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Variability in modelled airborne dust mineralogy derived from global soil composition uncertainties

María Gonçalves Ageitos

Matt Dawson, Vincenzo Obiso, Martina Klose,
Ron Miller, Oriol Jorba, and Carlos Pérez
García-Pando

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Background and motivation



Relevance of dust mineralogy

- Mineral dust aerosols interact with different elements of the climate system.
- Rather than a homogeneous species, as many Earth System Models (ESMs) assume, dust is a heterogeneous mixture of different minerals with varying physical and chemical properties, which ultimately determine dust-climate interactions:
 - **Iron oxides** absorb solar radiation, while **calcite** and **quartz** interact mostly with long-wave radiation.
 - K-**feldspars** are considered efficient ice-nuclei, therefore influencing the formation of mixed-phase clouds.
 - **Calcite** and other alkaline compounds influence aerosols' pH, therefore altering atmospheric chemistry. They also favor coatings of dust by acidic species, which increase dust hygroscopicity favoring cloud formation processes.
 - **Iron** and **phosphorous** compounds in dust can act as nutrients for ocean and terrestrial ecosystems, therefore affecting global biogeochemical cycles.
- Explicit representation of minerals in ESMs is challenging, due to: (1) existing uncertainties on the mineral composition at dust sources, and on the resulting (2) emitted minerals Particle Size Distribution (PSD), (3) high computational demand, due to the increased number of tracers in models.

Aim

- This work aims **to assess the variability of global dust composition due to uncertainties in the characterization of the parent soil mineralogy.**
 - We use two available global Soil Mineralogy Atlases, developed by Claquin et al. (1999) –C1999- and Journet et al. (2014) –J2014-, which represent respectively 8 and 12 relevant minerals for climate.
 - We perform two 5-year long simulations at the global scale with the fully-coupled chemical weather prediction model MONARCH, considering C1999 and J2014 to derive the fractional mineralogy at emission.
 - Uncertainties in the soil mineralogical information are identified and the resulting modelled mineral fractions are compared to observations.

Methodology

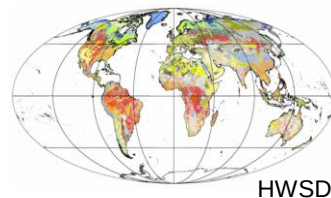
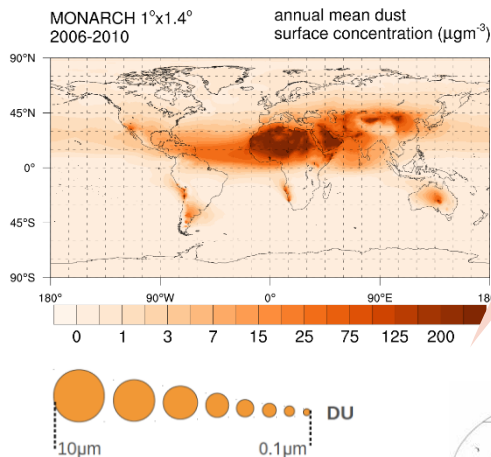


Dust mineralogy in the MONARCH model

The chemical weather prediction model, MONARCH (Klose et al. 2021, in review, and references therein), has the capability to explicitly trace minerals:

- Each mineral is defined through a sectional size distribution (8 bins, with diameters from 0.2 to 20 μm)
- The emission flux results from multiplying the normalized mass fraction of each mineral to the total dust flux calculated by MONARCH (per bin)

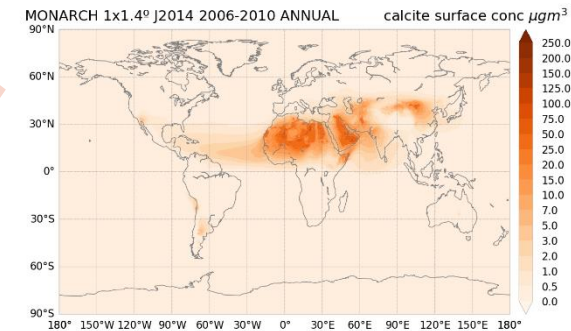
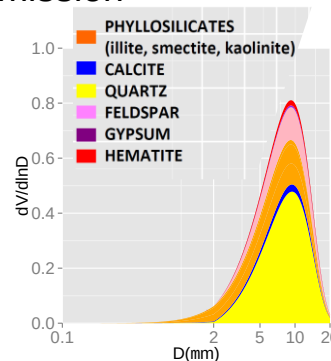
Homogeneous dust annual mean surface concentration ($\mu\text{g m}^{-3}$). Year 2006-2010



Soil
mineralogy
atlas

Size
resolved
mineral
fraction at
emission

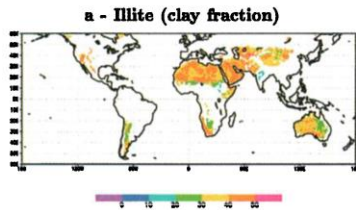
Flexible
implementation
into MONARCH
dust module



Calcite annual mean surface
concentration ($\mu\text{g m}^{-3}$). Year 2006-2010

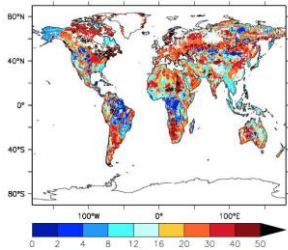
Global soil mineralogy atlases

Claquin et al. (1999)



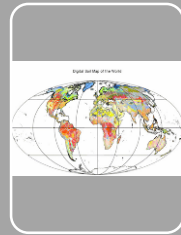
Focus on arid areas

Journet et al. (2014)



Arid and humid areas

Methodology



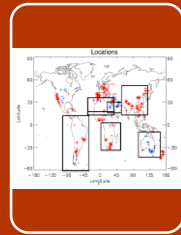
Soil types and units (depend on formation, physic-chemical characteristics, etc.)

- FAO map of the soils of the world
- FAO90, FAO74 soil units (HWSD)



Soil texture (%clay, %silt, %sand)

- Topsoil texture data (HWSD)
- Textural triangle (STATSGO-FAO)



Mean mineralogical tables

- Claquin et al. (1999), based on 239 soil descriptions. 8 minerals
- Journet et al. (2014), based on more than 700 soil descriptions. 12 minerals

Soil mineralogical composition (%w for selected minerals)

