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ATBD-EMIT-04

Earth Mineral dust source InvesTigation (EMIT)

EMIT L4 Algorithm: Radiative Forcing

Theoretical Basis

Version 0.2

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II.Change Log

Version	Date	comments
0.1	Oct, 2019	Initial Draft
0.2	Jan 2020	Post-PDR refinements

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1 Key Team Members

A large number of individuals contributed to the development of the algorithms, methods, and implementation of the L4 approach for EMIT. The primary contributors are the following:

- Natalie Mahowald (Cornell University) – EMIT Deputy PI, Earth System Modeler
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- Carlos Pérez García-Pando (BSC)- Mission co-I Earth System Modeler
- Paul Ginoux (GFDL) Mission co-I Earth System Modeler
- David R. Thompson (Jet Propulsion Laboratory) – EMIT Co-I, Instrument Scientist
- Robert O. Green (Jet Propulsion Laboratory) – Mission PI, Radiometric modeling

2 Historical Context and Background Information

Mineral dust aerosols originate as soil particles lifted into the atmosphere by wind erosion. Mineral dust created by human activity makes a large contribution to the uncertainty of direct radiative forcing (RF) by anthropogenic aerosols (USGCRP and IPCC). Mineral dust is a prominent aerosol constituent around the globe. However, we have poor understanding of its direct radiative effect, partly due to uncertainties in the dust mineral composition. Dust radiative forcing is highly dependent on its mineral-specific absorption properties. The current range of iron oxide abundance in dust source models translates into a large range of values, even changing the sign of the forcing (-0.15 to 0.21 W/m2) predicted by Earth System Models (ESMs) (Li et al., 2020). The National Aeronautics and Space Administration (NASA) recently selected the Earth Mineral Dust Source Investigation (EMIT) to close this knowledge gap. EMIT will launch an instrument to the International Space Station (ISS) to directly measure and map the soil mineral composition of critical dust-forming regions worldwide.

The EMIT Mission will use imaging spectroscopy across the visible shortwave and near-infrared (VSWIR) range to reveal distinctive soil mineral signatures, enabling rigorous mineral detection, quantification, and mapping. The overall investigation aims to achieve two objectives.

1. Constrain the sign and magnitude of dust-related RF at regional and global scales. EMIT achieves this objective by acquiring, validating and delivering updates of soil mineralogy used to initialize Earth System Models (ESMs).
2. Predict the increase or decrease of dust RF resulting from the expansion or contraction of available dust sources under future climate scenarios. EMIT achieves this objective by initializing ESM forecast models with the mineralogy of soils exposed within at-risk lands bordering present-day arid dust sources.

The EMIT instrument is a Dyson imaging spectrometer that will resolve the distinct absorption bands of iron oxides, clays, sulfates, carbonates, and other dust-forming minerals with contiguous spectroscopic measurements in the visible to near infrared region of the spectrum (0.4 – 2.5 μm). EMIT will map mineralogy to detect minerals at the one hectare scale and coarser, ensuring accurate characterization of the mineralogy at the grid scale required by ESMs. EMIT's fine spatial sampling will characterize the soil exposed within hectare-scale agricultural plots and open lands that border arid regions, critical to understanding climate feedbacks caused by mineral dust arising from future changes in land use, land cover, precipitation, and regional climate forcing.

The EMIT Project is part of the Earth Venture-Instrument (EV-I) Program under the auspices of the Program Director of the NASA Earth Science Division (ESD). EMIT is comprised of a Visible/Shortwave Infrared Dyson imaging spectrometer adapted for installation on the International Space Station (ISS).

Table 1 below describes the different data products to which the EMIT Mission will provide to data archives. This document describes the "Level 4" stage, which relies upon output from Level 3 algorithms that create a gridded map of soil mineral composition (as aggregated spectral abundance), which is expressed as normalized mineral band depths that can be used as a boundary condition for the calculation of dust aerosol composition by ESMs.

