Responses to the Referee #1

This study developed a global dataset of direct radiative effect efficiency (DREE) of mineral dust for ten dust size bins with geometric diameter from 0.1 µm to 100 µm, three sets of refractive indices (weak, mean, and strong absorbing), and two shapes (spherical and spheroidal). The monthly DREE dataset is derived from the Rapid Radiative Transfer Model (RRTM) model using CALIOP-based dust aerosol optical depth (DAOD) and vertical distribution along with atmospheric profiles from MERRA-2 and surface variables. The global direct radiative effect (DRE) of dust aerosols is then examined using the DREE-integration method and DAOD climatology from CALIOP and MODIS, respectively. It is found that different spatial distributions of DAOD may contribute to about 10% differences in shortwave DRE of dust even with the same global mean DAOD. The calculated DRE is also sensitive to refractive index (RI) and particle size distribution (PSD) but much less affected by dust shape. Improving the estimation of the DRE of dust is essential to reduce the uncertainties of radiative forcing of aerosols to the climate system. This observation-based study and newly developed dust DREE dataset will provide a useful tool to constrain model simulations and study dust DRE. Overall, the paper is very well written, with thorough description and analysis of DREE calculation, validation, uncertainty, and comparisons with previous studies. I have some minor comments for the authors to consider.

Reply: We would like to thank the reviewer for the insightful comments. We have addressed these comments in the revision. An item-to-item reply to the reviewer's comments is provided below.

1. Section 3.1, it's not clear here which version of PSD is used in the calculation. Moving the information about PSD in lines 467-468 to here could be helpful.

Reply: Sorry for the confusion. In section 3.1, we calculate dust scattering properties (i.e., Qe, ω and g) for each of ten size bins. Therefore, we only need to consider dust particle within the corresponding size bin in the calculation of scattering properties of the size bin, we do not need the information of dust PSD of full-size range. The dust particle number of each size bin (i.e., sub-bin dust size distribution dN/dD) is assumed to be uniformly distributed within each size bin.

2. Line 295, is the DRE^{SW} a vertical profile?

Reply: Thanks for the question. The DRE^{SW} in Eq (1) represents dust DRE^{SW} at TOA or surface. DRE^{SW} is not a vertical profile.

We include vertical profile of water vapor, ozone, and carbon dioxide in Eq (1) to indicate that we account for gas absorption by water vapor, ozone, and CO_2 in SW radiative transfer calculations for each size bin.

This is clarified in the paper by adding 'We include 3-hourly monthly mean vertical profile of water vapor, ozone, carbon dioxide ($\overline{H_2O(t)}, \overline{O_3(t)}, \overline{CO_2(t)}$) to account for gaseous absorption.'

3. Line 306, please add more details about surface emissivity. Is it also from satellite retrievals?

Reply: Thanks for the question. The surface spectral emissivity from Huang et al. (2016) is based on MODIS emissivity retrievals and modeled different types of surface spectral emissivity.

This part in the paper is modified as 'Surface spectral emissivity ('E') is obtained from Huang et al. (2016), which contains monthly mean spectral surface emissivity with 0.5-degree spatial resolution based on MODIS-retrieved mid-IR surface emissivity and modeled different types of surface spectral emissivity.'

4. Line 394, what about the uncertainties of ignoring the horizontal variations in dust particle size due to different dust lifetime?

Reply: Thanks for the great point. We added the limitation of ignoring the horizontal variation of dust size and modified the paper as 'First, possible vertical and horizontal variations of dust particle size in each grid box ($5^{\circ} \times 2^{\circ}$) are not accounted for in our calculation. The entire dust-loading column is assumed to have the same dust size distribution.'

5. In the simulation where Fennec-Fresh PSD is used in the dust belt (covering dust sources in the Sahara, Middle East, and eastern Asia) and AER-D PSD over other regions, it's interesting that shortwave DRE are much smaller over dust sources in the Indian subcontinent and Taklamakan Desert (Fig. 10), although DAOD is relatively high in these regions in both CALIOP and MODIS (Fig. 1). Can you comment on this?

Reply: Thanks for the comment.

