

# Improving the parameterization of dust emission threshold in the Community Earth System Model (CESM)

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## Abstract

A key challenge in accurate simulations of desert dust emission is the parameterization of the threshold wind speed above which dust emission occurs. However, the existing parameterizations yield a unrealistically low dust emission threshold in some climate models such as the Community Earth System Model (CESM), leading to higher simulated dust source activation frequencies than observed and requiring global tuning constants to scale down dust emissions. Here we develop a more realistic parameterization for the dust emission threshold in CESM. In particular, we account for the dissipation of surface wind momentum by surface roughness elements such as vegetation, rocks, and pebbles, which reduce the wind momentum exerted on the bare soil surface. We achieve this by implementing a dynamic wind drag partition model by considering the roughness of the time-varying vegetation as quantified by the leaf area index (LAI), as well as the time-invariant rocks and pebbles using satellite-derived aeolian roughness length. Furthermore, we account for the effect of soil size on dust emission threshold by replacing the currently used globally constant soil median diameter with a spatially varying soil texture map. Results show that with the new parameterization dust emissions decrease by 20–80% over source regions such as Africa, Middle East, and Asia, thereby reducing the need for the global tuning constant. Simulated dust emissions match better in both spatiotemporal variability and emission frequency when compared against satellite observed dust activation frequency data. Our results suggest that including more physical dust emission parameterizations into climate models can lessen bias and improve simulation results, possibly eliminate the use of empirical source functions, and reduce the need for tuning constants. This development could improve assessments of dust impacts on the Earth system.

# Improving the parameterization of dust emission threshold in the Community Earth System Model (CESM)

**Improving the parameterization of dust emission threshold in the Community Earth System Model (CESM)**  
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**1. Introduction/motivation**

- A key challenge in simulating direct dust emission is the parameterization of the threshold wind speed above which dust emission occurs.
- However, existing parameterizations yield anomalously low thresholds in coarse climate models such as the Community Earth System Model (CESM), leading to higher modeled emission temperatures than observed.
- A major reason for the low-threshold weakness is the coarse-resolution effects of spatial variability of soil particle sizes and sheltering of the soil from the wind due to wind momentum absorption by surface vegetation.
- Here we develop a more realistic parameterization of dust emission threshold by quantifying effects of soil size and

**2. Methodology**

**3. Obtaining a global map of aggregated soil median diameter**

1. Use the model threshold wind speed  $U_{th}$  to modify the threshold wind speed  $U_{th}$  to obtain the aggregated soil median diameter  $D_p$  as large particles (0.1 and 0.2  $\mu\text{m}$ ) are known to fall below model particles (0.1 and 0.2  $\mu\text{m}$ ) are more abundant.

$$U_{th} \propto \sqrt{A_1 D_p + \frac{A_2}{D_p}}$$

Nevertheless, some global models utilize CESM as a globally averaged  $D_p = 75 \mu\text{m}$  that corresponds to the median  $D_p$  of this case.

**4. A hybrid drag partition scheme**

**I. Modify the drag partition  $f_{drag}$  model**

Surface roughness elements decrease part of the wind momentum, thereby decreasing wind velocity and dust emission. To, we will be able to discuss the velocity-to-Kol's dust emission  $F_d$

$$U_{d,s} = U_s f_{eff}$$

$$F_d \propto U_{d,s} (U_{d,s}^2 - U_{th}^2)$$

where  $f_{drag}$  is the drag partition factor from 0 to 1 dependent on the amount of surface obstacles. Mahajan et al. (2010) proposed a wind drag partition equation based on roughness length  $z_0$

$$f_{eff} \propto 1 - \ln(z_0)$$

**II. Modify the drag partition  $f_{drag}$  for model**

Prigent et al. (2012) used a remote sensing method to derive global roughness length  $z_0$  that represent well over the real regions.

We substitute the  $z_0$  into Mahajan's drag partition equation to obtain a  $U_{d,s} = 0.2 \cdot 0.2 \cdot U_{th}$  map for real regions.

**5. Rigidifying high-resolution quantities into coarser model grid**

CESM runs typically in  $2.5^\circ \times 2.5^\circ$  grid coarser than the observations provide ( $0.25^\circ \times 0.25^\circ$ ).

Since dust emission is sensitive to  $z_0$ , we cannot rigidify by simply averaging  $f_{drag}$  and  $D_p$  to coarse resolution.

Instead, we derive coarse  $f_{drag}$  and  $D_p$  by an "iteration-weighted" averaging: e.g.  $f_{drag} = \frac{1}{F} \sum F_i f_{drag,i}$

We first compute the FHS for the high-resolution dust emissions  $F$  with coarse drag partition  $f_{drag}$  for the 10 low grid cells in CESM coarse grid and sum them up to yield a total emission.