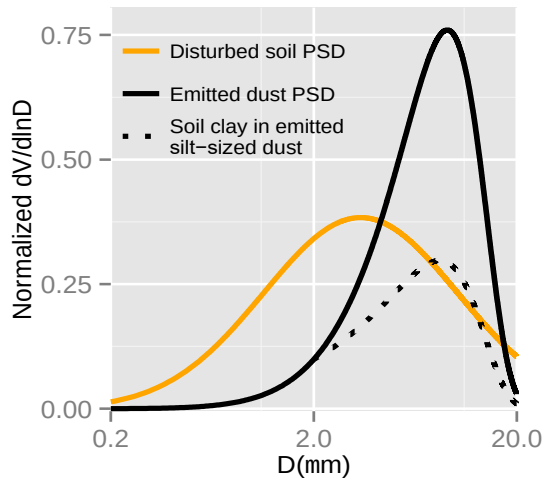
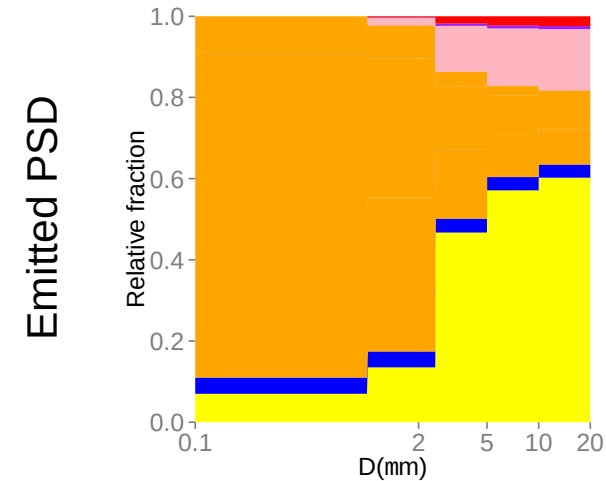
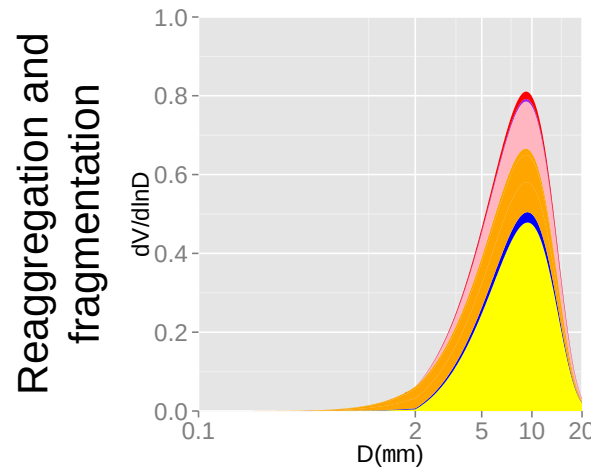
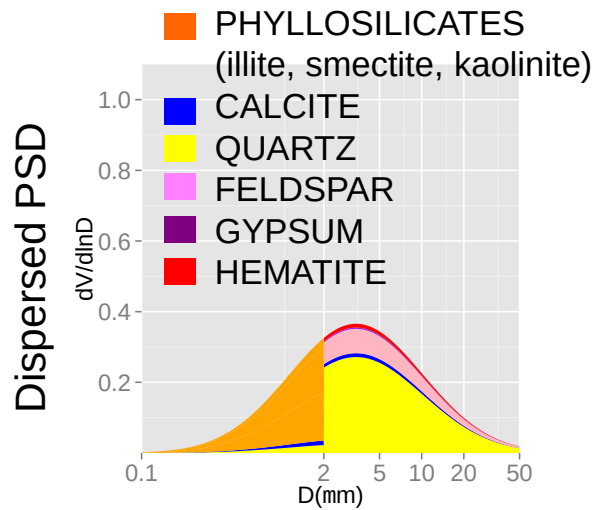
2 size classes: clay ($\phi < 2 \mu\text{m}$) and silt ($\phi 2-63 \mu\text{m}$)

Spatial resolution up to 0.00083°

Minerals considered in clay and silt fractions

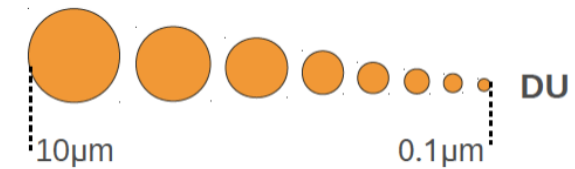
Clay ($\phi < 2 \mu\text{m}$)		Silt ($\phi 2\text{-}63 \mu\text{m}$)	
C1999 <i>(Claquin et al. 1999)</i>	J2014 <i>(Journet et al. 2014)</i>	C1999 <i>(Claquin et al. 1999)</i>	J2014 <i>(Journet et al. 2014)</i>
Quartz	Quartz	Quartz	Quartz
	Feldspars	Feldspars	Feldspars