Data Product	**Description**	**Initial Availability**	**Median Latency Post-delivery**	**NASA DAAC**
Level 0	Raw collected telemetry	4 months after IOC	2 months	LP DAAC
Level 1a	Reconstructed, depacketized, uncompressed data, time referenced, annotated with ancillary information reassembled into scenes.	4 months after IOC	2 months	LP DAAC
Level 1b	Level 1a data processed to sensor units including geolocation and observation geometry information	4 months after IOC	2 months	LP DAAC
Level 2a	Surface reflectance derived by screening clouds and correction for atmospheric effects.	8 months after IOC	2 months	LP DAAC
Level 2b	Mineralogy derived from fitting reflectance spectra, screening for non-mineralogical components.	8 months after IOC	2 months	LP DAAC
Level 3	Gridded map of mineral composition aggregated from level 2b with uncertainties and quality flags[1]	11 months after IOC	2 months	LP DAAC
Level 4	Earth System Model radiative forcing and uncertainties	16 months after IOC	2 months	LP DAAC

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[1] L3 includes mineral composition as aggregated spectral abundance.

3 Rationale for Development of the Algorithms

The goal of the Level 4 product is to provide a best estimate and uncertainty of the radiative forcing based on the new (Level 3) normalized band depth for different minerals surface products provided by the EMIT project. Radiative forcing is most broadly defined as the change in the top of atmosphere net radiative flux due to a particular constituent, for this case, mineral aerosols (Myhre et al., 2013). In the atmosphere, we cannot observe the effect of removing a constituent. Thus, it is impractical to estimate radiative forcing from observations, so that models are necessary (Myhre et al., 2013). Specific definitions of radiative forcing that are used might include initial rapid adjustments by stratospheric temperature change or tropospheric adjustment (e.g. Hansen et al. 2005; Forster et al. 2016). For mineral dust, stratospheric adjustments are small, reflecting the small dust concentrations in this layer, while tropospheric adjustments are in practice highly model-specific. To calculate the radiative forcing, we simply calculate the radiative fluxes with and without the constituent, ignoring any adjustments.

While dust radiative forcing calculations are enabled in most ESMs, only the Community Atmospheric Model (CAM), the atmospheric component of the Community Earth System Model (CESM) (Hurrell et al., 2013; Liu et al., 2012; Neale et al., 2013) and the atmospheric component of the Goddard Institute of Space Studies ModelE (Schmidt et al. 2014), have the ability to calculate dust radiative forcing based not on assumed globally uniform aerosol composition, but rather based on the temporally and spatially varying mineralogical content of dust (Li et al., 2020; Obiso et al., 2020; Scanza, 2016). The basis of this document is to describe forcing calculations from these two models given the normalized band depth from Level 3 as inputs.

4 Algorithm Description

4.1 Input data

The mineral-speciated dust radiative forcing is calculated within an ESM. Input data for the ESM is required for this element, as described in more detail elsewhere for the CESM (Hurrell et al., 2013; Liu et al., 2012; Neale et al., 2013 and publicly available online: http://www.cesm.ucar.edu/models/cesm2/release_download.html) and for the GISS ModelE (Miller et al. 2006; Perlwitz et al. 2015a). For this version of the CESM, the input data required includes land surface datasets to allow the prognostic vegetation model to operate, ocean sea surface temperature datasets, as well as input files that contain the various constants used across the model. The version of the model used for this study is described in detail in previous papers (Li et al., 2020; Scanza, 2016), and the model code, scripts and input data files are available (upload final version of the model and get DOI). For the GISS model, dust source regions are identified by geomorphological criteria (Ginoux et al 2001, Prospero et al. 2002) and a prescription of vegetation characteristics (specifically leaf area index).

For this document, we describe briefly the requirements to calculate the radiative forcing. Optical properties for the minerals included in the model were compiled from the literature and included in (Li et al., 2020; Obiso et al., 2020; Scanza, 2016), as well as available (upload final version of the model and get DOI). Most importantly to EMIT, the surface mineral dataset (normalized band depth) from EMIT L3 is used as input to the models to describe the soil mineral composition where dust is emitted.

4.2 Theoretical description

4.2.1 Development of input mineral map database at Earth system model resolution

ESMs calculate the total emitted aerosol mass at each location. Given the mineral mass fractions of the soil, the emitted aerosol mass of each mineral is calculated. We create the database of soil mineral mass fractions for input into the model using the area averaged, normalized spectral abundance for different minerals as described in the EMIT L3 document. The EMIT mission “Level 3” product is a global map at

