Response to RC1

Recent studies suggest growing importance of mineral types in estimating the role of dust to the Earth's climate. However, the impact of soil and dust mineral types is still highly uncertain, while most of global models assume a homogeneous mineral mixture. The present study reports a modeling study of the impact of the mineralogy map to climate system using the GFDL AM4 model. This work starts with the how mineralogy map by Claquin et al. (1999) is implemented to GFDL AM4, and how model experiments and optical properties are setup. The model simulations are evaluated with the observations by di Biagio et al. (2019) and AEROENT data. The present study further examines the impact of dust mineralogy to climate system mainly over North Africa with various parameters such as, radiative fluxes, precipitation, surface temperature, temperature profile, etc.

The method used in the present work is scientifically sounding and it presents several interesting results that might be a beneficial for the potential readers. The paper is well organized and reasonably well written. I would recommend the paper to "minor revision", however I also have suggestions in many places which I would like to see in the revision.

Major comments:

One of the major questions I have is what is the reason for HD2.7% is used as a standard GFDL AM4 models if the hematite fraction is too high? The present study suggests that HD0.9% would be more realistic than HD2.7%. However, the reference study by Balkanski et al. (2007) suggested HD1.5% as the best hematite fraction in the mixture. I would like to see the result of HD1.5% even with a brief result only. Also, it would be good to provide more discussion on this. I would say the differences from 0.9 to 1.5 and to 2.7 % are not negligeable.

Reply: Thanks for the comments.
The reason of using HD2.7% in the standard GFDL AM4 model:
Fixing 2.7% hematite content for dust particles was decided during the development of the previous GFDL Climate Model CM3 (Donner et al., 2011) when it was found that dust absorption was unrealistically high (by a factor 3) in CM2 (Delworth et al., 2006) compared to AERONET observations (Balkanski et al., 2007). The conjunction in CM3 of a sharp decrease of black carbon (strong aerosol absorber) with a new emission inventory and the switch to more scattering dust had a negative effect on precipitation bias, and late 20th century warming (see Donner et al., 2011 for details). To limit this bias, selecting 2.7% hematite was adopted.
Reference: Donner, L.J., Wyman, B.L., Hemler, R.S., Horowitz, L.W., Ming, Y., Zhao, M., Golaz, J.C., Ginoux, P., Lin, S.J., Schwarzkopf, M.D. and Austin, J., 2011. The dynamical core, physical

parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. Journal of Climate, 24(13), pp.3484-3519.

The fractional content of hematite in dust aerosols along with its complex refractive index (CRI) determines dust absorptivity (e.g., SSA) in the shortwave spectrum. As we can see from Figure 5 (a) in the manuscript, AERONET retrieved dust SSA (0.938) is higher than both HD2.7% (0.853) and HD0.9% (0.929), given out choice of CRI (Figure1). This suggests that AERONET retrievals imply an equivalent or even lower hematite content in dust aerosols than 0.9%. Considering this, the SSA of HD1.5% would fall between the values for HD2.7% and HD0.9%, aligning better with AERONET than HD2.7% but not as well as HD0.9%. Therefore, HD1.5% is not used in this study.

In addition, the most appropriate suggested hematite content may vary across studies due to the significant uncertainty in the CRI of hematite. A higher hematite content, when paired with a lower imaginary part of the RI, would be equivalent in dust SSA to a combination of lower hematite content with a higher imaginary part of the RI. For example, Balkanski et al. (2007) took their hematite CRI from Bedidi and Cervelle (1994). This CRI has a lower imaginary part, corresponding to less absorption, than the value we choose following Scanza et al. (2015). (See our Figure 1 and Figure 4 of Obiso et al., 2024). This is one reason that we arrive at a lower optimal fraction of hematite than Balkanski et al. (2007).

The present work needs more background study for the existing research. At least I am aware of a similar recent work by Balkanski et al. (2021, https://doi.org/10.5194/acp-21- 11423-2021). How they are compared each other?

Reply: Thanks for the suggestion.
Balkanski et al. (2021) mainly focused on investigating the enhancement of precipitation over the Sahel induced by absorbing dust, using a fully coupled model compared to a no-dust condition. Our study uses an atmospheric model with prescribed SST and compares a mineralogy-resolving case with mineralogy non-resolving case. Nevertheless, our findings align consistently with theirs, indicating that more absorptive dust enhances precipitation over the Sahel region. Therefore, we have cited this paper to support our results regarding the enhancement of precipitation due to dust absorption.