That should be due to the difference in surface reflectance. Generally, dust induce a cooling effect in SW at TOA over dark surface (e.g., over ocean). However, when surface is bright, dust absorption is enhanced, dust SW cooling effect at TOA would be weakened or even turns to be a warming effect if surface is bright enough.

As we can see from the figure below, surface reflectance at visible band over Sahara Desert and Arabia is very high, thereby inducing warming effects in SW.

Over Indian subcontinent and Taklamakan Desert, surface reflectance is higher than surrounding ocean (e.g., Arabian Sea) but lower than Sahara and Arabia. The surface reflectance is not high enough to cause warming effect in SW but weakens the SW cooling effect.

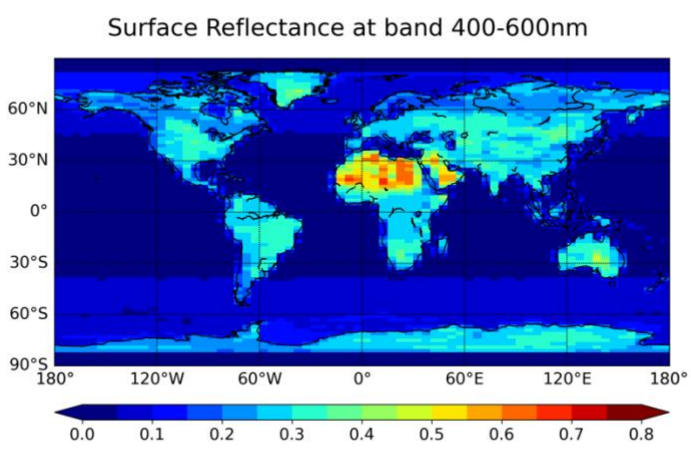


Figure 1. 4-year (2007-2010) annual mean surface reflectance at band 400nm to 600nm.

6. Line 676, consider providing more information about the dust RI used by Kok et al. (2017) for a brief comparison.

Reply: Thanks for the comment.

We add more information about dust RI used in Kok et al.2017. We modified this part of the paper as: ‘Second, the two studies use different dust RI. For example, the imaginary part of RI at 550nm in this study ranges from 0.00061 to 0.003, while that in Kok et al. (2017) ranges from 0.0014 as used in GEOS-Chem and GISS model based on Sinyuk et al., (2003) to 0.003 as used in WRF-Chem based on Zhao et al., (2010).’

References:

Sinyuk, A., Torres, O., and Dubovik, O.: Combined use of satellite and surface observations to infer the imaginary part of refractive index of Saharan dust, Geophys. Res. Lett., 30, https://doi.org/10.1029/2002GL016189, 2003.

Zhao, C., Liu, X., Leung, L. R., Johnson, B., McFarlane, S. A., Gustafson, W. I., Fast, J. D., and Easter, R.: The spatial distribution of mineral dust and its shortwave radiative forcing over North Africa: Modeling sensitivities to dust emissions and aerosol size treatments, Atmos. Chem. Phys., 10, 8821–8838, https://doi.org/10.5194/acp-10-8821-2010, 2010.

Responses to the Referee #2

This paper develops a dust direct radiative effect efficiency (DREE) climatology that is based upon the dust aerosol optical depth (DAOD). The purpose of the climatology is to allow a quick computation of the dust direct radiative effect (DRE) from the DAOD, which can be inferred from satellite datasets such as CALIOP. I think that this is a good paper that is suitable for publication, but I struggled a bit with the methodology.

Size-dependent SW and LW DRE are computed from the Rapid Radiative Transfer Model (RRTM) for six dust models with 10 size bins. The dust models include three complex refractive indices (low, medium, and high) and two shapes (spheres, spheroids). The real and imaginary refractive indices are coupled (low RRI is paired with low IRI, etc).

The RRTM is used to simulate monthly mean DRE using CALIOP DAOD; apparently this is done for each size bin (per line 273). As near as I can tell, though, all of the DRE calculations use the CALIOP DAOD for the computations, per Eq 1 and line 301. This isn't helpful for computing the actual DRE associated with the atmospheric state, except that the authors are targeting DREE (not DRE). Thus, their argument seems to be that the DREE of the different size bins are not coupled. I am ok with that, except

Reply: We would like to thank the reviewer for the insightful comments. We have addressed these comments in the revision. An item-to-item reply to the reviewer's comments is provided below.

