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Why Is Improvement of Earth System Models So Elusive? Challenges and Strategies From Dust Aerosol Modeling

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Abstract

Past decades have seen an accelerating increase in computing efficiency, allowing Earth System Models (ESMs) to represent a widening set of physical processes. Yet simulations of some fundamental aspects of climate like precipitation or aerosol forcing remain highly uncertain and resistant to progress. Dust aerosol modeling of soil particles lofted by wind erosion has seen a similar conflict between increasing model sophistication and remaining uncertainty. Dust aerosols perturb the energy and water cycles by scattering radiation and acting as ice nuclei, while mediating atmospheric chemistry and marine photosynthesis (and thus the carbon cycle). These effects take place across scales from the dimensions of an ice crystal to the planetary-scale circulation that disperses dust far downwind of its parent soil. Representing this range leads to several modeling challenges. Should we limit complexity in our model, which consumes computer resources and inhibits interpretation? How do we decide if a process involving dust is worthy of inclusion within our model? Can we identify a minimal representation of a complex process that is efficient yet retains the physics relevant to climate? Answering these questions about the appropriate degree of representation is guided by model evaluation, which presents several more challenges. How do we proceed if the available observations do not directly constrain our process of interest? (This could result from competing processes that influence the observed variable and obscure the signature of our process of interest.) Examples are presented from dust modeling, with lessons that might be more broadly applicable. The end result will either be clinical depression or the reassuring promise of continued gainful employment as the community confronts these challenges.

Challenge: How do we include the appropriate level of complexity?

Dust aerosols have many climate impacts: radiative forcing of the energy and water cycles (Figure 1), cloud microphysics (including ice nucleation), aerosol and ozone chemistry via heterogeneous reactions on the dust particle surface, the carbon cycle via iron fertilization of photosynthesis.

Many of these impacts depend upon the dust mineral content, which is known to vary regionally with the parent soil of the source region. However, almost all present-day dust models assume globally uniform particle composition.

Model complexity comes at the cost of increased CPU consumption. The minimum representation of physics can be identified by a hierarchy of model calculations with increasing complexity, each compared to observations, but this can be expensive, and the optimal model is likely to vary with the specific application.

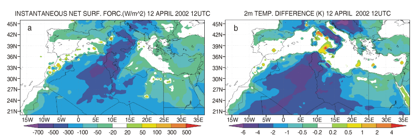

Figure 1: Midday (a) radiative forcing at the surface by a dust outbreak on April 12, 2002 (Wm^{-2}), and (b) contemporaneous change in surface air temperature attributed to dust (Pérez et al. *J. Geophys. Res.* 2006 doi:10.1029/2005JD006717).

Challenge: Range of spatial and temporal scales contributing to the dust cycle.

Dust is often emitted from dry lake beds or valleys where easily erodible particles are accumulated by erosion from the surrounding highlands. The scale of emission is small compared to typical resolution of a global Earth System Model. Downwind transport occurs on the planetary scale of the model circulation.

Dust emission is sensitive to wind gusts: fluctuations in speed that are rapid compared to the calculation of surface wind in ESMs. Wind speed probability distribution functions can represent gusts due to a variety of mechanisms, including convective stirring of the boundary layer, frictional mixing of momentum, and convective downdrafts (Figure 2). The art lies in relating the distribution parameters to physical processes in a way that captures the observed sensitivity. (e.g. How will dust emission by downdrafts change in a warmer climate as deep convection changes?)

Other examples of subgrid scales: dust as a nucleation site for ice crystals, removal of dust by precipitation. How do we include the appropriate level of complexity?

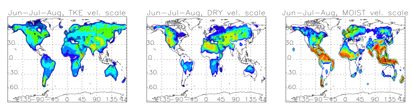

Figure 2: magnitude of surface wind gusts by friction, dry convection and moist convective downdrafts during NH summer, according to the parameterization of Cakmur (Ph.D. thesis, Columbia University 2004).

Challenge: How to attribute model errors to specific physical processes?

What can we learn from model evaluation? Given the inevitable disagreement with observations, how do we identify what went wrong? Most often, we have measurements after several processes have contributed to the observed variable: e.g. Aerosol Optical Thickness (AOT) that is influenced emission, transport and removal as calculated by our model, along with our assumed aerosol radiative properties. The measurements themselves can be ambiguous: e.g. AOT depends upon the assumptions of the retrieval algorithm, and often includes the effect of other aerosols, obscuring the contribution of dust. More discerning satellite instruments are on the horizon (e.g. polarimetry) that can more confidently identify the aerosol type.

Assimilation can help constrain uncertain model parameters (e.g. emission strength) by bringing the model into optimal agreement with a variety of observations, but this optimization can also inadvertently compensate for other model errors.

Sampling is also a challenge. For example, convective downdrafts over land most often occur in the evening, after the sun has set, precluding retrievals in the visible spectrum (Figure 3). We can make the comparison to observations consistent using satellite 'simulators', but at the cost of partially 'blinding' the model by excluding certain periods from the model diagnostics.

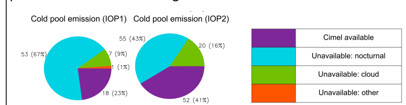

Figure 3: Availability of Sun photometer AOTs when dust is emitted by convective downdrafts (Allen et al. *J. Geophys. Res.* 2015, doi:10.1002/2014JD022655).

Challenge: How to obtain global input data?

Calculation of the dust cycle depends upon dust sources and soil mineral content that vary at scales far below the resolved scale of the model. These inputs require high resolution observations of the Earth surface that exist only for limited regions. As an alternative, satellites provide good spatial coverage (e.g. Figure 4), although they introduce retrieval uncertainties into the ESM boundary conditions, and must be evaluated with direct observations from the Earth surface that were limited to begin with.

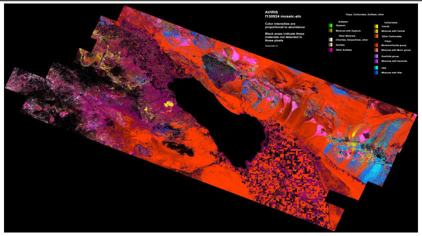

Figure 4: Clay minerals retrieved by the Airborne Visible and Infrared Imaging Spectrometer near the Salton Sea, California.

Challenge: How do we understand model behavior?

Why do we need to understand? Why can't we just run the most realistic version of our model and trust its projections?

It is difficult to improve a model without understanding what physical processes need to be represented. (The alternative strategy is just increasing model resolution or blindly increasing complexity and hoping for the best.)

We also need to identify model behavior that is robust and likely to be reproduced and corroborated by other models. For example, rainfall anomalies caused by dust radiative forcing vary among models, and it is important to understand the physical origin of the variations. Are they due to contrasting calculations of radiative forcing or the imposed model dust distribution? Do some common features of the response have an underlying physical basis that are likely to be reproduced in future experiments?

Identifying robust behavior can be aided by a hierarchy of more simple models that attempt to isolate the fundamental physics. These models allow hypotheses about cause and effect to be tested in a quantifiable way (Miller et al. in *Mineral Dust -- A Key Player in the Earth System,* 2014, doi:10.1007/978- 94-017-8978-3 13).

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