Calcite	Calcite	Calcite	Calcite
		Gypsum	Gypsum
Illite	Illite		
Kaolinite	Kaolinite		
Smectite	Smectite		
	Vermiculite		
	Chlorite		Chlorite
			Mica
	Hematite	Hematite (irox)	
	Goethite		Goethite

From soil mineral fractions to emitted PSD



*Perlwitz et al., 2015a,b;
Pérez García-Pando et al.,
2016; Pérez García-Pando
et al., in prep*

We get a mass fraction per mineral and bin in each model cell, which is applied to the dust emission flux



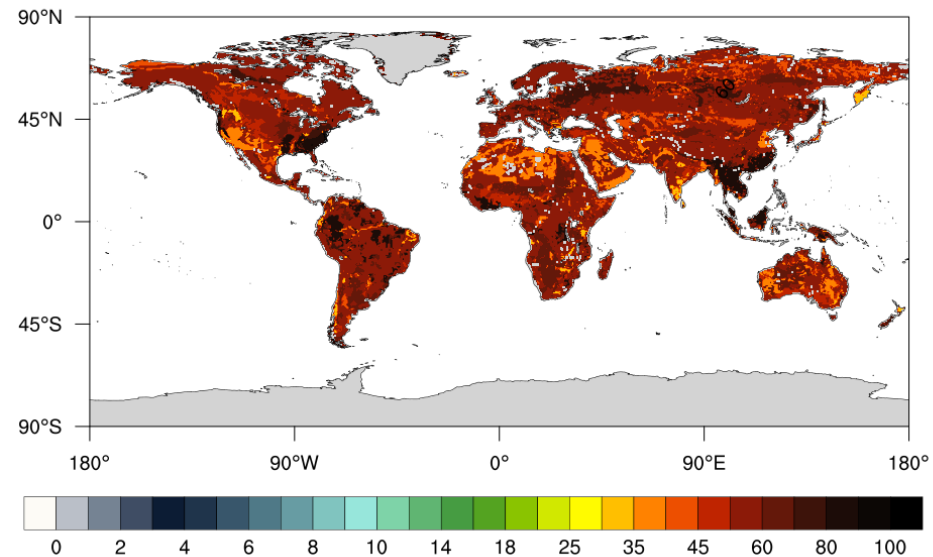
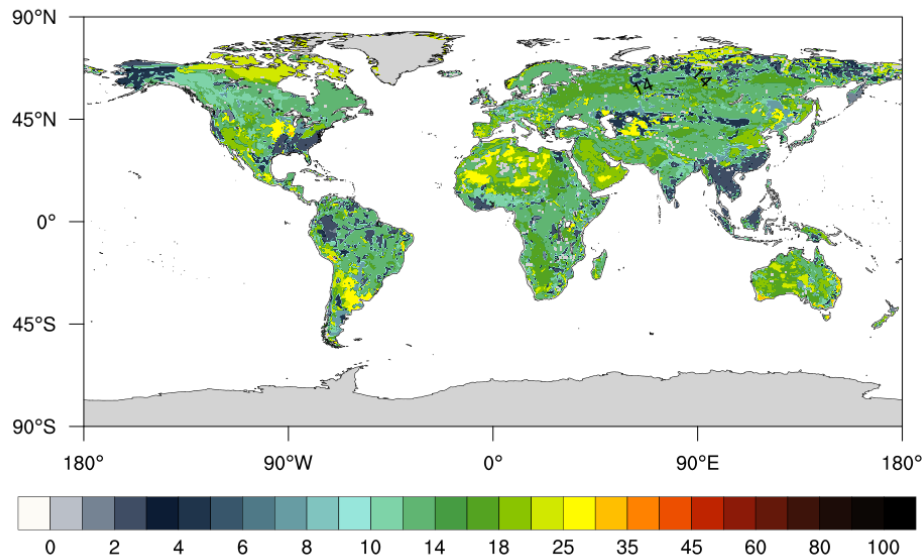
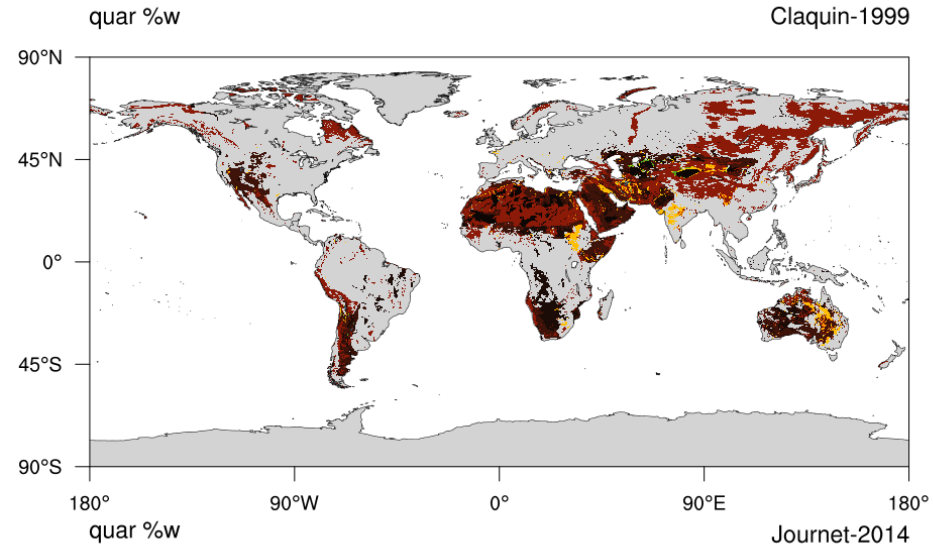
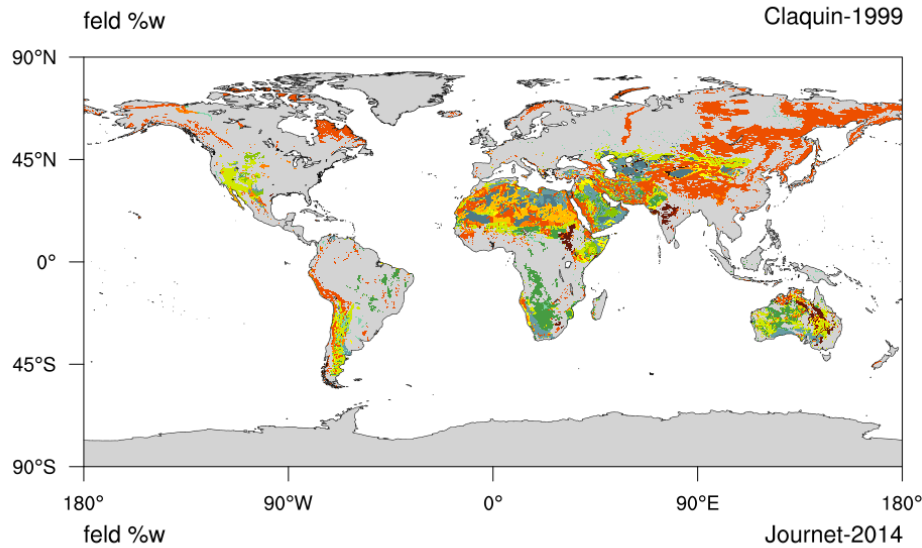
Intercomparison of soil mineralogy atlases



