Dear Dr. Chiu,

We would like to thank you for your effort on our paper. We’d also like to thank the three anonymous reviewers for their insightful and suggestive reviews, which have helped us improve the paper significantly.

Following the reviewers’ comments, we have revised the manuscript significantly. Important changes include:

- We changed the title to “Net Radiative Effects of Dust in Tropical North Atlantic Based on Integrated Satellite Observations and In Situ Measurements”
- Several figures have been updated following the suggestions of the reviewers.
- A discussion on the representativeness of our results has been added to the end of the revised manuscript with a new Figure (Figure 11).

Below are our point-to-point replies to reviewers’ comments.

Zhibo Zhang
Review 1

Q1. My main concern is that it is not clear how this study accounted for variation in the solar angle when calculating the DRE efficiencies. This is obviously a major factor affecting the outgoing SW fluxes, so the methodology for this should be clearly discussed.

Reply: Thanks for bringing up this point. The DRE efficiency is indeed dependent on SZA, which should be taken into account when estimating DRE efficiency when SZA has a significant variance.

However, in section 3, we only estimate the instantaneous DRE of dust in the selected region at the time of A-Train overpass which is about 1:30PM local time. Because the selected region is relatively small, the SZA at the A-Train overpass time in the domain only varies slightly among our selected cases, from 20 to 28 degree. We did some simple sensitivity test, in which we further divide the cases into two groups according the SZA value and we do not see significant differences in terms of DRE efficiency. Considering the limited sample size and the small SZA interval of selected cases, we therefore estimate DRE efficiency based on all the selected cases. Note in previous studies, such as Di Biagio et al. [2010], the DREE is compute for every 10 degree SZA interval.

Note that in Section 5, when computing the diurnally averaged DRE, we do consider the diurnal variation of SZA.

We added some discussion in the paper to clarify this.

Q2. The title is very long.
I’d recommending making it more concise to make it easier for readers to quickly comprehend what the study is about.

Reply: We change the title to “Net Radiative Effects of Dust in Tropical North Atlantic Based on Integrated Satellite Observations and In Situ Measurements” (Recommended by reviewer2).

Q3 It’s a bit unclear to me why the authors did not use AOD retrievals from MISR, which have the advantage of also providing information the aerosol type?

Reply: In this paper, we use the CCCM product, which is a merged product of CERES, CALIPSO, CloudSat and MODIS from the A-Train satellite constellation. MISR is on board of Terra, not part of the A-Train. So, we didn’t use its product.

Q4 I think the years over which the analysis is performed should be noted in the abstract for clarity.

Reply: We included from 2007 to 2010 in the abstract

Q5 The authors should explain their use of the term instantaneous DRE (first on line 163, I think).

Reply: The instantaneous dust DRE represents dust DRE derived under the conditions (e.g., solar position, atmospheric condition) at the measured/computed time to distinguish from the diurnally averaged DRE in section4.
Q6 Lines 334-335: Please be more specific here. Exactly which atmospheric profiles did you use? Ozone, water vapor, other greenhouse gases? Did this account for any fractional cloud cover of optically-thin clouds?

Reply: In the DRELW computations, we used the atmospheric profile and surface properties reported in the CCCM product, which are from the NASA GMAO GEOS system [Kato et al. 2011].

In this study, as explained in Section 3.1 we only select the cloud-free cases based on the cloud mask product from both CALIPSO and MODIS. The CALIOP lidar is very sensitive to thin clouds, which gives the confidence that the selected case should be free of optically thin clouds. Of course, the CALIOP lidar also has its detection limitation, but it is the best we can get at the moment.

Q7 The errors are alternately reported as 1 sigma and 2 sigma intervals. I recommend the authors choose one and keep this consistent to avoid confusion.

Reply: We consistently report DRE efficiency with 1-sigma error in this paper.

Q8: I understand and appreciate that you report both the MODIS and the CALIPSO-based estimates of the DRE and the DRE efficiency. However, it’s clear that the MODIS estimate is likely to be more accurate. I think your paper would therefore have more impact if you combine these estimates into a single number, either by using error propagation to weigh each estimate proportional to the inverse squared of their error; this will weigh the estimate towards the lower-error MODIS-based estimate.

Reply: Thanks for the suggestion. It is easy to combine the two observation-based DREE_SW based on MODIS and CALIPSO observations to get an averaged value. However, in our opinion, this averaged value does not seem to have much physical meaning. Neither does it provide any additional insight into the uncertainty in the observations. So, we hope to keep our original estimate of the uncertainty range.

Q9 Line 378: Could you include the exact definition of the extinction efficiency here, which differs somewhat between different sources?

Is this the extinction cross section normalized by the projected surface area of the irregular dust particle, or normalized by the projected surface area of the volume-equivalent sphere? Additionally, please clarify how the extinction efficiency is actually calculated for the mixed size distributions of Fennec and AERONET.

Reply: Thanks for bringing up this point. Indeed, the computation of the bulk scattering properties of nonspherical dust is complicated, which is explained below.

First of all, as we mentioned in Section 2.2, we assume volume equivalent radius for the AERONET-PSD to be consistent with Dubovik et al. [2006] and the maximum dimension for Fennec-SAL PSD to be consistent with Ryder et al. [2013b].
Secondly, the single-scattering properties of spheroid dust particles are from the database described in Meng et al. [2010]. In the database, particles are assumed to be randomly oriented. For each spheroid particle with the volume $V$ and aspect ratio $\epsilon$, the database reports its single scattering properties, such as extinction efficiency ($Q_e$), single scattering albedo ($\omega$) and scattering phase matrix, as well as the maximum dimension of the particle and the projected area averaged over random orientations.

Ideally, the bulk scattering properties of nonspherical dust (i.e., spheroid in this study) should be computed by averaging the single scattering properties of dust properties over a joint probability density function $n(r, \epsilon)$ that takes into account of the distribution over both dust size and shape. For example, the bulk scattering extinction efficiency should be computed from the following equation:

$$< Q_e(\lambda) > = \frac{\int_0^\infty \int_0^\infty Qe(\lambda, r_X, \epsilon) \cdot A(r_X, \epsilon) \cdot n(r_X, \epsilon) \cdot d\epsilon \cdot dr_X}{\int_0^\infty \int_0^\infty A(r_X, \epsilon) \cdot n(r_X, \epsilon) \cdot d\epsilon \cdot dr_X},$$

where, $r_X$ could be the volume- equivalent radius (i.e., $r_X = r'$) in case of the AERONET-PSD or the radius corresponding to the maximum dimension ($r_X = D_{max}/2$) in case of the Fennec-SAL PSD; $\epsilon$ is the aspect ratio of spheroid particle; $A(r_X, \epsilon)$ is the averaged projected area of randomly-oriented spheroid particle with the dimension $r_X$ and the aspect ratio $\epsilon$, which can be obtained from the Meng et al. 2010 database.

However, there is no such joint PDF in the literature, probably because it is difficult to measure the size and shape at the same time.

The aspect ratio distribution from Dubovik et al. [2006] in Figure 4 a is size-independent. In other words, $n(r, \epsilon) = n(r)n(\epsilon)$ in this case. As such, the bulk scattering properties can be easily computed from

$$< Q_e(\lambda) > = \frac{\int_0^\infty \int_0^\infty Qe(\lambda, r_X, \epsilon) \cdot A(r_X, \epsilon) \cdot n(\epsilon) \cdot d\epsilon \cdot dr_X}{\int_0^\infty \int_0^\infty A(r_X, \epsilon) \cdot n(\epsilon) \cdot d\epsilon \cdot dr_X},$$

where $\int_0^\infty n(r_X)dr_X = 1$ and $\int_0^\infty n(\epsilon)d\epsilon = 1$ are the normalized PSD and shape distribution, respectively.

In contrast, the aspect ratio distribution from Kandler [2009] in Figure 4 b is size-dependent. In this case, we assume that the size and shape are independent such that $n(r, \epsilon) = n(r)n(\epsilon)$ in each size interval (i.e., $<0.25 \mu m, 0.25\mu m \sim 0.5 \mu m$ and $>0.5\mu m$). Accordingly, the bulk scattering properties are computed from

$$< Q_e(\lambda) > = \frac{\sum_i \left\{ \int_{r_X, \epsilon, i} r_X \cdot n(\epsilon) \cdot d\epsilon \cdot dr_X \right\}}{\sum_i \left\{ \int_{r_X, \epsilon, i} A(r_X, \epsilon) \cdot n(\epsilon) \cdot d\epsilon \cdot dr_X \right\}},$$

where $n_i(\epsilon)$ is normalized in each size interval $\int_0^\infty n_i(\epsilon)d\epsilon = 1$ in each size interval. The PSD is normalized as $\sum_i \left\{ \int_{r_X, \epsilon, i} n(r_X) \cdot n_i(\epsilon) \cdot d\epsilon \cdot dr_X \right\} = 1$.

Q10. Please clarify what the physical reason is that causes a higher extinction efficiency for the Fennec size distribution.
Reply: To explain this, we made the figure below. Here we assumed the Dubovik et al. 2006 size-independent aspect ratio distribution. The two plots are $Qe$ as a function dust size at 0.55$\mu$m and 10$\mu$m (red), respectively, overlaid with the two PSDs, i.e., Fennec (solid blue) and AERONET (dashed blue). Note that we have converted both PSDs to dAdlnr because the bulk scattering extinction efficiency averaging is weighted by the area. Evidently, the AERONET PSD has a peak around r~ 0.1 $\mu$m where the $Qe$ is very small. In contrast, most of the Fennec PSD is in the region where $Qe$ is large. This explains why the bulk scattering $Qe$ based on the Fennec PSD is significant larger than that based on AERONET PSD.

![Figure](image-url)

Q11 Table 3: Please include here the LW DRE efficiency (based on 0.5 um AOD), as you did for your SW results, which is easier to compare between studies.

Reply: Following your suggestions, we have added the following table to the revised manuscript as Table 3.

<table>
<thead>
<tr>
<th>PSD</th>
<th>Refractive Index</th>
<th>Shape</th>
<th>TOA DRE$<em>{1W}$ efficiency (W/m²/AOD$</em>{0.5\mu m}$)</th>
<th>TOA DRE$_{1W}$ (W/m²)</th>
<th>Surface DRE$<em>{1W}$ efficiency (W/m²/AOD$</em>{0.5\mu m}$)</th>
<th>Surface DRE$_{1W}$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Dubovik</td>
<td>10.5</td>
<td>3.0</td>
<td>26.9</td>
<td>7.7</td>
</tr>
<tr>
<td>AERONET</td>
<td>OPAC-LW</td>
<td>Dubovik</td>
<td>6.3</td>
<td>1.8</td>
<td>16.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>Di-Biagio-LW</td>
<td>Dubovik</td>
<td>8.4</td>
<td>2.4</td>
<td>18.9</td>
<td>5.4</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Sphere</td>
<td>12.6</td>
<td>3.6</td>
<td>32.9</td>
<td>9.4</td>
</tr>
</tbody>
</table>

Q12 Lines 591 – 612: These two paragraphs compare their results to other studies. As such, this really belongs in your discussion section, not your conclusion section.

Reply: In the revised manuscript, we combine summary and discussion into one section ‘Section 6 Summary and Discussions’

Q13 Figure 3: Please include a, b, c, d labels. Also, the reference is Di Biagio et al., 2017 (not 2016).
Reply: Done

Q14 Figure 4a: Please include labels on your horizontal axis. Currently, the numbers are not clear.
Reply: Done.

