Measuring the Earth's Surface Mineral Dust Source Composition to Model Radiative Forcing and Related Earth System Impacts

V.J. Realmuto and R.O. Green

Jet Propulsion Laboratory

California Institute of Technology

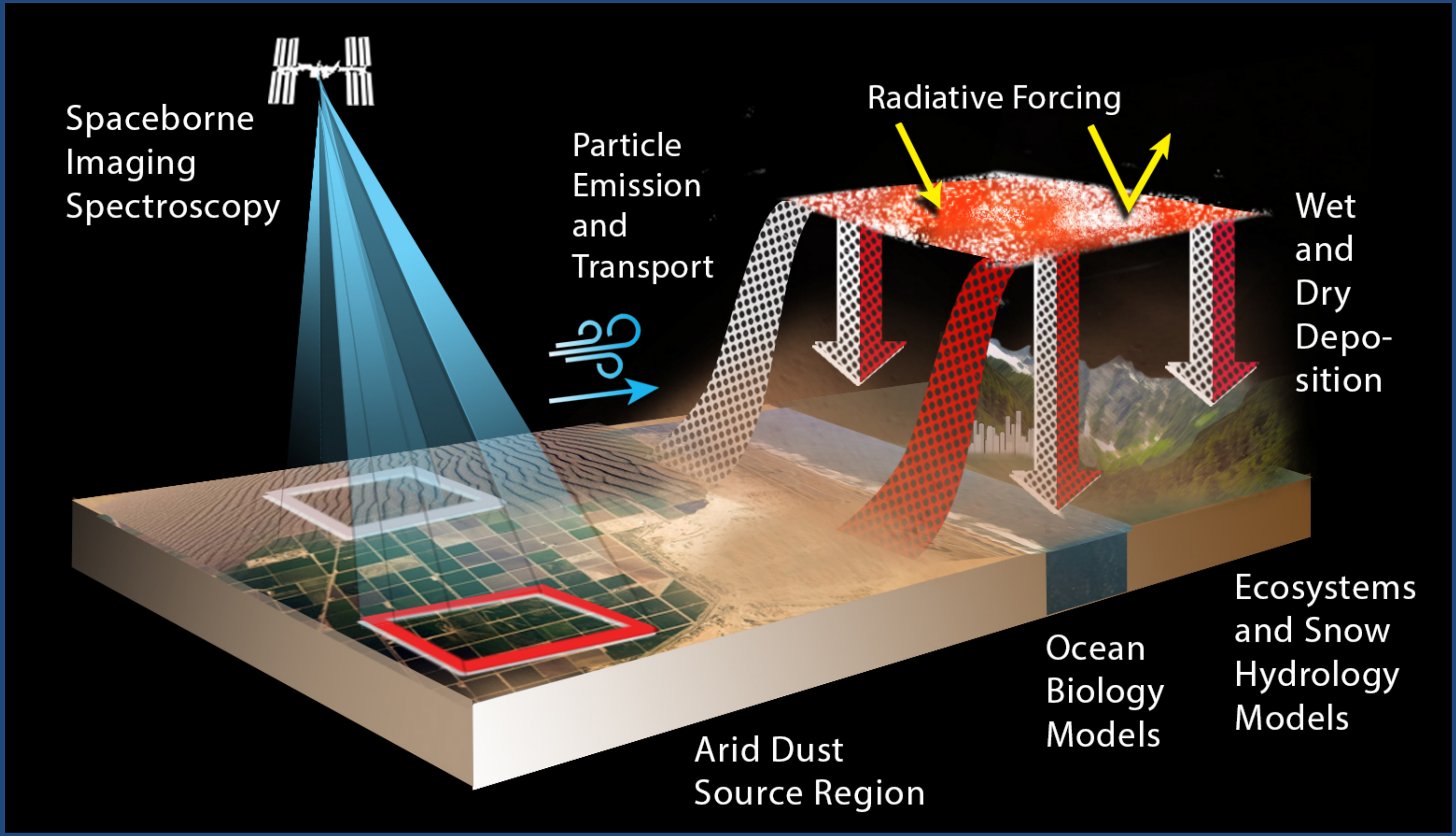
2017 HyspIRI Science Workshop

Contributors

- Roger Clark, Planetary Sciences Institute, CO
- Bethany L. Ehlmann, California Institute of Technology
- Paul Ginoux, National Oceanic and Atmospheric Administration, GDFL, NJ
- Olga Kalashnikova, Jet Propulsion Laboratory, California Institute of Technology
- Natalie Mahowald, Cornell University, NY
- Ron Miller, Goddard Institute for Space Sciences, NY
- Greg Okin, University of California, Los Angeles, CA
- Carlos Pérez García-Pando, Goddard Institute for Space Sciences, NY, & Barsalona Supercomputing Center, Spain
- Rachel Scanza, Cornell University, NY
- David R. Thompson, Jet Propulsion Laboratory, California Institute of Technology

The Dust Cycle in Earth System Modeling

- The mineral dust cycle has three phases: source, transport, and deposition
- Considerable investment in aerosol science to measure airborne mineral dust
- **Less investment in understanding the surface composition of mineral dust source regions**