The same procedure can be used for  $D_p$ .

**6. Preliminary runs and future work**

We implement the drag partition  $f_{drag}$  and soil diameter  $D_p$  maps into CESM to figure out more realistic dust emission thresholds  $U_{th}$ .

Due to sensitivity requirement in to compare simulations using the default  $D_p = 75 \mu\text{m}$  and new drag  $f_{drag}$  map, we run a 10-year simulation and emission  $F_d$  will change by year 2012.

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## 1. INTRODUCTION / MOTIVATION

- A key challenge in simulating desert dust emission is the parameterization of the threshold wind speed above which dust emission occurs.
- However, existing parameterizations yield unrealistically low thresholds in some climate models such as the Community Earth System Model (CESM), leading to higher modeled emission frequencies than observed.
- A major reason for the low threshold windspeeds is because it neglects effects of spatial variability of soil particle sizes and sheltering of the soil from the wind due to wind momentum absorption by rocks and vegetation.
- Here we develop a more realistic parameterization of dust emission threshold by **quantifying effects of soil size and wind drag partition**.

## 2. METHODOLOGY

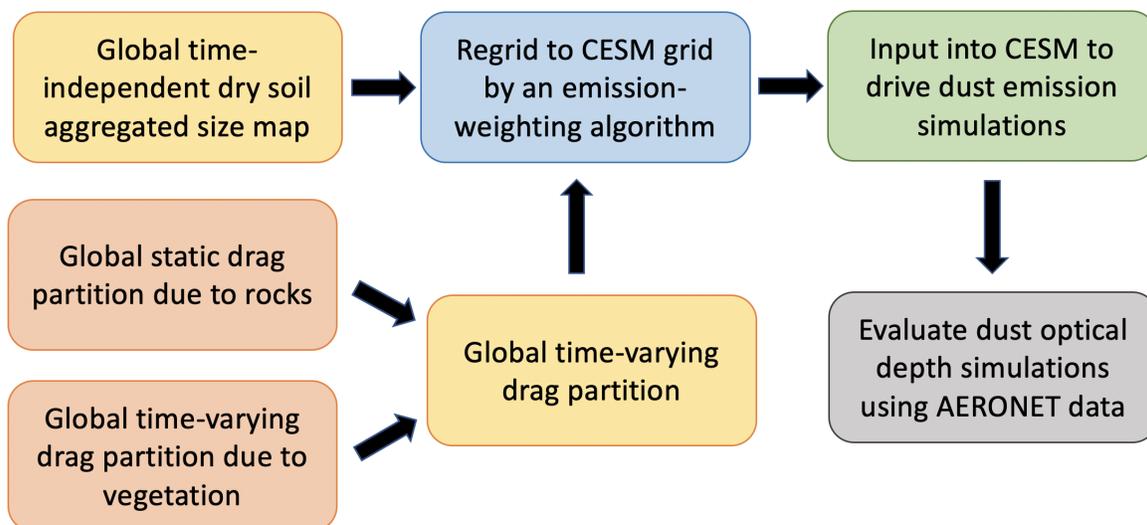


Fig. 1. A flowchart of the methodology to improve dust emission threshold parameterizations.

- We improve dust emission threshold  $u_{*t}$  parameterization in climate models in two main directions.
- First, we model a global map of dry, aggregated soil median particle size  $D_p$ , which increases dust emission threshold  $u_{*t}$ .
- Second, we account for dissipations of surface wind due to roughness elements including rocks and vegetation using a drag partition factor  $f_{\text{eff}}$ , which decreases wind frictional velocity  $u_*$ .
- We then use an "emission-weighted" averaging algorithm to regrid high-resolution ( $0.1^\circ$ ) datasets to CESM grid ( $1.9^\circ \times 2.5^\circ$ ) or any other model native grids.
- We implement the regridded datasets into the CESM and examine the corresponding changes in modeled dust emissions and aerosol optical depth (AOD).

In this study, we use the Kok et al. (2014b) dust emission equation combined with the Shao and Lu (2000) dust emission threshold equation. Kok et al. (2014b) equation calculates dust flux in  $\text{kg m}^{-2} \text{s}^{-1}$ :

$$F_d \propto u_* (u_*^2 - u_{*t}^2)$$

$$u_* > u_{*t}$$

We will implement the modifications in this paper to another default emission scheme (Zender et al., 2003) in CESM in future.