0.5°x0.5° resolution, holding Aggregated Spectral Abundance measures, denoted in this document as ASA_j^* for each mineral j. Asterisks indicate the result of an EMIT measurement. All calculations are performed independently for each grid square. The SA values represent the average spectral band depth in that grid cell for each EMIT mineral, relative to the depth of its corresponding library spectrum. Statistically, ASA_j^* signifies the expected band depth, relative to the pure library minerals, that would be observed for a spectral reflectance measurement of bare soil at a random location within that grid cell. These spectral abundances do not necessarily sum to unity. In addition, the EMIT level 3 product contains two ancillary channels to represent all other mineral detections, grouped broadly into "iron oxides," and "all other minerals, excluding quartz and feldspar." We define the complete set of EMIT minerals as M_{EMIT}:

$$M_{EMIT} = \left\{ \begin{matrix} \text{calcite, chlorite, dolomite, goethite, gypsum, hematite, illite,} \\ \text{kaolinite, montmorillonite, vermiculite,} \\ \text{other iron oxides, and all other excluding iron oxides} \end{matrix} \right\} \tag{1}$$

In contrast, the input mineralogical information to an ESM is the normalized mass fraction, MF_j^*, defined as the proportion of mineral mass in mineral category j. This contrasts with the original estimate, denoted MF_j, before incorporating EMIT measurements. All Mass Fractions are based on a different set of minerals, including quartz and feldspar which are not measured by EMIT. We define the set of ESM minerals as M_{ESM}:

$$M_{ESM} = \left\{ \begin{matrix} \text{calcite, feldspar, goethite, gypsum, hematite,} \\ \text{illite, kaolinite, montmorillonite, quartz} \end{matrix} \right\} \tag{2}$$

Several minerals - vermiculite, chlorite, dolomite, and the ancillary categories – do not appear in the ESM list (goethite was added to the Earth System Models after the proposal was submitted). We assign each of these minerals to the ESM mineral with the most similar optical properties. Dolomite is a carbonate treated as calcite. We group the phyllosilicates vermiculite and chlorite with illite. Ancillary iron oxides are grouped with hematite, and all other ancillary detections with kaolinite.

We first translate Spectral Abundance values to Volume Fractions using a geographic mixing assumption in which a mineral detected on the surface has the same signature as the pure library spectrum and subtends some fraction of its grid square. That is, spectra of pure materials arranged on a flat surface combine in proportion to their area; Similarly, for geographic mixing the spectral abundance of a mineral indicates its areal coverage. Absent regional information relating areal coverage to the volume fraction, we use the operating assumption that the entrainable volume of each mineral is directly related to its areal extent. For a grid square g and mineral i from the EMIT and ancillary lists, we define the revised volume fraction VF_j^* as:

$$VF_j^* = \begin{cases} \dfrac{SA_j^*}{\sum_{k \in M_{EMIT}} SA_k^*} & if \quad 1 < \displaystyle\sum_{k \in M_{EMIT}} SA_k^* \\ SA_j^* & if \quad 1 \geq \displaystyle\sum_{k \in M_{EMIT}} SA_k^* \end{cases} \tag{3}$$

This has the effect of bounding the volume fractions of the detected EMIT minerals at 100%. If the EMIT retrievals suggest less than 100% composition (that a missing mineral has a contribution to the composition), for the missing fraction, we use the relative amounts of quartz and feldspar amounts from other sources to fill in the remaining amount. Specifically we use the soil type conversion to mineralogy from previous studies (Claquin et al., 1999a; Journet et al., 2014; Li et al., 2020; Scanza et al., 2015a) and map these onto the soil datasets from the Food and Agricultural Organization (FAO/UNESCO) WGB84 at 5` x 5` arc minutes with soil legend from FAO/UNESCO Soil Map of the World in 1976 (Batjes, 1997) and then regridding onto CAM grids. We then apply the following transformation, with VF_j representing the original volume fraction estimate and VF_j^* the revised estimate after EMIT measurements:

$$VF_{quartz}^{*} = \begin{cases} 0 & if \;\; 1 \leq \sum_{k \in M_{EMIT}} SA_k^* \\ \frac{VF_{quartz}}{VF_{quartz}+VF_{feldspar}} \left(1 - \sum_{k \in M_{EMIT}} SA_k^*\right) & if \;\; 1 > \sum_{k \in M_{EMIT}} SA_k^* \end{cases} \tag{4}$$