Q15 Figure 8: It’s confusing here that the red and blue dashed lines, which denote model calculations with particular microphysics, have the same color as the observation-based lines. Please adjust.
Reply: Done
Review 2

Q1. The title is rather long. It could be shortened for clarity, e.g.: “Radiative effects of dust in tropical north Atlantic from integrating satellite observations and in situ measurements of dust properties”
Reply: We change the title to “Net Radiative Effects of Dust in Tropical North Atlantic Based on Integrated Satellite Observations and In Situ Measurements” (Recommended by reviewer2).

Q2. The abstract is also too long and carries to many details. I recommend trimming this down and reporting only the most crucial numerical estimates; there are currently 12 DRE or DRE efficiency estimates, which is too much to digest.
Reply: We have revised the abstract accordingly.

Q3. The introduction is very good, covering the issues very well but it would be good to add a sentence or two after line 65 explaining why it is important to quantify dust DRE as accurately as possible. For instance, dust radiative effects have an influence on global and regional climates, and changes in dust DREs play a role in anthropogenic climate change and climate feedbacks.
Reply: We added some brief discussion with relevant references.

Q4. The manuscript uses the original terminology for aerosol effects (“direct radiative effect”, “indirect effect”, “semi-direct effect”). Although most readers will know what these mean it would be a good to refer to the new terminology, following IPCC AR5 conventions: “instantaneous radiative effect” for the direct effect, “aerosol-radiation interactions” for direct + semi-direct effects, and “aerosol-cloud interactions” for indirect effects (or refer to both if necessary). Please also make it clear in the methods if the DREs calculated in this study are indeed equivalent to the "instantaneous radiative effect”.
Reply: Indeed, our definition of DRE is same as the “instantaneous radiative effect” in AR5. Note that in the paper, we calculated both instantaneous DRE and diurnally averaged DRE, where instantaneous DRE is defined as dust DRE derived under the condition (solar position, atmospheric condition) at the measured/computed time to distinguish from the diurnally averaged DRE in section4. To avoid confusion, we added some clarifications to the terminologies we used in the paper.

Q5. In many places the sign of radiative effects is indicated by describing them as “cooling” or “warming” effects (e.g. Lines 81, 88, and many other places). Whilst it can be helpful to indicate the likely cooling or warming impact this way of explaining the sign can be misleading or even nonsensical. For instance, what does it mean to “yield a cooling effect at TOA”; there is no air at the TOA. Please give the sign of radiative changes explicitly in the text. The likely cooling/warming tendency can be given in addition, if desired, e.g. line 81 could read “. . . this leads to a negative DRE at the TOA that is likely to cool the climate system”. The same argument applies when expressing DREs at the surface; please state the sign rather than indicating this via the expected temperature change. Sometimes absorbing
aerosols can reduce net radiation at the surface (yielding a negative DRE) yet cause surface
temperatures to rise if the surface and absorbing aerosol layer are thermally coupled. When
describing changes in OLR it is also not completely clear to say the OLR is “colder” or
“warmer” (e.g. Lines 468 – 473, 514-515). Reducing OLR makes the planet look cooler from
space but generally leads to a warming of the climate system. Please simply state if OLR is
increased or reduced, or indicate the sign of the radiative effect.
Reply: Very good suggestion. We have revised the text accordingly.

Q6. Line 104. I do not agree that observations of dust PSD are “scarce”. There have been
many measurement campaigns and long-term remote sensing observations during the past
two decades. The problem is that dust PSDs are so variable and difficult to measure or
retrieve so broader sampling and more accurate measurements are still needed. Please could
the text be clarified accordingly. Also, it would be good to add some further references here
to indicate the breadth of measurements that are available, or if Mahowald et al. gives a good
summary of these then the citation could be changed to (“see Mahowald et al., 2014 and
references therein”).
Reply: Thanks for raising this point and the reference. They are added to the revised manuscript.

Q7. I am slightly surprised that the CERES-CALIOP and CERES-MODIS DRESW forcing
efficiency estimate are so different, even when they are taken from the same subset of 153
pixels. How reliable are AODs from CALIPSO compared to those from MODIS? There is
certainly a lot more scatter in the CALIPSO AODs and poorer regression against CERES
SW flux. Are there problems detecting dust when loadings are low, does the CALIPSO
retrieval fail to capture larger AODs > 1 due to saturation? These issues could potentially
lead to biases in the inferred DRESW efficiency? Of course, MODIS is not perfect either.
Could the authors comment on the relative accuracy or reliability of the CALIOP and
MODIS AOD retrievals and any likely impacts / biases on the inferred DRESW efficiency
estimates. It might be beyond the scope of the study to do a full evaluation, but to provide
some comment is important.
Reply: First of all, although the difference between CERES-CALIOP and CERES-MODIS
DRESW forcing is significant, it is still relative small if compared with the range of the DRE based
on radiative transfer simulations (i.e., Figure 8). So, this uncertainty does not affect our conclusion.
Second, as you pointed out the difference between CERES-CALIOP and CERES-MODIS
DRESW forcing is mainly due to the AOD retrieval difference between CALIOP and MODIS.
The potential reasons for the difference may be complicated and are beyond the scope of this study.
Since we haven’t really studied this topic, we don’t think we are able to offer any helpful insight.
So, we refer the readers to two recent comparison studies between the MODIS and CALIPSO
AOD retrievals by Kim et al. [2013] and Ma et al. [2013],

Q8. A second point on the analysis of CERES SW fluxes. The dust AOD is surely not the
only factor affecting the TOA SW flux. The main other factor would be solar zenith angle,
but the sea state and marine BL aerosol loading could also be non-trivial factors. These
factors may explain some of the scatter in Figure 5 but I think it is important to know if
they could potentially bias the regression of SW flux against dust AOD. Can the authors
demonstrate that these factors are not important? Otherwise I would recommend adding a comment to the text to caveat any potential biases or uncertainties that these factors may introduce when deriving the DRE efficiencies.

Reply: Thanks for raising this point. Indeed, in reality the TOA flux is influenced not only by AOD, but also many other factors, such as surface reflectance variation, meteorological conditions, boundary layer aerosols that are undetected by satellite, uncertainty in satellite retrieval algorithm. Although we account for some of these factors (e.g., meteorological conditions), the variability captured by radiation transfer simulation can be expected to be smaller than reality, which explains why the TOA flux vs. AOD relations based on the radiative transfer computations are much less scattered than those based on observations. The R² value for the computation-based regressions all exceed 0.95, much higher than the observation-based results in Figure 5.

We do not know whether these uncertainties would lead to a bias in our DRE estimation, because we do not know the variability of these factors. To quantify this the uncertainty caused by this, we reported the uncertainty based on the 1-σ range. We added some discussion on this point after the discussion of Figure 8.

Q9. Line 192-195. I wasn’t totally clear how the aerosol types were determined. Is the aerosol type information from MATCH a2D or 3D field (i.e. is it resolved in the vertical)? Also are the MATCH simulations operational real-time forecasts or reanalysis? Further, when the dust type is set to dust how are the optical properties of dust determined? Are they specified based on an assumed PSD, refractive index and shape distribution, or somehow constrained from the CALIOP retrievals.

Reply: In the CCCM product, the default aerosol typing is from the MATCH simulation, except when CALIPSO detects dust; then dust is used.

In this study, we select cloud-free, dust-dominant cases (at least 90% AOD are attributed to dust aerosols) based on the aerosol type provided in the CCCM product, which, as explained above, is from the CALIPSO observation.

Other than aerosol typing, the CCCM product does not provide any dust physical or optical property. In our radiative transfer simulations, we have to assume the dust PSD, refractive index and shape distribution as explained in Section 4.

Q10. Section 3.1. Could the low sampling rates (only 1.7% of CERES pixels are used) bias the results in any way? Dust properties and cloud cover (or lack of cloud) could well be related and co-vary as both are affected by the large-scale meteorological conditions. Would it be possible to check for any covariation in the data?

Reply: This is an excellent question.

First of all, the sampling rate of cloud-free dust dominant cases also seems surprisingly low to us. As explained in the paper, it is because this region is pretty cloudy making it difficult to find cloud-free CERES pixels. We certainly agree that our observational bases DRE efficiency estimations
would be more reliable if we have more samples. However, CCCM product only provides 5 years’
data at present and we have used them all. Therefore, this is the best we could do at the moment.

We appreciate your concern and question regarding the representativeness of our results. We think
a key question is whether the results derived from our cloud-free cases can be applied to the clear-sky part of those cloudy CERES pixels. To address this question, we investigated if the dust properties (e.g., AOD) and meteorological conditions (e.g., surface temperature and precipitable water) have any correlation with the cloud fraction. If it turned out that the statistics of the dust properties and meteorological conditions from the clear-sky cases are similar to those from the cloudy cases, then we can argue that our results are representative of not only the clear-sky dust dominant CERES pixels, but also the clear-sky part of cloudy and dust dominant CERES pixels.

We first checked the AOD. This time we identify the dust-dominant cases based on CALIPSO
observations regardless of the cloud fraction. Then, we divide the selected cases into 5 groups
according to the cloud fraction within the CERES pixel, i.e., 0~20%; 20~40% 40~60% 60~80% and >80%. The figure a) below shows the dust AOD histogram of each group. Apparently, the
AOD from our cloud-free cases tend to be smaller than those from the cloudy group. If the DRE
efficiency remains the same, then the DRE of our cloud-free cases would be smaller than those of
the cloudy group.

We don’t know whether and to what extent other dust properties, such as size, shape and refractive
index, co-vary with the cloud cover. Investigating this is extremely challenging, if not impossible,
using satellite observations. We have to leave this for future studies using other types of
measurements (e.g., in situ).
After AOD, we also checked the surface temperature, the dust layer temperature (weighted by the dust extinction coefficient from CALIPSO) and the total amount of water vapor in the column. These quantities are potentially important for the DRE\textsubscript{LW}. As shown in the figure above, in terms of the surface temperature (figure b)) and dust layer temperature (figure c)), the cloud-free cases are very similar to those cloudy-cases.

However, not surprisingly, we found that the cloud-free cases are drier than the cloudy cases (figure d). Note that, given the same dust properties, an increasing of water vapor increases the atmospheric opacity in the LW, which tends to reduce the dust DRE\textsubscript{LW}.

In summary, if the dust particles properties (i.e., dust size, shape and refractive index) remain the same, then the DRE\textsubscript{SW} of dust in the clear-sky part of cloudy CERES pixels would be slightly larger than that based on our results because of the larger AOD. In the LW, the larger AOD of the clear-sky part of cloudy CERES pixels would lead to a larger DRE\textsubscript{LW}, but on the other hand, they are also more humid which would counteract the effect of larger AOD. The net result is dependent on the relative importance of these two competing factors.

We hope these analyzes address your questions. We have added the figure above to the revised manuscript as the new Figure 11 and also discussed the representativeness of our results.

11. Section 3.2. Why has the CERES-CALIOP DRE efficiency been calculated only from the 454 cases where MODIS is unavailable? Why not include all 607 pixels? Wouldn’t this provide the “best” estimate from CERES-CALIOP. Limiting it to cases when MODIS was unavailable could introduce some sampling bias.

12. Line 319. The text isn’t totally clear when it says “the other 454 cases. . . . are also included. . .”. This might be read that all 607 cases were included but the caption for Figure 5c, states it includes only 454 cases. Please clarify.

Reply: to Q11 & Q12:
Sorry for the confusion. The text was correct, and the figure caption was a mistake.

We think that the confusion might partly be caused by the fact that, all selected cases have CALIPSO AOD retrievals but only a fraction has MODIS AOD retrievals. In the revised manuscript, we simplified the discussion in this part, by getting rid of the original Figure 5b, because it does not seem to provide any additional insights but might cause confusion.