### 3. OBTAINING A GLOBAL MAP OF AGGREGATED SOIL MEDIAN DIAMETER

#### I. How to model threshold windspeed $u_{*t}$ ?

In models, the threshold windspeed  $u_{*t}$  varies with soil particle size  $D_p$ , as large particles (sand,  $>63 \mu\text{m}$ ) are heavier to lift and smaller particles (silt and clay,  $<63 \mu\text{m}$ ) are more cohesive:

$$u_{*t} \propto \sqrt{A_1 D_p + \frac{A_2}{D_p}}$$

Nevertheless, some global models such as CESM assume a globally constant  $D_p = 75 \mu\text{m}$  that corresponds to the minimum  $u_{*t}$  of this curve.

#### II. Prepare for soil texture data

To model the threshold more realistically, we prepare soil texture data from the SoilGrids database (Hengl et al., 2017) for informing soil particle size ( $0.1^\circ \times 0.1^\circ$ ):

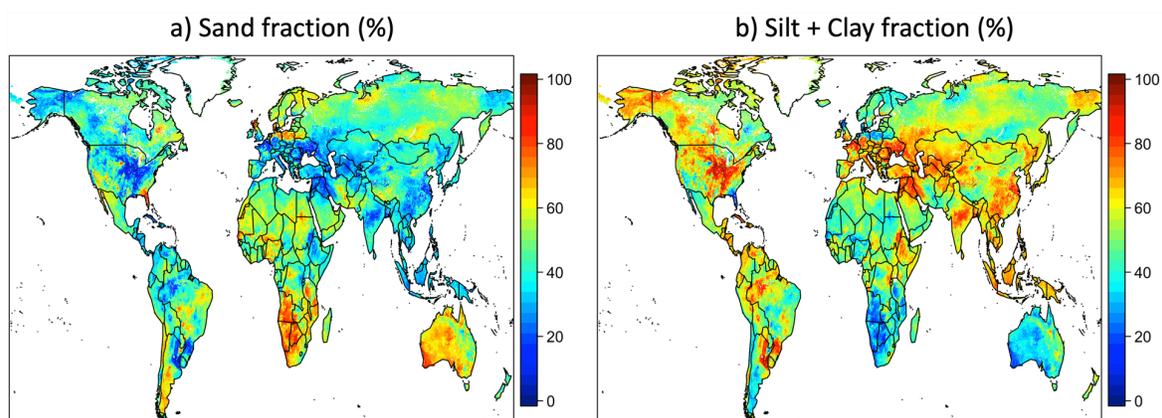


Fig. 2. The SoilGrids database (Hengl et al., 2017) soil texture used to derived median soil particle size in this study. (a) sand ( $D_p > 63 \mu\text{m}$ ) fraction  $f_{\text{sand}}$ , and (b) total silt (silt + clay,  $D_p < 63 \mu\text{m}$ ) fraction  $f_{\text{tot silt}}$ .

#### III. Construct an empirical relationship between $D_p$ and $f_{\text{tot silt}}$

We employ in-situ measurements from past studies and found strong relationships between the dry soil aggregate  $D_p$  and the total silt fraction  $f_{\text{tot silt}} = f_{\text{clay}} + f_{\text{silt}}$ .

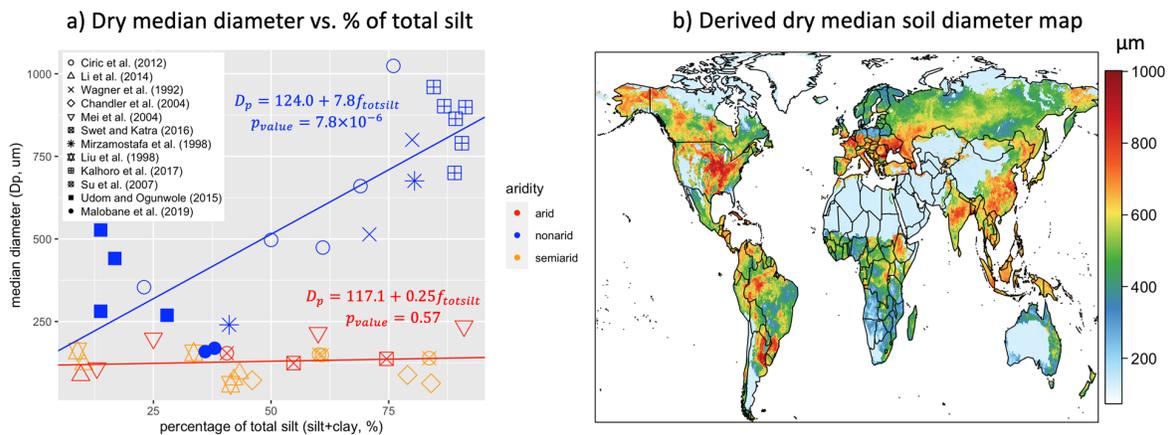
$f_{\text{tot silt}}$  is likely a good indicator for soil particle cohesion since silt and clay are "glue" in soil.

