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Summary and Final Report
Workshop on Dust Emission, Chemistry, and Transport
September 26-27, 2017, Chicago IL

On September 26-27, 2017, a group of 27 scientists from various universities, research institutions, and federal agencies gathered in downtown Chicago, IL to discuss ongoing research challenges and opportunities in the areas of dust emission, chemistry, and transport. The purpose of the meeting was primarily the identification of scientific challenges related to the overall topic of atmospheric dust, from a diverse array of research perspectives. In attendance were scientists from fields spanning environmental chemistry, atmospheric science, and engineering, ranging in scales all the way from single-particle dynamics to climate processes. Below is a summary of the presentations and discussions.

Aeolian, soil, and erosion processes

Current status:

- Progress has been made trying to identify common characteristics of highly erosive "hot spots" – surface regions more prone to emission of dust than others. Playas and ephemeral lakes fall into this category, which highlights the fact that not all exposed surfaces emit in the same way. Satellite remote sensing is continually becoming more important for global identification of these "hot spots", particularly in regions where *in situ* measurements are unavailable.
- Continual monitoring of dedicated research sites (e.g. the National Wind Erosion Research Network, White Sands, Jornada Experimental Range) has proven fruitful for observing systematic increases in dust emission, including regions in the western U.S. The spatially-diverse monitoring efforts highlight the need for standard protocols for measuring dust fluxes, especially in the presence of vegetation or topography.
- Topographical modulation of soil erosion and the effect of microtopography (e.g. soil surface crusts) on dust emission has been greatly enhanced by high-resolution scanning techniques (e.g. lidar), which can potentially be used to understand more general relationships for predicting dust loading in hilly or dune-filled regions, especially when coupled with numerical models.
- Saltation fluxes can be at least partially constrained and predicted by simple parameterizations based on energetic arguments, but the necessary inclusion of empirical constants and other tuning coefficients, combined with the lack of and potential complexity of observational datasets, limits the universality of these predictions.

Main challenges:

- One of the primary challenges identified was the heterogeneity of soil type and erodibility. Anecdotally, the high erosion of a field on one side of a highway compared to a non-eroding (but otherwise identical) field on the other side illustrated the main issue: erodibility depends on factors that are not necessarily visible, such as moisture content, salt content, and cohesiveness of surface minerals and their interactions with microscale variations of the wind.
- As noted by one participant, the "grand challenge" associated with wind erosion is the connection between microscale cohesive forces in the soil to the macroscale predictions of loading over, for example, an entire geographic region. The degree to which small-scale

heterogeneity influences bulk scale emission remains almost completely unknown and difficult to quantify.

- Many of the erosion models are based on a surface shear stress threshold (i.e., where emission only begins above a certain threshold of friction velocity), but this model is inherently limited. First, it's unclear what "surface shear stress" even means in the presence of vegetation and highly varying topography, and erosion can be hysteretic with friction velocity. Erosion based on area-averaged values of friction velocity, or friction velocity estimated using Monin-Obukhov similarity theory will not capture small-scale or instantaneous variability such as wakes, turbulent fluctuations, or small dunes, which may enhance or suppress erosion. Research is greatly needed to adjust "flat" parameterizations for saltation fluxes to more complex scenarios.
- Perhaps the biggest universal challenge is in the lack of observational data. This includes basic soil physical and chemical properties and their variability in many parts of the world, but also data on the cohesiveness and erodibility of various soil/mineral types. This is exacerbated by the fact that by testing the soil, the local soil properties will be altered. The horizontal and vertical emission fluxes from varying surface type is data-scarce as well.