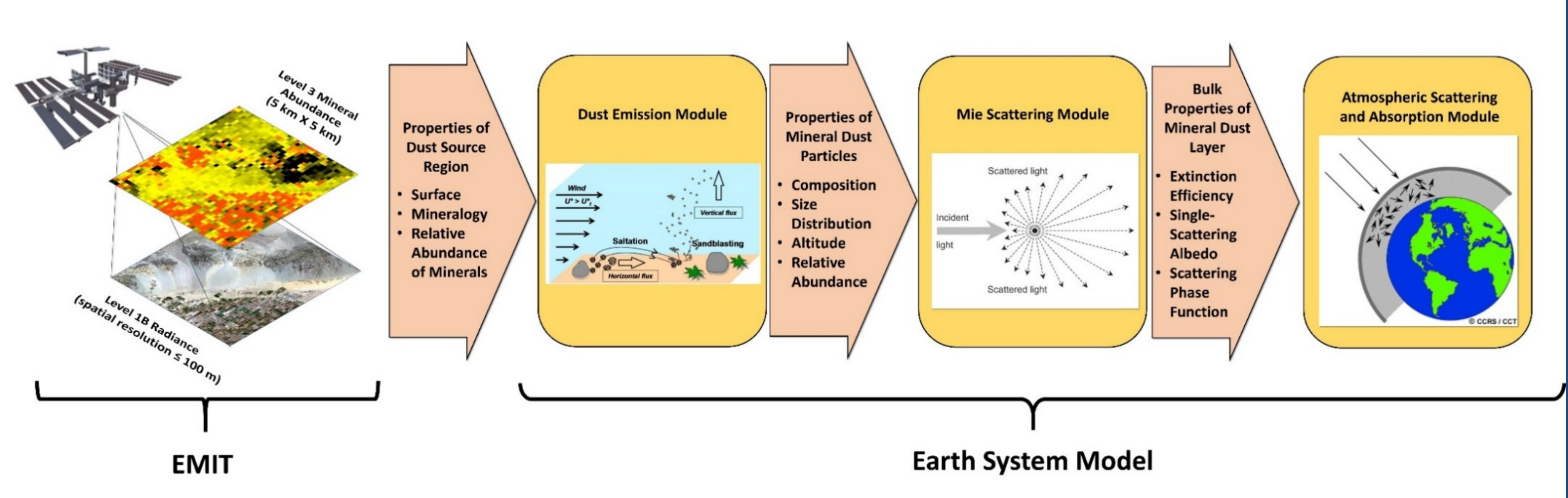


Impacts of Mineral Dust on Earth System

Process	Example References
Direct radiative forcing	Tegen et al., 1996; Sokolik and Toon, 1999; Dufresne et al., 2002, Boucher 2013
Indirect radiative forcing by modifying cloud properties	Kauffman et al., 2005, Forster et al., 2007, Mahowald et al., 2013, Rosenfeld et al., 2001, Atkinson et al., 2013, DeMott et al.,2003, Mahowald and Kiehl, 2003
Melting of snow/ice	Krinner et al., 2006, Painter et al. 2007, 2012
Modification of regional precipitation	Miller et al., 2004, 2014; Yoshioka et al., 2007
Modification of atmospheric sulfur cycle and mitigation of acidic aerosol deposition	Dentener et al. 2006; Vet et al. 2014
Modification of tropospheric ozone through nitrogen uptake	Bian et al. 2003; Dentener; Crutzen 1993; Dentener et al. 1996
Modification of carbon cycle through supply of iron to aquatic ecosystems	Jickells et al., 2005, Krishnamurthy et al., 2009, (Mahowald et al., 2010), Okin et al. 2011
Modification of carbon cycle through supply of phosphorous to terrestrial ecosystems	Swap et al., 1992, Okin et al., 2004, Yu et al., 2015
Impacts on air quality, visibility, and respiratory health	Gills, 1996; Prospero, 1999; Morman 2013; Buck et al., 2013; Metcalf et al, 2015; Mahowald et al. 2007; Huszar and Piper, 1989

