Principal Author:
Natalie Mahowald, Cornell University

Co-Authors:
Greg Okin(1), Carlos Perez (2), Paul Ginoux (3), Olga Kalashnikova (4), Ron Miller (5), Roger Clark (6), Robert O. Green (4)
1 University of California, Los Angeles
2 Columbia University
3 National Oceanic and Atmospheric Administration
4 Jet Propulsion Laboratory, California Institute of Technology
5 Goddard Institute for Space Sciences
6 Planetary Sciences Institute

Title
Closing the Earth Surface Dust Source Composition Gap for Earth System Understanding and Modeling

Description:
Mineral dust emitted to the atmosphere impacts direct & indirect radiative forcing, tropospheric chemistry, ecosystem fertilization, & human health & safety. Although source composition is as important as dust amount, dust composition is poorly constrained. Global space spectroscopic measurement of surface mineralogy closes this knowledge gap.

White Paper

What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

Mineral dust emitted from the Earth surface into the atmosphere affects climate through direct radiative forcing and indirectly through cloud formation as well as changes in the albedo and melting of snow/ice. Based on their chemistry, the minerals in dust react and modify tropospheric photochemistry and acidic deposition. Mineral dust aerosols affect ocean and terrestrial ecosystem biogeochemical cycling by supplying limiting nutrients such as iron and phosphorus. In populated regions, mineral dust is a natural hazard that affects human health and safety. A summary of Earth system processes impacted by mineral

Table 1. Mineral dust impacts a broad range of physical and chemical Earth system processes.

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

dust emitted from the Earth's surface is given in Table 1. Importantly, all of these impacts are quite different for different minerals, and yet for most of these impact we assume soils are homogeneous across the planet. Studies which attempt to differentiate the various mineralogical impacts on climate and biogeochemistry suggest that the mineralogy is just as, if not more, important than the amount of dust (Sokolik, 1999,Atkinson, 2013, Shi, 2012).

To accurately understand the Earth's current and potential future mineral dust cycle, measurement and modeling of the source, transport, and deposition of the dust cycle are required. For the transport component, considerable investments have been made in space-based observation (MISR, MODIS, etc.) and more are planned (ACE and international). In contrast, the current mineral dust source knowledge for the Earth is primarily constrained by analyses from agricultural soil maps with mineralogy traced to ≤5000 soil mineralogical analyses globally and the most prolific dust sources lack sufficient sampling.

To close this knowledge gap of surface dust source composition, a new space-based spectroscopic measurement of the Earth's surface mineral dust source regions could be acquired in one to two years. Spectroscopic measurements in the 380 to 2510 nm range with 10 nm contiguous spectral sampling and ≤100 m spatial sampling are required. Such a measurement would improve mineral dust source knowledge by sampling of order one million more areas and support a number of science communities and as well as provide direct societal benefit.

Current Earth system models are ready to accept accurate Earth surface mineral dust source composition. For example, NASA/GISS ModelE2 (Miller et al. 2006; Schmidt et al., 2014) and NCAR CESM (Hurrell et al, 2013), with the embedded atmospheric model CAM5 (Neale et al., 2012, Mahowald et al., 2006). Both models contribute to the Climate Model Inter comparison Projects (CMIP), which contribute to the IPCC. Comparisons of model predictions of mineral distributions with *in situ* dust sampling cannot simulate all features (Scanza et al., 2015), hence the need for comprehensive and direct measurement of surface dust source composition.

In addition to global impacts, the arid regions of the Earth are vulnerable to small shifts in climate and the related impacts of surface emitted mineral dust. For example, the largest changes in precipitation recorded in the 20th Century have occurred over the Sahel region of North Africa (e.g. Stocker et al., 2013). Climate modeling demonstrates that the incorporation of realistic mineral dust models improves predictions of temperature and precipitation changes over arid regions (e.g., Miller and Tegen, 1998; Yoshioka et al., 2007; Mahowald et al., 2010), and the impact of dust is a function of the mineralogy and spatial distribution of soils in dust source regions (e.g. Perlwitz et al., 2001; Ginoux et al., 2012; Ward et al., 2014; Miller et al., 2014; Scanza et al., 2015).