Example of differences in soil datasets: feldspars and quartz in silt

Soil mineralogy in silt fraction

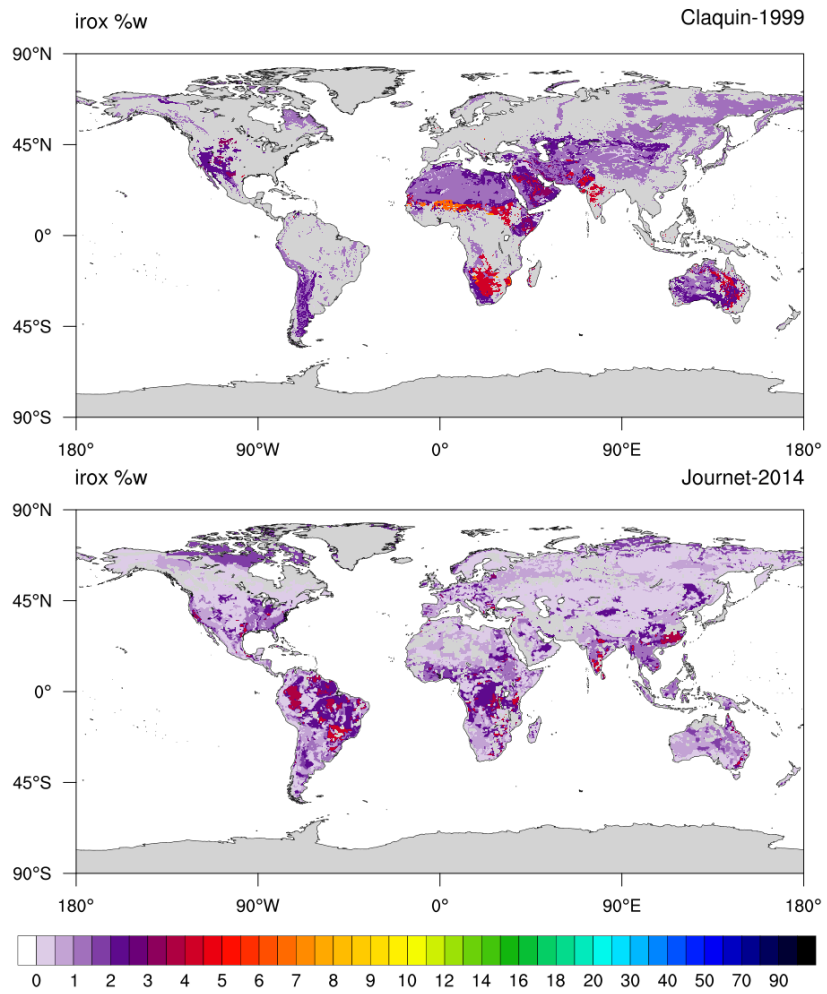
Soil mineralogy in silt fraction



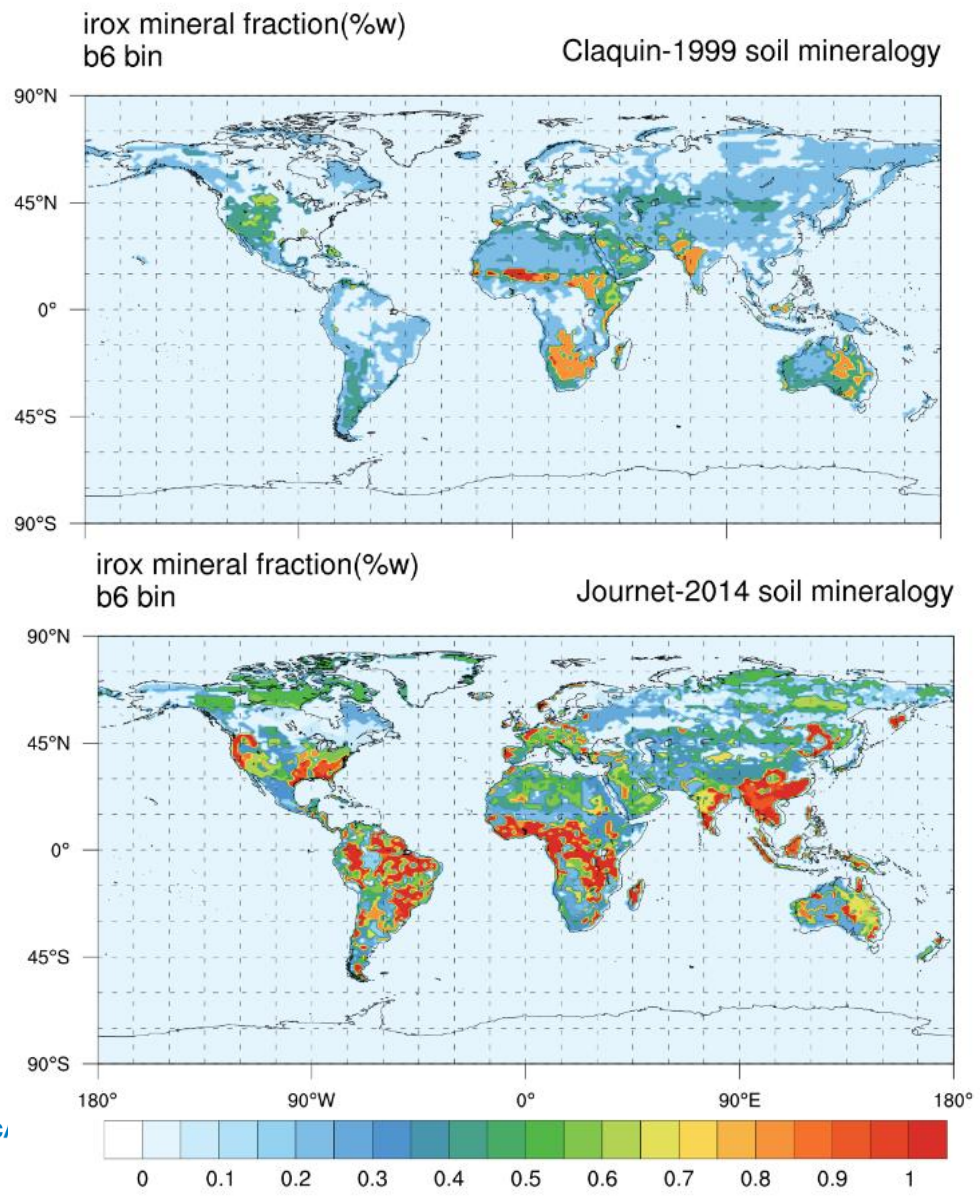
MONARCH mineralogy: from soil to emission

Soil atlas: silt, iron oxides
(dispersed PSD)

Soil mineralogy in silt fraction



Fraction of iron oxides in MONARCH bin6
at emission (over total dust flux)
(emitted PSD)



Modelled mineral fractions at surface concentration



2006-2010 Annual mean surface concentration of dust

MONARCH model

Global domain at $1 \times 1.4^\circ$
resolution

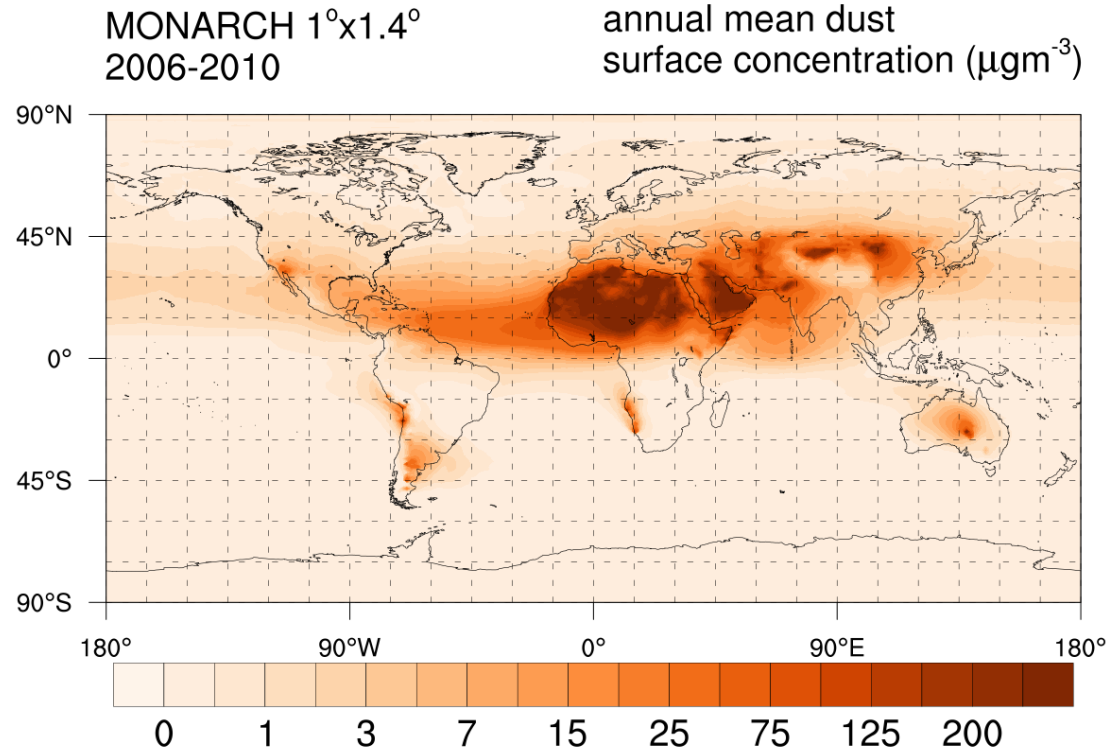
48 vertical layers up to 10 hPa

2 experiments of 5 years (2006-2010), with 1 year of spin-up

Homogeneous dust traced as a reference

C1999 experiment: 8 minerals
(illite, montmorillonite, kaolinite,
calcite, gypsum, quartz,
feldspars, hematite)

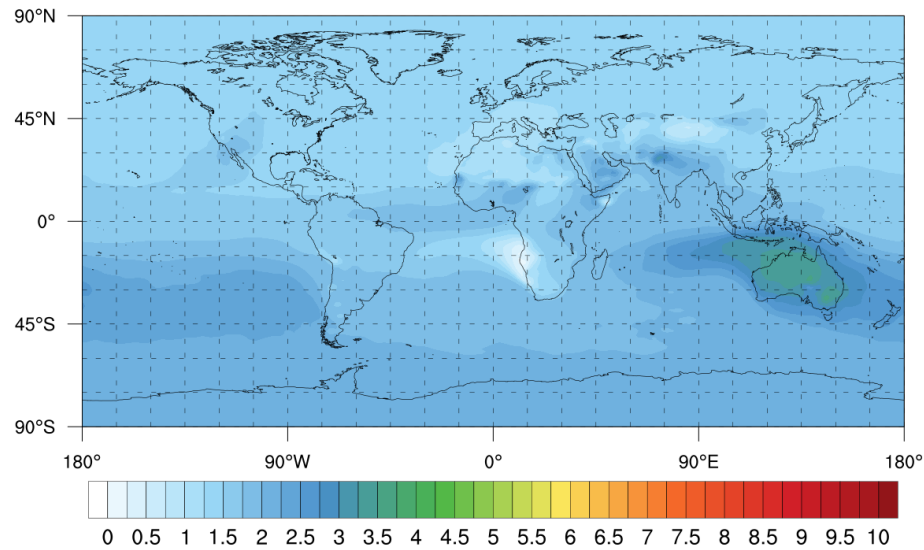
J2014 experiment: 11 minerals (illite, montmorillonite, kaolinite, vermiculite, chlorite, calcite, gypsum, quartz, feldspars, iron oxides, mica)



2006-2010 mean iron oxides and calcite fraction (%w) at surface conc.