Modeling the Dust Cycle ≠ Aerosol Science

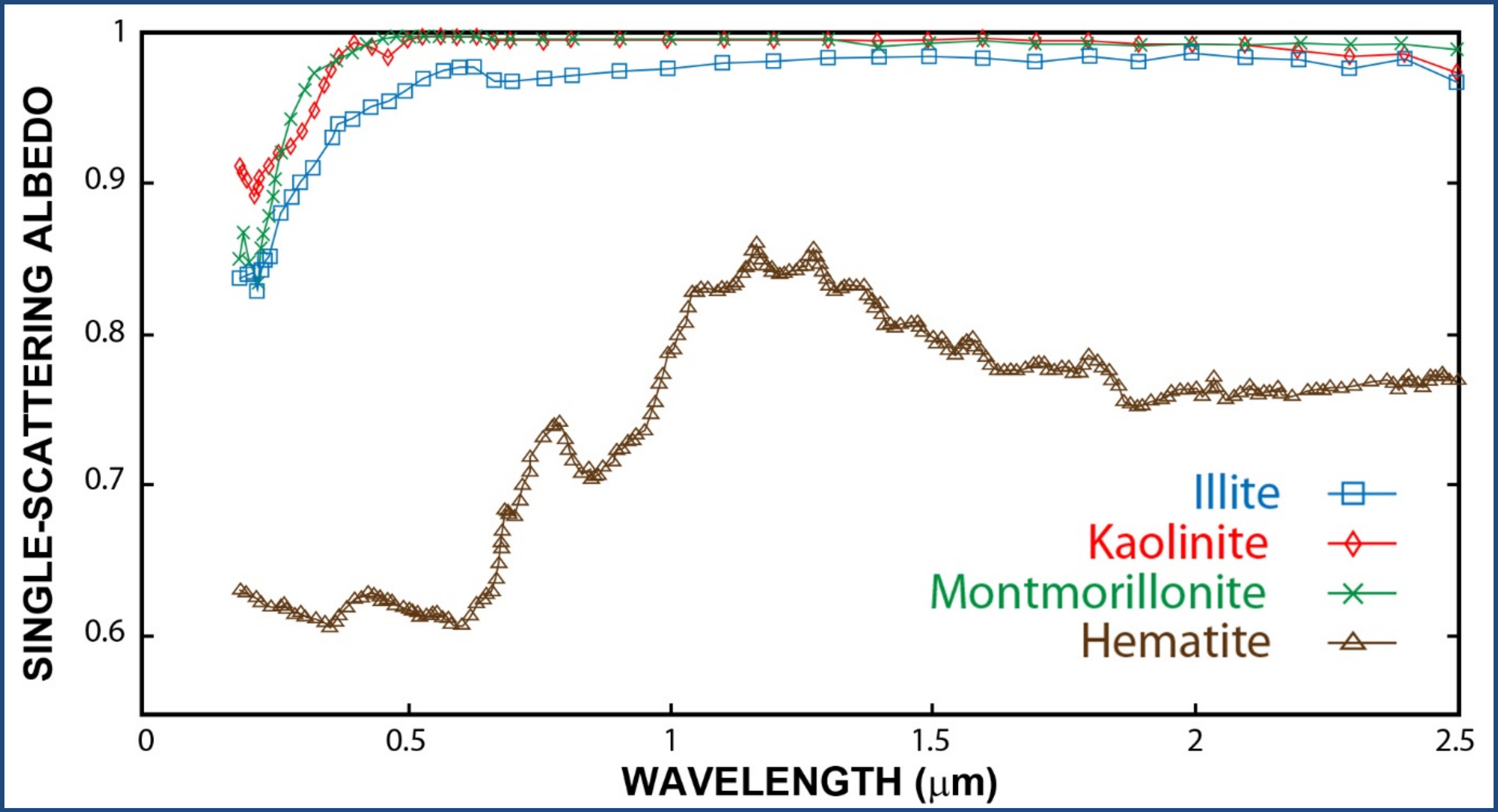
- Aerosol Optical Depth (AOD) is **NOT** an input to Earth System Model (ESM)
- Forecasts of AOD are compared to satellite- and ground-based retrievals of AOD to evaluate forecasting skill of ESM
- ESM simulates mineral dust based on **surface composition of dust source regions**
- Goal of Imaging Spectroscopy: Improve knowledge of surface composition of dust source regions



Mineral Dust: Role in Radiative Forcing

Mineral composition is a key control of single-scattering albedo (SSA), the ratio of scattering extinction to total extinction (figure modified from Sokolik and Toon, 1999)

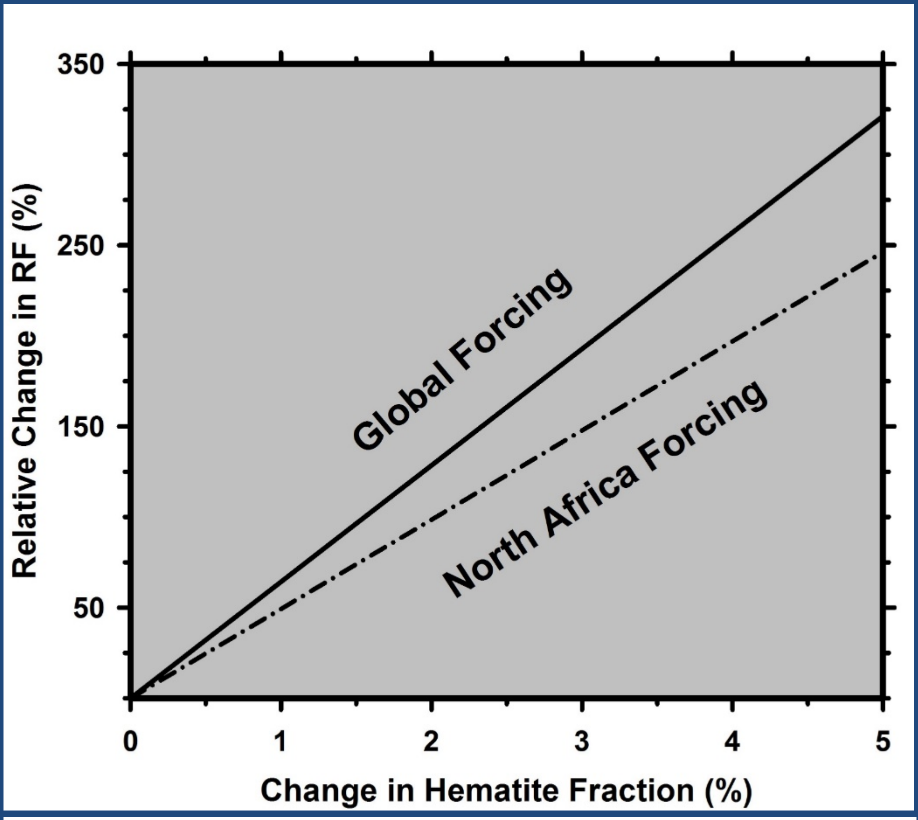
- Hematite is a strong absorber (SSA < 1.0) in the VSWIR, contributing to positive forcing (warming)
- Clay minerals (illite, kaolinite, and montmorillonite) are strong scatters (SSA ≈ 1.0), contributing to negative forcing (cooling)



