplift" dust emission. The case was sampled by Fennec b610, 25 June 2011 09:15 to 10:45 UTC (Ryder *et al.*, 2013). The sampled mean *d* was around 7.4 μm. Figure 14 shows the calculated *d* and the BT of 8.7,10.8, 12.0 μm bands versus time of the 25<sup>th</sup> of June 2011 at the location (25.8N, 7.4W). Emissivity of 8.7 μm band at the location is 0.712. The average *d* between 0800 to 1130 UTC is calculated to be 6.2 μm which is again expected given the low-level sampling which probably selected larger particles due to inhomogeneous fresh dust cloud as in Case 1.

#### 4.2. Case 3: Mauritania; 24-26 June 2011:

This case is a case of long transported dust and covers a relatively large area which was sampled by four Fennec flights missions over three days (Ryder *et al.*, 2013). The emissivity of 8.7 μm band at the location is 0.732. Figure 15 shows the calculated *d* and the brightness temperature of 8.7,10.8, 12.0 μm bands versus time of the 25<sup>th</sup> to 26<sup>th</sup> of June 2011 roughly in the centre of the sampling area (23.7N, 10.3W). In this case the sampled and retrieved effective diameter *d* showed very good agreement. The average sampled *d* for the three days around the flight hours was 7.1 μm while the model retrieval shows *d* of 6.0 μm.

The SEVIRI readings were taken in 30 minutes' steps. For each reading, the effective diameter is calculated using the model. The standard deviation is calculated from the deviation from the mean sampled value for all time steps during the sampling period. Table 1 provides a summary of the testing results. Overall, the model gave promising results. In cases#1 and #3 the sampled value was within 95% confidence interval for a single value, and in case#2 it was just outside this interval.

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Case Number	Location	Sampled (µm)	Modelled (µm)	95% confidence interval for a single value (μm)
Case #1	Mali; 17-18 June 2011 "Recent uplift"	12.3	$11.4\pm0.7$	10.7 to 12.1
Case #2	Mauritania; 25 June 2011 "Recent uplift"	8.6	$7.4 \pm 0.3$	7.1 to 7.7
Case #3	Mauritania; 24-26 June 2011 "Long transported"	5.9	$7.1 \pm 1.5$	5.6 to 8.6

Table 1: Summary of the model testing results with one standard deviation and 95% confidence interval from a single value.

#### 4.3. Discussion of results

- 10 The accuracy of the numerical solution for the coefficients *A*, *α*, *C* and *E* in the model can be improved if more in-situ data were used in the calculation. This is important to dilute the bias made by individual in-situ measurements. An example of the bias that could be avoided is the one resulting from constraining the sampling to altitudes lower than 2400 meters, with most samples acquired in a lower part of this air mass (Ryder, Highwood, Rosenberg, *et al.*, 2013). The sampling will be more representative of the column average from the satellite perspective- if it is extended to higher levels and if sampling time were more evenly distributed vertically. There is also lack of intense dust storms in the published sampled data, with most aircraft sampling being undertaken during relatively low to moderate dust emission events. This is probably for safety reasons, but it does limit the validation of the method for major dust events with larger particle sizes. It will be interesting to observe the use of emerging drone technology to sample dust in intense to severe dust storms. Such data should help to clarify many aspects of dust storms dynamics in general and, fine-tune this model in particular.
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Another limitation originates from the spherical assumption of the dust particle. The effect of non-sphericity is not considered here. 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 developed by, e.g. Cheng et al.(2010); Dubovik et al.(2002); Dubovik et al. (2002b); Wang et al. (2003). The chemical composition of dust particles also has an effect on optical properties of dust

25 aerosols. Different dust sources have different dust composition. And as with non-sphericity, the chemical composition affects the refractive index of dust. Klüser *et al.*(2015, 2016) give a detailed analysis on the effect of nonsphericity and chemical composition on spectral bands in the thermal infrared region. At this stage, the extent of the effect of nonsphericity and chemical composition is not known when using  $\Delta T_{8-12}$ . Hence, it is still crucial to develop localised accuracy assessment of the algorithm to compensate the difference in the dust particle morphology and composition.