A similar relationship holds for feldspar. We translate the revised volume fractions VF_{quartz}^* into mass fractions MF_j^* by applying the relative mass of each mineral, and renormalizing so that the resulting ESM mass fractions sum to unity within each grid square. Each is partitioned into the portion assigned to clay substrate (MFC) and silt substrate (MFS). The original ESM inputs ensured:

$$MF_j = MFC_j + MFS_j \text{ for all } j \in M_{ESM}, \qquad \text{and} \tag{5}$$

$$1 = \sum_{j \in M_{ESM}} MF_j \tag{6}$$

We retain the proportion of each mineral assigned to each substrate, producing revised estimates MFS_j^* for silt and MFC_j^* for clay:

$$MFS_j^* = MF_j^* \frac{MFS_j}{MFS_j + MFC_j} \tag{7}$$

$$MFC_j^* = MF_j^* \frac{MFC_j}{MFS_j + MFC_j} \tag{8}$$

This procedure retains the original clay/silt partitioning of all minerals.

At the 60 m ground-level resolution of EMIT, a single spectrum may contain multiple mineral signatures. This can occur when the EMIT detection algorithms match a spectrum to a library signature of a mixed sample. It also occurs when two different library spectra match to different spectral regions, e.g. when a spectrum contains a hematite signature in visible wavelengths as well as a clay mineral signature in a shortwave interval. It is not generally not possible to diagnose from the spectrum alone whether such cases are mixtures, coatings, or disjoint subpixel geographic arrangements of pure minerals. In the EMIT calculations described above for level 3 and 4 products, all signature depths contribute equally to the aggregate spectral abundance values irrespective of other features that are present. Consequently, no mineral is “favored” above others for dust production whenever multiple minerals appear in the same measured spectrum.

To evaluate the uncertainties from EMIT retrievals, we use the uncertainty error estimates provided by L3, and assume high and low mineral amounts for hematite and goethite, and recalculate the radiative forcing within the CESM (described below).

4.2.2 Brief model description of mineral speciated CAM

The radiative forcings for the current climate will be calculated using CAM (either version 5 or 6) with modal aerosol model (MAM). The dust emission, transport, and deposition are simulated by the Dust

Entrainment and Deposition model (DEAD, Zender et al., 2003) which was described in details previously (Mahowald et al., 2006, 2010; Zender et al., 2003). The emission over non-vegetated, dry soils, is initiated once the calculated friction velocity exceeds the threshold friction velocity, which is a function of the soil state (e.g., soil moisture, snow cover, surface crust, vegetation, etc.) and near-surface meteorology (e.g., air density, horizontal wind). Vegetation tends to protect the soil from wind erosion by reducing the transfer of wind momentum to the soil. This suppression effect is represented via a linear dependence of grid cell numbers on the leaf area index below $0.3\ \mathrm{m^2 m^{-2}}$ (Mahowald et al., 2006) in the model. No dust emission occurs over grid cells with the exceeding this threshold. The threshold wind speed for dust entrainment also increases with soil moisture. A semi-empirical relation of Fecan et al., (1999) with additional optimization from the traditional dependence of the square of clay mass fraction (Fecan et al., 1999; Zender et al., 2003) is used to account for this influence. Currently, the default dust model still utilizes a prescribed source function (Ginoux et al., 2001) associating dust emissions to topographical depressions where abundant erodible sediment accumulates (Ginoux et al., 2001; Mahowald et al., 2006; Zender et al., 2003). In this study, we use an updated dust emission scheme developed by Kok et al. (2014) based on the brittle fragmentation theory (Kok, 2011), which has been shown to improve model-observation comparisons without the source function. CESM only considers the climatologically most relevant portion of dust ranging from 0.1-10 μm in size.

Dust species carried within each mode are internally mixed with each other and with other non-dust species but externally mixed among different modes in CAM5 and CAM6. In CAM5 and CAM6, all minerals are internally mixed with each other and other aerosols in each mode, while they are all externally mixed between modes. Within each bin or mode, advected species are assumed to follow a lognormal size distribution, which is also used in the offline Mie calculation. Aerosols in these atmospheric models are subdivided into interstitial and cloud-borne particles for purpose not limited to a better representation of advection and deposition processes, as documented in Liu et al. (2011). CAM6 has been updated to an improved two-moment prognostic cloud microphysics (MG2) from MG used in CAM5.

