application of hyperspectral data. It is anticipated that current results will be further enhanced through improved physical modeling, a less constrained operational environment allowing use of higher spectral and spatial resolution and cloudy data, and the effective exploitation of the new infrared hyperspectral data about to become available from the Infrared Atmospheric Sounding Interferometer (IASI) on the European METOP series of operational satellites, the Cross-track Infrared Sounder (CrIS) on the U.S. National Polar-Orbiting Operational Environmental Satellite System (NPOESS) series of operational satellites, and the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) is being considered for flight on the International GeoLab experimental satellite.

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MEETINGS

Linking the Scales of Observation, Process, and Modeling of Dust Emissions

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Each year, approximately four billion tons of dust are mobilized from dry landscapes and remain in the atmosphere from hours to weeks before being deposited. These large atmospheric dust loadings directly affect atmospheric dynamics and global climate [*Intergovernmental Panel on Climate Change*, 2001], human health [*Plumlee and Ziegler*, 2003], and soil fertility, and also influence ecosystem dynamics in ocean basins.

Although some progress has been made in quantifying feedbacks (see Figure 1 on the *Eos* Electronic Supplement at http:www.agu.org/eos_elec/000931e.html) in the atmospheric dust cycle, the critical factors controlling the entrainment and transport of dust at differing spatial and temporal scales remain poorly quantified.

Certain key questions remain:

- What land-surface and climate conditions give rise to dust emission, and what geomorphic processes influence the capacities of these settings to generate dust?
- What portion of the emissions is attributable to anthropogenic disturbances through land-use practices, climate change, or changes in land-use practices resulting from climate change [*Zender et al.*, 2004]?
- How can we forecast changes in the above factors to assess future dust emissions, on the scale of seasons to a few decades?

Dust processes span more than 12 orders of magnitude in spatial and temporal scales, from individual grain-to-grain collisions that take place in fractions of a second, to global transport of dust over glacial-interglacial cycles (Figure 1a). The methods used to study dust cycle processes vary over a similar range of scales (Figure 1b).

Traditionally, studies have explored the controls on dust emission, transport, and deposition using either "top-down" (global modeling) or "bottom-up" (small-scale process) approaches. Global or regional models typically consider atmospheric processes that trigger dust storms and control dust transport, but lack the ability to predict how small-scale surface sources may change in both space and time.

In contrast, local-scale process studies focus on relations among particle movement, wind stress, surface roughness, wind stress, and dust mobilization. This information, however, is rarely applied beyond regional scales to examine the continental-scale spatial distribution of dust entrainment and transport. Moreover, emerging information from geologic-geomorphic investigations of dust sources, along with detailed mapping of sources from remote platforms, have not yet been folded comprehensively into regional or global models of dust emission.

The integration of the global modeling and local-scale process approaches offers a ripe and essential opportunity to quantify dust emission potential (wind erosion vulnerability) at spatial scales suitable for linking to mesoscale and global climate models.

A workshop held recently in Boulder, Colorado, brought together dust researchers studying different aspects of the dust cycle with the aims of (1) developing a dialogue between the dust-modeling, field, and experimental research communities and (2) outlining strategies to link the approaches that examine dust-emission at different spatial and temporal scales.

Participants identified the following critical topics for future research.

- Soil texture characteristics and sediment availability are driving forces for understanding dust emissions. Surface texture (particle-size distribution) is critical for accurate simulation of dust emissions, and remains to be adequately addressed in most models. A global data set quantifying the proportions of clay, silt, and sand available in surface soils remains to be developed. The diverse opinions expressed regarding which characteristics are most important to dust entrainment emphasized that further field research and sensitivity studies are required.
- Vegetation type, cover, and distribution strongly influence dust emissions. Vegetation cover is a primary controlling factor, where regions with >15% vegetation cover emit minimal dust. In regions of sparse cover, the pattern or distribution of vegetation can result in vastly different dust emissions. Importantly, senescent or dead vegetation can play a major role in stabilizing surfaces, thereby reducing dust emissions. Although vegetation cover is regularly incorporated in dust emissions model schemes, the above effects remain to be adequately evaluated.
- Crusts inhibit dust emissions. In sparsely vegetated regions, sedimentological, biological, and salt/precipitation crusts can all inhibit