Turbulence and modeling

<u>Current status:</u>

- Mesoscale modeling of dust transport can be done by coupling models such as WRF with lofting schemes such as that developed at the Air Force Weather Agency. This strategy can be used for operational forecasts of dust loading, and validation data is available from the Army Research Laboratory at White Sands.
- In the turbulent atmospheric boundary layer, vertical dust transport is primarily balanced between gravitational settling and turbulent flux. Under certain idealized conditions, this balance leads to similarity-based relationships which connect elevated mean dust concentrations with surface fluxes. Under the right conditions, this finding can allow for estimating surface emission based on elevated concentration measurements. The difference between transport of dust by shear-induced versus buoyancy-induced turbulence in the boundary layer is quite large, and must be taken into consideration.
- In addition to saltation processes, turbulent transport of dust/sand grains near the surface may be highly influenced by both shape and inertia. The inability of the particles to follow fluid streamlines will alter their vertical turbulent flux, while non-sphericity of shape can lead to large deviations in aerodynamic drag compared to an assumed spherical shape (which nearly all models assume).
- While downscaling is traditionally easier/more common than upscaling, certain upscaling techniques have been developed in other contexts, such as groundwater hydrology, which may be of use. Combining heterogeneous surface types or modeling particle-particle interaction may benefit from advanced upscaled transport models (e.g. fractional models, random walk models)
- On the scale of the entire atmospheric boundary layer, large-scale turbulent structures have a strong influence on surface stress as well as transport. Signatures of these motions have been seen in field observations, laboratory experiments, and turbulence-resolving numerical simulations

<u>Main challenges:</u>

- One of the primary challenges associated with modeling dust emission and transport is the lack of knowledge of surface conditions. Soil type, particle size, aggregate stability, moisture, salt content, etc. will control emission, and in many applications these quantities are completely unknown. Satellite imagery is highly useful, but still limited in resolution and information that it can provide. Additional progress in remote sensing is required.
- Even in the case where one has perfect knowledge of the surface soil type, representing small-scale variability on coarse model grids is a challenge that requires a great deal of effort. A combination of mathematical upscaling methods, high-quality validation data, and quantification of uncertainty are likely necessary to improve numerical predictions.
- The transport of particles through the atmospheric boundary layer depends on a host of factors, including atmospheric stability, particle size, and particle shape. Similar to other challenges, the small-scale details of sand/dust grains have a large impact in their overall transport, highlighting the continued need for high-resolution experiments and observations.
- Turbulence near the ground surface is intermittent, and can be influenced significantly by topography, vegetation, large-scale coherent structures, and atmospheric stability. Predicting surface emission and transport will be subject to inherent uncertainty due to these factors, and quantifying this should be a continued effort.

Particle dynamics

<u>Current status:</u>

- At the microscale, particle shape significantly influences particle transport in a turbulent flow. High-resolution, three-dimensional laboratory observations have been crucial in better quantifying these effects, and have demonstrated the need for taking into consideration the lack of axisymmetry in particle aerodynamic drag. History of what particles have "seen" is important for determining their current orientation in turbulent flows.
- Advances in laboratory technology, postprocessing algorithms, and experimental techniques have allowed for unprecedented views of small-scale dynamics in laboratory contexts. Therefore studies which isolate specific physical effects at the small scales are continually increasing in their ability to bridge scale gaps towards atmospheric scales.
- In turbulent flows, the gravitational settling of particles is influenced significantly by particle inertia. By sweeping into specific regions of the flow, particles can fall with an effective settling velocity several times faster than their own terminal fall velocity. Again, laboratory experiments are crucial in uncovering the basic physics of particle-turbulence dynamics.

<u>Main challenges:</u>

- The multiscale nature of dust and sand emission and transport is partly manifested in the strong coupling between small-scale particle-turbulence interaction and atmospheric transport. While laboratory experiments have been instrumental in elucidating the basic physics of particle transport, *in situ* observations at this scale are almost completely nonexistent and difficult to carry out.
- The sheer range in size, mass, shape, hygroscopicity, physical stability, and chemical reactivity of atmospheric dust particles presents challenges with developing universal transport

parameterizations as they traverse the boundary layer and the broader environment. At present, it remains unclear how to incorporate single-particle-scale effects into large-scale transport models.