13. The estimates of dust DRE\textsubscript{LW} throughout the paper are given as “between 2.7+- 0.32 to 3.4+- 0.32 Wm-2”. This is rather confusing. Does this mean that the DRE\textsubscript{LW} estimate is between 2.38 – 3.72 Wm-2? The problem arises because no decision is made as to whether the 0.7Wm-2 discrepancy between CERES and RRTM should be subtracted from the DRE\textsubscript{LW} estimate or not. It would be much clearer if this discrepancy was either: (i) treated as a bias and subtracted from the DRE\textsubscript{LW} estimate, so that only the lower DRE\textsubscript{LW} estimate was given, (ii) considered as a potential error and included when calculating the uncertainty range on the upper estimate.
Reply: Thanks for this good suggestion. To avoid confusion, we have decided to consider 0.7 W/m² as a bias in our clear-sky flux computation. We have revised the text and updated the Table 4 accordingly. It does not affect our conclusion, but it indeed simplifies the discussion.

14. Line 575. I am not familiar with the term “semi-observation-based”. Has this terminology been used elsewhere in the literature? If not it might be better to define it or just explain what information was used, e.g. “we derive a set of DRELC estimates by comparing CERES observations with dust-free radiative transfer calculations from RRTM”.
Reply: “semi-observation-based” is now defined at the end of section 3.

15. Line 589. It would be worth stating the years and months from which data was included. The authors might also like to comment on the merit of extending the analysis to other season / regions / years in future studies.
Reply: Now we include from 2007 to 2010 in that sentence and add some comments on the merit of extending this study.

Technical corrections:

1. Line 61. It isn’t necessary to draw the reader to Figure 1 at this point.
Reply: We delete Figure 1 in line 61.

2. Line 90. Is there a reference to back up the statement that surface emissivity is an important factor in dust LW effects?
Reply: We add a reference to back up the statement. [Yang et al. 2009 ‘Net radiative effect of dust aerosols from satellite measurements over Sahara’]

3. Line 273. It would be more useful to give the spectral bands in terms of wavelength intervals in units of microns (to be consistent with section 2.2).
Reply: We convert wavenumber to wavelength intervals in units of microns.

4. Line 348. “In the analysis followed” probably means “In the following analysis”.
5. Line 577. Please insert: “. . .we use the RRTM radiative transfer model”.
Reply: revised accordingly.
Review 3

1. Only 5% pixels are cloud free in the analysis region and season. Such a small occurrence would make readers wonder to what extent the dust DRE calculated in this study contribute to the dust all-sky radiative forcing in this region. I can see that dust radiative forcing in cloudy sky is complicated and beyond the scope of this study, but it is still helpful to discuss the possible influence of different types of clouds at different levels on the dust radiative forcing at both TOA and surface.

Reply We appreciate your concern and question regarding the representativeness of our results. We think a key question is whether the results derived from our cloud-free cases can be applied to the clear-sky part of those cloudy CERES pixels. To address this question, we investigated if the dust properties (e.g., AOD) and meteorological conditions (e.g., surface temperature and precipitable water) have any correlation with the cloud fraction. If it turned out that the statistics of the dust properties and meteorological conditions from the clear-sky cases are similar to those from the cloudy cases, then we can argue that our results are representative of not only the clear-sky dust dominant CERES pixels, but also the clear-sky part of cloudy and dust dominant CERES pixels.

We first checked the AOD. This time we identify the dust-dominant cases based on CALIPSO observations regardless of the cloud fraction. Then, we divide the selected cases into 5 groups according to the cloud fraction within the CERES pixel, i.e., 0~20%; 20~40% 40~60% 60~80% and >80%. The figure a) below shows the dust AOD histogram of each group. Apparently, the AOD from our cloud-free cases tend to be smaller than those from the cloudy group. If the DRE efficiency remains the same, then the DRE of our cloud-free cases would be smaller than those of the cloudy group.

We don’t know whether and to what extent other dust properties, such as size, shape and refractive index, co-vary with the cloud cover. Investigating this is extremely challenging, if not impossible, using satellite observations. We have to leave this for future studies using other types of measurements (e.g., in situ).
After AOD, we also checked the surface temperature, the dust layer temperature (weighted by the dust extinction coefficient from CALIPSO) and the total amount of water vapor in the column. These quantities are potentially important for the DRE\textsubscript{LW}. As shown in the figure above, in terms of the surface temperature (figure b)) and dust layer temperature (figure c)), the cloud-free cases are very similar to those cloudy-cases.

However, not surprisingly, we found that the cloud-free cases are drier than the cloudy cases (figure d). Note that, given the same dust properties, an increasing of water vapor increases the atmospheric opacity in the LW, which tends to reduce the dust DRE\textsubscript{LW}.

In summary, if the dust particles properties (i.e., dust size, shape and refractive index) remain the same, then the DRE\textsubscript{SW} of dust in the clear-sky part of cloudy CERES pixels would be slightly larger than that based on our results because of the larger AOD. In the LW, the larger AOD of the clear-sky part of cloudy CERES pixels would lead to a larger DRE\textsubscript{LW}, but on the other hand, they are also more humid which would counteract the effect of larger AOD. The net result is dependent on the relative importance of these two competing factors.

We hope these analyzes address your questions. We have added the figure above to the revised manuscript as the new Figure 11 and also discussed the representativeness of our results.

2. How is the dust DRE sensitive to the altitude of dust layer? It is a non-trivial question for the longwave radiation. Also, the analysis region is away from the source region, so there should be some variability of the dust layer height.
Reply: Generally, under clear sky conditions, as dust layer altitude increasing, LW dust DRE at TOA increases but surface LW dust DRE decreases. (Under clear sky conditions, SW dust DRE is not sensitive to altitude of dust layer). In our study, we take into account the dust layer height variability by specifying dust aerosol extinction coefficient profile for each case based on CALIPSO retrieval. In future study, we will analyze how the dust layer height influence the DRE\textsubscript{LW}.

3. Would dust outflows over the North Pacific exhibit similar DRE as the values reported in this study?
Reply: Dust DRE depends on dust aerosol optical depth and dust physical properties such as dust size distribution, refractive index and particle shape. Those physical properties are highly dependent on dust source region and dust aerosol transport processes. Considering the difference in dust AOD and dust source region between dust aerosol over North Pacific and North Atlantic, we would not say they have the similar or different DRE values. We plan to investigate this in future studies.

4) Fig. 7 and 9. Hard to distinguish lines in those figures. Please consider using color plots.
Reply: We changed them to color plots.

5) L84, is it supposed to be [Zhang et al., 2016]? Also Xu et al. [2017, AE] is relevant here and should be cited as well.
Reply: Thanks for suggestion, we fixed our citation and cited the paper Xu et al., 2017.

6) The title is a little bit wordy. Suggest to remove “Through Integrating Satellite Observations and In Situ Measurements of Dust Properties”
Reply: We changed the title to “Radiative effects of dust in tropical north Atlantic based on integrated satellite observations and in situ measurements”
Net Radiative Effects of Dust in Tropical North Atlantic Based on Integrated Satellite Observations and In Situ Measurements

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For publication in *Atmospheric Chemistry and Physics*
Abstract

In this study, we integrate the recent in situ measurements with satellite retrievals of dust physical and radiative properties to quantify the dust direct radiative effects on the shortwave (SW) and longwave (LW) radiation (denoted as DRE_{SW} and DRE_{LW}, respectively) in the tropical North Atlantic during summer months from 2007 to 2010. Through linear regression of CERES measured top-of-atmosphere (TOA) flux versus satellite aerosol optical depth (AOD) retrievals, we estimate the instantaneous DRE_{SW} efficiency at the TOA to be \(-49.7\pm7.1\) W/m\(^2\)/AOD and \(-36.5\pm4.8\) W/m\(^2\)/AOD based on AOD from MODIS and CALIOP, respectively. We then perform various sensitivity studies based on recent measurements of dust particle size distribution (PSD), refractive index, and particle shape distribution to determine how the dust microphysical and optical properties affect DRE estimates and its agreement with abovementioned satellite-derived DREs. Our analysis shows that a good agreement with the observation-based estimates of instantaneous DRE_{SW} and DRE_{LW} can be achieved through a combination of recently observed PSD with substantial presence of coarse particles, a less absorptive SW refractive index, and spheroid shapes. Based on this optimal combination of dust physical properties we further estimate the diurnal mean dust DRE_{SW} in the region of \(-10\) W/m\(^2\) at TOA and \(-26\) W/m\(^2\) at surface, respectively, of which \(~30\%\) is canceled out by the positive DRE_{LW}. This yields a net DRE of about \(-6.9\) W/m\(^2\) and \(-18.3\) W/m\(^2\) at TOA and surface, respectively. Our study suggests that the LW flux contains useful information of dust particle size, which could be used together with SW observation to achieve more holistic understanding of the dust radiative effect.
1. Introduction

Mineral dust is the most abundant atmospheric aerosol component in terms of dry mass [Choobari et al., 2014, Textor et al., 2006]. The Sahara is the largest source of atmospheric dust aerosols, with an estimated emission of 670 Mt yr\(^{-1}\) [Rajot et al., 2008, Washington et al., 2003]. African dust from Sahara is regularly lifted by strong near-surface winds and transported westwards within the Saharan Air Layer (SAL) over to the tropical North Atlantic during northern summer [Cuesta et al., 2009, Karyampudi et al., 1999]. During the transport, dust aerosols can scatter and absorb both shortwave solar (referred to as “SW”) and longwave thermal infrared (referred to as “LW”) radiation, and thereby influence Earth’s energy budget [McCormick et al., 1967, Tegen et al., 1996, Yu et al., 2006]. This is known as the direct radiative effect (DRE) of dust, which can have a significant influence on the global energy balance [Boucher et al. 2013], as well as regional weather and climate [e.g., Miller and Tegen 1998, Evan et al. 2006, Lau and Kim 2007]. Therefore, it is important to quantify dust DREs as accurate as possible. Moreover, mineral dusts can also influence the life cycle and properties of clouds, by altering thermal structure of the atmosphere (known as semi-direct effects) [Ackerman et al., 2000, Hansen et al., 1997, Koren et al., 2004], and by acting as cloud condensation nuclei and ice nuclei (known as indirect effects) [Albrecht, 1989, Rosenfeld et al., 1998, Twomey, 1977]. In addition, when African dust aerosols are deposited into Atlantic Ocean and Amazon Basin, they supply essential nutrients for the marine and rainforest ecosystems [Yu et al., 2015], which has important implications for the biogeochemical cycles [Jickells et al., 2005]. In this study, we focus on the quantification of dust direct radiative effect on both SW and LW radiation.

Substantial effort has been made to understand and quantify the DRE of mineral dust since the 1980s [Carlson et al., 1980, Cess, 1985, Liao et al., 1998, Ramaswamy et al., 1985]. Most
studies have focused on the SW DRE (DRE$_{SW}$) of mineral dust under clear-sky (cloud free) conditions [Myhre et al., 2003, Tegen et al., 1996, Yu et al., 2006]. Through scattering and absorption, dust aerosols reduce the amount of solar radiation reaching the surface, inducing a negative (cooling) effect at the surface. The DRE$_{SW}$ of dust at the top of the atmosphere (TOA) depends also strongly on the albedo of the underlying surface [Keil et al., 2003, Yu et al., 2006]. Over a dark surface, the scattering effect of dust dominates, it leads to a negative DRE at TOA that cools the climate system [Myhre et al., 2003, Tegen et al., 1996]. In contrast, high reflectance of a bright surface enhances the absorption by dust aerosols and could yield a positive dust DRE$_{SW}$ (warming effect on the climate system) at TOA when the surface albedo exceeds a critical value [Zhang et al. 2016, Xu et al., 2017]. Different from other aerosol types (e.g., smoke and sulfate aerosols), dust aerosols are large enough to have significant LW direct radiative effect (DRE$_{LW}$) [Sokolik et al., 1999, Sokolik et al., 1998]. Lofted dust aerosols absorb the LW radiation from the warm surface and re-emit the LW radiation usually at lower temperature, thereby reducing the outgoing LW radiation and leading to a positive DRE at TOA that tends to warm the climate system. At the same time, they emit the LW radiation downward that generates a warming effect at the surface. The dust LW effect depends strongly on surface emissivity [Yang et al., 2009] and the vertical profile of atmosphere temperature. The net radiative effect (DRE$_{net}$) of dust is the summation of its DRE$_{SW}$ and DRE$_{LW}$. Note that DRE$_{SW}$ only acts during daytime, whereas DRE$_{LW}$ operates during both day and night.