5 Figure 16: Diurnal change of brightness temperature for a clear sky taken for a point over the desert (16.7N, 34.4E).

Although the extinction efficiency in Figure 1 implies that  $T_{12.0}$  should be greater than  $T_{10.8}$  for  $d < 11.3 \mu$ m; the actual SEVIRI reading in a low dust concentration atmosphere are  $T_{12.0} < T_{10.8}$  in general, except for parts of sandy desert where 10.8  $\mu$ m surface emissivity is significantly low. Figure 16 shows a diurnal change of  $T_{12.0}$  compared to  $T_{10.8}$  during a

- 10 relatively low dust concentration atmosphere. The slight cooling in the 12.0 µm band is explained by higher water vapour absorption in the lower part of the atmosphere (Eumetsat-MSG, 2016). With increasing dust particle concentration, their contribution of the radiation falling on the satellite sensor will increase and hence, the information content about dust optical properties in the signal increases. Thus, when dust concentration is low, it is expected that the model bias to grow. Klüser *et al.* (2015) gives detailed explanation of the problem in terms of reduction of degrees of freedom for signal when the AOD
- 15 decreases or dust layer temperature increases.

#### 5. Use of the algorithm

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Potential applications for the model include:

- To provide an independent reference data for atmospheric aerosol model comparison. This application is crucial a. because of the scarcity of airborne aerosol in-situ measurements.
- Horizontal visibility forecasting. A sudden drop in horizontal visibility during dust storms is known to be the most b. direct and hazardous effect of dust storms. Since horizontal visibility is particle diameter dependent, combining particle diameter data from this model with the carrying air mass trajectory forecast from atmospheric models can give an indication of the horizontal visibility from a few hours to a couple of days depending on the location of the emission source.
- Solar energy system performance forecasting. The performance of the solar power systems depends on the turbidity of the atmosphere which depend on AOD as well as the number of dust particles precipitates over the solar panels which correlate with the effective particle diameter. The technique can give an indication of the amount of dust that will precipitate on solar energy systems from an upcoming dust event.
- 15 d. Assist in studying the transport behaviours of dust in the atmosphere.

A severe dust storm is presented here as an example of the model use. The aim is to check model behaviour in severe cases and how dust particle size will change over an extended period. The dust storm originated on 1<sup>st</sup> of April 2015 over the Arabian Peninsula and affected a large area of western Asia. The brightness Temperature T of the three SEVIRI bands and effective diameter retrieval d was plotted against time around the dust cloud passage for three locations along the track of the dust cloud movement.

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Location #1 was chosen to be close to the emission source and downstream of wind flow to pick the maximum concentration of emitted dust. The location is at around 300 km southeast the centre of the emission source (Figure 17). The average background aerosol effective diameter in the early hours of  $3^{rd}$  of April is calculated to be 6.7  $\mu$ m which is not

25 far from the reported background dust of 7.2 by Fennec aircraft campaign during June 2011 (Ryder et al., 2013). The slight difference can be explained by the heat low pressure, that develops during summer over the desert and helps to keep larger dust particles longer in the air through dry convection. The maximum d in this case was around 18.5  $\mu$ m (Figure 18) which is within the range of the reported d by Fennec aircraft campaign  $(2.3 - 19.4 \,\mu\text{m})$ .



Figure 17: SEVIRI dust RGB for 01.04.2015 11:15 UTC, showing the location where the brightness temperature of 8.7, 10.8, 12 µm bands were plotted (Figure 18). The black arrow indicates the direction of the dust storm movement.



Figure 18: T of 8.7,10.8,12.0  $\mu$ m bands (left axis) and *d* (right axis) versus time of the 1<sup>st</sup> & 2<sup>nd</sup> of April 2015 at location#1 (27.0 N and 47.8 E) which is approximately 300 km from the centre of the dust emission source, ahead of the dust cloud movement. The time of the satellite image in Figure 17 is shown.