- Connections between the particle aerodynamic characteristics and their emission location remain at least as uncertain as the emission source identification highlighted above.
- While laboratory measurements are crucial for understanding isolated transport mechanisms, they are limited in size and scope. Branching scales relevant to atmospheric processes will require some combination of technological, numerical, and observational advance.

Aerosols and geochemistry

<u>Current status:</u>

- Dust aerosols are highly heterogeneous in their composition, and may not reflect the composition of the bulk soil they were emitted from due to flaking/release of fine coatings from coarse soil grains, fracturing of saltators, differential erodibilty of different minerals, etc.
- Aerosols should not be simply categorized into types such as “dust/mineral”, “salt”, etc. Each dust particle in the atmosphere, especially after undergoing transport, has a variety of species, and this is changing continuously as they go through cloud activation, heterogenous reactions with organic species and other atmospheric gases and aerosols, and other atmospheric processes.
- Chemical treatments for dusty surfaces (i.e. roads) will inevitably be released as dust particles are emitted from the surface. These and other surface processes are crucial for properly assessing health impacts of airborne dust.
- Surface mineral properties, including salt content and moisture, will in large part determine the original composition of emitted dust aerosols as well as the erodibility of soil. Being able to characterize these properties, especially from remote sensing sources, will significantly advance our prediction capabilities of dust emission and transport.
- Advances in instrumentation for ground- and aircraft-based aerosol sampling and analysis techniques has increased our ability to measure size & composition of dust aerosol particles. This include mass spectrometry, Raman spectroscopy, and size filtering. These techniques, however, are somewhat cumbersome and/or expensive to deploy in the field, and are typically representative only of a single point in space (i.e. quantities like vertical distributions are lacking).
- Advances in unmanned aircraft are pioneering new methods for sensing and collecting dust aerosol size and composition measurements. These measurements have the potential to provide an unprecedented view of dust aerosol chemistry by providing data from elevations and locations previously inaccessible.
- Dust aerosol composition plays a huge role in direct and indirect radiative effects. The degree of radiative absorption/scattering by particles is determined in part by the chemical composition, and the ability of particles to modify water droplet and ice particle formation in clouds is significant.

<u>Main challenges:</u>

- The sensitivity of cloud properties on dust aerosol composition is enormous. In many cases, even the basic qualitative effects (e.g. "fewer, larger droplets" versus "more, smaller droplets") is unknown. Basic understanding of droplet and ice processes is lacking, and yet plays a huge role in atmospheric dynamics.
- *In situ* measurements of dust composition as a function of height are nearly nonexistent. While knowing local soil composition is somewhat helpful in predicting the dust composition at areas of emission (though even this can be difficult), connecting this with aerosol composition at varying heights is very difficult due to dis/agglomeration and differential transport of various sizes and shapes of particles. When dust-laden air is transported in the free troposphere far from the aerosol source, even less detail may be known. Thus predicting atmospheric processes associated with dust chemistry (e.g. radiative properties) is not simply a matter of characterizing surface compositions, and as a result is subject to huge uncertainty. Included in this challenge is the presence of biological species in the soil (fungi, bacteria, etc.) carried along with the mineral dust, and how they may modulate the atmospheric aerosol.
- Fast, inexpensive, mobile, and highly accurate measurements of dust aerosol chemical composition are currently nonexistent. With advances in this field, better validation data can be obtained, and therefore a better understanding of radiative and emission processes can be gained.