Accurate and comprehensive measurement of the Earths mineral dust source regions are required now to reduce the uncertainty in current understanding and modeling of this component of the Earth system and for future prediction of how the Earths dust cycle may evolve under a range of future climate scenarios.

Why are these challenge/questions timely to address now especially with respect to readiness?

The Earth's mineral dust cycle impacts multiple components of the Earth system (Table 1). The dust cycle consists of a source, transport and deposition phase. The current poor knowledge of the composition of the Earth's mineral dust source regions is limiting current understanding and modeling research and future projections of the dust cycle as the climate system changes including feedbacks. Earth system models are ready to accept accurate constraint of the composition of surface mineral dust source regions.

The technology for the required measurements is now ready based on investments over the past decade by the for the 2007 HyspIRI Decadal Survey mission. A 2014 and follow-on 2015 study shows an imaging spectrometer with full spectral coverage from 380 to 2510 nm with 10 nm sampling as well as a 185 km swath and 30 m spatial sampling could be accommodated on a small satellite and launch from a low cost Pegasus rocket. This global terrestrial mission would fully meet the requirements to measure the Earth dust source mineral composition. Such a mission would complement the current and planned fine and coarse spatial sampling multispectral missions (Landsat, VIIRS, etc.) as well as enable new scientific research and application across a range of disciplines based on the full spectroscopic measurement.

Why are space-based observations fundamental to addressing these challenges/questions?

The mineral dust source regions are distributed across the arid lands of the terrestrial surface in the Southern and Northern hemispheres typically between +-54 degrees latitude. The spatial area is estimated at $2.8x10^7$ km^2. Given the large area and territorial access factors, no ground or airborne strategy can provide the compressive and uniform measurements required to address this Earth system science challenge. Even if airspace access could be arranged, measurement of the Earth dust source regions could take >10 years and cost in excess of $150M and would be heterogeneous in space and time. The current possible future international space based target sampling imaging spectrometer missions are designed to strictly focused mission requirements and do not have the collection capacity or low distortion measurements required to address this challenge. Comprehensive space based spectroscopic observations of the Earths arid land regions are the fundamental observation required to provide the uniform compositional knowledge of mineral dust source regions and adjacent lands at risk for desertification that is needed to address this Earth system science challenge.

A demonstration of this approach has been tested at the Salton Sea, CA area with measurements acquired by the high altitude Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)(Figure 1). The Salton Sea is a known mineral dust source region. The capability to measure the surface dust source mineral composition was demonstrated using spectral fitting to the distinct spectral signatures of the minerals of interest.

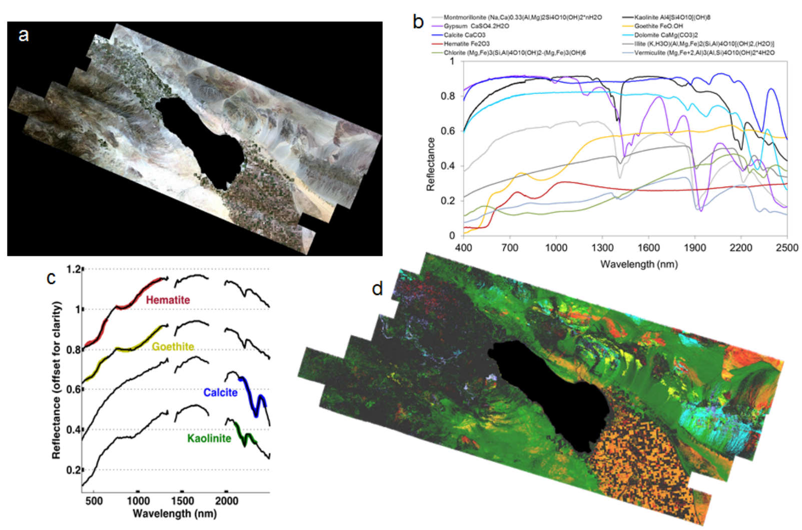

Figure 1. (a) Airborne imaging spectrometer measurement of the Salton Sea, CA mineral dust source area used to map surface mineral dust source composition. (b) Spectra of key dust source minerals in the spectral range from 380 to 2510 nm. (c) Spectral fitting results to derive surface mineral composition. (d) Spectroscopically derived surface mineralogy for the Salton Sea, CA dust source region.