CAM simulates the eight minerals described in the Claquin et al. (1999) soil map with an additional mineral goethite when using the Journet et al. (2014) map. The radiative flux at each vertical layer, 19 and 14 shortwave, and 16 longwave bands for CAM4 and CAM5 (CAM6), respectively, is computed by the rapid radiative transfer method for GCMs (RRTMG) (Iacono et al., 2008) per model hour during model day with the aerosol optical properties determined from their size and mass. Specifically, in CAM5 aerosol wet size and volume are predicted by assuming the hygroscopic growth following the Kohler theory (Ghan and Zaveri, 2007) according to their dry radius, density, and hygroscopicity and the ambient relative humidity and temperature. Then the total aerosol optical properties are parameterized via a pre-calculated two-dimensional look up table containing the aerosol extinction, scattering, and asymmetric factor varying by the spectral band and aerosol volume (the volume mixing rule) in MAM. We utilize the density of each mineral taken from Scanza et al. (2015) with an exception of goethite, the density of which is 3800 $\mathrm{gm^3}$, and prescribe the same hygroscopicity for all minerals by assuming a much smaller influence on the interaction of mineral dust with solar and infrared radiation compared to other optical properties (e.g., the complex refractive index, dust mineralogy, the size distribution, etc.), also following Scanza et al. (2015). Due to lack of information about the optical properties, we add chlorite, vermiculite, and mica to kaolinite in the clay fraction, and use the tracer for kaolinite to take these three minerals in the silt fraction. Because of the same reason, we assume that the goethite is very absorptive only second to hematite and the hygroscopicity identical to hematite.

CAM6 and CAM5(4) are configured with default 0.9° x 1.25° and 2.5° x 1.9° horizontal resolutions and the simulated wind U, V, and air temperature T are nudged toward Modern-Era Retrospective analysis for Research and Applications (MERRA) dynamics version2 and version 1, respectively, for 2006-2011 with the first-year simulation as model spin-up using the anthropogenic emissions from 2000. The nudge is done at 6-hours relaxation time scale. All CAM models have 56 vertical layers up to 2 hPa, but the nudging is not done on the simulated updraft.

The TOA direct radiative forcing (DRF) from dust is calculated per model time step as the difference between fluxes with all aerosol species on the climate diagnostic list and values solely without dust.

4.2.3 Brief model description of mineral speciated GISS model

The NASA Goddard Institute for Space Studies (GISS) Earth System ModelE2.1 calculates dust mineral composition and the associated radiative forcing. ModelE2.1 is an update of GISS ModelE2 (Schmidt et al., 2014) used by Perlwitz et al., (2015a,b) and Pérez García-Pando et al., (2016) and participates in the coordinated experiments of Coupled Model Intercomparison Project 6 (Kelley et al., 2020). ModelE2.1 has horizontal resolution of 2.5° longitude by 2° latitude with 40 vertical layers extending to 0.1 hPa, just above the stratopause.

In ModelE2.1, dust enters the atmosphere where strong winds exceed a prescribed threshold that increases with soil moisture. The mass of emitted dust is largest within basins where erodible particles have accumulated and there is limited vegetation to protect the soil from the force of the wind (Ginoux et al. 2001). Emission depends upon the calculated model wind speed, but also ephemeral gusts, whose magnitude is parameterized (Cakmur et al., 2004). Dust particles are transported within bins characterized by particle diameter that ranges from 0.2 to 25 µm. Additional information about emission and transport is given by Miller et al. (2006) with an updated description of wet deposition in Perlwitz et al. (2015a).

Prognostic calculation of dust mineral composition is described by Perlwitz et al. (2015a,b) and Pérez García-Pando et al. (2016). The emitted mass of each mineral is calculated based upon mass fractional abundance in the soil derived from EMIT retrievals or else measurements of wet-sieved soils by Claquin et al. (1999). The emitted size distribution of each mineral follows a semi-empirical fit to measurements for particle diameters less than 10 um (Kok 2011). For larger diameters (up to 50 um diameter), the size distribution is constrained from measurements of concentration adjusted to account for deposition (Kandler et al. 2009; Pérez García-Pando, personal communication, 2019).

The model simulates a suite of 8 minerals. Each mineral is transported separately as part of an external mixture. This results in the preferential removal of goethite and hematite due to their higher density. Hematite and goethite are also transported as trace constituents internally mixed with the remaining minerals. Their trace concentration mixed within less dense host minerals allows hematite and goethite to travel farther than in their pure form.