Location #2 is the city of Abu Dhabi (Figure 19) and correspond to 24 hours later than Figure 17. Figure 20 shows that the maximum calculated d has dropped to 16.5  $\mu$ m from 18.5  $\mu$ m at Location#1 24-hour prior. This drop coincides with the fact that d in a dust cloud is inversely proportional with time, because as time progresses large dust particles precipitate leaving smaller particles in suspension.

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Location #3 is chosen to investigate the evolution of the effective diameter of long transported dust after three days from emission (Figure 21 and Figure 22). Xu et al. (2010) found that the volume average diameter of dust particles coming from the sources in western Asia ranged between 3.2 to 4.2  $\mu$ m over the central Himalaya. For Location#3 in the research reported here and following several cloud animations, on average, the air mass carrying the dust needs around 5.5 days to move from a source over the centre of the Arabian Peninsula and to the central Himalaya. The calculated three-hour average of *d* after three days was 6.4  $\mu$ m between 06 to 13 UTC on the 4<sup>th</sup> April. Although central Himalaya is outside SEVIRI coverage , there are still 2.5 days to *d* to reduce to the average diameter presented by Xu et al. (2010).



15 Figure 19: SEVIRI dust RGB for 02.04.2015 11:00 UTC. The dust cloud is over Location#2.



Figure 20: *T* of 8.7,10.8, 12.0  $\mu$ m bands (left axis) and *d* (right-axis) versus time of the 1<sup>st</sup> to 3<sup>rd</sup> of April 2015 over Location#2 (Abu Dhabi). The time of the satellite image in Figure 19is shown.



Figure 21: SEVIRI dust RGB for 04.04.2015 12:00 UTC. The dust cloud is over Location#3.



Figure 22: T of 8.7,10.8, 12.0 bands (left axis) and d (right axis) versus time of the 3<sup>rd</sup> to 5<sup>rd</sup> of April 2015 over Location# 3 (21.9N, 67.9E). The time of the satellite image in Figure 21 is shown.



Figure 23: A 4 km resolution raster shows effective diameter on the 1<sup>st</sup> April 2015 18:15 UTC calculated using the algorithm. Most of the clouds were screened out. However, few water clouds are still evident in this product (e.g., South East coast of Yemen).

The effective diameter d can be represented in a 2D map. Figure 23 shows an example for 1st April 2015 18:15 UTC. Most of the clouds were screened out; however, a few water clouds still manifest themselves in this product (e.g. Southeast coast of Yemen). The use of a sophisticated cloud screening algorithm could improve this aspect of the results.

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Future work will include testing the model with another satellite radiometer outside SEVIRI coverage area. One candidate is the new Advanced Himawari Imager (AHI) on board the Himawari-8 satellite. This instrument provides data that potentially can be exploited to retrieve effective diameter for dust clouds over Australia and central/east Asia. Another interesting feature in Himawari-8 AHI is its extra spectral band in the thermal infrared range. In principle, with more spectral bands, the accuracy of retrieval should increase especially on the larger dust size.

#### Conclusions 6.

Dust cycles are an important part of the earth system. The current in-situ sampling data of dust particle size are sparse and expensive. Thus, remote sensing retrieval methods have an important role in covering the gap. In this paper, an empirical

15 algorithm has been presented to estimate effective aerosol diameter d using satellite-based observations. The infrared brightness temperature difference of SEVIRI bands  $\Delta T_{8-12}$  were used in the retrival. The algorithm showed promising consistency with the other means of estimating d in the literature (Table 1). The accuracy of estimating the coefficients in the empirical model is expected to improve if more in-situ d measurements are used in the numerical solution. The model can assist in predicting horizontal visibility when used with air-mass trajectory forecasting and improve prediction of solar 20 energy performance in regions with high dust storm prevalence.

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