From space, a comprehensive measurement of the Earth's surface mineral dust source regions could be acquired with spectroscopic measurements spanning in the 380 to 2510 nm spectral region with 10 nm contiguous sampling and 30 m sampling from the ISS or a smallsat polar orbiter in one or two years. This new space based measurement of the Earth's dust source region will improve the state of knowledge of mineral dust source composition by $\geq 10^6$. This advance benefits a diverse range of science communities: climate through the dust impacts of direct radiative forcing and indirectly through cloud formation; cryosphere through changes in the albedo and melting of snow/ice; atmospheric composition through the chemical impact of mineral on tropospheric photochemistry and acidic deposition; and terrestrial and ocean ecosystems through supply of limiting nutrients such as iron and phosphorus. In addition to indirect impacts to society in the science disciplines above, there are direct societal impacts in populated regions where mineral dust is a natural hazard that affects human health and safety

References

Atkinson, J., B. Murray, M. Woodhouse, T. Whale, K. Baustian, K. Carslaw, S. Dobbie, D. O'Sullivan, and T. Malkin (2013). The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds, Nature, 498, 355-358. doi:310.1038/nature12278.

Bian, H., M. Prather, and T. Takemura (2003). Tropospheric aerosol impacts on trace gas budgets through photolysis. J. of Geophys. Res., 108. doi:10.1029/2002JD002743.

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. Satheesh, S. Sherwood, B. Stevens, and X.-Y. Zhang (2013). Chapter 7: Clouds and Aerosols, Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T., D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Medigley, eds., Cambridge University Press, 573-657. ISBN:978-1-107-05799.

Buck. B., D. Goossens, R. Metcalf, B. McLaurin M. Ren, and F. Freudenerger (2013). Naturally Occurring Asbestos: Potential for Human Exposure, Southern Nevada, USA, Soil Sci. Soc. of Am. J., 77, 6, 2192-2204. doi: 10.2136/sssaj2013.05.0183

DeMott, P., K. Sassen, M. Poellet, D. Baumgardner, D. Rogers, S. Brooks, A. Prenni, and S. Kreidenweis (2003). African dust aerosols as atmospheric ice nuclei, Geophys. Res. Lett., 30, 1732. doi:1710.1029/2003GL017410.

Dentener, F., and P. Crutzen (1993). Reaction of N2O5 on tropospheric aerosols: impact on the global distributions of NOx, O3 and OH, J. of Geophys. Res., 98, D4 7149-4162. doi:10.1029/92JD02979.

Dentener, F., G. Carmichael, Y. Zhang, J. Lelieveld, and P. Crutzen (1996). Role of mineral aerosol as a reactive surface in the global troposphere, J. of Geophys. Res., 101, 22, 869- 889. doi:10.1029/96JD01818.

Dentener, F., J. Drevet, J. Lamarque, I. Bey, B. Eickhout, A. Fiore, L. Horowitz, U. Kulshrestha, S. Rast, and T. Van Noije (2006). Nitrogen and sulfur deposition on regional and global scales: a multimodel evaluation, Global Biogeochem. Cy., 20. doi:10.1029/2005GB002672

Dufresne, J.-L., C. Gauier, P. Ricchiazzi, and Y. Fouquart (2002). Longwave Scattering Effects of Mineral Aerosols, J. Atmos. Sci., 59, 1959-1966. doi:10.1175/1520-0469(2002)059

Forster, P., V. Ramasway, P. Artaxo, T. Berntsen, R. Betts, D. Fahey, J. Haywood, J. Lean, D. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Shulz, and R. Van Dorland (2007). Chapter 2: Changes in atmospheric constituents and in radiative forcing, Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, eds., Cambridge
University Press, 129–234. ISBN:978-0521-88009.

Gill, T. (1996). Eolian sediments generated by anthropogenic disturbance of playas: Human impacts on the geomorphic system and geomorphic impacts on the human system, Geomorphology, 17, 207– 228. doi:10.1016/0169-555X(95)00104-D.

Huszar P., and S. Piper (1986). Estimating the Off-Site Costs of Wind Erosion in New Mexico, J. Soil Water Conserv., 41, 6, 414- 416.