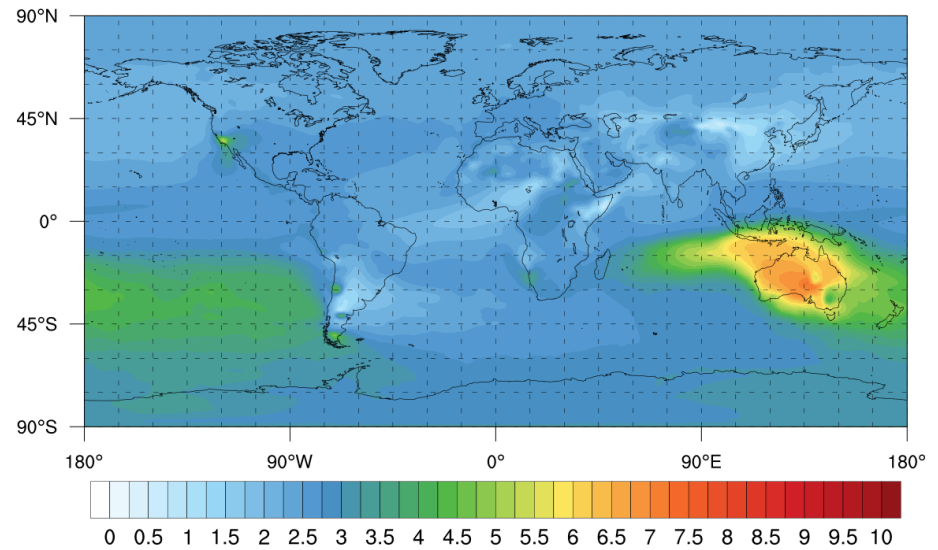
MONARCH 1°x1.4°
C1999 2006-2010

annual mean hema
mineral fraction (%w)



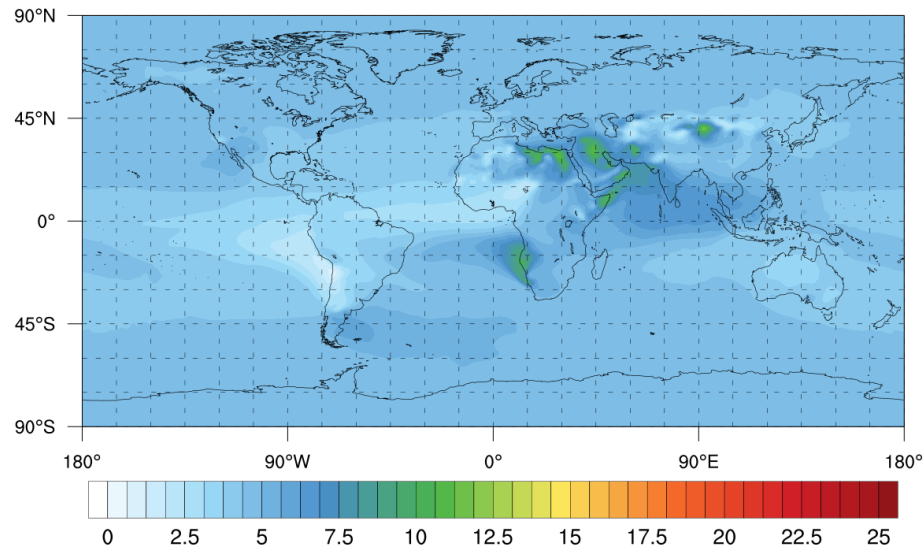
MONARCH 1°x1.4°
J2014 2006-2010

annual mean hema+goet
mineral fraction (%w)



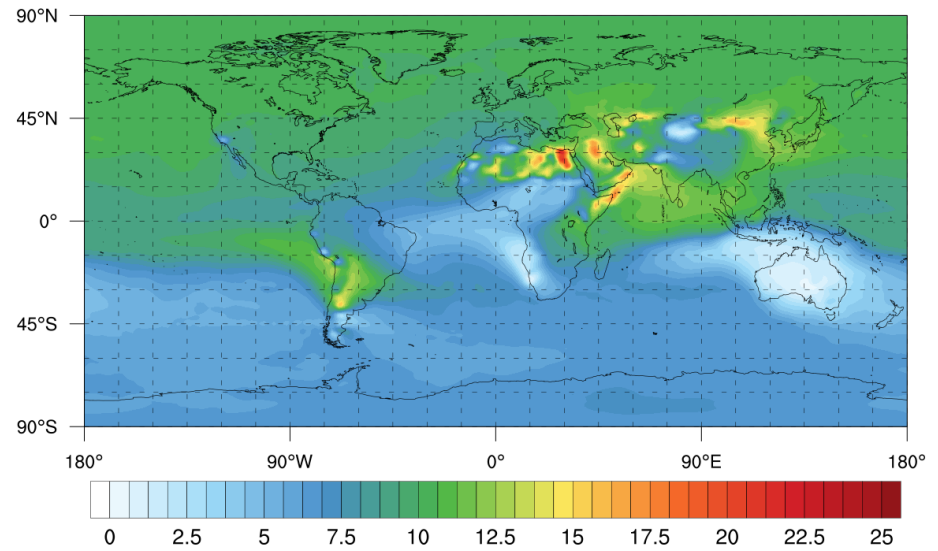
MONARCH 1°x1.4°
C1999 2006-2010

annual mean calcite
mineral fraction (%w)



MONARCH 1°x1.4°
J2014 2006-2010

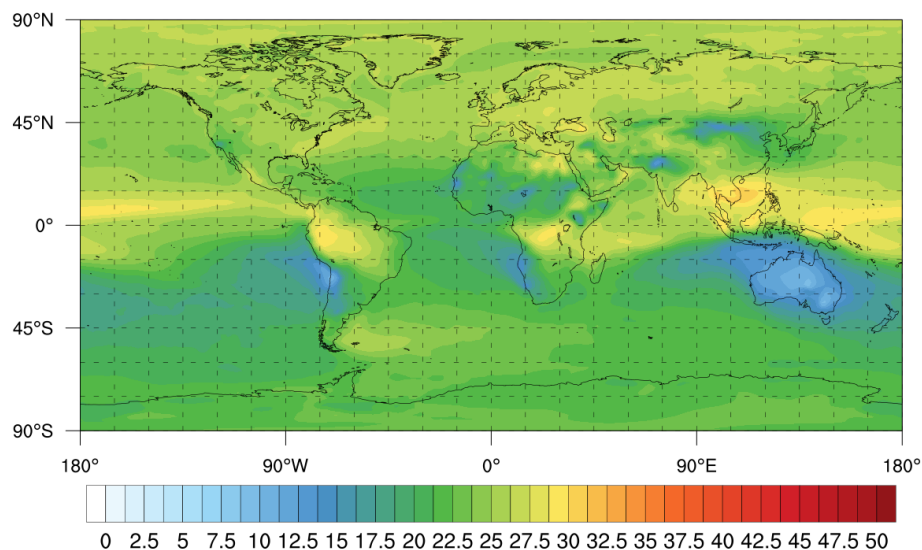
annual mean calcite
mineral fraction (%w)



2006-2010 mean illite and montmorillonite fraction (%w) at surface conc.