Although the relationship is much weaker for desert soils, they in general have larger  $D_p$  than CESM assumed.

**Projecting the linear relations on the SoilGrids soil textures yield a new global  $D_p$  map.** Here we define MODIS leaf area index (LAI)  $< 0.3$  as arid regions and otherwise as non-arid regions.

We yield much larger soil  $D_p$  than  $75 \mu\text{m}$  around the globe over both arid and non-arid regions.

**We will input this map into CESM to calculate a new map of dust emission threshold  $u_{*t}$  (see Fig. 7), expecting  $u_{*t}$  to increase.**



**Fig. 3.** The global soil diameter map (in  $\mu\text{m}$ ) derived from the Soilgrids (Hengl et al., 2017) soil texture data. (a) A scatterplot of soil particle diameter vs. % of total silt  $f_{\text{tot silt}}$ . (b) A global median dry soil diameter map derived using the relation in Fig. 3a and soil texture ( $f_{\text{tot silt}}$ ) from Fig. 2.

We will explore other possible predictors such as soil organic carbon (SOC), pH, and  $\text{CaCO}_3$  to explain and predict  $D_p$  in the future.

Note: it is important to characterize the soil particle "aggregated" size obtained by "dry" sieving in laboratories, since wet sieving will wash and disaggregate soil particles that adhere together (Chatenet et al., 1996). We only use soil studies that employed dry sieving here.

## 4. A HYBRID DRAG PARTITION SCHEME

### I. How is the drag partition $f_{eff}$ modeled?

Surface roughness elements dissipate part of the wind momentum, thereby decreasing wind erosion and dust emission. So, we add a factor to discount the velocity in Kok's dust emission  $F_d$ :

$$u_{*s} = u_* f_{eff}$$

$$F_d \propto u_{*s} (u_{*s}^2 - u_{*t}^2)$$

where  $f_{eff}$  is the drag partition factor from 0 to 1 dependent on the amount of surface obstacles.

Marticorena et al. (1997) proposed a wind drag partition equation scaled with **roughness length  $z_0$** , which characterizes the amount of obstacles:

$$f_{eff} \propto 1 - \ln(z_0)$$

### II. How to obtain $z_0$ for rocks?

Prigent et al. (2012) used a remote sensing method to detect global roughness length  $z_0$  that represent rocks over the arid regions.

We substitute the  $z_0$  into Marticorena's drag partition equation to obtain a  $0.1^\circ \times 0.1^\circ f_{eff}$  map for arid regions:

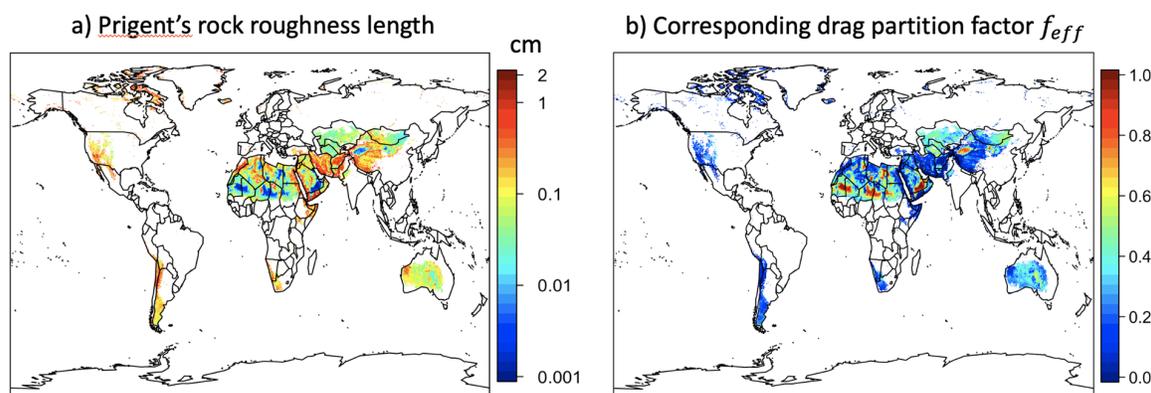


Fig. 4. Rock roughness length and drag partition over dust emission regions (defined as LAI < 0.3). a) Satellite-derived roughness length ( $z_0$ ) obtained by Prigent et al. (2012). b) The corresponding drag partition factor ( $f_{eff}$ ) by substituting  $z_0$  into Marticorena's 1997 drag partition equation.