1.) why do you need CALIOP DAOD to do this? Why not just compute DAOD and DREE from the size and RI that you used to compute DRE? Perhaps that is what is being done, but the writing was not clear to me.
Reply: Thanks for the question.

In this part (Eq 1 ~ Eq 5 in Section 3.2), our target are DREE calculations of each size bin. The monthly mean DRE^{SW} of k^{th} size bin calculated in Eq (1,2,3,4) do not represent the actual DRE^{SW} contributed by k^{th} size bin since they are calculated based on CALIOP DAOD of a full-size range. They are intermediate variables used to calculate $DREE^{SW}$ in Eq (5).

The DAOD from each size bin depends on both RI and dust particle size distribution (PSD) over a full-size range. Without the accurate knowledge of dust PSD over full-size range, we are not able to get DAOD of each size bin. Therefore, considering dust DRE is approximately linear to DAOD, we simply use CALIOP DAOD to calculate dust DRE and further calculate DREE of each size bin through dividing dust DRE by the corresponding CALIOP DAOD.

To clarify this, we added 'Worth to mention, our target in this section is $DREE_{k,i,j}$ calculations. Considering dust DRE is approximately linear to DAOD (Satheesh and Ramanathan, 2000), the DAOD used in dust DRE calculations will not affect dust DREE results significantly, we simply calculate dust $DRE_{k,i,j}$ with respect to $DAOD_{i,j}^{532nm}$ from CALIOP-based DAOD climatology. As a result, $DRE_{k,i,j}$ calculated in this section are only intermediate variables used to calculate dust DREE, they do not represent actual DRE contributed by k^{th} size bin.' in section 3.2.

2.) is it really necessary to carry water vapor, ozone, and CO2 in the DRE calculations of Eq 1 when we are assuming that the aerosols in the 10 size bins are decoupled (and hydrophobic)? There is much overlap in the extinction efficiencies in Fig 3, so I would expect that the neighboring size bins have a significant influence on the radiation field (in the SW, at least).

Reply: Thanks for your question and comment.

Carrying water vapor, ozone, and CO_2 vertical profile in Eq (1) indicates that we account for gas absorption by water vapor, ozone, and CO_2 in SW radiative transfer calculations for each size bin. This is clarified in the paper by adding 'We include 3-hourly monthly mean vertical profile of water vapor, ozone, carbon dioxide ($\overline{H_2O(t)}, \overline{O_3(t)}, \overline{CO_2(t)}$) to account for gaseous absorption.'

It is quite possible that I read Section 3.1 incorrectly, though. However, that means that other people might struggle as well. I recommend clarifying Section 3.1. This probably won't take too much effort if you focus on describing Figure 4, which makes sense to me.

How many streams are the authors using in the RRTM? Apparently they are using a two-stream approximations (since they are using asymmetry parameters and not using phase functions). This needs to be mentioned.

Reply: Thanks for your question.

Four streams are used in DISORT. The Henyey-Greenstein phase function is used and only the first moment of the phase function (i.e., asymmetry parameter) needs to be specified in the RRTM. This clarification is added in section 3.1 line 273-275.

Since you are using CALIOP DAOD, I think that there should be some discussion about the CALIOP lidar ratio assumption. For instance, CALIOP uses a single lidar ratio for dust worldwide, and this will contribute to the regional CALIPSO/MODIS DAOD bias (that the authors mention on page 6) if the real-world dust lidar ratio varies regionally. A regionally-variable lidar ratio could be caused by regionally variable mineralogy, which would also cause regionally variable refractive indices. This would also impact how the tables should be applied. For instance, one would want to assume the highest imag refractive indices in dust regions with the highest proportions of iron.

Reply: Thanks for your great suggestion.

Yes, the use of globally uniform dust lidar ratio in CALIOP dust retrievals do contribute to the regional CALIOP/MODIS DAOD difference. Several potential reasons of causing the CALIOP/MODIS DAOD difference are discussed in Song et al. (2021).