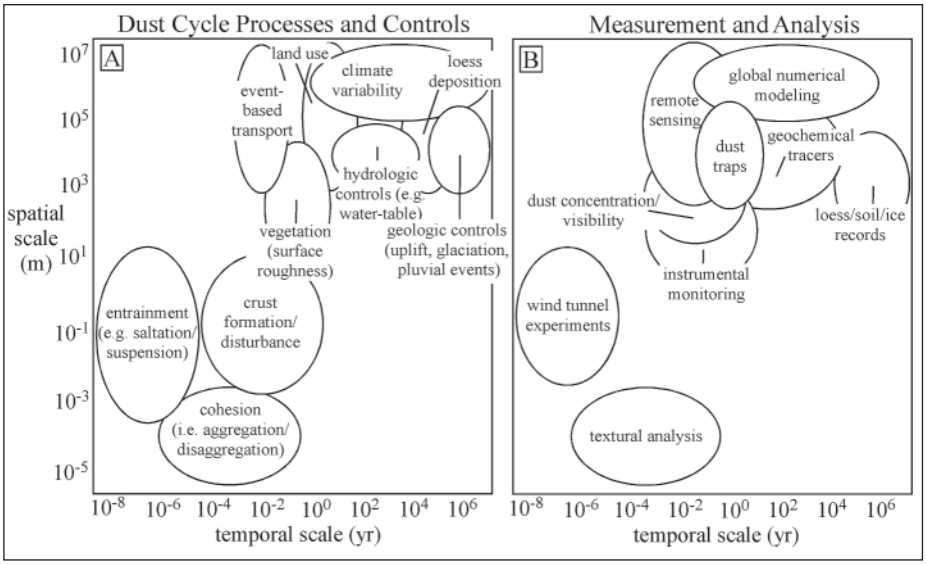

Fig. 1. (a) Dust processes span more than twelve orders of magnitude in spatial and temporal scales. (b) The methods used to study dust-cycle processes must address these ranges of scales.

dust emissions. Deflation requires that the energy of impacting grains overcome the binding strength of soil crusts, which can vary tremendously both spatially and temporally. Crusting processes remain to be incorporated into dust models, and their importance to both regional and global dust budgets has not been quantified.

- Moisture, both precipitation and groundwater, has a strong control on dust emissions at a given site. Moisture often operates with temporal lags of different scales, depending on the process that it influences. The effect of moisture upon dust emissions appears to depend on the frequency and magnitude of precipitation, and the effect on dust emission can be positive or negative.
- Small-scale surface stresses and their interaction with surface topography are crucial for understanding where dust is mobilized. Correctly simulating surface wind shear at smaller scales is perhaps the greatest challenge for modeled winds data sets that are used in global models, and underscores the need for regional, mesoscale climate models to bridge the gap between the two scales.
- Identification of dust emission "hot spots" from satellite imagery needs more fieldwork for "ground truth" verification. Despite the importance of the Sahara as a dust source, the specific geomorphic settings (i.e., playa margins, fan surfaces, wadi mouths) that are hot spots [*Gillette*, 1999] are poorly understood.

Workshop participants agreed that field experiments are needed to link small-scale processes controlling surface emissions to remotely sensed characteristics, at scales applicable to dust models. A successfully designed field experiment would serve as a "proof of concept" that field programs are capable of integrating small-scale observations with regional-to-global scales in dust research.

While many regions would be outstanding locations for integrated field research, the workshop identified the desert regions of western North America, with the Mojave Desert as a focal point. Western North America is historically significant because land management practices have dramatically altered its dust emissions. For instance, the desiccation of Owens Lake, California, created a large source of alkaline dust [*Cahill et al.*, 1996].

The Mojave Desert, the western Great Plains, and northern Mexico collectively contain several types of dust emission settings that have generated dust storms. Logistically, the Mojave Desert already has extensive documentation of geological, ecological, and surface characteristics, anthropogenic activities, and climate changes.

Thus, the proposed field study could take advantage of the monitoring, instrumentation, and geologic knowledge of the Mojave Desert while expanding to encompass a larger setting of dust emissions (see Figure 2 on the *Eos* Electronic Supplement at http:www.agu.org/eos_elec/000931e.html). Importantly, this region is an area of current interest for which there already exists a tremendous resource of field expertise.

The collective capabilities in mesoscale modeling, remote sensing, and field geology will enable the examination of a wide range of dust emission settings in western North America and in other deserts of the world.

Several participants agreed to serve on a committee that will design an experiment combining modeling, field studies, and monitoring. Ideally, this experiment would later be expanded, applied, and tested in other dust-producing regions around the world. Updates concerning the progress of this committee will be posted on the workshop Web site: http://esp.cr.usgs.gov/info/dust/.

The workshop, "Linking the Scales of Observation, Process, and Modeling of Dust Emissions," was hosted by the U.S. Geological Survey, and was held 21–22 October 2004 in Boulder, Colorado.

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