CHALLENGES AND OPPORTUNITIES IN ATMOSPHERIC DUST EMISSION, CHEMISTRY, AND TRANSPORT

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Atmospheric dust has widespread commercial, health, societal, meteorological, and climatic impacts, and the accurate prediction of its emission, chemical evolution, and transport is necessary for hazard planning and understanding dust-related influences on weather and climate. One of the overarching challenges, and one of the major themes of the workshop, is that dust processes occur over scales ranging from submicron to global and that these scales interact in multiple nontrivial ways. Thus, its continued study requires a collaborative mixture of scientific disciplines, modeling strategies, and experimental/observational techniques. Detailed below is a summary of the outcomes of the workshop, broken into five subtopics, including the current state of the art, as well as suggestions for future progress.

WORKSHOP ON DUST EMISSION, CHEMISTRY, AND TRANSPORT

What: A workshop attended by 27 scientists from universities, research laboratories, and federal agencies was held to discuss scientific challenges and opportunities in the areas of atmospheric dust emission, chemistry, and transport from a diverse array of research perspectives.
When: 26–27 September 2017
Where: Chicago, Illinois

LAND SURFACE, SOIL, AND EROSION PROCESSES. To predict the transport and feedback of dust throughout the atmosphere, its emission from the land surface must first be properly understood. In recent years, much progress has been made in identifying the common characteristics of highly erosive "hot spots"—landforms such as playas that are more prone to the emission of dust than others. Coupled with satellite remote sensing, the global identification of preferential source areas (Bullard et al. 2011) allows for better-constrained global emission estimates, particularly from remote dryland areas where in situ measurements are unavailable. At the same time, the continued monitoring of long-term, dedicated research sites (e.g., the new National Wind Erosion Research Network; Webb et al. 2016) have been critical for directly observing wind erosion processes and ground-truthing satellite estimates.

For specifying surface dust emission, numerical model parameterizations often utilize a surface shear stress threshold. This strategy is widely used

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and relatively simple to implement but is subject to fractal-scale soil characteristics, moisture content, and geochemistry. Furthermore the strategy is ambiguous and/or inaccurate near vegetation or microtopography (small dunes or hills). Detailed microscale measurements on actual land surfaces show strong violations of area-averaged theory, highlighting the need to adjust "flat" parameterizations to more complex real-world scenarios. Likewise, large-scale turbulent coherent structures and their associated extremes in fluctuating velocity are often the drivers of erosion, as opposed to the mean velocity. Finally, another confounding issue is the dynamics of saltation (Kok et al. 2012). Some of the basic physics of sand transport is well known, but the effects of moisture, turbulence, and complex terrain are problematic.

TURBULENCE AND MODELING. In addition to the dearth of knowledge regarding small-scale surface variations (soil texture, microtopography, etc.) and their control on dust emission, atmospheric turbulence and small-scale flow heterogeneity are additional sources of uncertainty in dust emission and transport models. Surface features including topography and vegetation change not only the emission of dust but also its near-surface transport. Combinations of high-resolution wind-tunnel experiments, lidar scanning, and computational fluid dynamics models have combined for better understanding of wakes and effects of surface heterogeneity, but much remains unknown. Likewise, turbulence-resolving numerical simulations, such as large-eddy simulation, have yielded greater understanding of the turbulent transport of dust and sand (Freire et al. 2016). For instance, so-called flux-profile relationships, where surface emission rates are theoretically linked to concentrations aloft, have been shown to be highly influenced by atmospheric stability and surface heterogeneity. These relationships can be influenced by both shape and inertial effects of individual sand/dust particles near the surface, modifying the interpretation of airborne concentration measurements and the inferred surface emissions below (Richter and Chamecki 2018).

Future modeling strategies for dust transport will require advanced upscaling techniques in order to capture sources of small-scale variability. Stochastic models, for example, random walk models, may play an increasing role in modeling processes whose controlling factors (turbulence intermittency, microscale soil conditions) will not be known exactly or will be numerically difficult to parameterize. Continued collection of high-quality validation data will be critical, however, to ensure accurate model components and physical understanding.

PARTICLE DYNAMICS. At the microscale, factors governing the dynamics of single particles have outsized influences on their collective effect at larger scales. Detailed experimental studies have shown the profound effects of particle shape on particle drag and orientation, which in turn causes great uncertainty in seemingly simple but important quantities. For instance, the average settling velocity of particles through a turbulent flow, which determines the atmospheric lifetime and deposition of dust, can be up to several times larger (or smaller) than the terminal velocity of a single particle in quiescent conditions, based solely on turbulence levels, particle shape, and/or particle orientation (Wang and Maxey 1993; Nemes et al. 2017).

The confidence in our understanding of ice nuclei effects on clouds also remains very low: models do not capture the range of ice nuclei concentrations observed in nature. Dust is lumped in with a general ice nuclei category in most models, but this is clearly simplistic. Accurately determining what particles are good ice nuclei and their natural abundances around the globe remains challenging.

The sheer range in size, mass, shape, hygroscopicity, physical stability, and chemical reactivity of atmospheric dust particles presents significant challenges with developing universal transport parameterizations as they traverse the boundary layer and broader environment. The strong linkage between microscale, single-particle dynamics and large-scale transport highlights the need for continued research in this area. In situ measurements of particle dynamics, including emission, turbulent transport, chemical evolution, and in-cloud processes, are almost completely nonexistent because of the difficulty in making such observations. Advances in remote sensing, unmanned aerial vehicles, and transportable measurement equipment are beginning to open the door for this kind of much-needed data.