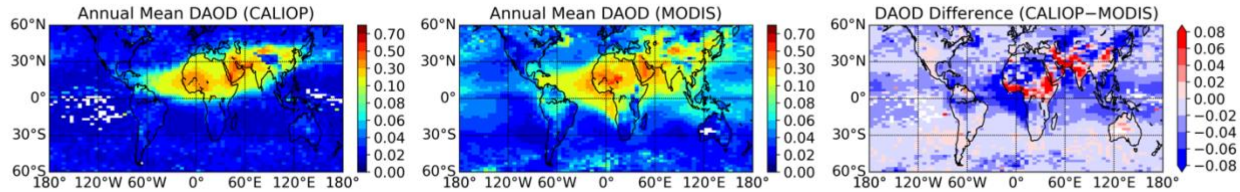
We modified Line 111-116 as 'Song et al. (2021) also compared dust retrievals, in particular DAOD, based on different methods (i.e., CALIOP-based and MODIS-based DAOD retrievals), showed that DAOD often differ significantly between the different products and further discussed the potential reasons of causing the differences (e.g., instrument calibration errors and errors in discriminating cloud from aerosol, dust Lidar Ratio assumption in CALIOP DAOD retrieval and so on).' Interested readers are referred to Song et al. 2021 for more detailed discussion.

Why are the maps in Figure 1 so small?? It is really difficult to concur the text with the figures on page 10 when the authors are using so small of a figures. You might also consider replacing these maps with a difference map, since you are mostly discussing differences between the two maps in the text.

Reply: Thanks for your comment and suggestion.

Following your suggestion, we add a map of DAOD difference between CALIOP and MODIS to show the DAOD difference in magnitude between the two DAOD products. We keep the DAOD map of each product for readers to see the difference in DAOD spatial pattern.

The modified Figure 1 is shown below.



MINOR POINTS

Real and imaginary refractive indices are not necessarily coupled. Thus, high real indices don't necessarily pair with high imaginary refractive indices. No need to change methodology on this point, but that should be mentioned.

Reply: Thanks for pointing that out.

In both SW and LW, we use three different RIs to represent dust with weak, medium, and strong absorptivity. Dust absorptivity mainly depends on imaginary part of RI. Therefore, weak, medium, and strong absorptivity are corresponding to low, medium, and high imaginary part of RI, respectively. In other words, we use imaginary part of RI as standard to define the Min, Mean, Max RI described in Table 1.

line 204:

Authors refer to another paper for the two dust shapes, but the two shapes are merely spheres and spheroids. Why not just tell the reader such simple info up front?

Reply: Thanks for the question.

The two dust shapes indicate spherical dust shape and spheroidal dust shape distribution shown in Figure 4 (a) in Song et al. 2018 (see Figure 1 below).

Spherical shape is very easy and does not need to be shown. However, spheroidal shape is determined by aspect ratio. Aspect ratio smaller than 1 represents oblate shape, while larger than 1 represents prolate shape. The spheroid used in this study is not a single shape, it is a shape distribution. Figure 4 (a) in Song et al. 2018 shows the aspect ratio distribution of the spheroidal dust.

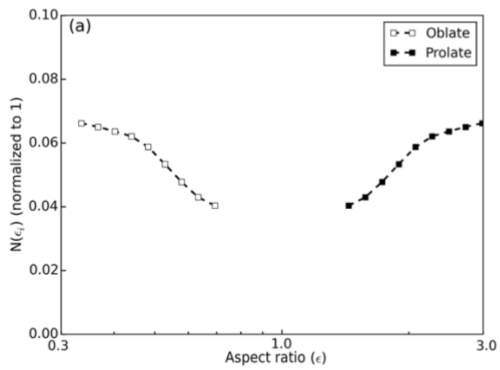


Figure 2. Spheroidal shape distribution from Figure 4 (a) in Song et al. 2018.