Quantification of the DRE$_{SW}$ and DRE$_{LW}$ of dust remains challenging and there is a large range of estimates in the literature. Take the Tropical Atlantic for example. Yu et al. [2006] found that the seasonal (JJA) average clear-sky aerosol DRE$_{sw}$ at TOA in this region varies from $-5.7$ W/m$^2$ to $-12.8$ W/m$^2$ based on observations and from $-3.7$ W/m$^2$ to $-10.4$ W/m$^2$ based on model
simulations. An important reason is that dust DRE depends on many factors, including both the microphysical (e.g., dust particle size and shape) and optical (e.g., refractive index) properties, as well as the surface and atmospheric properties (e.g., surface reflectance and temperature, atmospheric absorption). Sokolik et al. [1998] showed that for the sub-micron dust particles, the DRE_{SW} is dominant and DRE_{LW} is negligible, whereas for super-micron dust particles, DRE_{LW} is more important [Sokolik et al., 1996, Sokolik et al., 1999]. Therefore, an accurate measurement of the particle size distribution (PSD) is highly important for estimating the DRE of dust. However, dust PSDs are highly variable and difficult to measure or retrieve, and, as a result, the observations of dust PSD are usually subjected to large uncertainties [see Mahowald et al., 2014 and references therein]. PSD inferred from AERONET observations [Dubovik et al., 2006] relies on observations at shortwave channels, which could bias the dust size low. In fact, more and more observations are emerging to suggest that dust PSD even in regions far from source regions contains substantial fraction of coarse particles. Based on the airborne in-situ measurement of dust PSD in Caribbean Basin from the Puerto Rico Dust Experiment (PRIDE) campaign, Maring et al. [2003] noted that dust particles appear to settle more slowly than expected from the widely used Stokes gravitational settling model. Similarly, recent measurements from the latest Fennec project [Ryder et al., 2013b] and the Saharan Aerosol Long-range Transport and Aerosol-Cloud-interaction Experiment (SALTRACE) [Weinzierl et al., 2017] all suggest that transported dust aerosols in the SAL are significantly coarser than expected based on the Stokes gravitational deposition. Such unexpected existence of coarse particles has important implications for understanding the DRE of dust. In a case of significant fraction of coarse particles, the warming effect on LW radiation (positive) DRE_{LW} would partly cancel the DRE_{SW} leading to a less negative or even positive DRE_{net}. Most recently, Kok et al. [2017] argue that most of the current global climate models tend to
underestimate the size of dust particles and therefore overestimate the cooling effects of dust. Their estimate of the global mean dust DRE\textsubscript{net} is between $-0.48$ and $+0.20$ W m\textsuperscript{-2}, which includes the possibility that dust causes a net warming of the planet.

In addition to dust particle size, particle shape and refractive index also have significant influence on dust DRE. Dust particles are generally nonspherical in shape, which make their single-scattering properties (i.e., extinction efficiency, single-scattering albedo and scattering phase matrix) fundamentally different from those based on spherical models. A few dust particle shape models have been developed [Dubovik \textit{et al.}, 2006, Kandler \textit{et al.}, 2009], which have been increasingly used in aerosol remote sensing and modeling [Levy \textit{et al.}, 2007]. Räisänen \textit{et al.} [2013] found that replacing the spherical dust models in a GCM with nonspherical model leads to negligible changes in the DRE of dust at TOA. However, a recent GCM-based study by Colarco \textit{et al.} [2014] suggests that the influence of nonsphericity on dust DRE can be significant at surface and within the atmosphere, depending on the refractive index of dust. Similarly, Kok \textit{et al.} [2017] argue that a spherical model significantly underestimates the extinction of dust, leading to errors in estimate of dust DRE.

Over the past few decades, substantial efforts have been made to measure the spectral refractive index of dust, mostly limited to the SW spectral range [Balkanski \textit{et al.}, 2007, Dubovik \textit{et al.}, 2002, Dubovik \textit{et al.}, 2006, Formenti \textit{et al.}, 2011, Hess \textit{et al.}, 1998, Levoni \textit{et al.}, 1997]. The current widely-used LW refractive index of dust was measured using rather old techniques in the 1970s and 1980s [e.g., Volz 1972, 1973, Fouquart \textit{et al.} 1987]. Recently, Di Biagio \textit{et al.} [2014, 2017] compiled a comprehensive dust aerosol refractive index database in the LW spectrum ranging from 3 to 15 \textmu m, based on 19 natural samples from 8 dust regions over the globe. This database is the first one as far as we know to document the regional differences in dust LW
refractive index due to the regional characteristics of dust chemical composition. We also call special attention to a newly developed database of Saharan and Asian dust [Stegmann and Yang, 2017]. Satellite observations have long become indispensable for studying the dust aerosols. In particular, the combination of passive (e.g., MODIS and CERES) and active (e.g., CALIPSO) sensors on board of NASA’s A-Train satellite constellation provides unprecedented data to study dust aerosols, from long range transport [e.g., Liu et al. 2008, Yu et al. 2015] to dust DRE [e.g., Yu et al. 2006, Zhang et al. 2016]. As A-Train observations become mature, substantial efforts have been made to collocate and fuse the observations from different sensors to make the use of A-Train observations easier for the users. A prominent example is the CERES- CALIPSO-CloudSat-MODIS (CCCM) product developed by Kato et al. [2011], which has become a popular dataset for studying the radiative effects of clouds and aerosols and for evaluating GCMs.

The present study is inspired and motivated by the latest measurements of the microphysical and optical properties of dust, namely the in-situ dust PSD from the Fennec field campaign [Ryder et al. 2013a, 2013b] and the dust LW refractive index from Di Biagio [2014, 2017], as well as the recent studies (e.g., Kok et al.[2017]) suggesting that cooling effects of dust is overestimated in most climate models due to the underestimation of dust size. The study is carried out in three steps, each with a distinct objective. First, we attempt to derive a set of observation-based instantaneous dust DREsw and DRELw for the tropical North Atlantic based on the A-Train satellite observations reported in the CCCM product, without imposing any assumptions on dust size, shape or refractive index. Here, the instantaneous dust DRE represents dust DRE derived under the conditions (e.g., solar position, atmospheric condition) at the measured or computed time to distinguish from the diurnally averaged DRE in Section 4. Then, we perform
multiple sets of radiative transfer computations of the *instantaneous* dust DRE in the North Atlantic region based on the same dust extinction profiles from CCCM in combination with different dust physical and optical properties. The objective is to understand the sensitivity of dust DRE\textsubscript{SW} and DRE\textsubscript{LW} to the PSD, nonsphericity, and refractive index of dust and to obtain a set of dust properties that yield the best agreement with satellite flux observations (e.g., CERES). In the third step, we use the derived dust properties and extend the radiative transfer computations to *diurnal mean* and to DRE at surface. The rest of this paper is organized as follows: Section 2 describes the data and model used. Section 3 presents the sensitivity of dust DRE to dust size, shape and refractive index. Section 4 discusses diurnally averaged net DRE of dust aerosols and uncertainty analysis. Section 5 concludes the article.

2. Data and Models

2.1 The CERES- CALIPSO-CloudSat -MODIS (CCCM) product

To estimate instantaneous dust DRE, we use aerosol and radiation remote sensing products from the A-Train satellite sensors, namely, the integrated CERES, CALIPSO, CloudSat, MODIS merged product (CCCM) developed by [Kato et al., 2011]. In the CCCM product, high-resolution CALIOP, CloudSat and MODIS retrievals are collocated with 20-km CERES footprints. For each CERES footprint, the CCCM product provides the TOA flux observations (both SW and LW) from CERES, aerosol (MOD04 “Dark Target” product [Remer et al., 2005]) and cloud (MOD06 [Platnick et al., 2003]) properties retrieved from MODIS, aerosol optical thickness for each aerosol layer from CALIOP [Winker et al., 2010] and cloud vertical profile from the combination of CALIOP and CloudSat [Kato et al., 2010]. Up to 16 aerosol layers identified by CALIOP are kept within a CERES footprint. *Figure 1* shows the JJA mean aerosol optical depth (AOD) from the
CALIOP observations reported in the CCCM product. Clearly, the transported dust aerosols lead to enhanced AOD in the tropical North Atlantic region.

In addition to the “raw” retrievals, the CCCM product also provides post-processed flux computations for each CERES pixel based on derived aerosol and/or cloud extinction profiles, which is done in the following steps. First, the CALIOP aerosol retrievals within each CERES pixel are averaged to obtain the aerosol extinction profile at the 0.5 µm reference wavelength. Then, the aerosol type and associated spectral optical properties, e.g., extinction coefficient, single-scattering albedo, and asymmetry factor are specified mostly based on the aerosol type simulations from the Model of Atmospheric Transport and Chemistry (MATCH [Collins et al., 2001], with the exception of dust aerosols. If CALIOP observes dust aerosols (dust and polluted dust), the aerosol type is set to dust. This is based on the consideration that the depolarization observation capability of CALIOP is ideal for dust detection because the nonsphericity of dust can cause significant depolarization in contrast to most other types of aerosols. Finally, the aerosol extinction profiles and the aerosol spectral optical properties are used to compute the broadband fluxes at both TOA and surface and for both SW and LW under 2 conditions: 1) with aerosol, 2) without aerosol, so that the aerosol DRE can be derived from the difference of the two conditions. Temperature and humidity profiles used in flux computations are from the Goddard Earth Observing System (GEOS-5) Data Assimilation System reanalysis [Rienecker et al., 2008].

### 2.2 Dust Physical and Optical models

To investigate the sensitivity of dust DRE to microphysical and optical properties of particles, we use several sets of widely used or newly obtained dust size distribution, dust shape distribution and dust refractive index.
Two dust particle size distributions (PSD) shown in Figure 2, are considered in this study.

One PSD is inferred based on AERONET ground-based retrievals at Cape Verde site (16°N, 22°W) from [Dubovik et al., 2002] (referred to as “AERONET” PSD). The other dust PSD is obtained from the recent airborne measurements of transported Saharan dust from the Fennec 2011 field campaign over both the Sahara (Mauritania and Mali) and the eastern Atlantic Ocean, between the African coast and Fuerteventura. Ryder et al. [2013a] separate the PSD measurements from this campaign into three broad categories: fresh, aged, SAL (acronym for “Saharan Air Layer”). The fresh category over the Sahara represents dust uplifted no more than 12 hours prior to measurement; the aged category over the Sahara represents dust aerosols mobilized 12 to 70 hours prior to measurement; the SAL category represents dust aerosols transported over the adjacent east Atlantic, mostly from flights over Fuerteventura, Canary Islands (28°N, 13°W). All these categories come from the mean of vertical profile observations (excluding the marine boundary layer for SAL categories). The Fennec airborne PSD dataset is particularly novel, in that larger particle sizes were measured than has been done previously in dust layers, with the exception of Weinzierl et al., 2011, and that errors due to sizing uncertainties have been specifically quantified (see Ryder et al., 2013b and Ryder et al., 2015 for full details). Because this paper focuses on the Tropical Atlantic Ocean region, we use dust size distribution in the SAL category (referred to as the “Fennec-SAL PSD”). Evidently from Figure 2, the Fennec-SAL PSD, which peaks around 5~6 µm and has a significant fraction of particles with \( r > 10 \mu m \), is much coarser than the AERONET PSD, which peaks around 1~2 µm and has almost no particles \( r > 10 \mu m \).