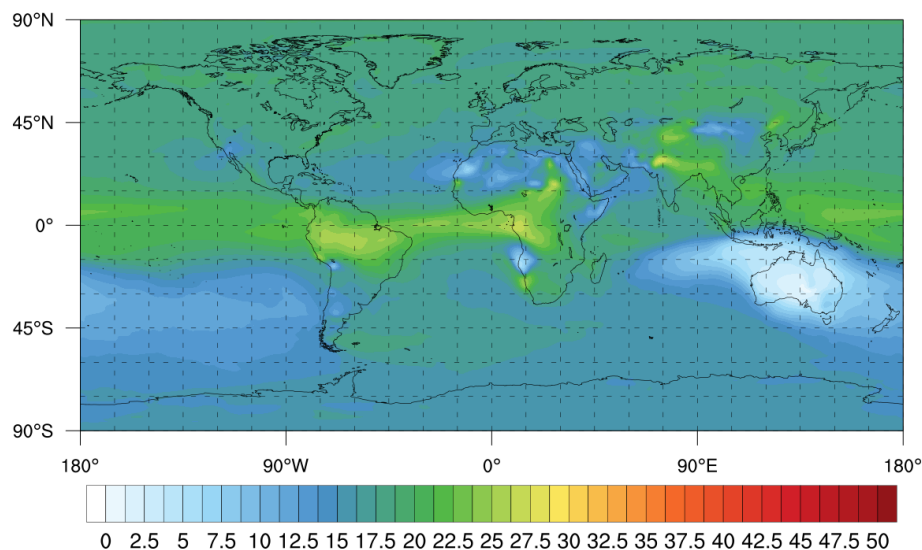
MONARCH 1°x1.4°
C1999 2006-2010

annual mean illite
mineral fraction (%w)



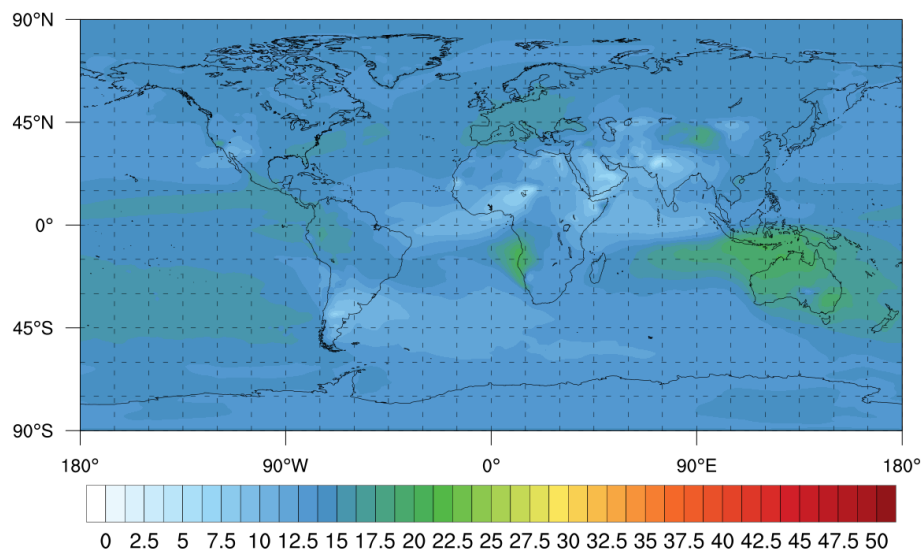
MONARCH 1°x1.4°
J2014 2006-2010

annual mean illite
mineral fraction (%w)



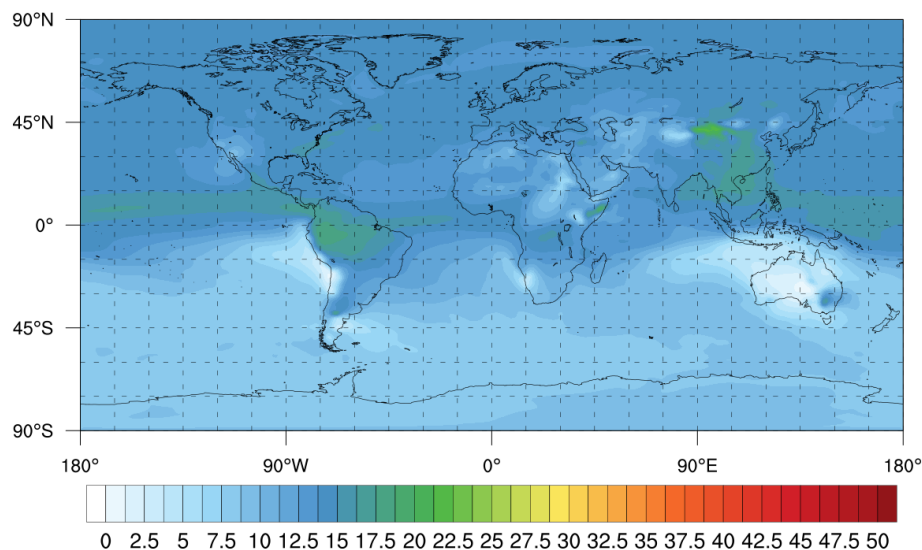
MONARCH 1°x1.4°
C1999 2006-2010

annual mean montmorillonite
mineral fraction (%w)



MONARCH 1°x1.4°
J2014 2006-2010

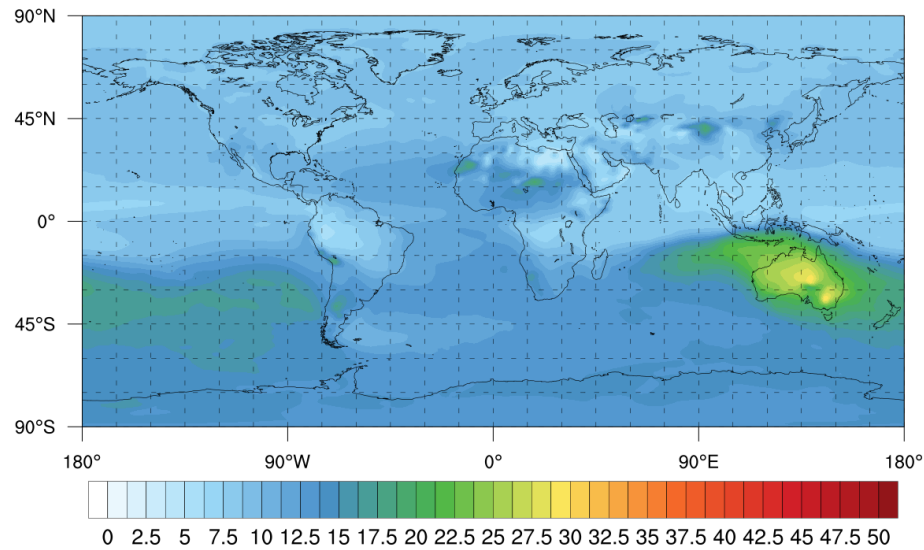
annual mean montmorillonite
mineral fraction (%w)



2006-2010 mean feldspars and quartz fraction (%w) at surface conc.

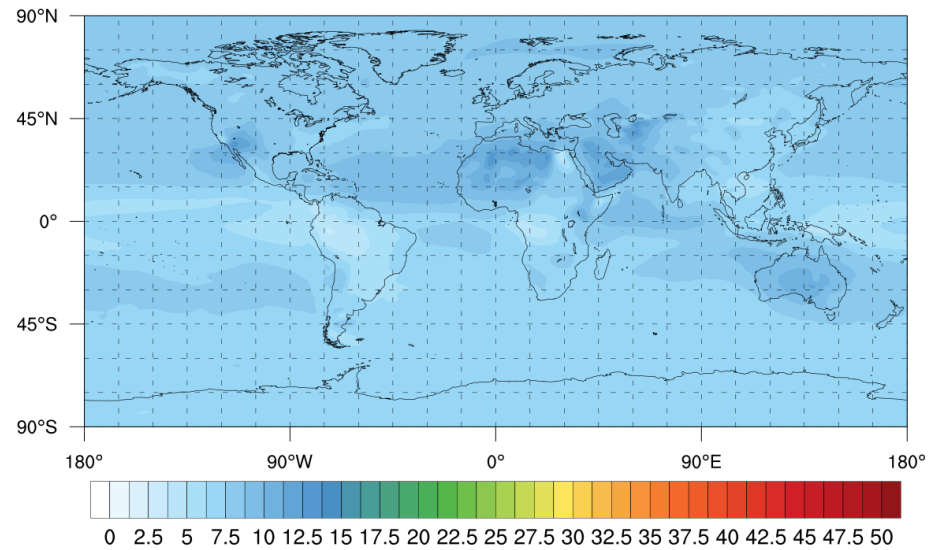
MONARCH 1°x1.4°
C1999 2006-2010

annual mean feldspars
mineral fraction (%w)