Analysis of dust and mineral mass distribution such as horizontal and vertical distribution, and size dependence of distribution is not covered at all in the manuscript, although these are an important step before analyzing climate impact.

Reply: Thanks for the great comment.

We have included an analysis of the global distribution of dust optical depth (DAOD) in Figure 2 to provide a proxy of the vertically integrated dust distribution in the main text. The size dependence of global dust (or mineral) mass has been added in the section S2 in the supplement. We have added the discussion about the added figures as:

'In addition to the globally averaged dust properties listed in Table 3, we illustrate the global distribution of DAOD (Figure 2) and the distribution of global dust mass across 5 size bins (Figure S3 in the Supplement) for the three experiments: before (e.g., HM27 and HD09) and after (e.g., BM) resolving mineralogy. The global dust size distribution across the 5 size bins remains largely unchanged across experiments. Besides the subtle difference (~10%) in global mean DAOD across the three experiments as listed in Table 3, the global distribution of DAOD responds differently in HD09 and BM. Compared to HD27, reducing hematite content in HD09 generally decreases DAOD, except over the Sahel region. In contrast, resolving mineralogy decreases DAOD over the Sahara region while increasing DAOD over the Sahel and Asia regions. The reduction in DAOD over the Sahara region further contributes to the decrease in dust absorption over the region, primarily attributed to the change in dust optical properties, such as the enhancement in dust SSA. The indistinct variation in DAOD across different experiments results from the feedback of dust interactions with radiation (Miller et al.,2004; Pérez et al., 2006; Miller et al., 2014), which is influenced by the distinct scattering properties of dust aerosols in each experiment as shown in Table 3.'

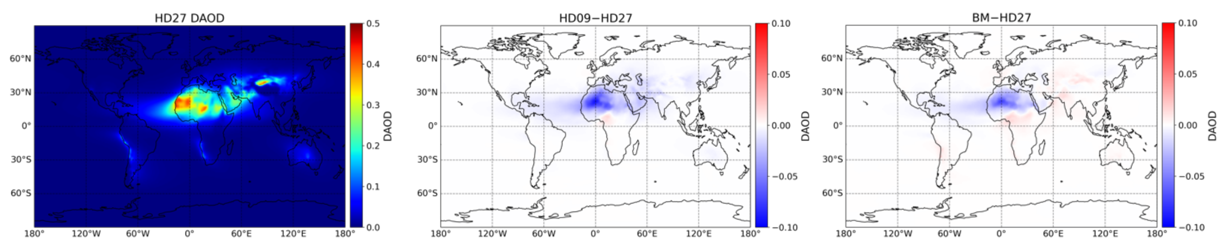


Figure 2 in the main text. The global distribution of dust optical depth (DAOD) for HD27, and the difference in DAOD between HD09 and BM from HD27. The global mean DAOD values ($\overline{DAOD}$) of each experiment are shown in Table 3 in the main text.