### III. How to obtain $z_0$ for vegetation?

For vegetation, we implement a parameterization for time-varying roughness of vegetation using MODIS leaf area index (LAI) (Pierre et al., 2012; Klose et al., submitted). In Klose's model,  $z_0$  is a function of LAI:

$$z_0 \propto LAI^3$$

And this roughness length is substituted back to Marticorena's equation for yielding the  $f_{eff}$  map for vegetation.

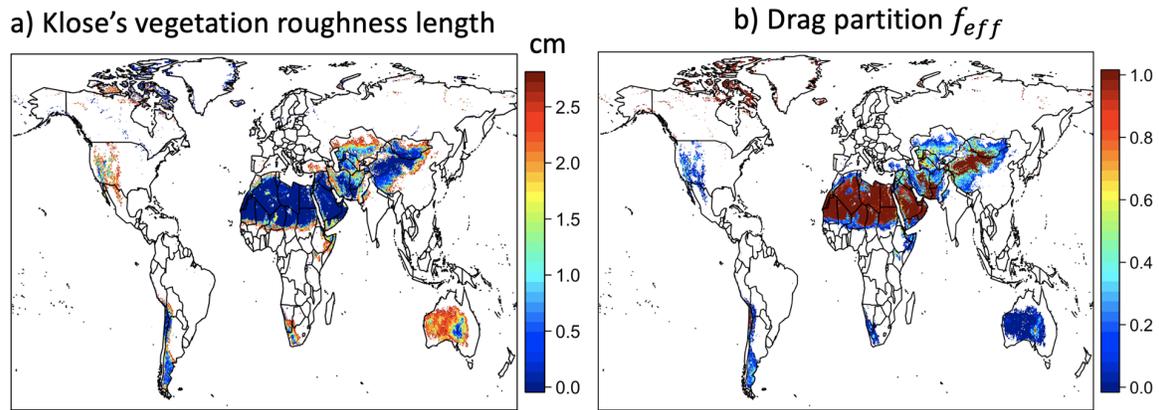


Fig. 5. Klose's parameterization of (a) vegetation roughness length  $z_0$ , and the corresponding (b) drag partition  $f_{eff}$ .

#### **IV. How to combine the drag partition effects from both rocks and vegetation?**

For any timestep, when the vegetation roughness is larger than the rock roughness, we will use vegetation roughness instead for computing drag partition in climate models (plants grow and rocks do not!).

## 5. REGRIDDING HIGH-RESOLUTION QUANTITIES INTO COARSER MODEL GRID

CESM runs typically in  $1.9^\circ \times 2.5^\circ$ , much coarser than the datasets we provide ( $0.1^\circ \times 0.1^\circ$ ).

Since dust emission is nonlinear to  $u_*$ , we cannot regrid by simply averaging  $f_{eff}$  and  $D_p$  to coarser resolutions.