Laboratory measurements show that shortwave absorption is mainly the result of iron oxides like hematite and goethite (Moosmuller et al., 2012; Wagner et al., 2012; Di Biagio et al., 2019). We relate shortwave radiative forcing by dust to the concentration of hematite based upon measurements by Di Biagio et al. (2019). The empirical laboratory relations are extended to an arbitrary size distribution based upon theoretical models of scattering (Obiso et al., 2020).

4.3 Dust Radiative Forcing and its uncertainty

4.3.1 Dust Radiative Forcing in the present day

Soil mineral fractions retrieved by EMIT (Section 4.2.1) are used to calculate dust radiative forcing in the present day. The dust aerosol burden or load is intimately related to meteorological processes like wind that raise and transport dust and precipitation that removes aerosols from the atmosphere. We attempt to match thse processes as observed by relaxing winds toward reanalysis values from MERRA2 (Gelaro et al., 2017). We use reanalysis values between 2006 and 2016. This period is chosen to allow comparison to previous sensitivity studies by Li et al. (2020) along with observations and retrievals including MODIS and AERONET Aerosol Optical Depth. Sea surface temperature (SST) and sea ice are prescribed from observations during this period. During the first year, the dust cycle 'spins up' to statistical equilibrium and is excluded from an average over the subsequent decade. These experiments with NCAR CESM and GISS ModelE, denoted as 'Current_BASE' in Table 2, are our best estimate of the present-day dust radiative forcing.

Table 2: Model runs for the current climate

Case name	**Model(s)**	**Description**
Current_BASE	**GISS and CESM/E3SM**	**Best estimate from EMIT using MERRA2 reanalysis meteorological datasets**
Current_online	**GISS and CESM/E3SM**	**Using best estimate from EMIT, and online calculated meteorology**
Current_high_ Hem/Geo	**GISS and CESM/E3SM**	**High hematite and geothite estimate from EMIT using MERRA2 reanalysis meteorological datasets**
Current_low_ Hem/Geo	**GISS and CESM/E3SM**	**Low hematite and geothite estimate from EMIT using MERRA2 reanalysis meteorological datasets**
Current_Claquin /Journet	**GISS and CESM/E3SM**	**Pre-EMIT mineral datasets from Claquin or Journet using MERRA2 reanalysis meteorological datasets**

4.3.2 Uncertainties in present-day dust RF

Additional experiments simulating the present-day dust cycle are carried out to estimate the uncertainty of our best estimate RF ('Current_BASE'). These are also listed Table 2. Previous work (Li et al., 2020) demonstrates that the soil mass fraction of hematite and goethite make the largest contribution to RF uncertainty. We carry out two additional experiments, 'Current_high_Hem/Geo' and 'Current_low_Hem/Geo' perturbing the hematite and goethite soil fractions by one standard deviation above and below their 'best' estimate, respectively. This assumed correlation of hematite and goethite errors in soil composition is intended to bound the uncertainty in radiative forcing. To assess the effect of EMIT retrievals of soil composition compared to previous estimates by Claquin et al. (1999) and Journet (2014), we estimate RF in two additional experiments using these prior estimates of soil minerals, referred to as 'Current_Claquin' and 'Current_Journet', respectively.

Reanalyses are not available to drive calculations of future dust RF at the end of the twenty-first century, necessitating the use of winds computed prognostically by each ESM. For comparison of present-day and future experiments, we add a present-day experiment 'Current_online' where dust RF is calculated with prognostic winds.

4.3.3 Understanding dust RF uncertainty due to mineral speciation before EMIT

Uncertainty of dust RF prior to the availability of EMIT mineral composition retrievals was estimated by Li et al. (2020) using a wide range of sensitivity studies with the CAM models, as well as complementary experiments with ESMs from GISS, the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and the Barcelona Supercomputing Center (BSC). These experiments focused upon the forcing uncertainty due to poorly constrained speciation of soil minerals before EMIT. Two different approaches to estimating the mineral content of soils were used (Claquin et al., 1999b; Journet et al., 2014). Based on the soil mineral ranges in Claquin et al. (2001), Li et al. calculated the 95% confidence interval of mineral fraction for each soil type. Radiative forcings were then calculated in sensitivity studies based on the high and low distribution of mineral content in the soils following the approach of Li et al.). This analysis showed that RF uncertainty is highly dependent on the hematite and goethite mass fractions, with little dependency upon other mineral fractions, especially those not detected by EMIT. Overall the range of dust radiative forcing is calculated to be -0.41 to 0.47 W m^{-2}, and about 41% of this uncertainty is due to uncertainty in the soil mineralogy (Li et al., 2020). Smaller uncertainty results from different estimates of aerosol mineral composition by different models (despite using the same *soil* mineral composition).