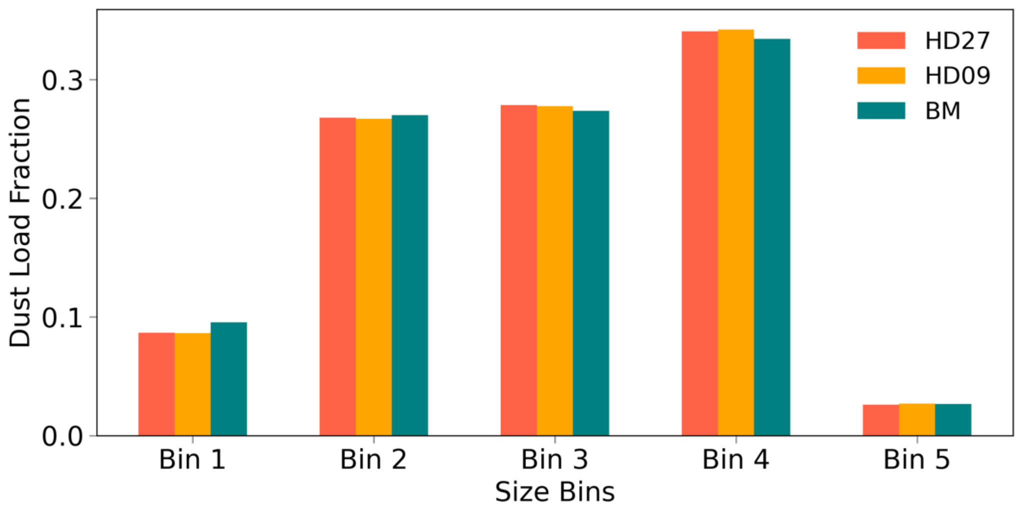


Figure S4 in the Supplement (bin1: 0.2 – 2 μm, bin2: 2 - 3.6 μm, bin3: 3.6 – 6 μm, bin4: 6 – 12 μm, bin5: 12 - 20 μm). The dust load fraction in each size bin is analyzed for two homogeneous dust experiments (e.g., HD27 and HD09) and a mineral-resolved experiment (e.g., BM). These fractions are calculated based on the 19-year (2001-2019) global dust load.

The title includes "Earth", however the present paper is limited in North Africa only. There is a brief result in Supplementary Material. I would suggest to expand the work or change the title.

Reply: Thanks for the comment. The title is changed to 'Modeling impacts of dust mineralogy on fast climate response'
We think this is a global study using a climate model. The dust optical properties (e.g., SSA) are compared over global scope. The impacts of dust mineralogy on climate are also investigated in global scope (in supplementary). However, the statistically significant anomalies primarily occur over North African in JJA, therefore, we focus on North Africa in section 5 of the main text to discuss the impacts of dust mineralogy.

Method section needs more work to make it more clear and specific. I listed a few.

Other comments:

L24-26: It is unclear the reduction of what and is reduced from what?

Reply: Thanks. We clarified the statement by saying that 'Over the 19-year (from 2001 to 2019) modeled period during JJA (June-July-August), resolving dust mineralogy leads to a reduction of over 50% in net downward radiation across the Sahara and approximately 20% over the Sahel at top of atmosphere (TOA) compared to the baseline bulk dust model version.'

L101: "Section 2 provides ...." Split the paragraph to a different on.

Reply: Thanks. Done

L110-111: Please be specific if the present work is participating to the AMIP projects.

Reply: Sorry for the confusion. This work is not participating in the AMIP projects. We have revised the sentence to avoid confusion.
'We conduct a series of experiments with GFDL AM4.0 (Zhao et al. 2018a, b) over the period 2001-2019 using the AMIP protocol, meaning sea surface temperature (SST) and sea-ice are imposed based upon average monthly observations (see Gates, 1992 for details) .'

L137, 138: Change soil map to soil mineralogy map.

Reply: Done

L137: Change "to resolve dust (" to "to resolve dust mineralogy (".

Reply: Done

L139-141: Please discuss more detail how BFT is implemented to GFDL AM4.0.

Reply: Thank for the comment. We have included a brief description of implementing dust mineralogy following BFT as follows.
'The soil map is based on soil analyses that are usually done after wet sieving, which disperse mineral aggregates into small particles. This dispersal is particularly relevant for the phyllosilicates, typically found in the form of aggregates in soils. They are detected in the atmosphere with higher proportions at coarser (silt) sizes than those reported in the soil maps (Perlwitz et al., 2015b; Perez Garcia-Pando et al., 2016). These recent studies also show that the Brittle Fragmentation Theory (BFT; Kok, 2011) represents a practical framework to generate the emitted particle size distribution based on the dispersed soil PSD, which facilitates the utilization of soil mineralogy maps. In our simulations, we employ BFT to reconstruct the mineral aggregates emitted from the original undispersed soils, following the methods described in Gonçalves Ageitos et al., 2023.'

L139: Change "disperse" to "fully disperse".

Reply: Done

L146-147: The sentence "Moreover, ..." needs to be further elaborated. Please include the difference of goethite and absorption in outside of visible spectrum.

Reply: Thanks! We have provided further elaboration on the statement and included a reference to support it.
'Goethite and hematite are the two major types of iron oxides present in soils. Goethite is less absorptive than hematite and is not resolved in C1999. So, iron oxides are represented by hematite in this study. Hematite has larger density than other minerals, so that hematite deposits more quickly and is not able to be transported to remote regions when not aggregated or internally mixed with lighter clay minerals. Moreover, among the minerals considered here, hematite is the strongest absorber at ultraviolet (UV) and visible wavelengths, while it does not have noticeable absorption at infrared wavelengths (IR) compared to other minerals (Sokolik and Toon, 1999).'