The dust refractive indices are taken from three sources:

(1) The Optical Properties for Aerosols and Clouds database (OPAC) [Hess et al., 1998], which has been widely used in climate models and satellite remote sensing algorithms.
(2) A merger of remote sensing based estimates of dust refractive indices in the shortwave from 0.5 µm to 2.5 µm [Colarco et al., 2014], drawn from Kim et al. [2011] in the visible, and Colarco et al. [2002] in the UV and (referred to as “Colarco-SW”). Kim [2011] collected the AERONET (V 2) retrievals from 14 sites over North Africa and the Arabian Peninsula. Then the dust refractive index is derived from the dust dominant cases for these sites selected based on the combination of large aerosol optical depth (AOD ≥ 0.4 at 440 nm) and small Ångström exponent (Åext≤0.2) to select the dust cases. Colarco et al. [2002] derived the dust refractive index in the UV by matching the simulated dust radiative signature in the UV with the satellite observations from the Total Ozone Mapping Spectrometer.

(3) The refractive indices in the LW from 3µm ~15µm from Di Biagio et al. [2017] (referred to as “Di-Biagio-LW”). This database is based on the laboratory measurements of 19 natural soil samples from 8 regions: northern Africa, the Sahel, eastern Africa and the Middle East, eastern Asia, North and South America, southern Africa, and Australia. The refractive index from the Mauritania site is selected for this study because it is geographically close to the Fennec field campaign.

Figure 3 compares the real and imaginary parts of the refractive index for each of these data sets. In the SW, the imaginary part of the OPAC refractive index is much greater than that of Colarco-SW, which implies that dust aerosols based on the OPAC refractive index is more absorptive. In the LW, the Di-Biagio-LW refractive index is smaller than the OPAC values in terms of both the real and imaginary parts.

Dust aerosols are generally nonspherical in shape. Spheroids have proven to be a reasonable first-order approximation of the shape of nonspherical dust [Dubovik et al., 2006, Mishchenko et al., 1997]. The shape of a spheroid particle is determined by the so-called aspect...
ratio, i.e., ratio of the polar to equatorial lengths of the spheroid. In our study, two spheroidal shape distributions are used for computing the optical properties of non-spherical dust: (1) a size-independent aspect ratio distribution from Dubovik et al. [2006] (see Figure 4a) and (2) a size-dependent aspect ratio distribution extracted from Table 2 in Koepke et al. [2015], which is discretized from measurement data of Kandler et al. [2009] (Figure 4b). The Dubovik et al. [2006] shape distribution employs both oblate (aspect ratio < 1) and prolate (aspect ratio > 1) spheroids, while the Kandler et al. [2009] shape distribution considers only prolate spheroids. For comparison purpose, we also include spherical dust in our sensitivity studies. We use the Lorenz-Mie theory code of Wiscombe [1980] to compute the optical properties of spherical dust particles. The optical properties of spheroidal dust particles are derived from the database of Meng et al. [2010]. Note that we assume volume equivalent radius for the AERONET-PSD to be consistent with Dubovik et al. [2006] and the maximum dimension for Fennec-SAL PSD to be consistent with Ryder et al. [2013b].

2.3 Radiative transfer modeling

The Rapid Radiative Transfer Model (RRTM) [Mlawer et al., 1997] is used to compute both SW and LW radiative fluxes for both clear and dusty atmospheres. RRTM retains reasonable accuracy in comparison with line-by-line results for single column calculations. It divides the solar spectrum into 14 continuous bands ranging from 0.2 µm to 12.2 µm and the thermal infrared (3.08 µm -1000 µm) into 16 bands. We explicitly specify the spectral AOD, ω and g of dust aerosols for every band in the radiative transfer simulations.

3. Case Selection and Observation-based Estimate of Instantaneous Dust DRE

3.1 Selection of cloud-free and dust-dominant cases in the CCCM product
In this study, we focus on the Saharan dust outflow region in North Atlantic marked by the box in Figure 1 (10° N ~ 30° N, 45° W ~ 20° W). This selection is based on several considerations.

Firstly, during the summer months (JJA) this region is dominated by transported dust aerosols from Sahara. Secondly, because the ocean surface is dark, dust aerosols have a strong negative DRE_sw in this region. Thirdly, the abovementioned AERONET Cape Verde and Fennec-SAL PSD measurements are made in the vicinity of this region. Finally, the dust DREs in this region have been extensively studied in the literature, making it easier for us to compare our results with previous work.

We first select cloud-free and dust-dominant CERES pixels in the region from four summer seasons (2007~2010) of the available CCCM product. Within each CERES pixel, the CCCM product report two cloud masks, one from CALIOP and the other from MODIS. The former is more sensitive to optically thin clouds but has a very narrow spatial sampling rate available only along the CALIOP ground track. The latter provides the cloud mask for the entire CERES pixel but may miss thin clouds. Because of the relative large footprint size (~20 km), the cloud-free condition actually poses a very strong constraint on the CERES product. Out of the total 36165 of CERES pixels in this region from 4 seasons of data, we found 1663 (only 5%) of cloud-free pixels according to the CALIOP cloud mask. The sampling is further reduced to 464 (only 1.3%) if the MODIS cloud mask is used to ensure the entire CERES footprint is cloud-free. This result is not surprising because the MODIS cloud mask is more “clear-sky conservative”, i.e., it tends to label a pixel as cloudy if there is any ambiguity in its cloud mask test [Ackerman et al., 1998]. A comparison of collocated CALIOP and MODIS cloud mask along the CALIOP track by [Holz et al., 2008] reveals that MODIS masks more pixels as clear-sky than CALIOP does in the tropical Atlantic dust outflow region (see their Fig. 3a), which is consistent with our result.
After selecting the cloud-free cases, we use the aerosol type information in the CCCM product to further select dust-dominant cases (i.e., more than 90% of the aerosols within a given CERES pixel are attributed to dust, in terms of area coverage). As aforementioned, the CCCM product relies on CALIOP observations for detecting dust aerosols. After imposing the dust-dominant condition, we are left with a total of 607 and 245 cloud-free and dust-dominant CERES pixels, if CALIPSO and MODIS cloud mask are used, respectively. Furthermore, we found that within these selected pixels 153 out of 607 cases and 87 out of 245 cases have both CALIOP and MODIS aerosol optical depth (AOD) retrievals in the CCCM product, and the rest (454 out of 607 cases and 158 out of 245 cases) have AOD retrievals only from the CALIOP, but no AOD retrieval from MODIS. The reason for this is unclear and beyond the scope of this study, but perhaps due to the more rigorous quality control used in the passive aerosol retrieval from MODIS [Remer et al., 2005].

3.2 Observation-based estimate of instantaneous dust DRE

Many previous studies have shown that the aerosol DRE_{sw} over the dark ocean surface is approximately linear with the AOD. The increasing rate of the magnitude of DRE_{sw} with AOD is called the DRE_{sw} efficiency which is an important and useful quantity in many applications such as aerosol model evaluation [Zhou et al., 2005]. We note that DRE_{sw} depends on solar zenith angle (SZA). However, Because the selected region is relatively small, the SZA at the A-Train overpass time in the domain only varies slightly among our selected cases, from 20° to 28°. Considering the limited sample size and the small SZA variation, we therefore estimate DRE efficiency based on the combination of all selected cases without breaking them into smaller SZA intervals. Because of the nearly linear relationship between DRE_{sw} and AOD, the CERES TOA flux
observation and the collocated AOD retrievals from either CALIOP or MODIS can be combined to derive an observation-based estimate of the instantaneous dust DRE. Figure 5 shows linear regressions of CERES measured upward SW flux at TOA with satellite retrieved AOD for the selected cloud-free and dust dominant cases. Black dots and lines are for selected cases using the CALIOP cloud mask. For the 153 cases with both CALIOP and MODIS AOD retrievals, the combination of CERES and MODIS (Figure 5a) leads to a DRE$_{SW}$ efficiency of dust $-49.7 \pm 7.1$ W/m$^2$/AOD (AOD is at 0.5 µm) with a linear regression $R^2$ value of 0.69. The uncertainty, i.e., $\pm 7.1$ W/m$^2$/AOD, associated with the regression line coefficients is estimated based on the 1-σ (one standard deviation) errors following Hsu et al. [2000]. The combination of CERES flux and CALIOP AOD (Figure 5b) leads to a DRE$_{SW}$ efficiency of $-36.5 \pm 4.8$ W/m$^2$/AOD based on 1-σ error with a $R^2$ value of 0.5. To investigate the impact of different cloud mask, we also show the regression results derived from the cases selected based on MODIS cloud mask in Figure 5 (red dots and lines). We notice that the results are very similar to those based on the CALIOP cloud mask. Therefore, we conclude that the selection of cloud mask has negligible impact on our estimation of DRE and the main uncertainty is associated with the AOD retrieval. Considering that the MODIS and CALIOP aerosol retrievals are based on completely different methods, some difference between the two are not surprising. The tighter correlation between MODIS AOD and TOA upward SW flux is expected because MODIS retrieval is based on the reflected spectral solar radiation, whereas the CALIOP AOD retrievals are based on the inversion of backward scattering lidar signals. The potential reasons for the differences between CALIOP and MODIS AOD retrievals are beyond the scope of this study. Interested readers are referred to a couple of recent comparison studies by Kim et al. [2013] and Ma et al. [2013].
In summary, the *instantaneous* dust DRE$_{SW}$ efficiency in the selected region during summer season is $-49.7 \pm 7.1$ W/m$^2$/AOD based on CERES-MODIS observations and $-36.5 \pm 4.8$ W/m$^2$/AOD based on CERES-CALIOP observations. With the DRE$_{SW}$ efficiency the DRE$_{SW}$ can be easily derived from the AOD observations. The *instantaneous* DRE$_{sw}$ estimated from the CERES-MODIS and CERES-CALIOP data is $-14.2 \pm 2.0$ W/m$^2$ and $-10.4 \pm 1.4$ W/m$^2$, respectively (see Table 1).

In addition to the SW flux measurement, the CCCM product also provides the CERES measurement of LW flux at TOA. Figure 6 shows the histograms of the broadband outgoing longwave radiation (OLR) measured by CERES for the selected cases. Note that besides dust AOD, OLR also strongly depends on other factors such as surface temperature, atmospheric profiles and dust altitude. As a result, there is a high variability in those abovementioned factors among the selected 607 cases. Therefore, it is not possible to derive the DRE$_{LW}$ efficiency and DRE$_{LW}$ in the same way as we did for the SW. Here we use a different method. To estimate the DRE$_{LW}$, we first computed the dust-free OLR based on ancillary data of surface temperature and atmospheric profiles reported in the CCCM which is from the GEOS Model of NASA’s Global Modeling and Assimilation Office (GMAO) [Kato et al. 2011]. Then, the DRE$_{LW}$ can be estimated from the difference between CERES observed OLR (i.e., blue solid line in Figure 6) and the computed dust-free OLR (i.e., black dashed line in Figure 6). We refer to this method as “*semi-observation based*” as it is based on the combination of observed dust-laden OLR and computed dust-free OLR. To test if our computed dust-free OLR has any potential bias due to, for example, errors in the ancillary data (i.e., atmospheric gas and temperature), we selected 75 cloud free cases in the same region and season with no dust detected by CALIPSO. Note that because of the small dust loading in these cases the computed OLR at TOA mainly depends on the accuracy of ancillary data of
surface temperature and atmospheric profiles. Therefore, the comparison between the computed OLR and CERES measurements of those cases can inform us if there is any potential bias in our computation of dust-free OLR. It turns out that the difference between RRTM and CERES OLR has a mean value around 0.7 W/m² with standard deviation around 3.8 W/m² (not shown). Therefore, in the following analysis all our dust-free OLRs are reduced by 0.7 W/m² to account for this positive bias, which leads to a semi-observation-based instantaneous DREₜₗw of dust at 2.7 ± 0.32 W/m² with the 95% confidence level.