4.3.4 Future desert dust projections, radiative forcings and uncertainty estimates

Objective 2 of this project requires the use of EMIT data products to constrain future desert dust radiative forcing, as a result of changes in dust source area from climate change. In order to achieve this objective, the CAM and ModelE ESMs are run with prognostic winds to simulate future climate in the decade 2090-2099: experiments denoted by 'Future_BASE' in Table 3. To diagnose future changes in dust radiative forcing, based the EMIT datasets, this simulation is contrasted to the present-day 'Current_online' experiment in Table 2. Future experiments take atmospheric composition (including CO2 and concentrations of non-dust aerosol species) and ocean surface conditions (including SST and sea ice) from coupled experiments that are part of the standard CMIP6 suite carried out separately with the CESM and ModelE ESMs. Here we propose simply to complete a separate set of studies to estimate dust RF, using EMIT surface datasets and the mineral speciated version of each model.

Our dust RF is necessarily uncertain due to the spread of 21st century projections. Uncertainty of future dust RF will be characterized using different scenarios, as projected by the CESM and ModelE ESMs to at least partially cover the spread among late twenty-first century climate projections by CMIP6 (Flato et al., 2013; Pachauri et al., 2014). It is beyond the scope of our cost-capped mission to fully explore and characterize the effect of future climate uncertainty upon the uncertainty of future dust RF. Nonetheless, because NCAR CESM and GISS ModelE have markedly different climate sensitivities (with the NCAR CESM warmer and wetter than ModelE with correspondingly faster wet removal of dust), the contrast will give some information about the sensitivity of dust RF to SSP and future climate.

Table 3 lists a number of sensitivity studies. As with the present-day experiments (Table 2), we include simulations spanning the uncertainty range of soil mass fractions of hematite and goethite retrieved by EMIT, denoted by 'Future_high_Hem/Geo' and 'Future_low_Hem/Geo', respectively. Separate experiments show the effect of EMIT retrievals compared to using prior soil mineral datasets, denoted by 'Future_Claquin' and 'Future_Journet'.

A key uncertainty of future dust RF projections results from uncertain projections of vegetation. Previous studies suggest that most models predict an increase in leaf area index (LAI) coverage in the future (Mahowald et al., 2016), suggesting a likely decrease in dusty source regions, although this is likely to be sensitive to the assumptions of carbon dioxide fertilization (Mahowald, 2007). CESM calculates vegetation prognostically, whereas vegetation is presescribed in ModelE. For the standard 'Future_Base' scenario, GISS uses LAI from CESM. We assess the effect upon dust RF of vegetation scenarios that span the uncertainty of CMIP6 future projections with high and low LAI cases driving ModelE (denoted in Table 3 by 'Future_High_Veg' and 'Future_Low_Veg', respectively. To see the effect of LAI changes upon RF over the twenty-first century, we carry out an additional experiment with 2090-2099 atmospheric composition but present-day vegetation ('Future_Cur_Veg').

Finally, we consider the sensitivity of dust RF to late twenty-first century atmospheric composition according to the CMIP6 high and low scenarios, using CESM whose vegetation responds prognostically to this range of forcing (`Future_high_Emis' and `Future_low_Emis' in Table 3).

Table 3: Model runs for the future climate

Case name	Model(s)	Description
Future_BASE	**GISS and CESM**	**Best estimate from EMIT using future online winds using SSP2-4.5 Scenario, CESM veg**
Future_high_ Hem/Geo	**GISS and CESM**	**High hematite and geothite estimate from EMIT using future online winds using SSP2-4.5 Scenario, CESM veg**
Future_low_ Hem/Geo	**GISS and CESM**	**Low hematite and geothite estimate from EMIT using future online winds using SSP2-4.5 Scenario, CESM veg**
Future_Claquin /Journet	**GISS and CESM**	**Pre-EMIT mineral datasets from Claquin or Journet using future online winds using SSP2-4.5 Scenario, CESM veg**
Future_Cur_Veg	**GISS**	**Best estimate from EMIT using future online winds using SSP2-4.5 Scenario using current vegetation**
Future_High_Veg	**GISS**	**Best estimate from EMIT using future online winds using SSP2-4.5 Scenario using high future vegetation estimate**
Future_Low_Veg	**GISS**	**Best estimate from EMIT using future online winds using SSP2-4.5 Scenario using low future vegetation estimate**
Future_high_Emis	**CESM**	**Best estimate from EMIT using future online winds using high emission RCP8.5 Scenario**
Future_low_Emis	**CESM**	**Best estimate from EMIT using future online winds using high emission RCP2.6 Scenario**

