Dust emission and deposition in regional models

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In recent years, there have been significant advances in representing mineral dust in various regional (mesoscale) models, ranging from the chemical transport models (*Carmichael et al., 2003*), regional climate models (e.g., *Zakey et al., 2006*), to numerical weather prediction models (e.g., *Perez et al., 2006*). Such increasing interest is driven to a large extent by a number of advantages offered by the regional models compared to the global scale circulation models. Regional (mesoscale) circulation models, in particular, are well suited for simulations of individual dust outbreaks. Their finer spatiotemporal resolution and multiple physical parameterizations allow for more realistic representation of the topography, soil conditions, mesoscale circulations, and enable better validation against observations.

1. Representation of dust emission in regional models

Despite some apparent advantages, regional models, similarly to global models, rely on dust emission parameterizations to model atmospheric dust loadings. Dust emission schemes that have been developed and used in the regional models range from simple type schemes, in which the vertical dust flux depends on a prescribed erodible surface fraction and fixed threshold friction velocity [*Gillette and Passi, 1998*; *Uno et al., 2001*] to advanced schemes, in which the surface characteristics are taken into account explicitly in the parameterizations of the threshold friction velocity, and horizontal and vertical fluxes [*Marticorena and Bergametti, 1995*; *Shao et al., 1996*; *Shao, 2004*].

Dust emission schemes calculate the mass of the emitted dust particles, which is quantified by the vertical dust flux F ($g\ cm^{-2}s^{-1}$). In the simple schemes F is commonly expressed in a general form as: $F = CfP(u_*^n)$, where C is a dimensional, scheme-specific constant of proportionality, f is the erodible fraction of the model grid cell, P is a polynomial of degree n, and u_* is the model friction velocity. Dust modeling systems, such as CFORS [*Uno et al., 2001*], COAMPS [*Liu and Westphal, 2001*], DREAM [*Nicovic et al., 2001*] and CARMA-MM5 [*Barnum et al., 2005*], have utilized simple dust emission schemes ($F \sim P(u_*^3)$, $F \sim P(u_*^4)$) to model vertical dust fluxes. Some critical limitations of these schemes are that the normalization constant C is not known, the erodible fraction must be prescribed for pre-defined active dust sources, and the threshold friction velocity is fixed regardless of land surface conditions. But an obvious advantage of simple schemes is that they are easy to implement within the regional or global models, though associated errors are large.

The advanced, physically-based dust production schemes provide more realistic representation of the emission process. However, they require additional information on land surface properties and input parameters, as well as are much more complicated to implement. Some data and variables are readily available within a regional model framework, since it is designed to simulate the meteorological fields as well as land surface characteristics involved in land-atmosphere interaction processes. Other critical data (especially, undisturbed soil particle size distributions and aeolian surface roughness) that are needed to support physically-based schemes are largely missing for the majority of the dust source regions.

The physically-based dust emission models can be broadly classified into energy-based [*Alfaro and Gomes, 2001*; *Shao et al., 1996*] and volume removal based [*Lu and Shao, 1999*; *Shao, 2004*], depending on the linkage between dust emission and saltation. The intensity of saltation is quantified by the saltation (horizontal) flux Q ($g\ cm^{-1}s^{-1}$), which is commonly expressed as a function of the friction velocity u_* and threshold friction velocity [*Owen, 1964*]. The threshold friction velocity is a minimum friction velocity required to initiate soil particle motion. It is a property of the soil surface and depends on the soil type, type of roughness elements, surface crusting, salt concentration, and soil moisture.