Mineral Dust: Role in Radiative Forcing

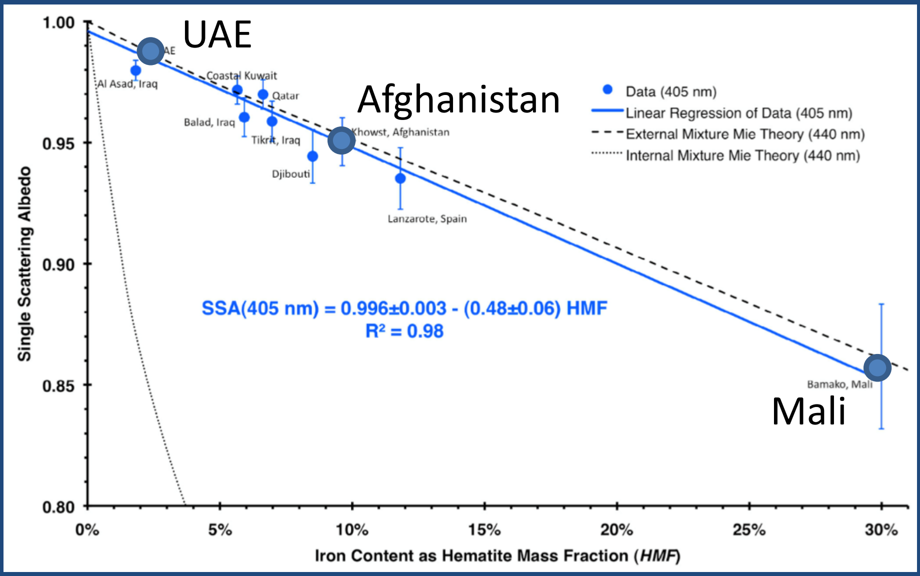
The relative abundance of hematite in dust source regions has a significant impact on dust-related radiative forcing

- 2% increase in the hematite content of North Africa (NA) source region results in increases of 130% and 100% in simulations of global (solid line) and regional forcing over NA (broken line)
- Modeling courtesy of R. Scanza, Cornell University



Large variation in hematite mass fraction (HMF) over arid dust source regions (Moosmuller et al., 2012)

- United Arab Emirates: ~2% HMF
- Afghanistan: ~10% HMF
- Mali : 30% HMF

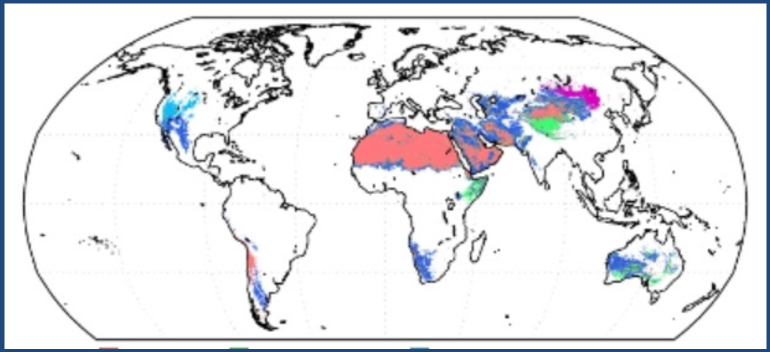


Dust Source Regions: Current Inputs to ESM

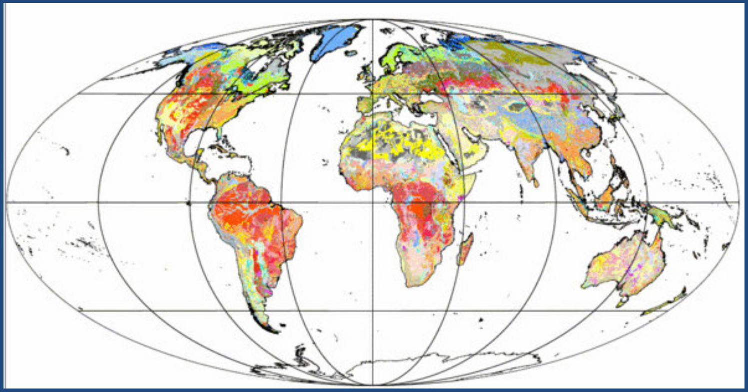
- Arid source regions for mineral dust are identified by the World Meteorological Organization (WMO) globally

- Currently, estimates of surface dust source composition for Earth system models are derived primarily from the 1:5,000,000 scale United Nations, Food and Agriculture Organization (FAO) soil map.

- This FAO source has challenges
  - Derived from about 5000 soil analyses mostly in agricultural regions
  - The soil surveys focus on agricultural soil with limited sampling of nonagricultural regions
  - The FAO records soil descriptions (types) and many assumptions are required to infer surface mineralogy
  - The gridded spatial sampling of ~9 x 9 km points is coarse for the heterogeneity of many mineral dust source regions