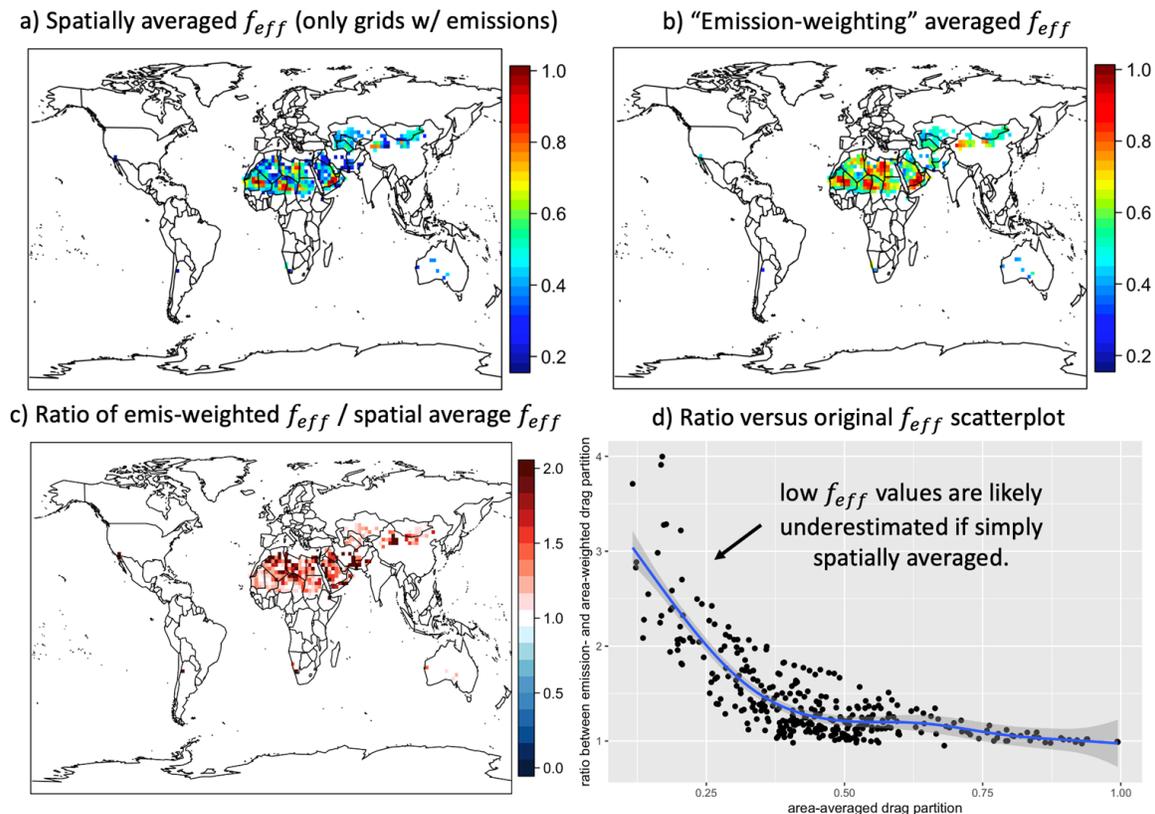
Instead, we derive coarse  $f_{eff}$  and  $D_p$  by an "emission-weighted" averaging. E.g., for  $f_{eff}$ :

$$F^{coarse}(f_{eff}^{coarse}) = \sum_{n=1}^N F_n^{fine}(f_{eff,n}^{fine})$$

We first compute (for R.H.S.) the high-resolution dust emissions  $F^{fine}$  with known drag partition  $f_{eff}^{fine}$  for the  $N$  fine grids within a CESM native grid, and sum them up to yield a total emission.

Then, we compare this total emission against the CESM-modeled emission  $F^{coarse}$  (L.H.S.) to estimate the required coarse  $f_{eff}^{coarse}$  for CESM (Fig. 6).

This emission-weighted approach will always generate a higher  $f_{eff}$  than a spatially averaged  $f_{eff}$ , except when  $f_{eff}$  is already close to 1 (Fig. 6d).



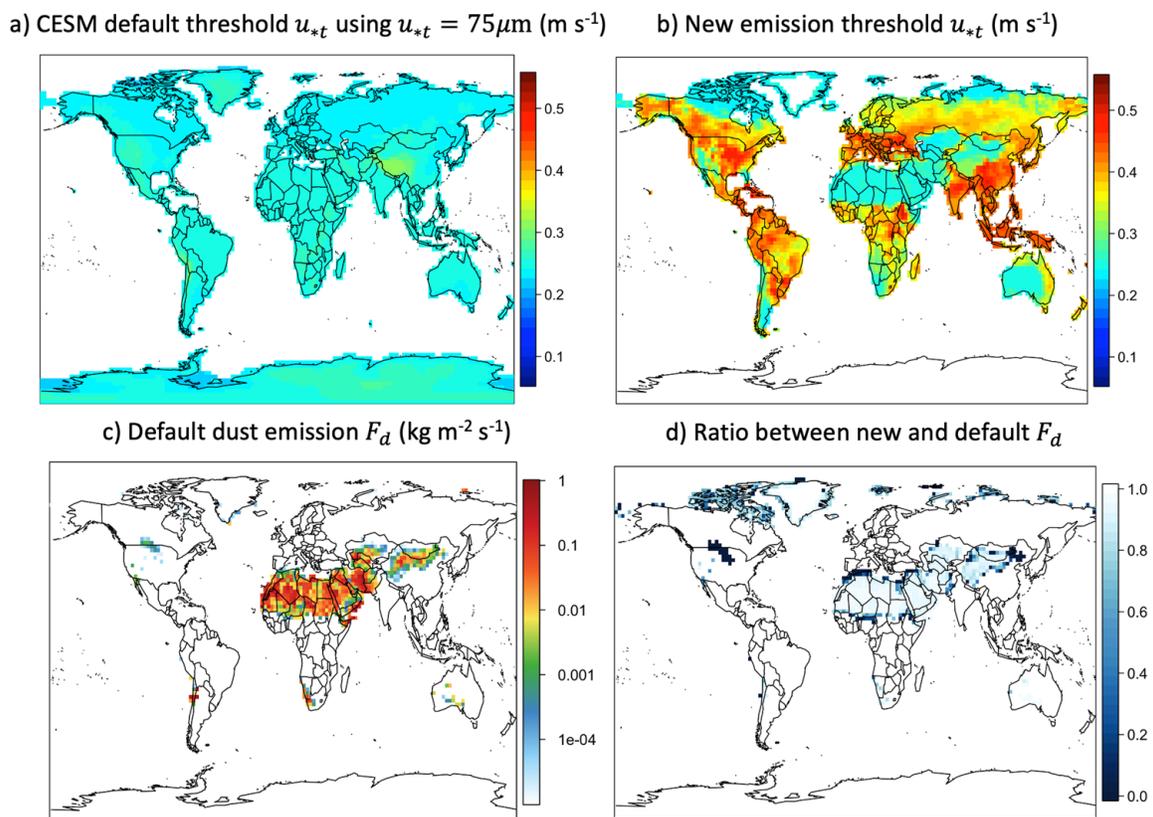
**Fig. 6.** The difference between using a simple spatial averaging and "emission-weighted averaging" approach to yield drag partition factor  $f_{eff}$  in CESM (coarse) resolution. (a) a spatial average of high-resolution  $f_{eff}$  (Fig. 4b) to CESM grid. (b) The "emission-weighted" average drag partition factor  $f_{eff}$  in CESM resolution. (c) Ratio of emission-weighted  $f_{eff}$  (Fig. 6b) and to spatially averaged  $f_{eff}$  (Fig. 6a). (d) The ratio in Fig. 6c. vs. the spatially averaged  $f_{eff}$  in Fig. 6b.