4. Sensitivity of Dust DRE to Microphysical and Optical Properties of Particles

The cloud-free and dust-laden cases from the CCCM product facilitate an ideal testbed for investigating the sensitivity of dust DREs to the microphysical (i.e., PSD and shape) and optical (i.e., refractive index) properties of dust. We use the aerosol extinction profiles at the 0.5 µm from the CCCM product (which is based on CALIOP/CALIPSO observations) and different combinations of the dust properties to drive multiple sets of radiative transfer simulations of dust DREs. Through comparisons of the radiative transfer simulations with CERES observation, we study how the physical and optical properties influence both the DREₜw and DREₗw of dust. It should be mentioned here that the CCCM product also use the same methodology to generate the aforementioned post-processed flux profile. In the analysis, we will also compare our dust DRE simulations with the results provided in the CCCM products.

4.1 Sensitivity to dust size and refractive index

In the first sensitivity study, we study the influences of dust size and refractive index on the dust scattering properties and consequently dust DREs. Based on different combinations of the
PSDs (AERONET vs. Fennec-SAL) and SW refractive index (OPAC vs. Colarco-SW), we simulate four sets dust spectral scattering properties (Figure 7), and correspondingly four sets of dust DREsw efficiency (Figure 8). In the simulations, dust particles are assumed to be spheroidal and the aspect ratio distribution from Dubovik et al. [2006] (see Figure 4a) is used. The OPAC-LW refractive index is used. The impacts of dust shape distribution and LW refractive index on dust DRE will be discussed later.

Figure 7 shows the scattering properties for the four different combinations of dust PSD and refractive index. The extinction efficiency ($Q_e$) based on the Fennec-SAL PSD is significantly larger than that based on the AERONET PSD (Figure 7a). The spectral shape is also different. The $Q_e$ based on the Fennec-SAL PSD is rather flat in the SW region due to its large size whereas the $Q_e$ based on the AERONET PSD decreases with wavelength. The $Q_e$ shows no sensitivity to refractive index in Figure 7a. It is because the Colarco-SW and OPAC-SW are different only in the imaginary part (see Figure 3) which has minimal influence on $Q_e$. In contrast, the single scattering albedo (SSA) in Figure 7b shows more sensitivity to refractive index. As expected, the Fennec-SAL PSD and OPAC-SW combination (i.e., larger size and more absorptive refractive index) has the smallest SW SSA while the AERONET PSD and Colarco-SW (i.e., smaller size and less absorptive refractive index) has the largest SW SSA. The other two combinations yield similar SW SSA that are in between the abovementioned two extremes. The asymmetry factor ($g$) in Figure 7c shows a primary sensitivity to size and a secondary sensitivity to refractive index.

Figure 7d shows spectral variation of dust AOD normalized with respect to AOD at 0.5 $\mu$m. The peak wavelength of solar radiation (0.5 $\mu$m) and peak wavelength of terrestrial thermal radiation (10 $\mu$m) are highlighted with dashed lines. The 0.5 $\mu$m AOD is used as the reference for normalization because as aforementioned, we use the 0.5 $\mu$m aerosol extinction profile in the
CCCM derived from CALIOP to drive our radiative transfer simulations. After spectral normalization, one can see that given the same 0.5 µm AOD the 10 µm AOD based on the Fennec-PSD is much larger than that based on the AERONET PSD by around 80%. This is an important feature that has important implications for the DRE_{LW} of dust. The SW reflection of dust depend not only on AOD, but also SSA and g. Figure 7e shows spectral variation of AOD*SSA*(1-g), where AOD indicates dust load, is multiplied by SSA to take the scattered fraction, and then multiplied by (1-g) to take the backscattered portion. It is a quantity more relevant for understanding dust SW reflection. Evidently, this index suggests that the combination of smaller size (AERONET PSD) and less absorptive refractive index (Colarco-SW) leads to most reflective dust among the four sets of simulations, whereas the larger size (Fennec PSD) and more absorptive refractive index (OPAC) combination generates least reflective dust. The other two combinations are in between and somewhat similar.

Figure 8 shows the four sets of simulated TOA upward SW fluxes as a function of the input AOD at 0.5 µm. For comparison purpose, the DRE_{SW} efficiency regression results based on observations in Figure 5, as well as the results reported in the CCCM products, are also plotted. Focusing on our computations first, we note that as expected the most reflective dust based on the combination of AERONET PSD and Colarco-SW refractive index leads to the largest DRE_{SW} efficiency (~70.5 W/m^2/AOD), while the least reflective dust based on the combination of Fennec-SAL PSD and OPAC ref yields the smallest DRE_{SW} efficiency (~30.6 W/m^2/AOD). Clearly, these results are outside of the range based on observations (i.e., ~36.5±4.8 ~ 49.7±7.1 W/m^2/AOD), suggesting they are too extreme. The other two combinations, i.e. AERONET PSD+OPAC-SW and Fennec-SAL PSD + Colarco-SW, generate similar DRE_{SW} efficiency at ~47.6 and ~53.3 W/m^2/AOD, respectively, both comparable to the CERES-MODIS based value. Interestingly, the
DRE\textsubscript{SW} efficiency based on the flux computations reported in the CCCM product is \(-81\) W/m\textsuperscript{2}/AOD, even larger than that based on AERONET PSD + Colarco refractive index, suggesting that the dust model used in the CCCM flux computations is too reflective in the SW. The instantaneous DRE\textsubscript{SW} and DRE\textsubscript{SW} efficiency at surface for the two combinations that agree with the CERES observation, i.e., AERONET PSD+OPAC-SW and Fennec-SAL PSD + Colarco-SW, are given in the Table 2.

One additional point to note in Figure 8 is that, the TOA flux vs. AOD relations based on the radiative transfer computations are much less scattered than those based on observations. The $R^2$ value for the computation-based regressions all exceed 0.95, much higher than the observation-based results in Figure 5. This is because, in reality the TOA flux is influenced not only by AOD, but also many other factors, such as surface reflectance variation, boundary layer aerosols that might not be undetected by satellite, uncertainty in satellite retrieval algorithm. Most of these factors are not accounted for in the radiative transfer computations, leading to a near perfect correlation between TOA flux and input AOD. This should not be interpreted as a lack of variability, rather than a smaller uncertainty.

On one hand, the results in Figure 8 are encouraging, as they suggest that a relatively simple combination of dust size and refractive index can enable us to simulate the dust DRE\textsubscript{SW} that are comparable with observations. On the other hand, the fact that two different dust models lead to similar DRE\textsubscript{SW} efficiency simulation, both comparable with observation, points to a long-lasting problem in aerosol remote sensing. That is, different combinations of aerosol microphysical and optical properties can lead to similar radiative signatures. The combination of smaller dust size with more absorptive refractive index is as good as the combination of larger size with less absorptive refractive index, as long as DRE\textsubscript{SW} is concerned.
But are the two combinations also equal in terms of closing the LW radiation? This is an important question, because ideally an appropriate dust model should close both SW and LW radiation. To address this question, we extend our radiative transfer simulations to the LW. It is important to point out that the LW and SW dust radiative properties are not independent but related through the physical properties of dust. For example, the AOD at a given wavelength $\lambda$ in LW is related to the visible AOD through

$$AOD(\lambda) = AOD(0.5\mu m) \frac{Q_e(\lambda)}{Q_e(0.5\mu m)},$$

where $Q_e$ is the extinction efficiency that is determined by dust size, shape and refractive index. The dust size and shape are obviously independent of wavelength and therefore connect the SW and LW. Even the refractive index in the SW and LW regions should be physically self-consistent because refractive index is determined by the chemical composition of dust. Unfortunately, because the refractive index measurements are often made either for SW only or LW only, there is a lack of measurement of dust refractive index measurement from visible all the way to thermal infrared.

In our computations, we first use the LW dust refractive index from OPAC to compute the dust LW scattering properties and the corresponding OLR. Based on the same OPAC-LW refractive index, the Fennec-SAL PSD yields an instantaneous DRE$_{LW}$ of +3.0 W/m$^2$ at TOA and +7.7 W/m$^2$ at surface (see Table 3). The results based on the AERONET PSD are significantly smaller, +1.8 W/m$^2$ at TOA and +4.7 W/m$^2$ at surface. This difference between the two PSDs can be easily understood with Figure 7b. Given the same visible AOD, the coarser Fennec PSD has a larger infrared AOD than the AERONET PSD, and therefore stronger warming effects in the LW.

The more important question is which one, Fennec or AERONET PSD, leads to OLR simulations that agree better with the CERES observation? The differences between the computed
OLRs and the CERES measurements of OLR for the selected dust cases are shown in Table 4, together with the significance test results, i.e., ‘t-score’ and ‘p-value’ from the Student’s t-test. Interestingly, the OLRs based on the combination of AERONET PSD + OPAC-LW refractive index are systematically warmer (larger) than CERES measurements by an average of 0.9 W/m². The high t-score of 2.36 and low p-value of 0.02 indicate this warm bias to be statistically significant. In contrast, the OLRs based on the combination of Fennec PSD + OPAC-LW refractive index have a bias only at –0.5 W/m² and a p-value (0.55) significantly larger than the commonly used 0.05 threshold, which means that OLR of this dust model is statistically indistinguishable from the CERES measurements. Then, to investigate the sensitivity of the computation to LW dust refractive index, we performed the computations again based on the Di Biagio et al. LW refractive index. As shown in Table 4, the OLR based on Fennec PSD is still better than that based on the AERONET PSD, even though both sets deteriorate slightly in comparison with the results based on the OPAC LW refractive index. Overall, the size difference is the primary reason for the fact that the OLR based on Fennec PSD is systematically smaller than that based on the AERONET PSD. As shown in Figure 7, due to size difference, the Qe based on the Fennec-SAL PSD (coarser) decreases at a slower rate than that based on the AERONET PSD (finer). As a result, according to Eq. (1) given the same SW AOD, the Fennec-SAL has a larger LW AOD and therefore less OLR than the AERONET PSD. In comparison with our results, the OLRs reported in the CCCM product (not shown here) are on average 3.1 W/m² larger than CERES measurements. This warm OLR bias of CCCM product in the LW is consistent with its “too reflective” bias in the SW in Figure 8.

The LW result in Table 4 is interesting and important. First of all, it suggests that the LW spectral region provides useful information content on dust properties that is complementary to SW. As we see from Figure 8, the Fennec-SAL PSD + Colarco-SW refractive index and
AERONET PSD + OPAC-SW SW refractive combinations yield very similar SW radiation simulations. However, only Fennec PSD can lead to reasonable LW radiation simulation. Secondly, although the main point here is more about the usefulness of the information content in LW, the fact that the coarser Fennec PSD leads to better OLR simulation than AERONET PSD and CCCM product (based on MATCH) aligns with the recent studies (e.g., Kok et al. [2017]) arguing that dust size tends to be underestimated in the aerosol simulation models.

Finally, as expected, the combination of Fennec PSD + OPAC-LW also yields the best simulation of the dust DRE\textsubscript{LW}, at 3.0 W/m\textsuperscript{2}, in comparison with the result derived from the CERES OLR observations and RRTM dust-free OLR computation with ancillary data provided by CCCM product (i.e., +3.4±0.32 W/m\textsuperscript{2} based on CERES-CALIPSO combination).