Jickells, T., Z. An, K. Anderson, A. Baker, G. Bergametti, N. Brooks, J. Cao, P. Boyd, R. Duce, K. Hunter, H. Kawahata, N. Kubilay, J. LaRoche, P. Liss, N. Mahowald, J. Prospero, A. Ridgwell, I. Tegen, and R. Torres (2005). Global iron connections between desert dust, ocean biogeochemistry, and climate, Science, 308, 67–71. doi:10.1126/science.1105959.

Kaufman, Y.J., I. Koren, L.A. Remer, D. Rosenfeld, and Y. Rudich (2005). The effect of smoke, dust and pollution aerosol on shallow cloud development over the Atlantic Ocean, P. Natl. Acad. Sci. USA, 102, 32. doi:10.1073/pnas.0505191102.

Krinner, G., O. Boucher, and Y. Balkanski (2006). Ice-free glacial northern Asia due to dust deposition on snow, Clim. Dynam., 27, 6, 613-625. doi:10.1007/s00382-006-0159-z.

Krishnamurthy, A., J. Moore, N. Mahowald, C. Luo, S. Doney, K. Lindsay, and C. Zender (2009). Impacts of increasing anthropogenic soluble iron and nitrogen deposition on ocean biogeochemistry, Global Biogeochem. Cyc., 23. doi:10.1029/2008GB003440.

Lee, Christine M.; Cable, Morgan L.; Hook, Simon J.; et al., "An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities " REMOTE SENSING OF ENVIRONMENT Volume: 167 Special Issue: SI Pages: 6-19 Published: SEP 15 2015

Mahowald, N., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, Albani, S., Doney, S., Bhattacharya, A., Curran, M., Flanner, M., Hoffman, F., Lawrence, D., Lindsay, K., Mayewski, P., Neff, J., Rothenberg, D., Thomas, E., Thornton, P., and Zender, C.: Observed 20th century desert dust variability: impact on climate and biogeochemistry, Atmospheric Chemistry and Physics, 10, 10875-10893, 2010.

Mahowald, N., and T. Koop (2013). Atmospheric Science: The Seeds of Ice in Clouds, Nature, 498, 302-303. doi:10.1038/nature12256.

Mahowald, N., and L. Kiehl (2003). Mineral aerosol and cloud interactions, Geophys. Res. Lett., 30, 9. doi:10.109/2002GL016762.

Mahowald, N., S. Engelstaedter, S. Kloster, J. Moore, and S. Mukhopadhyay (2010). Observed 20th century desert dust variability: impact on climate and biogeochemistry, Atmos. Chem. Phys., 10. doi:10.5194/acp-10-10875-2010.

Mahowald, N., J.-A. Ballentine, J. Feddema, and N. Ramankutty (2007). Global trends in visibility: implications for dust sources, Atmos. Chem. Phys., 7, 3309-3339. doi:10.5194/acp-7-3309-2007.

Metcalf, R., and B. Buck (2015). Genesis and health risk implications of an unusual occurrence of fibrous NaFe3+- amphibole, Geology, 43, 1, 63-66. doi:10.1130/G36199.1 .

Miller, R.L., I. Tegen, and J. Perlwitz (2004). Surface radiative forcing by soil dust aerosols and the hydrologic cycle, J. Geophys. Res., 109, D4, 203. doi:10.1029/2003JD004085.

Miller, R.L., G. Schmidt, L. Nazarenko, and N. Tausnev (2014). CMIP5 historical simulations (1850–2012) with GISS ModelE2, J. Adv. Model. Earth Syst., 6, 441–477. doi:10.1002/ 2013MS000266.

Miller, R.L., P. Knippertz, C. Pérez García-Pando, J.P. Perlwitz, and I. Tegen, 2014: Impact of dust radiative forcing upon climate. In Mineral Dust: A Key Player in the Earth System. P. Knippertz, and J.-B.W. Stuut, Eds. Springer, 327-357, doi:10.1007/978-94-017-8978-3_13.

Morman, S., and G. Plumlee (2013). The role of airborne mineral dusts in human disease, Aeolian Res., 9, 203-212. doi:10.1016/j.aeolia.2012.12.001.