4.4 Practical description

Both the CESM and the GISS model are written to run on supercomputers, and the CESM has been ported to the JPL computer. The code is millions of lines long, using mostly Fortran95, but has elements in other languages, which link together during compilation, and need to be run using scripts. The code, and scripts required to complete the runs described here are archived (doi: to be done) and tutorials on how to run the model are available (http://www.cesm.ucar.edu/events/tutorials/?ref=nav).

The NASA GISS ModelE can be downloaded at https://www.giss.nasa.gov/tools/modelE/, and is run on the NASA Discover supercomputing cluster, operated by the NASA Center for Climate Simulation.

4.5 Output

4.5.1 Delivered Products

For each of the experiments in Tables 2 and 3, L4 dust radiative forcing (Wm^{-2}) is archived as a monthly mean of net, shortwave and longwave fluxes on the native grid of each model, as well as averaged field over a common 2 degree latitude by 2.5 degree longitude horizontal model grid, representing the arithmetic mean of forcing calculated by the two models. The forcing uncertainty can be derived by contrasting the various sensitivity experiments in Tables 2 and 3 with the 'Current_BASE' and 'Future_Base' experiments.

The model configurations and scripts for each experiment will be made available at INSERT web site.

4.5.2 Auxilliary Products

Aerosol mineral concentration (kg of each mineral per kg of air) computed by each model and experiment is archived as a function of region and height.

5 Calibration Needs/Validation Activities

5.1 Model validation

The CESM model has multiple papers describing how it is compared to observations and how it is documented (http://www.cesm.ucar.edu/models/), and participates in the Climate Model Intercomparison Project (CMIP) which includes comparisons to many observations and to other models (https://www.wcrp-climate.org/wgcm-cmip).

The CESM dust module and the speciated dust versions have been compared to available data in previous papers (Albani et al., 2014; Hamilton et al., 2019; Kok et al., 2014; Li et al., 2020; Mahowald et al., 2014; Scanza et al., 2015b, 2018; Smith et al., 2017; Zhang et al., 2015). Similarly, the GISS model has been involved in many model-data comparisons (Tegen and Miller, 1998; Perlwitz et al., 2001; Miller et al., 2004; Cakmur et al., 2006; Miller et al., 2006; Huneeus et al., 2011; Perlwitz et al., 2015a, 2015b; Pérez García-Pando et al., 2016). For this study, Table 4 from the proposal describes the comparisons that will be made:

Table 4: Model validation

Variable	Metric	Performance test	Example citation
Soil mineral content	nRMSE	<50%	Journet et al. (2014)
Kaolinite/Illite ratio: compiled measurements	Correlation	>0.5	Scanza et al. (2015)
Fractions of minerals	nRMSE	<50%	Perlwitz et al. (2015b)
Iron distribution in dust deposits	Correlation	>0.5	Zhang et al. (2015)
Iron distribution in dust deposits	Mean model/obs	>0.8 and <1.2	Zhang et al. (2015)
AERONET SSA in dust regions	Spatial correlation	>0.3	Holben et al. (2001); Scanza et al. (2015); Obiso et al., (2020)

Comparison to observed RF estimates	Area mean	<10% error	Scanza et al. (2015); Patadia et al.(2009); Zhang and Christopher (2003)

6 Constraints and Limitations

Aerosol radiative forcing is sensitive to the ESM used to calculate it (Li et al., 2020; Myhre et al., 2013; Shindell et al., 2013). As part of this L4 product, we will estimate the uncertainty in the radiative forcing due to the mineralogical input datasets, surface conditions (like future vegetation) and the propagated uncertainty.

The L4 product will include the uncertainties due to the propagation of mineral uncertainties. Other uncertainties due to model bias or other unknown problems cannot be included in the uncertainty estimates.

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