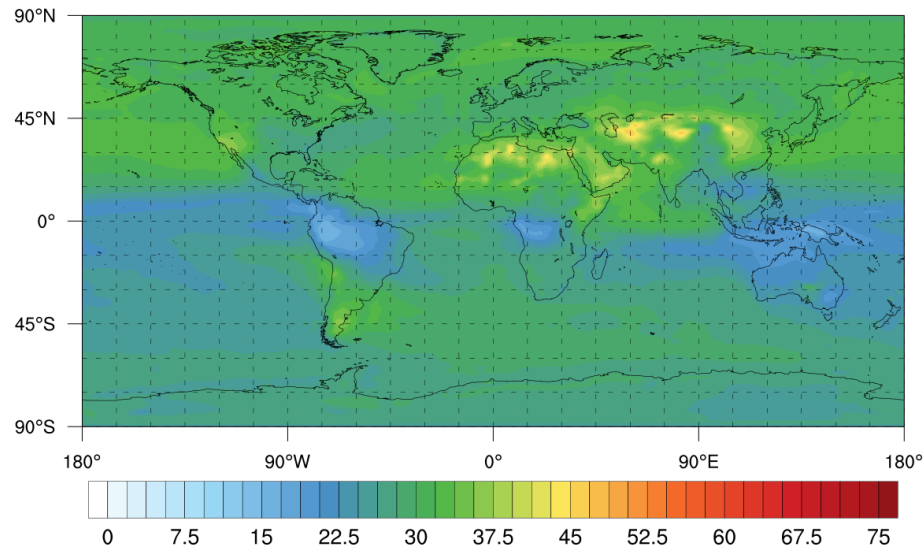
MONARCH 1°x1.4°
J2014 2006-2010

annual mean feldspars
mineral fraction (%w)



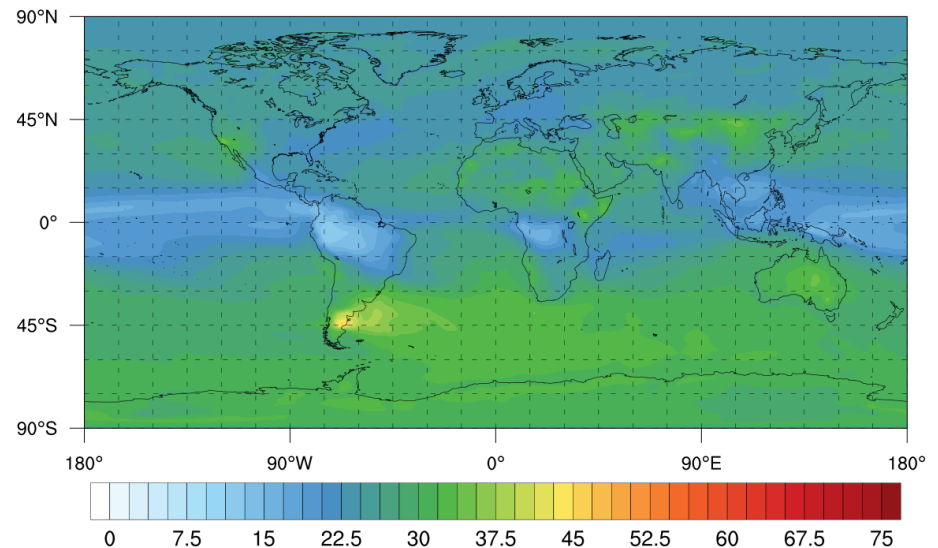
MONARCH 1°x1.4°
C1999 2006-2010

annual mean quartz
mineral fraction (%w)



MONARCH 1°x1.4°
J2014 2006-2010

annual mean quartz
mineral fraction (%w)



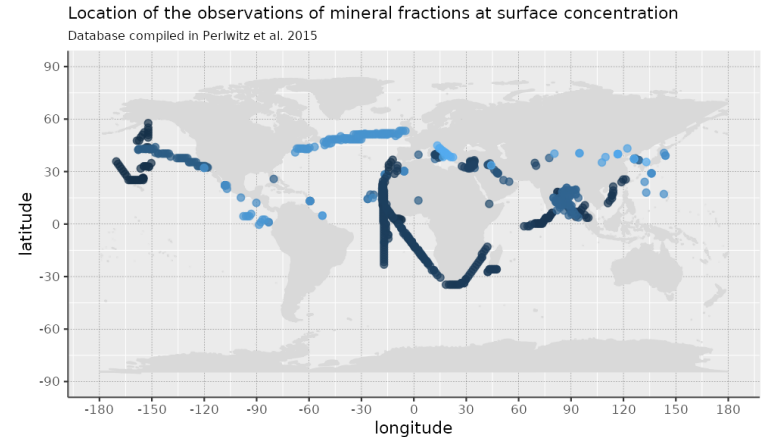
Evaluation



Methodology for minerals' evaluation

- Perlwitz et al. (2015b) compiles available observations of mineral fractions at surface concentration and dry deposition fields, from fixed lat-lon sites and cruises.

96 locations with information on mineral fractions at surface concentration



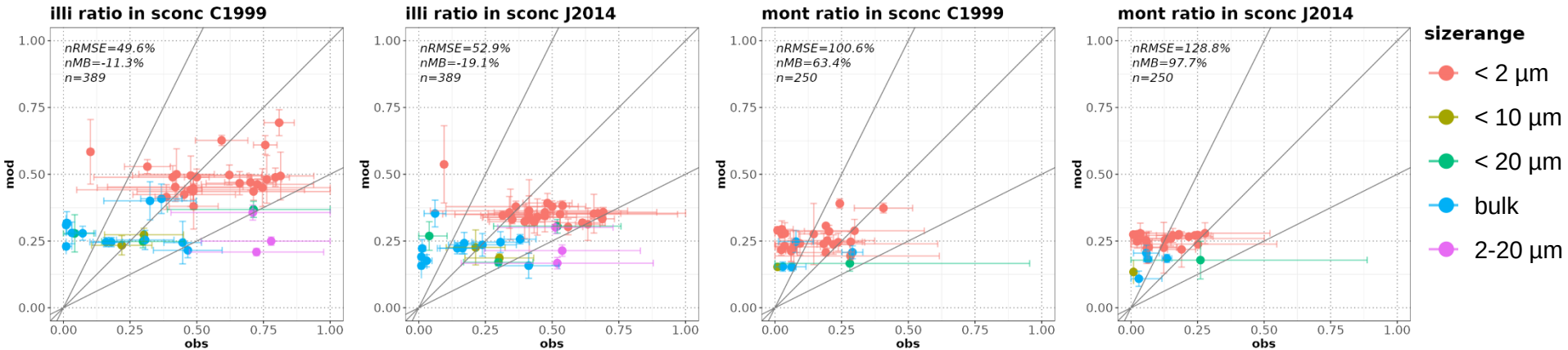
The evaluation procedure is as follows:

1. We calculate model monthly means collocated in time, space and considering the size fraction of the observations.
2. We calculate the mass fraction of those minerals that are common between observations and model for each sample
3. We obtain an observation uncertainty comparable to that of a modelled monthly mean, as in Perlwitz et al. (2015b) considering:
 1. The temporal representativeness of the measurement
 2. The sample size
 3. Occasionally extending the spread of the model to the observational value