### 4.2 Sensitivity to dust shape

In this section, we investigate the sensitivity of dust DRE to the shape (or shape distribution) of dust. For all the computations in the last section, we have used the spheroidal dust model with the aspect ratio distribution from Dubovik et al. [2006] (See Figure 4a). Now, we replace this model with another spheroidal dust model by Kandler et al. [2009] shown in Figure 4b. For comparison purpose, we also carry out another set of computation assuming spherical dust. For dust size and refractive index, we use the Fennec-SAL and Colarco-SW/OPAC-LW refractive index since dust DREs based on this combination has shown the best agreement with the observations.

In Figure 9, we compare the scattering properties of dust based on three different shape models. Overall, the two spheroidal models are very similar and both significantly different from the spherical model. More specifically, in the SW the \( Q_e \) based on spheroidal models is
significantly larger than that based on spherical dust model. In the LW it is the opposite. The $\omega$ in Figure 9b suggest that the spherical dust is more absorptive than spheroidal dust in the SW region, when other things are equal. Figure 9d and e show the normalized the AOD with respect to AOD(0.5 $\mu$m) and the spectral variation of the scattering index AOD*SSA*(1-g). From Figure 9d we can see that given the same SW AOD, the spherical model has the larger LW AOD than the two spheroidal models. The comparison in Figure 9e reveals that the spherical dust model is less reflective than the spheroidal model in the SW.

Figure 10 shows the radiative transfer simulations for the selected cases based on the three dust shape models. The DRE$_{SW}$ efficiency based on the Kandler et al. [2009] is $-48.3$ W/m$^2$/AOD, which almost identical to the $-47.6$ W/m$^2$/AOD based on the Dubovik et al. [2006] model. In contrast, the DRE$_{SW}$ efficiency based on the spherical dust model is much smaller $-39.8$ W/m$^2$/AOD, which can be expected from the results in Figure 9e (i.e., spherical dust is less reflective). Because the DRE$_{SW}$ efficiencies based on all three shape models are within the observation-based values, we cannot tell if the spherical dust model is better or worse than the spheroidal models.

As mentioned above, the two spheroidal dust models yield very similar OLR simulations and are both statistically indistinguishable from the CERES observations. In contrast, the OLR simulations based on the spheroidal dust models has a statistically significant $-0.8$ W/m$^2$ cold bias, with a p-value of 0.03 (See Table 4). Overall, the results in Figure 10 and Table 4 indicate that the two spheroidal models provide a slightly better, especially in LW, agreement with the observations. Note that different shape models may have different angular and/or spectral signature in terms of radiance, which is more important for satellite remote sensing. But this is beyond the scope of this study and will be investigated in future work.
5. Diurnally Mean Dust DRE in North Atlantic

The DRE computations in the last section (i.e., Table 1~Table 3) are instantaneous values corresponding to the overpassing time of Aqua around 1:30PM local time. The strong solar insolation makes the instantaneous DRE\textsubscript{sw} much larger than DRE\textsubscript{lw} in terms of magnitude, leading to a strong negative DRE\textsubscript{net} (cooling) of dust. However, the DRE\textsubscript{sw} operates only during daytime, while the DRE\textsubscript{lw} operates both day and night. In addition, because of the availability of satellite observations only at TOA, we have focused only on the DRE at TOA in the analyses above. To appreciate the relative magnitude of DRE\textsubscript{lw} with respect to DRE\textsubscript{sw} we extend our DRE simulations and analysis from instantaneous to diurnal mean, and also from TOA to surface. Over tropical ocean, the OLR is most sensitive to sea surface temperature (SST). Our sensitivity study based on the 3-hour MERRA (Modern-Era Retrospective analysis for Research and Applications) data suggests that the diurnal SST variation in the tropical North Atlantic region is so small that the diurnal mean OLR is close to the instantaneous value. Similarly, we also found that the diurnal variation of atmospheric profile (e.g., water vapor) has negligible impact on the diurnal DRE\textsubscript{sw} computation. Therefore, we only compute the diurnal variation of DRE\textsubscript{sw} due to the change of solar zenith angle and ignore the small diurnal variation of DRE\textsubscript{lw} as well as the impacts of atmospheric profile change on DRE\textsubscript{sw}.

Table 5 summarizes the key results of the diurnal mean DRE\textsubscript{sw} and DRE\textsubscript{sw} efficiency at TOA, as well as at surface. In the SW, the two most reasonable combinations of PSD and refractive index, Fennec-SAL PSD + Colarco-SW and AERONET-PSD + OPAC-SW leads to similar TOA DRE\textsubscript{sw} efficiency around $-29 \text{ W/m}^2/\text{AOD}$, which is at the center of the $-16 \sim -41 \text{ W/m}^2/\text{AOD}$ range reported in Yu et al. [2006]. At the surface, the DRE\textsubscript{sw} efficiency based on these two combinations are around $-83 \text{ W/m}^2/\text{AOD}$, which is significantly stronger than the $-27 \sim -68 \text{ W/m}^2/\text{AOD}$ range reported in Yu et al. [2006]. It should be noted that we have limited this study
to dust-dominant cases, whereas the values in Yu et al. [2006] are based on simple domain average and include other types of aerosol.

By combining the information in Table 3 and Table 5, we can easily derive the net DRE\text{net} of dust in the North Atlantic during summer. The TOA DRE\text{net} based on the combination of Fennec-SAL PSD + Colarco-SW + OPAC-LW refractive indices gives a regional mean DRE\text{net} of –6.9 W/m\textsuperscript{2} and –18.3 W/m\textsuperscript{2} at TOA and surface, respectively. In comparison, the corresponding values based on the combination of AERONET PSD + OPAC-SW + OPAC-LW refractive indices are –8.5 W/m\textsuperscript{2} and –22.5 W/m\textsuperscript{2}, respectively. It is interesting and important to point out that the DRE\text{Lw} is significant, about 17% ~ 36% (depending on the choice of PSD and refractive index) in terms of magnitude with respect to the DRE\text{Sw}, and therefore not negligible in the DRE\text{net} regardless whether for TOA or surface.

6. Summary and Discussions

In this study, we use A-Train satellite observations reported in the CCCM product and recent in situ measurements of dust properties to investigate the DREs of the dust aerosols in the North Atlantic African dust outflow region during summer months. First, we select about 600 cloud-free and dust-dominant CERES pixels from 5 seasons of CCCM product. Based on these cases, we first derive a set of observation-based instantaneous (corresponding to Aqua overpassing time) DRE\text{Sw} efficiency and DRE\text{Sw} using the combination of CERES-measured TOA flux and MODIS or CALIPSO retrieved dust AOD. The DRE\text{Sw} efficiency and DRE\text{Sw} based on CERES-MODIS observation are –49.7±7.1 W/m\textsuperscript{2}/AOD and –14.2±2 W/m\textsuperscript{2}, respectively. The values based on the CERES-CALIOP combination are –36.5±4.8 W/m\textsuperscript{2}/AOD and –10.4±1.4 W/m\textsuperscript{2}, respectively. Using the combination of CERES-measured OLR (i.e., with dust) and computed
dust-free OLR based on ancillary data, we also derive a set of semi-observation-based TOA
DRE\textsubscript{LW} between 2.38 ~ 3.72 W/m\textsuperscript{2}.

In the follow-up sensitivity study, we use the RRTM radiative transfer model to compute
the DRE of dust using the observed 0.5\mu m dust extinction profiles from CALIPSO under various
different assumptions of dust PSD, refractive index and shape distributions. We find that two dust
models, one based on Fennec-SAL PSD and Colarco-SW refractive index and the other on
AERONET PSD and OPAC-SW refractive index, provide the best fit to the observation-based
DRE\textsubscript{SW} efficiency and DRE\textsubscript{SW}. However, only the one based on the Fennec-SAL PSD, which is
much coarser than the AERONET-PSD, can also provide reasonable fit to the observation-based
DRE\textsubscript{LW}. We also find that the DREs based on the two spheroidal dust models are quite similar to
each other, but more different from those based on spherical dust, suggesting that the detailed
shape distribution is less important in the calculation of dust DRE. Based on the dust model that
provides the best fit to the observation-based DRE, we estimate the diurnal mean dust DRE\textsubscript{SW}
efficiency in the North Atlantic region during summer months (JJA) from 2007 to 2010 to be
around –28 and –82 W/m\textsuperscript{2}/AOD at TOA and surface, respectively. The corresponding DRE\textsubscript{SW} is
–9.9 W/m\textsuperscript{2} and –26 W/m\textsuperscript{2} at TOA and surface, respectively. The diurnal mean DRE\textsubscript{LW} is about 3
W/m\textsuperscript{2} at TOA and 7.7 W/m\textsuperscript{2} at surface. As dust aerosol properties varies temporally and spatially,
DREs of dust aerosols also have high spatio-temporal variation. Therefore, it is worthy to extend
the analysis to other regions and years in future studies.

Our estimation of the instantaneous TOA DRE\textsubscript{SW} efficiency is in reasonable agreement
with the values reported in a recent study by Mishra et al. [2017]. Their observations are from a
satellite instrument similar to CERES, called Megha-Tropiques-ScaRaB (MT- ScaRaB). Flying in
a low-inclination orbit, this instrument is able to observe the TOA radiation in the tropical region
at various local times. Using 4 years MT- ScaRaB radiation and MODIS AOD observation, Mishra et al. [2017] estimate that the instantaneous TOA DRE\textsubscript{sw} corresponding to a solar zenith angle of \(\sim 40^\circ\) in the North Atlantic region is about \(-40 \pm 3\) W/m\(^2\)/AOD, which is in between our range of 
\(-49.7 \pm 7.1\) W/m\(^2\)/AOD and \(-36.5 \pm 4.8\) W/m\(^2\)/AOD. Our estimation of the diurnal mean TOA 
DRE\textsubscript{sw} efficiency \((-28\) W/m\(^2\)/AOD) is in between the \(-18\) W/m\(^2\)/AOD reported in Mishra et al. 
[2017] and \(-35\) W/m\(^2\)/AOD reported in Li et al. [2004]. The difference may result from different 
selection of cases and domain. Note that our analysis is limited to cloud-free and dust-dominant 
cases that are selected based on MODIS and CALIOP observations.

Due to the lack of study on dust DRE\textsubscript{LW} in this region, it is difficult to find a comparable 
result the literature to validate our estimate of DRE\textsubscript{LW}. Nevertheless, our result that the positive 
DRE\textsubscript{LW} cancels about 30% of the negative DRE\textsubscript{sw} in the computation of the diurnal mean net dust 
DRE is in agreement with many previous studies attesting the importance of dust DRE\textsubscript{LW} (e.g., 
Zhang et al. 2003, Haywood et al. 2005). Note that over land, e.g., the Sahara Desert, the brighter 
surface reflectance will reduce the cooling effect of DRE\textsubscript{sw} or even leads to warming (positive) 
DRE\textsubscript{sw}. At the same time, the hot surface temperature during daytime may result in DRE\textsubscript{LW} 
significantly larger than that over ocean. Therefore, the DRE\textsubscript{LW} is expected to be even more 
significant in comparison with DRE\textsubscript{sw}, over land than over ocean, which is an interesting topic for 
future studies.

Another interesting result from this study is that given the same visible AOD dust particle 
size and dust absorption in the SW can compromise each other in determining dust DRE\textsubscript{sw}. As a 
result, it is difficult to specify both variables using the SW radiation alone. In such case, the LW 
radiation could provide complementary and important information on dust properties, especially 
dust particle size. Most of the current aerosol property retrieval algorithms use only SW radiation
observations. There are also a few algorithms to retrieve dust properties using only LW radiation
observation [e.g., Pierangelo et al., 2004, DeSouza-Machado et al. 2006, Peyridieu et al., 2010].

It is worth exploring in future studies the possibility and benefit of retrieving dust properties
utilizing both the SW and LW observations.