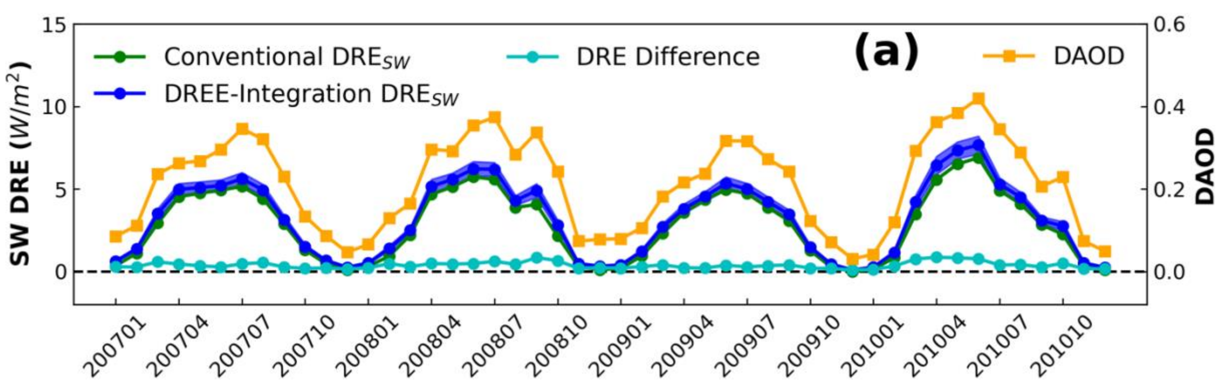
Line 305:
Eq 2 should immediately follow its introduction (i.e., immediately follow first sentence on line 305).
Reply: Done

Line 312-4:
Likewise, Eqs 3 and 4 should immediately follow their introduction.
Reply: Done

Fig 2 caption:
Briefly tell the reader the where you found these refractive indices (e.g., Di Biagio 2017, 2019; Balkanski 2007).
Reply: Done

Fig 3 caption:
Define the y-axis variables in the caption.
Reply: Done

Fig 8
Here again, I think that difference plots would be stronger than requiring a reader to surmise the differences between lines on a rather small y-axis.
Reply: Thanks for the comment. We added the DRE difference on the plot as shown below.



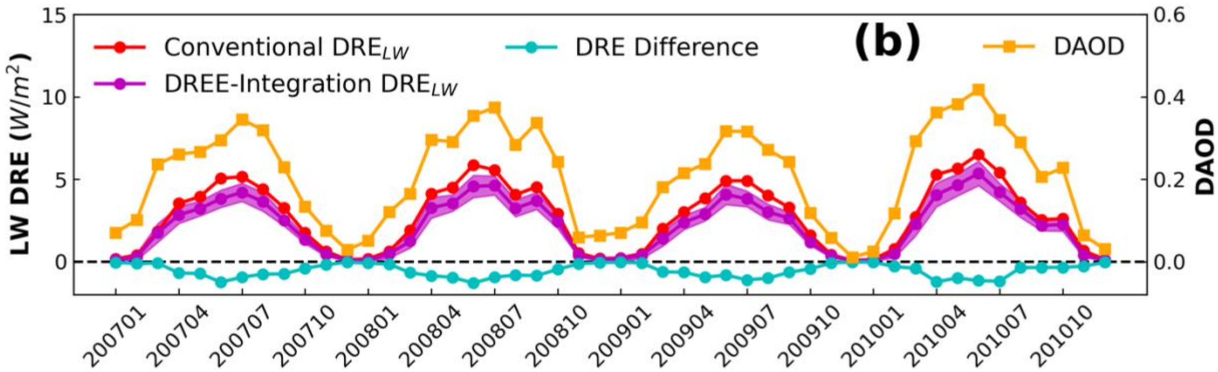


Figure 8 in the paper: Monthly mean dust DRE^{SW} (**a**) and DRE^{LW} (**b**) comparison between *Conventional* and *DREE-integration* calculation from 2007 to 2010 over Sahara Desert. The DRE Difference line represents the difference between *DREE-integration* and Conventional calculation. Shaded area along *DREE-integration* DRE indicates the one standard deviation caused by the atmospheric and surface variations as well as dust vertical distribution variation within the four years. Orange curves indicate CALIOP-based monthly mean DAOD. The variation of dust DRE match well with DAOD variation.

Figure S1 and S2 are way too small to be at all useful.

Reply: We modified the figures to be large.