WMO Dust Source Regions

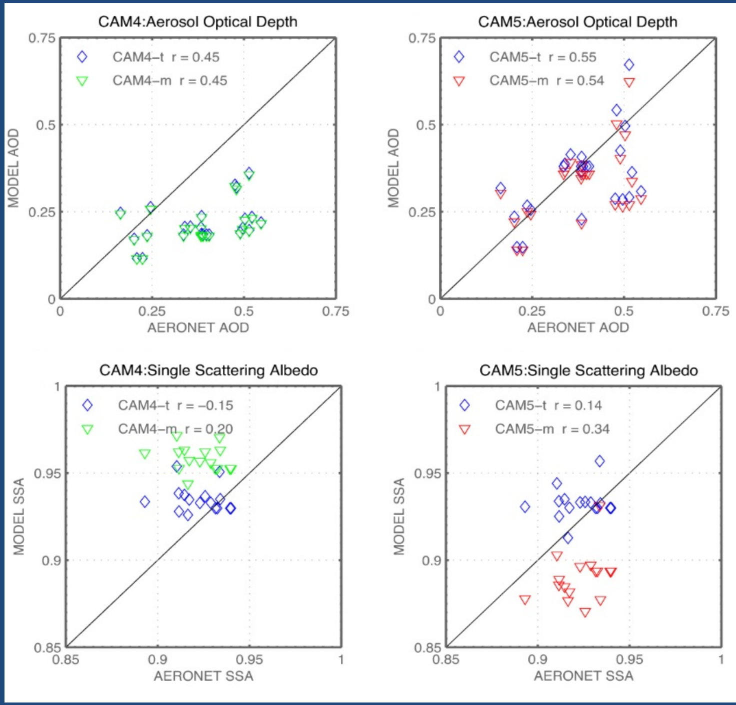


FAO Soil Map

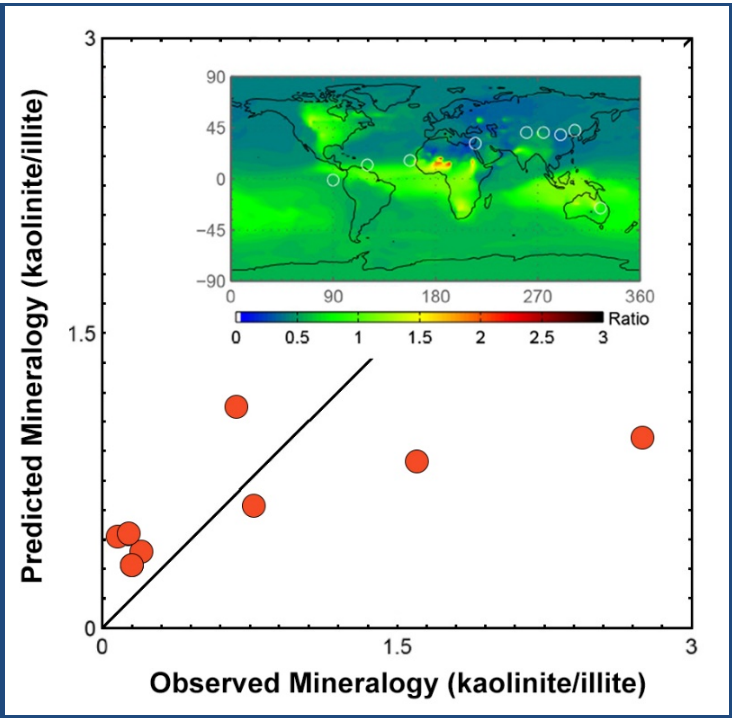
Dust Source Regions: Current Inputs to ESM

- Impact of dust mineralogy in the Community Atmosphere Model (CAM4/5) on forecast skill of the Community Earth System Model (CESM)
- Forecasts of AOD and SSA are not well-correlated with AERONET-based retrievals (Fig. a)
- Forecasts of mineralogy of dust deposits are not well-correlated with observed mineralogy (Fig. b)
- Will improvements in knowledge of surface composition of dust source regions improve forecasting skill?

(a)



(b)

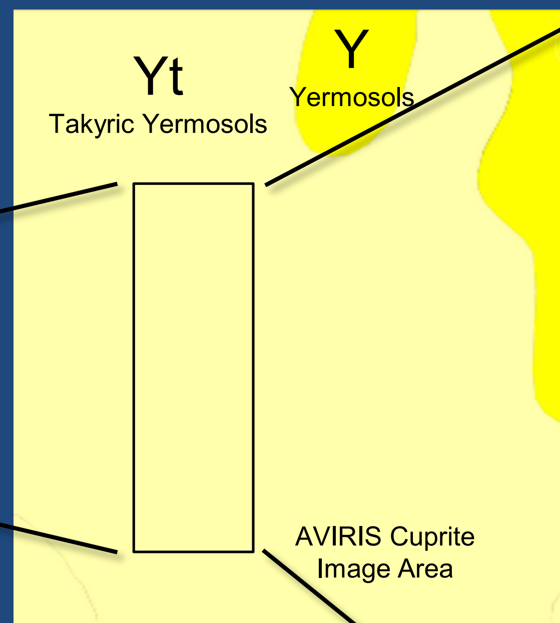


(*Figures modified from Scanza et al., 2015*)

Dust Source Regions: Current Inputs to ESM

Mineralogy inferred from extrapolated soil maps
vs. classifications based on imaging spectroscopy