Local and global atmospheric processes

<u>Current status:</u>

- Global aerosol models, such as the Naval Research Laboratory's NAAPS model, are oftentimes used to predict global transport of various kinds of aerosols, and the International Cooperative for Aerosol Prediction (ICAP) is a valuable resource for inter-model comparison and validation against observations (e.g. aerosol optical depth from satellite remote sensing).
- Satellite remote sensing, including the NASA Multi-angle Imaging SpectroRadiometer (MISR), is becoming an increasing valuable tool in global measurements of dust emission and loading. Used in various capacities, remote sensing products such as aerosol optical depth can be used to estimate radiative properties and identify dust source locations (e.g. regions within an individual desert). While direct radiative effects have been a historical focus of remote sensing campaigns, aerosol indirect effects and air quality have emerged as primary research targets.
- Dust-cloud interactions are uniquely complex, and mineral aerosols impact both droplet and ice formation (perhaps more of an impact on ice nucleation). Competing indirect effects can preclude knowledge of even the direction of the net effect, and aerosol composition and size is critical for accurate prediction.
- The Saharan Air Layer (SAL), which transports dust from the west coast of Africa to the Caribbean and southeast United States, has for 50 years been a natural laboratory for studying long-range transport and chemical evolution. Seasonal and drought signatures of African weather/climate have been identified in dust measurements in the Caribbean, and surprisingly little change is measured in the size distribution of dust as it travels across the Atlantic Ocean.
- For global weather and climate models, specifying dust sources is difficult due to the coarse grid resolution, but in certain regions, such as the Saharan Desert, the exact locations of dust emission sites are secondary to providing accurate predictions of surface winds.

Main challenges:

- Identifying source regions across the globe is very difficult, and future progress is likely to rely heavily on remote sensing. That being said, remote sensing has its own limitations (coverage, resolution, etc.) which must be overcome if it can be used to identify both the source locations as well as source soil characteristics. The challenges associated with the remote sensing of boundary layer processes are numerous as well, but if overcome would yield a wealth of data for better constraining emission in global models.
- Long-range transport and atmospheric processing of dust can be very difficult to access from an observational point of view, especially when dust is traversing ocean basins. The representation of in-transit chemical processing, as well as the vertical structure of features such as the SAL, remains difficult to predict and validate without additional measurements.
- The complexity of cloud-aerosol interactions, and the dependence of even the most basic indirect effects on microscale chemical and physical properties of dust aerosol, make parameterizing and measuring these processes extraordinarily difficult. Even in conditions where the emission size distributions, chemical compositions, etc. are known, these can change during cloud formation and long-range transport, and therefore models must be accurately validated in their treatment of the multiple processes occurring. This is impossible, however, without better *in situ* measurements and/or laboratory experiments.

SUMMARY:

The complexities associated with dust emission, transport, and chemistry are numerous, and span from the microscale to the global scale. Further, it is clear that aside from certain exceptions, these scales can interact in non-trivial ways, making small-scale representation in large-scale models crucial for a wide range of problems. This is certainly true for processes such as cloud-aerosol interaction, dust transport in the atmospheric boundary layer, and wind erosion/saltation over heterogeneous surfaces. 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. So is the development of more sophisticated in-situ physical sampling and chemical analysis systems for dust aerosols. Unmanned aerial vehicles are also a promising tool for probing vertical distributions of dust size and concentration, especially in remote areas that are difficult or impossible to access. Long-term dust measurement sites, such as those throughout the U.S., 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/laboratory studies, providing deeper understanding of fundamental processes. It was highlighted that sand and dust emission processes, while being of paramount importance, are still poorly predicted. To inform and validate the next generation of multi-scale models, the need emerges for direct comparisons with targeted field studies.

In the latter, multi-resolution measurements of particle transport are to be carried out in sites for which comprehensive morphological and geochemical information is available. The grand challenge is then to use multi-scale modeling to predict the measured particle size and concentration distribution in the first several meters of the atmospheric surface layer.

Finally, these advances must be matched by improvements in representing these processes in numerical models. In particular, the treatment of sub-grid processes (e.g. turbulence, erosion, particle saltation dynamics, aerosol activation, etc.) 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 surface soil type, land cover, etc.), techniques for quantifying this uncertainty and methods for representing certain processes stochastically must be advanced.