The physically-based dust emission schemes have been originally derived for different surface conditions, i.e. soil types, roughness elements, etc. Despite some similarities, these schemes employ different parameterizations of related physical mechanisms, as well as require different input data. Thus, dust schemes can produce quite different vertical fluxes even within the same regional model. A step-by-step intercomparison between dust schemes is necessary for identifying the sources of biases and their relative importance. *Zhao et al.* [*2006*] was the first study that investigated the differences in the dust emission calculated with two physically-based schemes (MB [*Marticorena and Bergametti, 1995*; *Alfaro and Gomes, 2001*] and Shao [*Shao, 2004*]) within the same mesoscale model. *Zhao et al.* concluded that the drag partition and moisture parameterizations of the threshold friction velocity played a central role in causing significant differences in modeled dust vertical fluxes in East Asia. More recently, *Darmenova et al.* [*2008*] investigated the similarities and differences between physical parameterizations employed in the MB and Shao [*Shao et al., 1996*] schemes by developing a new dust emission module (DuMo) within the NCAR WRF mesoscale model. For the first time, *Darmenova et al.* performed a comprehensive intercomparison between all involved parameterizations and required input parameters in a consistent fashion, focusing on the regional specifics of dust sources in Central and East Asia. This study highlighted a number of critical issues involved in implementation of dust schemes within the regional model. It also demonstrated that two different dust emission schemes still resulted in noticeable differences in dust horizontal and vertical fluxes, despite an effort to establish direct associations between input parameters required by these schemes. Thus, these studies reveal that the choice of the dust emission model along with the physics options of the regional model leads to the inherent uncertainty in the amount of emitted dust. A new methodology for bracketing the range of uncertainty (errors) in the regional dust models is urgently needed. This issue will be important for model validation against observations, as well as for model intercomparison.

Up to date, a number of regional dust modeling systems have incorporated physically-based dust emission schemes (with various modifications): for instance, LM-MUSCAT [*Heinold et al., 2007*], CEMSYS5 [*Shao, 2004*], CHIMERE-DUST [*Menut et al., 2004*], RegCM [*Zakey et al., 2006*], WRF-DuMo [*Darmenova et al., 2008*], NARCM [*Gong et al., 2003*], and MesoNH [*Grini et al., 2006*]). The modeling systems vary greatly in their choice of emission parameterizations and the set of input parameters driving the schemes. Some of the models employed external land surface datasets that are more appropriate for aeolian scales. For instance, CHIMERE-DUST, LM-MUSCAT and WRF-DuMo use satellite retrieved surface roughness, which is more suitable for dust emission modeling compared to the aerodynamic roughness used in regional models, especially for barren surface types. Furthermore, CHIMERE-DUST and WRF-DuMo employ undisturbed (dry-sieved) soil particle size distributions to describe better the desert soil conditions. To provide soil moisture in the topmost 1-2 cm soil layer required in the emission scheme, CHIMERE-DUST uses soil moisture computed by a hydrological model with fine vertical resolution. Instead of ingesting directly the modeled friction velocity, LM-MUSCAT and CHIMERE-DUST recalculate the friction velocity by using external roughness datasets and assuming logarithmic wind profile. WRF-DuMo has a flexibility to use either model-predicted or recalculated friction velocity. All the above factors will affect the amount and the spatiotemporal distribution of emitted dust.

Bridging the gap between the local wind erosion metrics and the mesoscale framework is another central issue in developing a regional dust modeling system. To account for the subgrid scale variability of the meteorological and land surface parameters, modelers often apply various parameterizations. For example, *Shao et al.* [*2002*] used mosaic approach to calculate vertical dust fluxes for land surface and friction velocity datasets available at different spatial resolutions. *Westphal et al.* [*1988*], *Grini et al.* [*2005*] and *Darmenova* [*2006*] considered Weibull and/or bivariate normal probability distribution of modeled surface winds to represent subgrid heterogeneity in the wind fields. The scaling issue of meteorological and land surface characteristics will be always relevant as long as we stay within a dynamical framework operating on metrics different from the aeolian ones. Therefore, not only improvement in dust schemes and the quality of input parameters will be advantageous, but also a new methodological framework for coupling the dust emission scheme with the other components of the regional model is needed.