Cuprite, Nevada



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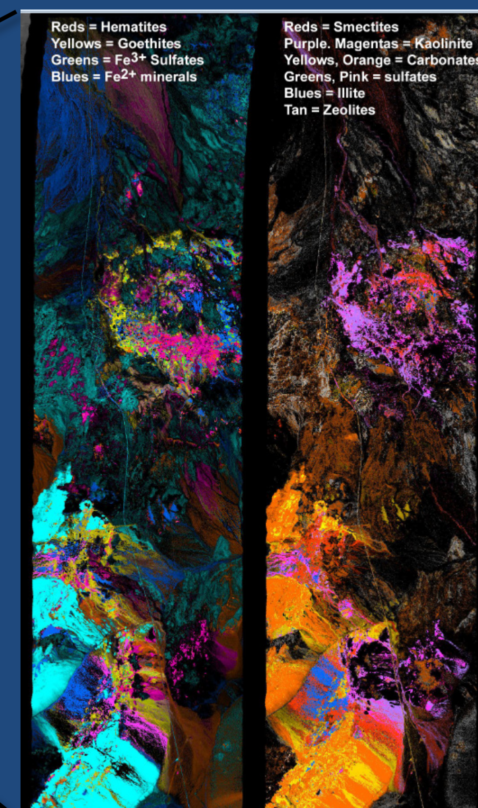
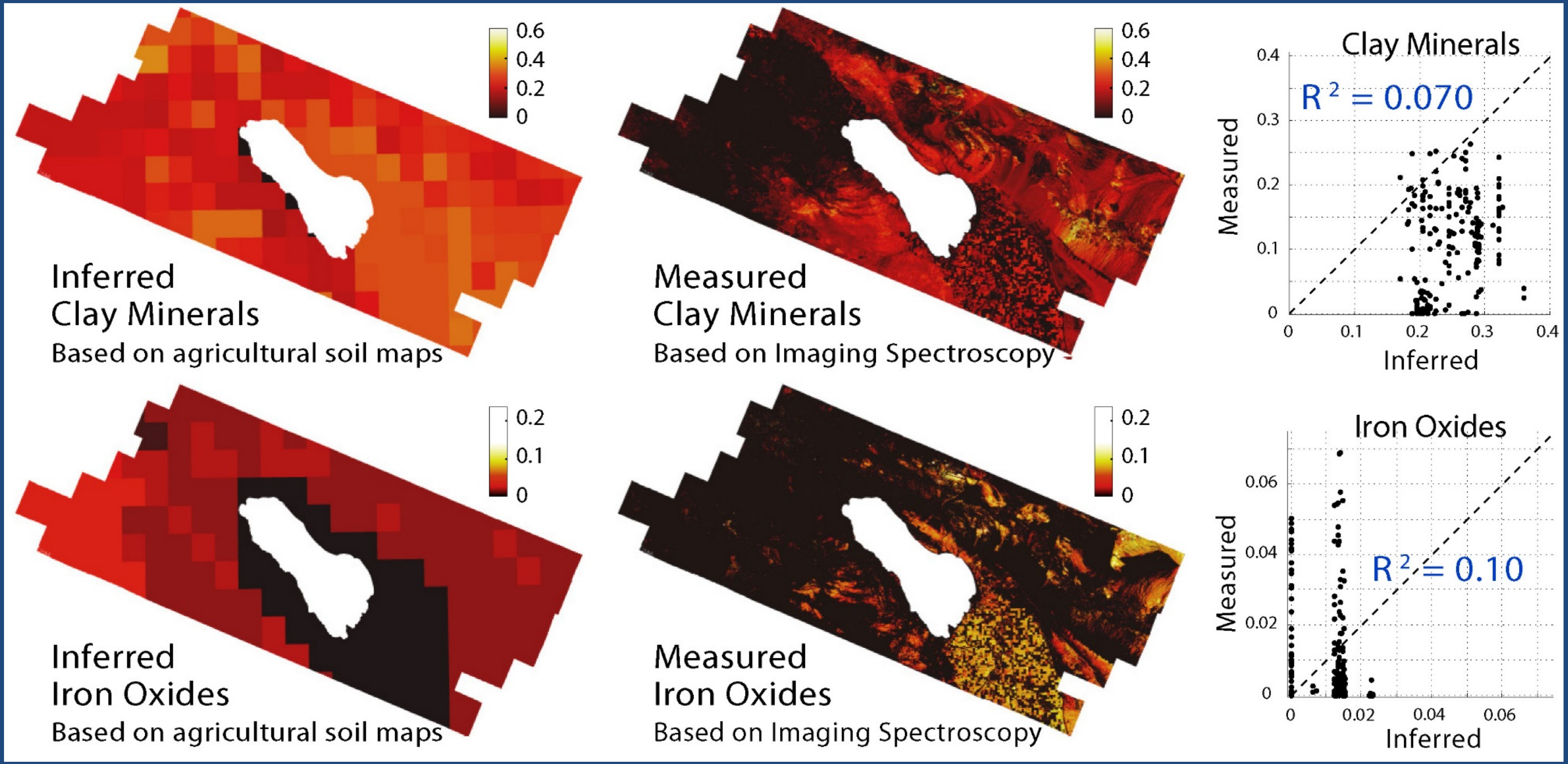