L150-156: This section of internally and externally mixed hematite is confusing and this section needs more improvement in the revision. First, what is the base of partitioning hematite to internal and external mixture in clay? How much of hematite is in internal mixture and external mixture? Second, what is the base of 5% mass fraction threshold for internal and external mixture of the hematite in accretions? Please be specific how Goncalves et al. (2023) used that assumptions. Thirdly, it needs more clear description on how hematite from soil mineral map is used. If the method follows Goncalves et al. (2023), the assumption of 5% is not necessary. Also I wonder how the internal and external mixture assumption is used in other mineral type?

Reply: Thanks for the comments.
I have modified this part by adding more references and clarifying the way of partitioning hematite into internally mixed and externally mixed portions.
'we partition hematite into two portions by defining two sets of tracers: one set of tracers carries the mass of the hematite that constitutes small accretions in clay minerals (i.e., internally mixed with clay minerals), are allowed to be up to 5 % of the masses of their host minerals at emission (Perlwitz et al., 2015; Gonçalves Ageitos et al., 2023). Given the low fractional mass of hematite compared to their host minerals, we assume that these accretions do not change the density of their host particles. These internally mixed accretions form the largest fraction of the emitted hematite. Another smaller set of tracers carries the mass of the remaining fraction of hematite, which is considered to be externally mixed with the other minerals, including the internal mixtures of hematite with clay. All other minerals are considered to be externally mixed.'

L162: Please specify the meaning of "clay433" here.

Reply: Thanks. We have specified the meaning of clay433 in the manuscript.
'The clay433 represents a mixed mineral comprising three clay minerals: illite, kaolinite and smectite, with mass fraction of 40%, 30%, and 30%, respectively (see detailed descriptions in Supplementary Section S1).'

L171-174: Optical tables are important for the experiment, and it needs more description here. Or add a sentence that more details will be discussed in Section 4.

Reply: Thanks for the suggestion. I have added a sentence stating, ‘More details about optical properties of minerals will be discussed in Section 4.’

L183: SSA and CRI of AERONET is Inversion product. Please specify in the text.