AEROSOLS AND GEOCHEMISTRY. As stated by Winkler (1973, p. 376), "the same net composition of an aerosol can be caused by an infinite variety of different internal distributions of the various compounds." Compounding the uncertainties in emission and transport of dust particles is the fact that dust aerosols are highly heterogeneous in their composition and often do not reflect the composition of the bulk soil they were emitted from because of fracturing during the emission processes or because of interaction with anthropogenic chemical treatments and emissions. Furthermore, it is becoming increasingly clear that the simple categorization of aerosols as "dust/mineral," "salt," "smoke," etc. is problematic, since each has a variety of species that interact and evolve continuously as processes such as cloud activation and chemical reaction occur. Thus, an aerosol population is an ever-changing mixture of mixtures, and this evolution changes the optical, ice nucleation, hygroscopic, and other properties of the mixture. Since it is well-known that dust aerosols have huge influences in direct and indirect radiative effects, constraining and understanding the chemical evolution of dust and dustborne compounds is critical.

While measurement advances for complex dust chemistry have been made, including Raman spectrometry, aerosol time of flight, and other mass spectrometry, the expense and difficulty of taking equipment to the field has limited their use. For example, in situ measurements of dust composition as a function of atmospheric height are nearly nonexistent yet are in great need to conceptually link surface soil conditions with aerosol composition aloft. Likewise, observations of dust's chemical evolution during emission and transport are limited as well. Included in this challenge is the role of biological species (fungi, bacteria, etc.) carried with the mineral dust and their influence on toxicological as well as radiative effects. Fast, inexpensive, mobile, and accurate measurements of dust composition during atmospheric transport do not yet exist and represent a key direction for future research.

LOCAL AND GLOBAL ATMOSPHERIC PROCESSES. At the large scale, representing dust in climate models is challenging and is hindered by both unresolved meteorological forcing (Evan et al. 2014; Evan 2018) and small-scale dust processes. For instance, while various climate models can simulate the mean state of dust (e.g., aerosol optical depth), higher-order statistics such as the dust size distribution are biased (Kok 2011). At the same time, satellite remote sensing, for instance, via the NASA Multiangle Imaging SpectroRadiometer (MISR), has become an increasingly valuable tool in global retrieval of dust emission and loading. From these large-scale observations, quantities such as aerosol optical depth can be validated (e.g., the International Cooperative for Aerosol Prediction provides a valuable tool for intermodel comparison of operational models; Sessions et al. 2015), and increased physical understanding can be garnered. In addition, specific large-scale phenomena, such as the Saharan air layer, have been targeted from Africa across the Atlantic to the Caribbean for many decades from field measurement, remote sensing, and modeling perspectives (Prospero and Mayol-Bracero 2013) because of their status as important natural laboratories for studying all phases of dust emission and transport in a coherent framework.

It is clear that satellite remote sensing will play a leading role in providing observations of dust processes in the future; new platforms such as *GOES-16* and Sentinel-2 are likely to spur significant advances. However, this can only be done with reliable on-ground validation data and will likely never reach the resolution needed to directly observe details including ground surface type, the evolution of dust chemical composition and physical properties, and turbulent transport at the microscale. Therefore, global dust and climate models will require continued development from both the top-down and bottom-up perspectives and will benefit from a combination of mathematical upscaling techniques, laboratory studies, numerical simulation, and long-term data collection.

FINAL SUMMARY. The major theme of the workshop was that the complexities associated with dust emission, transport, and chemistry are numerous, spanning the microscale to the planetary scale. Further, it is clear that, aside from certain exceptions, these processes can continuously interact in nontrivial ways at and between all scales, making small-scale representation in large-scale models crucial for a wide range of problems. It is also clear that for purposes of better predicting local visibility, predicting long-term climate, assessing public health impacts, and for understanding and forecasting landscape evolution, progress is greatly needed in each of the areas listed above.

In nearly all areas, the need for additional high-quality observational data is paramount. Remote sensing is a promising tool for obtaining this information; although it remains limited, new sensors bear great promise. The development of more sophisticated in situ physical sampling and chemical analysis systems for dust aerosols is also needed. Unmanned aerial vehicles are also a promising tool for probing vertical distributions of dust size, concentration, and chemistry as well as land surface properties, especially in remote areas that are difficult or impossible to access. Long-term dust measurement sites, such as several key aerosol sampling networks throughout the

United States, are, while sparse, also valuable datasets for model validation and development.

In addition to simply obtaining more data, carefully controlled experiments, either in the field or in the laboratory, will likely be the only way to bridge scale gaps and isolate physical and chemical processes that complicate the full dynamics of the dust-laden atmosphere. Advances in technology and processing power are allowing for more and more advanced field and laboratory studies, providing deeper understanding of fundamental processes, including saltation and emission. To inform and validate the next generation of multiscale models, the need emerges for direct comparisons with targeted field studies and remote sensing retrievals.

Finally, these advances must be matched by improvements in representing these processes in numerical models. In particular, the treatment of subgrid processes (e.g., turbulence, erosion, particle emission and saltation dynamics, aerosol activation, heterogeneous chemistry) must be validated against measurements, and proper upscaling techniques must be used to incorporate them into coarse-grained models. Since model representations will always be subject to uncertain (or even unknown) forcings (such as dynamics of surface soil type, land cover, etc.), techniques for quantifying this uncertainty and methods for representing certain processes stochastically must be advanced.

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