Tetracorder
Classification Maps

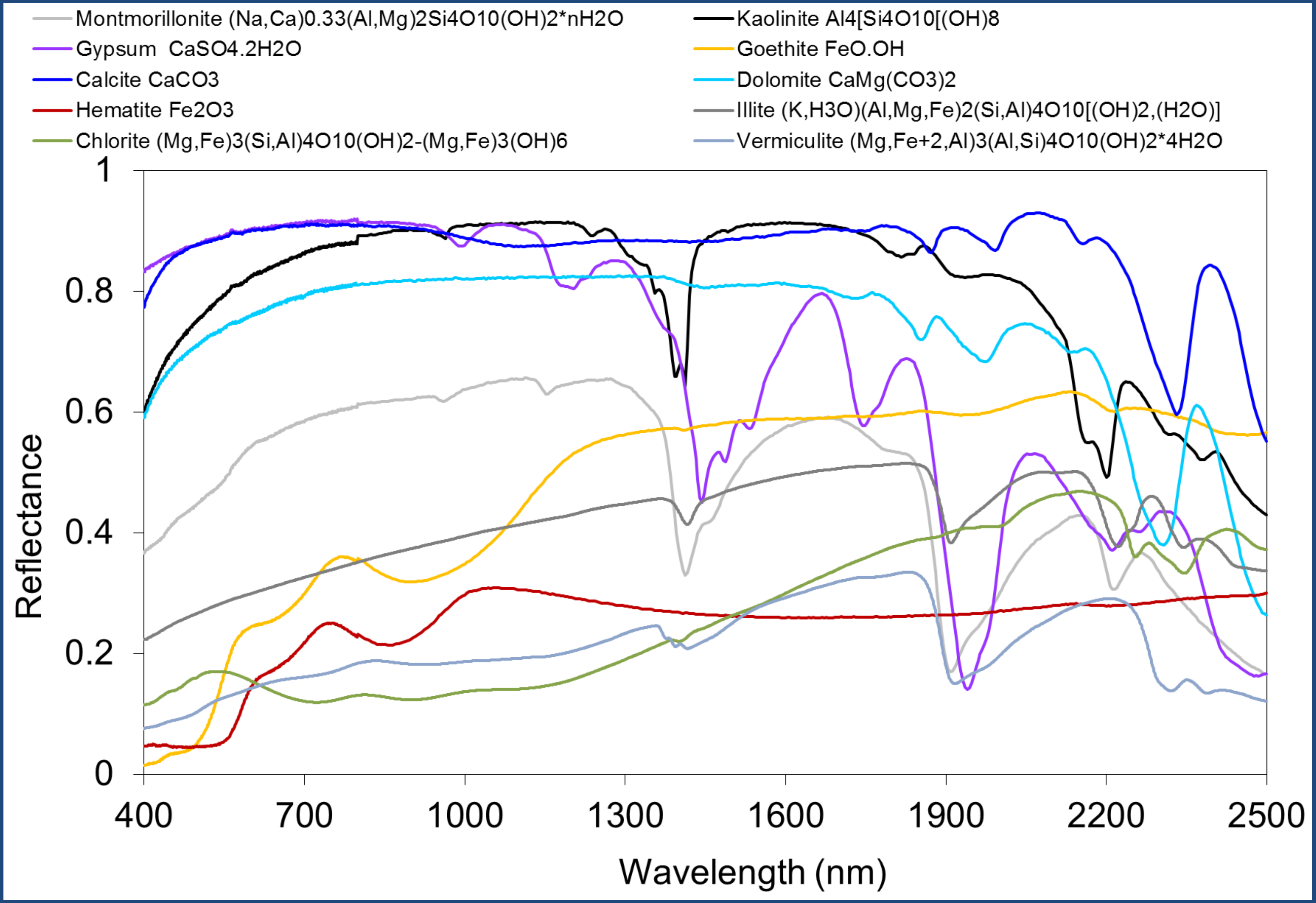
Salton Sea (CA) Region: Inferred Mineralogy vs. Imaging Spectroscopy

- Over-estimation of relative abundance of clay minerals
- Under-estimation of relative abundance of iron oxide minerals
- Errors in estimation can change the estimation of RF: net scattering (negative forcing) vs. absorption (positive forcing)



ESM Community: Top 10 Dust-Forming Minerals

- HyspIRI-class VSWIR imaging spectrometer will resolve unique spectral features of target minerals
- 100-m sampling of arid dust source regions yields ~10^9 spectra, exceeding soil map database by six orders of magnitude



Thank You for
Your Attention.

Mineral Dust: Role in Radiative Forcing

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The relative abundance of hematite in dust source regions has a significant impact on dust-related radiative forcing (Fig. b, modeling courtesy of R. Scanza, Cornell University)

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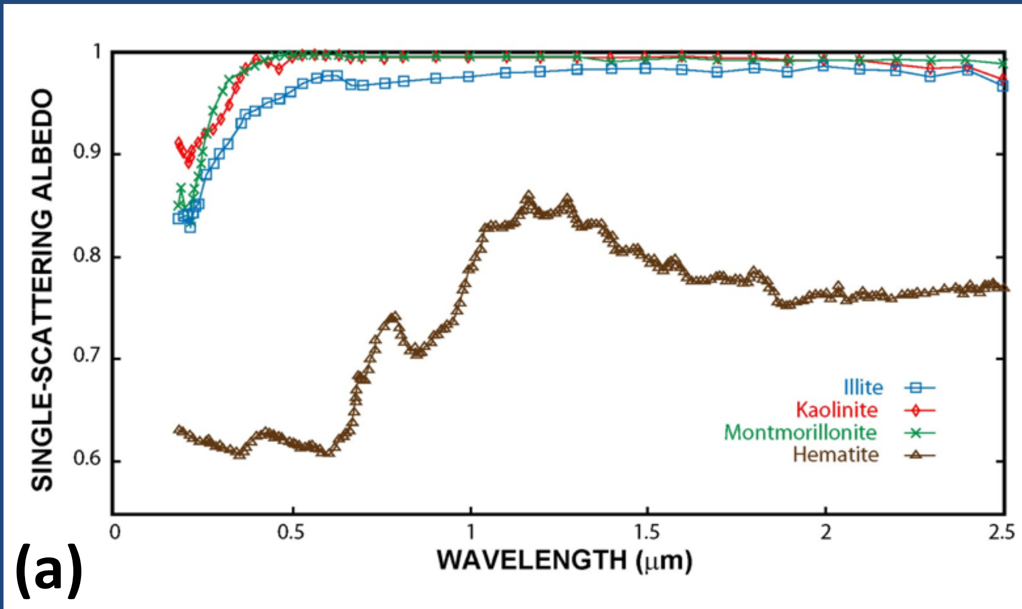