2. Representation of dust deposition in regional models

While an accurate modeling of dust emission rates is critical for improved simulations of 4D dust fields, quantification of dust removal rates is no less important and is needed for the complete characterization of the dust cycle. Mineral dust particles are removed from the atmosphere through dry deposition processes (such as surface deposition and gravitational settling) and wet deposition processes (such as rainout and washout). Although the importance of removal processes has been well recognized for some time, there has been little improvement in parameterizations of these processes in the regional models. The roots of the problem are in the limited measurements of dry and wet removal rates, the complex nature of dust particles (i.e., varying size, density, shape and solubility), and simplified representation of dust in the regional models.

Dry deposition depends on the variety of factors such as meteorological conditions near the surface, physiochemical properties of mineral dust and the nature of the surface itself. In the regional models dry deposition flux of dust particles is often quantified as the product of the dust concentration in the first model layer and the dust deposition velocity. Different parameterizations of the deposition velocity of particles have been developed in the literature. The most commonly used formulation is based on the resistance concept (e.g., *Wesely, 1989*). In this approach, dry deposition is represented as three resistances in series (aerodynamic resistance to transfer, resistance to transfer across the quasi-laminar surface layer and resistance to surface uptake) in parallel to a second pathway - gravitational settling velocity. The latter is computed from the slip-flow corrected Stokes law. *Venkatram and Pleim* [*1999*] pointed out that the electrical analogy is inconsistent with the mass conservation of particle dry deposition. They suggested an alternative formula for the calculation of the dry deposition velocity, which was adopted in CHIMERE-DUST. A commonly used model for computing size-resolved particle deposition velocity is that proposed by *Slinn* (*1982*). Alternative dry deposition models, which are largely based on the concepts of the *Slinn* model, have been used for calculations of deposition rates in the NARCM [*Zhang et al. 2001*], LM-MUSCAT [*Zhang et al., 2001*] CARMA-MM5 [*Shao, 2000*] and RegCM [*Giorgi, 1986, Zhang et al., 2001*]. Somewhat simpler expressions of the dry deposition velocity have been used in CFORS and COAMPS. The former calculates deposition velocity trough the *Stull* [*1988*] relation of the wind stress and wind speed while the latter uses the relationship between the wind speed at *10 m* and the drag coefficient. No regional models take into account nonspherical shape of dust particles and varying particle density in calculations of gravitational settling velocity.

Wet deposition of aerosols is usually partitioned between in-cloud scavenging (rainout) and below-cloud scavenging (washout). The former is efficient for submicron particles while the latter is important for particles in the coarse mode. In-cloud scavenging in regional (and global) models is described by using first-order rate loss operators. In addition, differentiation is made between wet removal in large-scale and convective precipitation. Efficiency of in-cloud scavenging depends mainly on dust solubility, which controls the dust particles scavenging efficiency. In turn, dust solubility depends on the mineralogical composition and the pH of the aqueous phase. None of the regional models treats explicitly the mineralogical composition and hence a simplified assumption on the soluble fraction of dust must be made. Some regional models do not include wet removal at all. Furthermore, both observational evidence and modeling suggest that solubility of airborne dust can change significantly during mid- and long-range transport due to internal mixing with other aerosol species and/or cloud droplets. The modeling of the mixing state of dust poses a large challenge in the regional models, so the rain-out removal rates of dust particles remain poorly constrained.

Similarly to the rainout, the rate of transfer of dust particles into rain droplets below a cloud (washout) is calculated via first-order rate loss ($\partial c/\partial t = -\lambda c$). The scavenging coefficient λ depends on the particle size and solubility, the collectors size distribution and fall speeds, and the precipitation rate and phase (rain or snow). *Jung and Shao* [*2006*] classified the below-cloud removal parameterizations into four types depending on the formulation of the scavenging coefficient. The first type calculates the scavenging coefficient as a function of raindrop size distribution and dust-raindrop collection efficiency (used in LM-MUSCAT). The second type estimates scavenging coefficient as a function of precipitation rate (used in COAMPS, CFORS). In the third type, an empirical relationship derived from direct measurements of scavenging coefficients is used. The forth type estimates the large-scale dust deposition trough a scavenging ratio. Recently, *Shao and Dong* [*2006*] performed an intercomparison of the wet deposition schemes used in regional and global dust models. They reported a great diversity in the type and level of complexity of employed parameterizations ranging from the use of fixed scavenging ratios below cloud to relatively sophisticated in- and below-cloud parameterizations.