Note: our method is general and can generate  $D_p$  and  $f_{eff}$  data at any resolution, for any other atmospheric and climate models (coarser than  $0.1^\circ \times 0.1^\circ$ ). We will make the data available for other models to use.

## 6. PRELIMINARY RUNS AND FUTURE WORK

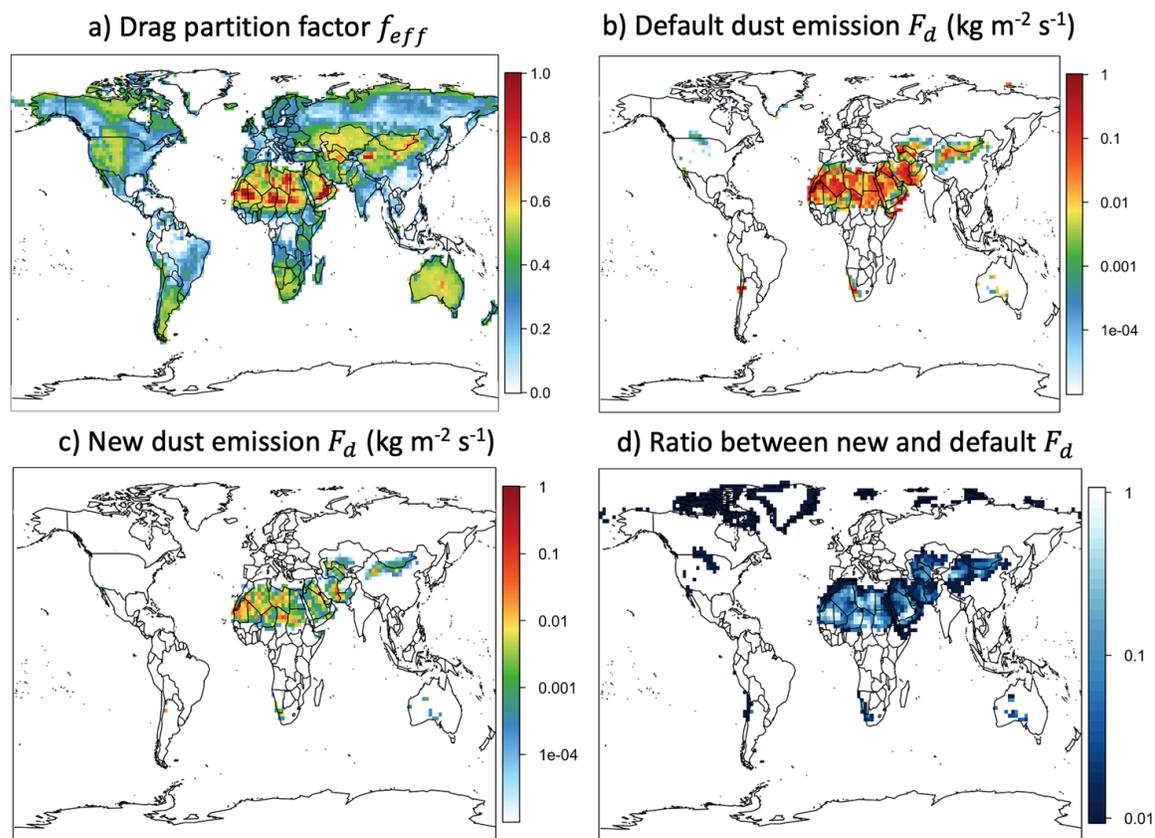
We implement the drag partition  $f_{\text{eff}}$  and soil diameter  $D_p$  maps into CESM to capture more realistic dust emission thresholds  $u_{*t}$ .