Okin G., I. Tegen, N. Mahowald, F. Dentener, R. Duce, J. Galloway, K. Hunter, M. Kanakidou, N. Kubilay, J. Prospero, M. Sarin, V. Surapipith, M. Uematsu, and T. Zhu (2011). Impacts of atmospheric nutrient deposition on marine productivity: roles of nitrogen, phosphorus, and iron, Glob. Biogeochem. Cycles, 25, 2. doi:10.1029/2010GB003858.

Okin, G., N. Mahowald, O. Chadwick, and P. Artaxo (2004). Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems, Glob. Biogeochem. Cycles, 18, 2. doi:10.1029/2003GB002145.

Painter, T., A. Barrett, C. Landry, J. Neff, M. Cassidy, C. Lawrence, K. McBride, and G. L. Farmer (2007). Impact of disturbed desert soils on duration of mountain snow cover, Geophys. Res. Lett., 34, L12, 502. doi:10.1029/2007GL030284.

Painter, T., S. Skiles, J. Deems, A. Bryant, and C. Landry (2012). Dust radiative forcing in snow of the Upper Colorado River Basin: A 6 year record of energy balance, radiation, and dust concentrations, Water Resour. Res., 48, W7, 521. doi:10.1029/2012WR 011985.

Prospero, J. (1999). Long-term measurements of the transport of African mineral dust to the southeastern United States: Implications for regional air quality, J. Geophys. Res., 104, D13, 15, 917–927. doi:10.1029/1999JD900072.

Rosenfeld, D., Y. Rudich, and R. Lahav (2001). Desert dust suppressing precipitation: a possible desertification feedback loop, P. Natl. Acad. Sci. USA, 98, 11, 5975-5980. doi:10.1073/pnas.101122798.
Sokolik I., and O. Toon (1999). Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths, J. Geophys. Res.: Atmos., 104, D8, 9423-9444. doi:10.1029/1998JD200048.

Sokolik I., and O. Toon (1999). Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths, *J. Geophys. Res.: Atmos.*, 104, D8, 9423-9444. doi:10.1029/1998JD200048.

Swap, R., M. Garstang, S. Greco, R. Talbot, and P. Kallberg (1992). Saharan dust in Amazon Basin, Tellus B., 44, 2, 133– 149. doi:10.3402/tellusb.v44i2.15434.

Tegen, I., and A. Lacis (1996). Modeling of particle size distribution and its influence on the radiative properties of mineral dust aerosol, J. Geophys. Res., 101, 19237-19244. doi:10.1029/95JD03610.

Vet, R., R. Artz, S. Carous, M. Shawk, C.-U. Ro, W. Aas, A. Baker, V. Bowersox, F. Dentener, C. Galy-Lacaux, A. Hou, J. Pienaar, R. Gillett, M. Forti, S. Gromov, H. Hara, T. Khodzher, N. Mahowald, S. Nickovic, P. Rao, and N. Reid (2014). A global assessment of precipitation chemistry and depositoin of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH and phosphorus, Atmos. Environ., 93, 3-100. doi:10.1016/j.atmosenv.2013.10.060.

Yoshioka M., N. Mahowald, A. Conley, W. Collins, D. Fillmore, C. Zender, D. Coleman (2007). Impact of desert dust radiative forcing on Sahel precipitation: relative importance of dust compared to sea surface temperature variations, vegetation changes, and greenhouse gas warming, J. Climate, 20, 1445–1467. doi:10.1175/JCLI4056.1.

Yu, H., M. Chin, T. Yuan, H. Bian, L. Remer, J. Prospero, A. Omar, D. Winker, Y. Yang, Y. Zhang, Z. Zhang, and C. Zhao (2015). The fertilizing role of African Dust in the Amazon Rainforest: A multiyear Assessment based on CALIPSO Lidar Observations, Geophys. Res. Lett.,

Mahowald, N., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, Albani, S., Doney, S., Bhattacharya, A., Curran, M., Flanner, M., Hoffman, F., Lawrence, D., Lindsay, K., Mayewski, P., Neff, J., Rothenberg, D., Thomas, E., Thornton, P., and Zender, C.: Observed 20th century desert dust variability: impact on climate and biogeochemistry, Atmospheric Chemistry and Physics, 10, 10875-10893, 2010.