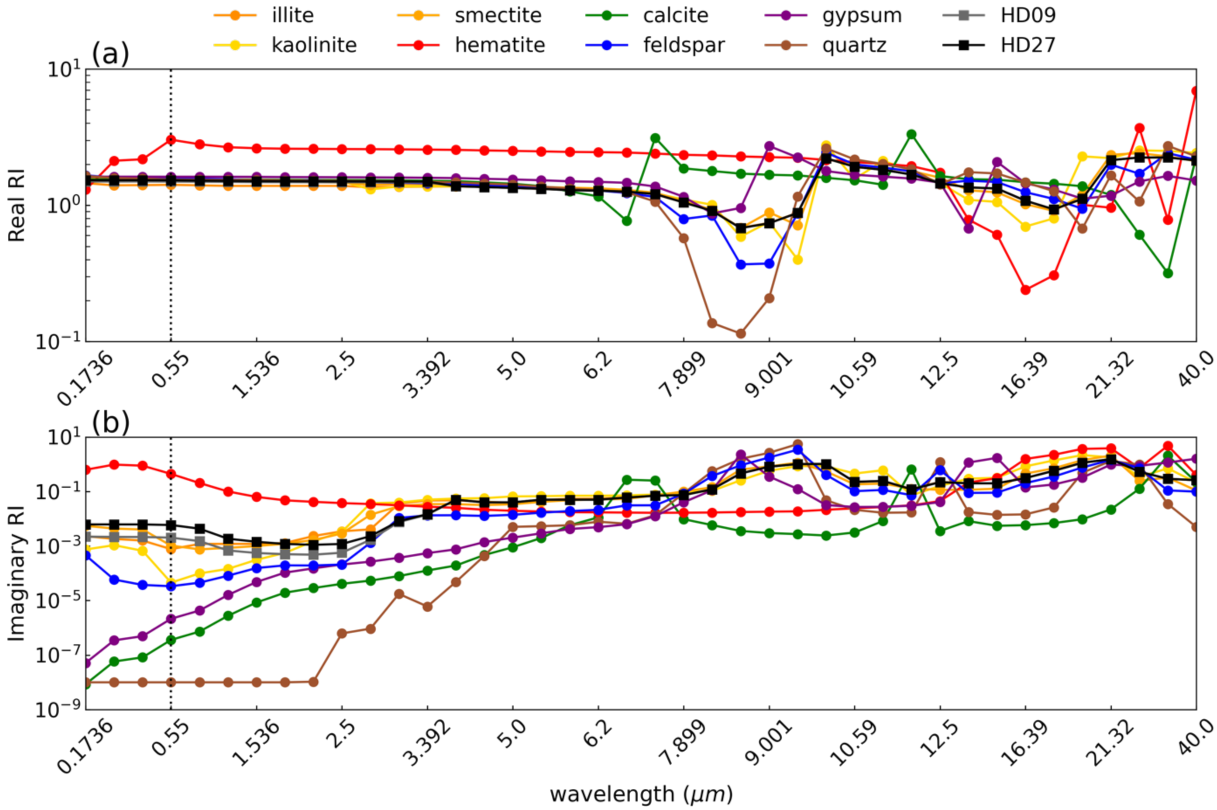
Reply: Thanks. Done

Table 2 BM-RT 2) and 3): Please specify how much of hematite and gypsum are removed. I am also curious why only LC, RH, and RG are considered among 9 mineral classes?

Reply: Thanks for the question.
I modified the Table 2 to make it clear that the tracers of hematite and gypsum are removed in BM-LCRH and BM-LCRHRG, respectively.
The reasons for considering LC, RH and RG are stated in Section 6 in details (see below). Other minerals are important to climate in various ways as discussed in the introduction. For example, internally mixed hematite is important for SW absorption of dust, calcite is important for chemistry, feldspar is important for ice nucleation, quartz is important for LW absorption.
For LC: ‘As discussed in section 4.1, the three clay minerals (i.e., illite, kaolinite, smectite) exhibit similar optical properties and perform similar functions in climate by hosting hematite. Hence, they can be combined in their interaction with radiation without significant impacts on climate.’
For RH: ‘Based upon the C1999 soil mineral composition that we use, externally mixed hematite is mainly concentrated over the Sahel region (Ginoux et al. 2023, in preparation) and cannot be transported to remote regions due to its high mass density. Obiso et al. (2023) shows that visible extinction due to externally mixed hematite is negligible compared to other mineral components including hematite internally mixed with other minerals. Thus, we further remove external hematite tracers in the second sub-experiment BM-LCRH (where ‘RH’ indicates ‘Remove externally mixed Hematite’).’
For RG: ‘Since there are no known specific impacts of gypsum on climate, we conducted the third sub-experiment, BM-LCRHRG (‘RG’ indicates ‘Remove Gypsum’), where gypsum was removed.’

Figure 1: CRI in longwave length is indistinguishable. I would suggest it to separate to shortwave and longwave.

Reply: Thanks for the comment. We have revised the figure to improve the clarity in LW.



L269-270: "weighted by solar spectrum"? Please be more specific the meaning.

Reply: Thanks for the comment. We have specified the solar spectrum as follows.
'Additionally, the spectrally averaged DAOD and SSA are always weighted by the TOA solar radiation intensity at the corresponding wavelengths, peaking around 0.50 μm, as shown in Eq. (1) and Eq. (2).

$$\overline{DAOD} = \frac{\int_{\lambda 1}^{\lambda 2} DAOD(\lambda)\, B(\lambda)\, d\lambda}{\int_{\lambda 1}^{\lambda 2} B(\lambda)\, d\lambda} \qquad \text{Eq. (1)}$$

$$\overline{SSA} = \frac{\int_{\lambda 1}^{\lambda 2} SSA(\lambda)\, DAOD(\lambda)\, B(\lambda)\, d\lambda}{\int_{\lambda 1}^{\lambda 2} B(\lambda)\, DAOD(\lambda)\, d\lambda} \qquad \text{Eq. (2)}$$

Where $B(\lambda)$ describes the solar radiation energy intensity, which can be calculated by means of the Planck's function B(T,λ), using the temperature of the Sun (T = 5800 K).'