Our 1<sup>st</sup> sensitivity experiment is to compare simulations using the default  $D_p = 75 \mu\text{m}$  and new dry  $D_p$  map, examining how threshold  $u_{*t}$  and emission  $F_d$  will change for year 2012.



**Fig. 7.** A CESM sensitivity experiment to compare simulations using the default  $D_p = 75 \mu\text{m}$  and new dry  $D_p$  map, for 2012. (a, b) The dust emission threshold  $u_{*t}$  simulated using (a) globally constant  $D_p = 75 \mu\text{m}$  and (b) global soil size (Fig. 3). (c) The simulated default total dust emissions  $F_d$  ( $\text{kg} / \text{m}^2 / \text{yr}$ ) with globally constant  $D_p$  as calculated by Kok et al. (2014). (d) The ratio between the new emissions with globally varying  $D_p$  map and the default emissions with globally constant  $D_p$ .

Our 2<sup>nd</sup> sensitivity experiment is to compare runs with and without the static drag partition effect  $f_{\text{eff}}$  for rocks, examining how threshold dust emission  $F_d$  will change for year 2012.



**Fig. 8.** A CESM sensitivity experiment for year 2012 with and without drag partition effect. (a) The drag partition factor  $f_{eff}$  as a coarse version of Fig. 5, as obtained by satellite-derived aeolian roughness length from Prigent et al. (2012) and regridded by the "emission-weighted" average algorithm in Sect. 5. (b) The default CESM dust emissions without the drag partition effect. (c) The dust emissions modified by the drag partition effect. (d) Ratio between dust emissions with drag partition effect and emissions without the effect.

The preliminary simulations increase modeled thresholds especially over regions with large soil grain sizes or with more roughness elements, leading to reduced dust emissions (and thus activation frequencies) into atmosphere.

To further make the spatiotemporal variability of dust thresholds and emissions more realistic, we will incorporate time-varying vegetation roughness in the climate models in the future.

**Our future work will include:**

- Explore other possible predictors apart from % of total silt to predict  $D_p$  in the future;
- Implementation of 3-D hybrid drag partition data into CESM with vegetation;
- Instead of inputting diagnostic data, compile CESM codes for prognostic drag partition simulations using CESM LAI;
- We are implementing another drag partition scheme by Okin et al. (2008);
- Compare simulations using different schemes of drag partition;
- Compare our data against AERONET and other AOD observations.

## ABSTRACT

A key challenge in accurate simulations of desert dust emission is the parameterization of the threshold wind speed above which dust emission occurs. However, the existing parameterizations yield a unrealistically low dust emission threshold in some climate models such as the Community Earth System Model (CESM), leading to higher simulated dust source activation frequencies than observed and requiring global tuning constants to scale down dust emissions. Here we develop a more realistic parameterization for the dust emission threshold in CESM. In particular, we account for the dissipation of surface wind momentum by surface roughness elements such as vegetation, rocks, and pebbles, which reduce the wind momentum exerted on the bare soil surface. We achieve this by implementing a dynamic wind drag partition model by considering the roughness of the time-varying vegetation as quantified by the leaf area index (LAI), as well as the time-invariant rocks and pebbles using satellite-derived aeolian roughness length. Furthermore, we account for the effect of soil size on dust emission threshold by replacing the currently used globally constant soil median diameter with a spatially varying soil texture map. Results show that with the new parameterization dust emissions decrease by 20–80% over source regions such as Africa, Middle East, and Asia, thereby reducing the need for the global tuning constant. Simulated dust emissions match better in both spatiotemporal variability and emission frequency when compared against satellite observed dust activation frequency data. Our results suggest that including more physical dust emission parameterizations into climate models can lessen bias and improve simulation results, possibly eliminate the use of empirical source functions, and reduce the need for tuning constants. This development could improve assessments of dust impacts on the Earth system.

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