Several central problems affecting the quality of simulated dust removal rates can be pointed out:

(1) Dust deposition parameterizations assume that particles are spherical. However, field measurements suggested that surface irregularities initiate perturbations in the flow around the grains during deposition, resulting in a lower fall velocity for the particle compared to a sphere of the same size and density [*Goossens, 2005*]. Giving that dust particles exhibit a variety of shapes, corrections of the settling velocity are hard to implement.

(2) Observational evidence suggests that during long-range transport large dust particles (> 7 μm) are often present in the atmosphere [*Maring et al., 2003*]. Dry deposition parameterizations relying on Stocks sedimentation remove very efficiently large particles. This could lead to a systematic underprediction of dust concentrations away from dust sources, especially for coarse dust mode.

(3) Problems in modeling of clouds and precipitation remain a long-standing issue. The values of the precipitation intensity are the mean value over the grid cell and do not reflect sporadic rain outbursts. Thus subgrid parameterization of the rain rate is highly desirable, especially for the GCM metrics [*Rostayn and Lohman, 2002*]. Still the soluble fraction of dust is not well known, so scavenging efficiencies are assigned to a fixed value. Thus they do not reflect regional specifics of dust properties and their dynamics (i.e., mineralogical composition, aging, etc.). As a result, the wet removal of dust is one of the major sources of uncertainty in calculating dust spatiotemporal distribution, especially in the marine environment downwind from the sources.

(4) The scavenging by snow and ice is poorly known. The uncertainties are related to the large variety of types and shapes of solid hydrometeors [*Sportisse, 2007*]. Also, if dust particles serve as ice nuclei, their removal might involve additional pathways.

(5) There is a lack of observations of the dry and wet removal of dust in the sources and during the transport in the atmosphere to test and constrain regional models.

3. Summary

The progress in dust modeling over the last decade has been significant, however a number of critical problems involving implementation of dust emission and removal processes in regional models still remain:

- Selection of the dust emission model along with the physics options inside the regional modeling system results in a noticeable difference in the calculated dust fluxes. A new methodology for bracketing the range of uncertainty in the regional dust models is required for the purpose of model intercomparison and validation.
- Critical data (especially, undisturbed soil particle size distributions and aeolian surface roughness) needed to support physically-based dust emission schemes are not available for the majority of dust source regions.
- Existing gap between the aeolian metrics and the mesoscale modeling framework; need for integrated datasets and/or improvement in boundary layer and land surface schemes performance in arid regions.
- Extremely limited measurements of vertical dust fluxes and dust (dry and wet)

deposition fluxes that can be used for model validation.

- Dust particles are assumed to be spherical that introduces bias in calculating dry removal rates.
- Limited data on solubility (and scavenging efficiency) of dust aerosols; solubility likely changes during transport and shows strong regional signature.
- Quality of model predicted precipitation rates especially at coarse resolutions; need for subgrid parameterization of sporadic violent convective precipitation.

With recent advances in satellite remote sensing many attempts have been made to retrieve input parameters such as soil moisture and surface roughness in arid regions, which are required for dust emission. An integrated approach that merges satellite data, ground based observations and regional modeling seems to be a promising strategy for combining the strength of individual datasets and providing comprehensive picture of dust processes on a regional level (Darmenov et al. 2008). Due to the large uncertainties in physical parameterizations and the quality of input parameters, development of new methods (e.g., an ensemble type modeling) will be required to improve modeling of mineral dust cycle.

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