Finally, as discussed in Section 3.1, because the selected region is quite cloudy, and the
footprint of CERES is relatively large, the sampling rate of cloud-free and dust dominant cases is
very low. An important question arises from the low sampling is whether our results are
representative. More specifically, one may wonder if our cloud-free cases are also representative
of the clear-sky part of those cloudy CERES pixels. To address this question, we investigated if
the dust properties (e.g., AOD and dust temperature) and meteorological conditions (e.g., surface
temperature and precipitable water) have any correlation with the cloud fraction. If the statistics
of the dust properties and meteorological conditions from our clear-sky cases are similar to those
from the cloudy cases, then our results are arguably representative of not only the clear-sky dust-
dominant CERES pixels, but also the clear-sky part of cloudy dust dominant CERES pixels. To
this end, we first check the AOD. This time we selected all the dust-dominant cases based on
CALIOP observations regardless of the cloud fraction. Then, we divided all the cases into 5 groups
according to the cloud fraction within the CERES pixel, i.e., 0~20%; 20~40% 40~60% 60~80%
and >80%. As shown in Figure 11a, the dust AOD from the cloudy groups is statistically larger
than that from our cloud-free cases, which also means larger DRESW if the DRE efficiency remains
the same. We don’t know whether other dust properties, such as size, shape and refractive index,
are correlated with cloud fraction. Investigating this is extremely challenging, if not impossible,
using satellite observations. We have to leave this for future studies using other types of
measurements (e.g., in situ). In addition to dust AOD, we also checked the surface temperature,
the dust layer temperature (weighted by the dust extinction coefficient from CALIOP) and the total
amount of water vapor in the column. These quantities are potentially important for the DRE_{LW}.
As shown in the Figure 11, in terms of the surface temperature (Figure 11 b) and dust layer
temperature (Figure 11 c), the cloudy dust-dominant cases are almost identical to our cloud-free
dust-dominant cases. However, not surprisingly, we found that the cloud-free cases are drier than
the cloudy cases (Figure 11 c). Note that, given the same dust properties, an increasing of water
core increases the atmospheric opacity in the LW, which tends to reduce the dust DRE_{LW}. In
summary, if the dust particles properties (i.e., dust size, shape and refractive index) remain the
same, then the DRE_{sw} of dust in the clear-sky part of cloudy CERES pixels would be slightly
larger than that based on our results because of the larger AOD. In the LW, the larger AOD of the
clear-sky part of cloudy CERES pixels would lead to a larger DRE_{LW}, but on the other hand, the
increased humidity under cloudy conditions counteract the effect of larger AOD. The net result is
dependent on the relative importance of these two competing factors.
Figures and Tables:

Table 1 Observation-based instantaneous (at A-Train overpassing time) DRE and DRE\textsubscript{SW} Efficiency at the top of atmosphere (TOA). The values in the parenthesis for DRE\textsubscript{LW} are based on the assumption of $0.7 \text{ W/m}^2$ bias in our clear-sky OLR computation. See text for detail.

<table>
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<th>TOA DRE\textsubscript{SW} Efficiency $[W \cdot m^{-2} \cdot AOD^{-1}]$</th>
<th>TOA DRE\textsubscript{SW} $[W \cdot m^{-2}]$</th>
<th>TOA DRE\textsubscript{LW} $[W \cdot m^{-2}]$</th>
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<td>-14.2±2.0</td>
<td>3.1±0.60</td>
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<tr>
<td>CERES-CALIPSO AOD</td>
<td>-36.5±4.8</td>
<td>-10.4±1.4</td>
<td>3.4±0.32</td>
</tr>
</tbody>
</table>
Table 2 Instantaneous DRe_sw and DRe_sw Efficiency at TOA and Surface based on different dust models (e.g., PSD, refractive index, and shape).

<table>
<thead>
<tr>
<th>PSD</th>
<th>Refractive Index</th>
<th>Shape</th>
<th>TOA DRe_sw efficiency (W/m^2/AOD_{0.5um})</th>
<th>TOA DRe_sw (W/m^2)</th>
<th>Surface DRe_sw efficiency (W/m^2/AOD_{0.5um})</th>
<th>Surface DRe_sw (W/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fennec-SAL</td>
<td>Colarco-SW</td>
<td>Dubovik</td>
<td>-47.6</td>
<td>-13.5</td>
<td>-179.4</td>
<td>-51.5</td>
</tr>
<tr>
<td>AERONET</td>
<td>OPAC-SW</td>
<td>Dubovik</td>
<td>-53.3</td>
<td>-15.5</td>
<td>-190.1</td>
<td>-55.0</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>Colarco-SW</td>
<td>Sphere</td>
<td>-39.8</td>
<td>-11.4</td>
<td>-200.4</td>
<td>-58.2</td>
</tr>
</tbody>
</table>
Table 3 Instantaneous $DRE_{LW}$ based on different dust models. Note that the diurnal mean values are almost identical to the instantaneous results due to small diurnal variation in the LW.

<table>
<thead>
<tr>
<th>PSD</th>
<th>Refractive Index</th>
<th>Shape</th>
<th>TOA $DRE_{LW}$ efficiency (W/m²/AOD$_{0.5μm}$)</th>
<th>TOA $DRE_{LW}$ (W/m²)</th>
<th>Surface $DRE_{LW}$ efficiency (W/m²/AOD$_{0.5μm}$)</th>
<th>Surface $DRE_{LW}$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Dubovik</td>
<td>10.5</td>
<td>3.0</td>
<td>26.9</td>
<td>7.7</td>
</tr>
<tr>
<td>AERONET</td>
<td>OPAC-LW</td>
<td>Dubovik</td>
<td>6.3</td>
<td>1.8</td>
<td>16.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>Di-Biagio-LW</td>
<td>Dubovik</td>
<td>8.4</td>
<td>2.4</td>
<td>18.9</td>
<td>5.4</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Sphere</td>
<td>12.6</td>
<td>3.6</td>
<td>32.9</td>
<td>9.4</td>
</tr>
</tbody>
</table>
Table 4 The difference in OLR between our computations and the CERES measurements for the selected dust cases. The values in the table are based on the assumption of 0.7 W/m² bias in our clear-sky OLR computation.

<table>
<thead>
<tr>
<th>PSD</th>
<th>Refractive Index</th>
<th>Shape</th>
<th>Mean Difference</th>
<th>Standard Deviation</th>
<th>T-score</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Dubovik</td>
<td>-0.2</td>
<td>3.8</td>
<td>-0.62</td>
<td>0.55</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>Di-Biagio-LW</td>
<td>Dubovik</td>
<td>0.3</td>
<td>3.7</td>
<td>0.83</td>
<td>0.41</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Kandler</td>
<td>-0.4</td>
<td>3.9</td>
<td>-0.9</td>
<td>0.54</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>OPAC-LW</td>
<td>Sphere</td>
<td>-0.8</td>
<td>4.0</td>
<td>-2.1</td>
<td>0.033</td>
</tr>
<tr>
<td>AERONET</td>
<td>OPAC-LW</td>
<td>Dubovik</td>
<td>0.9</td>
<td>3.7</td>
<td>2.36</td>
<td>0.02</td>
</tr>
<tr>
<td>AERONET</td>
<td>Di-Biagio-LW</td>
<td>Dubovik</td>
<td>1.5</td>
<td>3.7</td>
<td>3.94</td>
<td>8.5e-5</td>
</tr>
</tbody>
</table>
Table 5 Diurnally mean $DRE_{sw}$ and $DRE_{sw}$ Efficiency at TOA and Surface

<table>
<thead>
<tr>
<th>PSD</th>
<th>Refractive index</th>
<th>Shape</th>
<th>TOA $DRE_{sw}$ Efficiency (W/m²/AOD)</th>
<th>TOA $DRE_{sw}$ (W/m²)</th>
<th>Surface $DRE_{sw}$ Efficiency (W/m²/AOD)</th>
<th>Surface $DRE_{sw}$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fennec-SAL</td>
<td>Colarco-SW</td>
<td>Dubovik</td>
<td>-28</td>
<td>-9.9</td>
<td>-82.1</td>
<td>-26.0</td>
</tr>
<tr>
<td>AERONET</td>
<td>OPAC-SW</td>
<td>Dubovik</td>
<td>-29.4</td>
<td>-10.3</td>
<td>-85.7</td>
<td>-27.2</td>
</tr>
<tr>
<td>Fennec-SAL</td>
<td>Colarco-SW</td>
<td>Spherical</td>
<td>-22.8</td>
<td>-8.2</td>
<td>-89.6</td>
<td>-28.5</td>
</tr>
</tbody>
</table>
Figure 1 CALIPSO derived seasonal mean (JJA) dust aerosol optical depth (AOD) at 0.5 µm averaged over five summers (2007~2010) in cloud free sky condition from the integrated CALIPSO, CloudSat, CERES, MODIS merged product (CCCM).
Figure 2 Size distributions of mineral dust used in this study. Fennec-SAL curve is from a new in-situ measurement of Saharan dust taken during the Fennec 2011 aircraft campaign [Ryder et al. 2013]. The solid curve represents desert dust size distribution retrieved from AERONET observations at Cape Verde site reported in Dubovik et al. [2002].
Figure 3 a) real and b) imaginary part of the SW dust refractive index from OPAC [Hess et al. 1998] and Colarco et al. [2014]; c) real and d) imaginary part of the LW dust refractive index from OPAC [Hess et al. 1998] and Di Biagio et al. [2017].
Figure 4  Two spheroidal dust shape distributions models a) shows aspect ratio distributions from Dubovik et al. [2006]. The ln$\epsilon$-interval is 0.09. b) shows aspect ratio distributions as function of particle radius interval discretized from measurement of Kandler et al. (2009). The first point of each line covers the measurement data from $\epsilon$=1.0 to 1.3, the last point of each line covers $\epsilon$ > 2.9 and the other points cover $\epsilon$-intervals of 0.2 Koepke et al. [2015].
Figure 5 Linear regressions of CERES measured upward SW flux at TOA with satellite retrieved AOD for the selected cloud-free and dust dominant cases (Black points represent the cases selected using CALIPSO cloud mask along the ground track, red points represent the cases selected using MODIS cloud mask over the entire CERES footprint). a) shows the regression results based on MODIS AOD for cases (153 black points and 87 red points) with MODIS AOD retrievals. b) is for all cases (607 black points and 245 red points) with CALIPSO AOD retrievals.
Figure 6 PDF of observed OLR from CERES (i.e., with dust) and computed dust-free OLR based on the atmospheric profiles and surface temperature reported in CCCM.
Figure 7 a) Extinction efficiency (Qe), b) single scattering albedo (SSA), c) asymmetry factor (g) d) normalized AOD with respect to AOD @ 0.5 µm, and e) AOD*SSA*(1-g) of dust aerosols based on different combination of PSD and refractive index. PSD type and refractive index type are indicated in legends.
Figure 8 The four sets of simulated TOA upward SW fluxes as a function of the input AOD at 0.5 µm. For comparison purpose, the DRE\textsubscript{sw} efficiency regression results based on observations in Figure 5, as well as the results reported in the CCCM products, are also plotted.
Figure 9: Extinction efficiency ($Q_e$), b) single scattering albedo (SSA), c) asymmetry factor ($g$), d) normalized AOD with respect to AOD @ 0.5 µm, and e) AOD*SSA*(1-$g$) of dust aerosols based on different combination of PSD and refractive index. PSD type and refractive index type are indicated in legends.
Figure 10 shows the radiative transfer simulations for the selected cases based on the three dust shape models.
Figure 11 Histograms of a) dust AOD, b) surface temperature c) dust temperature and d) total column water vapor of dust dominant CERES pixels with different cloud fractions.
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