Preliminary evaluation results: mineral fractions at surface concentration

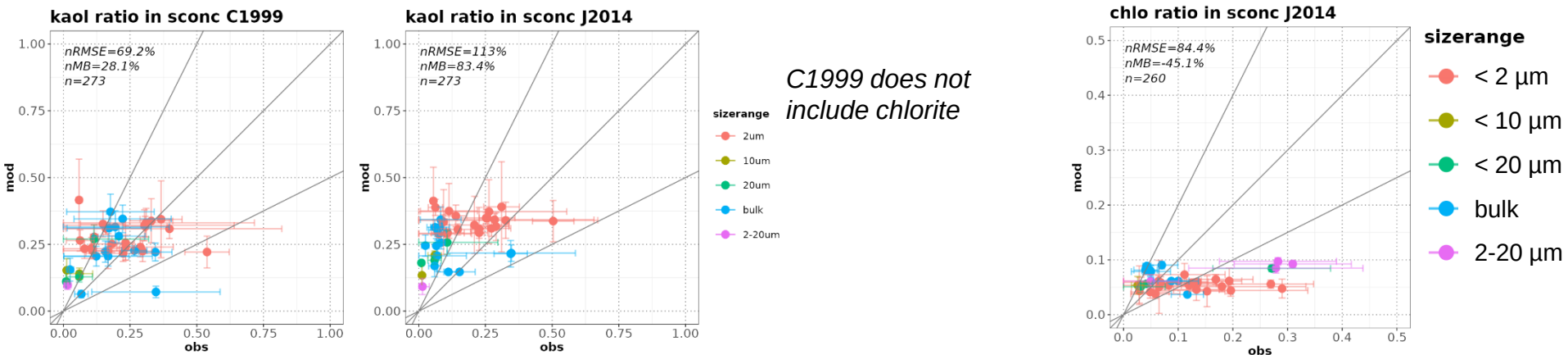
Illite fraction (%w)

Montmorillonite fraction (%w)



Kaolinite fraction (%w)

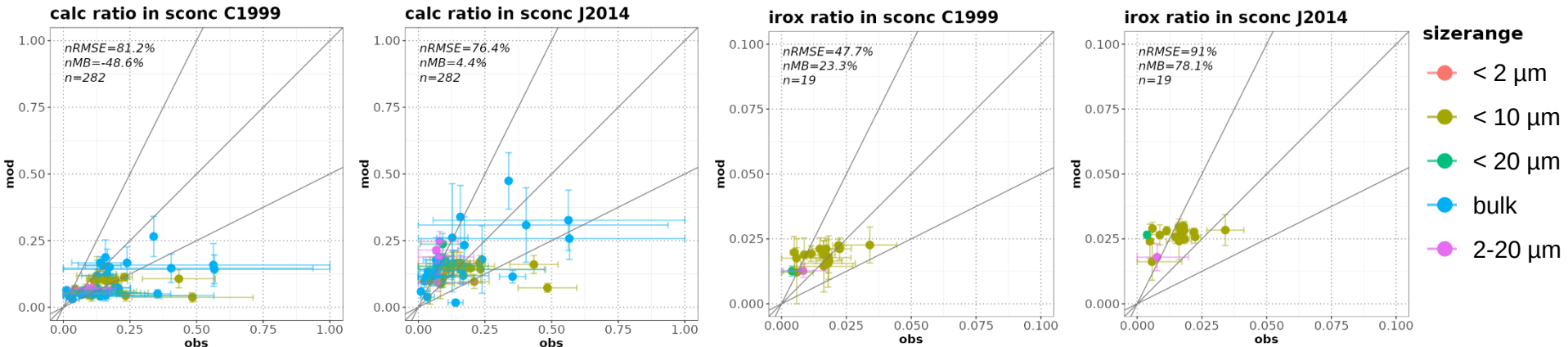
Chlorite fraction (%w)



Preliminary evaluation results: mineral fractions at surface concentration

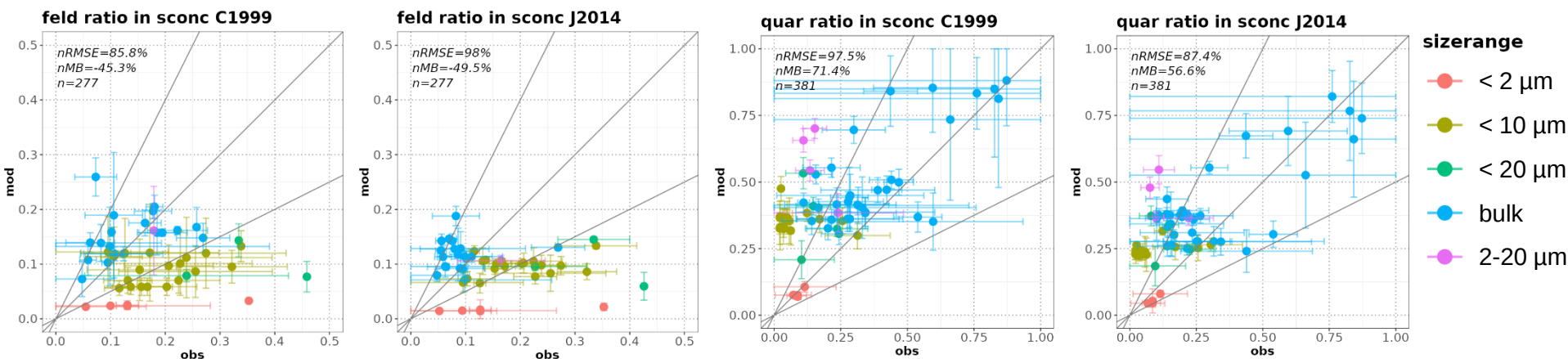
Calcite fraction (%w)

Iron oxides fraction (%w)



Feldspars fraction (%w)

Quartz fraction (%w)



Conclusions



Conclusions

- Currently available Soil Mineralogy Atlases (SMAs) rely on a limited number of observations, which are extended with empirical relationships and geographically extrapolated through the application of different hypothesis.
- J2014 considers a larger number of samples than C1999, but those are distributed into a larger number of soil units. The resulting soil mineral fractions differ over dust sources, particularly for the silt sized fraction.
- Additional choices, made when implementing the minerals in the model framework (e.g. mapping of soil units to the model grid, normalization of soil mineral fractions, projection of the size-distributed soil composition on the emitted size distribution), may result in non-negligible differences on the final modelled mineralogy.
- Using a common approach for the model implementation and experiment design, we find differences in modelled mineralogy arising solely from uncertainties in the SMAs.
- Clays (illite, smectite, kaolinite) are the less impacted by the choice on the soil mineralogy atlas.
- Calcite, iron oxides, and feldspars mass fractions at the surface show large differences between the C1999 and J2014 MONARCH experiments.

Conclusions

- When compared to observations, calcite mineral fraction is underestimated at the surface in MONARCH-C1999, while overestimated in MONARCH-J2014.
- Feldspars fraction at the surface is slightly underestimated both in MONARCH-C1999 and MONARCH-J2014. However, the hypotheses applied in J2014 to extend the mineralogy of the silt fraction derive in a lower variability for the fractions at diameters below 10 μm .
- Quartz fraction at the surface is overestimated in both MONARCH-C1999 and MONARCH-J2014, particularly at sizes below 10 μm .
- New approaches to project soil composition to the emitted PSD will be tested to add information on the preferential size distribution of the minerals (besides the crude discrimination used now, which only accounts for two soil size classes: clay and silt).
- Our results support the need for further observational constraints to better characterize the soil and thus the airborne dust composition. The experimental campaigns on airborne dust characterization planned in the framework of the FRAGMENT ERC project, as well as the soil characterization that will result from the EMIT NASA mission are promising initiatives in this sense.

Acknowledgments and references



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- We also thank Dr. Jan Perlwitz for his valuable contribution to the minerals' evaluation presented here, and Dr. Yves Balkanski and Dr. Emilie Journet for their help with the definition of the soil mineralogy maps. Finally, we wish to acknowledge the work of all the members of the BSC Earth Science Department group who contribute to MONARCH model and infrastructure developments.



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