Climate Dynamics Doctoral Dissertation, Spring Term 2023

Modeling and Predictability of Dust Storms and Atmospheric Dustiness over the Western United States

Janak Joshi, George Mason University

Windblown dust and dust storms impact the Earth's radiative energy balance and adversely affect public health. This dissertation addresses five major topics on windblown dust: model improvement (including source attribution of dust); predictability of the physics-based dust storm model; and physics-informed statistical modeling and predictions for, and climatology and variability of the observed, seasonal mean dustiness over the western United States.

Accurate dust modeling is essential for understanding and predicting changes in the Earth's climate system, as well as for guiding early warning systems and mitigation plans to reduce the adverse effects of dust. We have developed a high-resolution (1 km) dust modeling system by building upon an existing modeling framework consisting of the WRF (Weather Research and Forecasting) model, a dust emission model (FENGSHA), and the CMAQ (Community Multiscale Air Quality) model. The dust emission model utilizes new high-resolution data on land use, soil texture, and vegetation index, and new representations, such as for dust source mask, sandblasting efficiency, and roughness correction to threshold friction velocity. All those changes lead to drastic improvements in the model performance, as demonstrated by comparing a simulation of a severe, frontal dust storm in Arizona with observations from ground stations, meteorological radar, and satellite retrievals. The results show promise for developing the model into an operational dust storm-early warning system.

Croplands (as opposed to desert) are traditionally ignored or improperly represented in models. Analysis of the frontal dust storm simulation indicates that croplands contributed over 50% of PM_{10} (the concentration of particles with a diameter less than 10 µm) in the Phoenix area, exceeding US EPA-established ambient air quality standards. The results also suggest cropland dust being the most likely cause of a dust-related traffic accident associated with minor injuries. These results imply the importance of including cropland dust sources in emission inventories and air quality simulations.

Results from model sensitivity experiments have strong implications for representing the dust aerosol in air quality and climate models. Specifically, our sensitivity analysis strongly suggests using a dynamic, rather than a static, dust source mask; a physics-based, rather than a clay-based, expression for sandblasting efficiency; and up-to-date, rather than old, data for land use in a dust emission model. The analysis further suggests that meteorological nudging may be advantageous for hindcasts and warns the research community to be careful about choosing the large-scale meteorological fields to drive the WRF model; in the studied case, NARR-driven WRF-runs produced better dust simulations than NAM-driven ones that led to severe underpredictions.

We used the physics-based model to conduct perhaps the first study of short-range (1–8 days) predictability of a dust storm. Here, we simulated uncertainty in meteorological initial conditions with a time-lagged ensemble method. Wind speed V is generally the most important meteorological variable for dust emission. The spread of V among ensemble members was only moderately sensitive to initial condition because of the influence of the domain's prescribed lateral boundary conditions. The corresponding dust simulations, however, had a much larger spread, and differed increasingly from observations with lead time. As expected, ensemble spread for V increased with domain size.

We used dust optical depth data based on the MODIS Deep Blue aerosol product to analyze seasonal mean dustiness (occurrence frequency of high optical depth values) over the western United States for 2003–2020 (longer than previous studies). Dustiness had a consistent upward trend for a southwestern region in fall and summer. Ground bareness and precipitation explained most of the observed trends in dustiness. Multiple linear regression shows that seasonal mean dustiness depends on precipitation, bareness, relative humidity, planetary boundary layer height, soil wetness, temperature, and wind speed, but the contributions of these factors depend on the region and the season. The roles of V and V^3 in seasonal predictions were generally insignificant. The regression model explains $\sim$ 40–80% of the observed variability in dustiness, and the corresponding seasonal predictions made using the dust-controlling environmental variables from two different climate models (GFDL-SPEAR and NASA-GEOS-S2S) indicate a promising potential for seasonal predictions a few seasons in advance.

Finally, a comparison between seasonal mean dustiness based on the MODIS data and MERRA-2 data showed a general mismatch between the two data sets, indicating a need to evaluate the MERRA-2 data in more detail.

The findings from this dissertation research should prove useful for both dynamical and statistical modeling for windblown dust and dust storms, in addition to alerting the community to the relative strengths or weaknesses of various data sets. Moreover, the study informs on the climatology and trends of observed dustiness. Finally, the results from the source attribution case study should provide an impetus to better represent in models the various dust sources with their dynamic (varying in space and time) nature represented well.