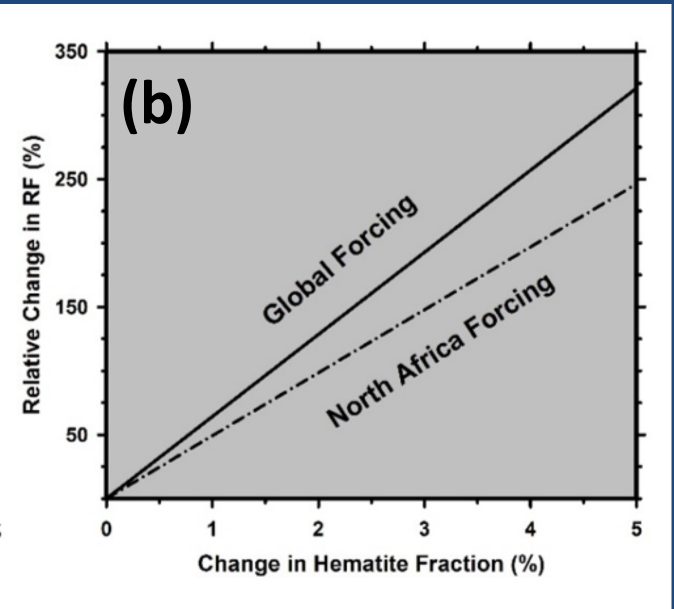

Science Traceability

Science Target	Science Objectives	Scientific Measurement Requirements		Instrument Performance		Mission Requirements
		Physical Parameters	Observables	Parameter	Reqts	
Advance NASA's Climate, Atmospheric Composition and Earth Surface Research Goals: • Characterize the Emissions of Radiatively-Active Mineral Dust from the Earth's Surface • Describe and Predict the Role of Mineral Dust in Radiative Forcing • Refine/Augment Earth System Modeling Capabilities • Earth Surface and Atmosphere Interactions http://science.nasa.gov/earth-science/focus-areas/ • Reduce mineral dust RF uncertainty identified in the IPCC AR5	(QESO1) Acquire a comprehensive inventory of key surface minerals available for dust emission in arid regions, based on ≥28 X 10^6 km^2 of the surface, demonstrate improved model skill, and update climate RF predictions in dust impacted regions of the Earth.	Occurrence and fractional abundance (0-1.0 with uncertainty) of dust source minerals expressed at the surface of arid dust source regions and adjacent land at risk for desertification: • Montmorillonite • Kaolinite • Gypsum • Goethite • Calcite • Dolomite • Hematite • Illite • Chlorite • Vermiculite Confounding factors: • Fractional surface cover for green and non-photosynthetic vegetation • Identification and flagging of other materials (water, snow, human infrastructure)	**Top of Atmosphere Radiance Spectra** **Spectral Characteristics** • Mineral Composition with uncertainty: – Iron: 450–1250 nm – Sulfates, Clays & Carbonates: 1450–2450 nm • Atmospheric correction: – Aerosols: 410–780nm – Water vapor: 880–1250 nm – Cirrus clouds: 1360–1400 & 1845–1905 nm • Surface vegetation cover – Pigments/red edge: 450–800 nm – Non-photosynthetic components: 2000–2350 nm	**Spectral Requirements:** Minimum Wavelength (nm) Maximum Wavelength (nm) Sampling (nm) FWHM (nm) Spectral calibration uncertainty (%)	 ≤ 410 ≥ 2,450 ≤ 15 ≤ 20 ≤ 5	**Coverage:** Single cloud-free measurement for ≥80% of arid dust source and adjacent lands when local solar elevation ≥ 45° **Orbit Altitude:** 350 - 750 km **Mission Lifetime:** ≥At least 1 year
	(QESO2) Measure surface mineral composition available for new dust sources in agricultural and sparsely vegetated lands that border source regions (≥4 X 10^6 km^2), and predict evolution of dust sources and related RF under future climate scenarios.		**Spatial Characteristics** • Spatial resolution sufficient to resolve hectare-scale features (100x100 m) – Mineralogy of fallow fields and small exposed areas – Continuity with Landsat, Hyperion, and ASTER data records – Robust aggregation to L3 and Earth System model grids • Geolocation knowledge sufficient to composite, aggregate and tie to digital elevation data use in dust models. • Swath sufficient to measure required areas in a one year period	**Spatial Requirements:** Sampling @ nadir (m) FWHM @ nadir (m) Knowledge (m) post processing Swath (samples) Field of Regard (°)	 ≤ 100 ≤ 125 ≤ 100 ≥ 1000 ≥ 30	
			Radiometric Characteristics • Avoid saturation over highly reflective surfaces (≥ 80%) • Accurate radiometry for atmospheric correction (≤10% uncertainty) • 1% precision in depth of absorption features in accessible mineral absorption spectral regions	**Radiometric Requirements:** Range (% of max Lambertian) Radiometric uncertainty (%) Precision (SNR vs band depth)	 0 to ≥ 80% ≤ 10% Figure 5.	