Dust Emission and Deposition in the Southwestern United States – Integrated Field, Remote Sensing, and Modeling Studies to Evaluate Response to Climatic Variability and Land Use

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ABSTRACT: Geomorphic processes in arid regions are particularly sensitive to climatic variability. In this context, integrated studies are being conducted to understand the response of dust emission and deposition to climatic and land-use change in the arid southwestern United States. Several approaches are taken to monitor wind erosion and characterize modern dust – its sources, flux, and composition – to document the potential for desertification under future climatic conditions. Wind erosion is monitored at ecologically sensitive sites, using meteorological stations that measure sand flux within the saltation layer. Dust deposition is also monitored at these and many other sites using different types of dust collectors. In addition, new remote sensing methods detect the location, frequency, magnitude, and duration of large dust-emission events. Remotely sensed images of vegetation change, combined with those that illustrate high soil reflectivity, complement dust-detection methods to identify areas especially susceptible to wind erosion. Dust trapped in collectors and in snow is characterized for its physical, mineralogic, and chemical properties. Combined with soil and weather data, such characterization sheds light on: (1) the relation between dust storms and synoptic climatic conditions; (2) the importance of Owens (dry) Lake (California) as a dominant source of southwestern U.S. dust, for as much as 400 km downwind; (3) the impacts of human disturbances in the desert, revealed by signatures of agricultural and construction dust; and (4) the composition and flux of regional background dust composition and flux. Past dust flux is studied from late Quaternary eolian deposits, partly using a new combination of magnetic and chemical methods developed to recognize eolian dust in soils and surficial deposits over large regions. Such studies have applications to understanding current plant distribution, substrates for biologic soil crust, and paleoenvironmental histories of ecosystems.

A wind-erosion model based on wind strength, atmospheric shear stress on the surface, and atmospheric stability is being developed. This model will be constrained by remote sensing and ground-based observations and will then be linked with a regional climate model and interactive vegetation package to forecast how various climatic and land-use scenarios interact with critical wind speeds required to move surface materials. We will attempt to answer the following questions: How does wind strength vary with natural climate cycles on decadal and century time scales? To what extent will winds become stronger or weaker under future climate scenarios? How have soil moisture and vegetation changes affected wind erosion in the past, and what can we expect in the future? As an example of possible future conditions, projections of doubled atmospheric CO_2 (above pre-industrial levels) for the southwestern U.S. suggest a decrease in winter soil moisture, which may enhance wind erosion.

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INTRODUCTION

A major objective of global change studies is to understand how climatic variability influences surficial geologic processes and thus affects land surfaces. Another goal is to predict future regional landscape impacts through climate modeling. Understanding the effects of climate changes, past and future, on rates of surficial processes requires knowledge about how these processes respond today to changes in controlling variables so that appropriate process-response models can be developed. We report here on interdisciplinary studies of responses of eolian processes to climatic and land-use changes in the semi-arid to arid southwestern United States (Fig. 1). These studies have only just started, and this paper, with a focus on wind erosion and eolian sediment transport, accordingly emphasizes the design, development of new methods, and goals of the current work. This work builds on earlier important studies of wind erosion and dust emission in the southwestern U.S. (Nakata et al., 1976; Gillette et al., 1978, 1982, 1989; Wilshire, 1980; Reheis and Kihl, 1995; Brazel and Nickling, 1987; Gill, 1996; Bach et al., 1996; Cahill et al., 1996; Lancaster, 1997; Marticorena et al., 1997).

Continued progress in understanding wind erosion and the environmental effects of eolian dust transport requires scientific advances on several fronts. First, we need improved wind-erosion models that describe dust emission (flux), based on soil conditions and land-surface characteristics (e.g., Gillette et al., 1982). Such models will yield more reliable predictions for the occurrence of dust storms. Moreover, we need better ways to monitor dust storms and dust transport pathways, especially over high-reflectivity desert surfaces. Finally, we have much to learn about the role of deposited dust in arid-land ecosystem dynamics (e.g., nutrient delivery) and in ecosystem history, inasmuch as the amounts and types of dust change over time under different environmental conditions.

Although dust emission in the southwestern United States is minor on a global scale, it is important regionally for management of lands vulnerable to wind erosion, for issues of human health and safety, for potential damage to equipment and infrastructure, and for ecosystem function (Goudie, 1978; Pye, 1987). Moreover, some National Parks and Federally designated wilderness areas in the western United States have protected viewsheds and thus are required to maintain certain high standards of visibility. Such standards, however, are commonly exceeded, but the causes of visibility degradation are still poorly understood. In particular, it is difficult to reconstruct the contributions of distant sources of haze caused by mineral or non-mineral aerosols, and to determine the relative roles of natural processes and human activities, such as agriculture and urbanization, in producing atmospheric haze. Moreover, if models of dust emission can be developed for southwestern United States, they can also be applied to deserts elsewhere.

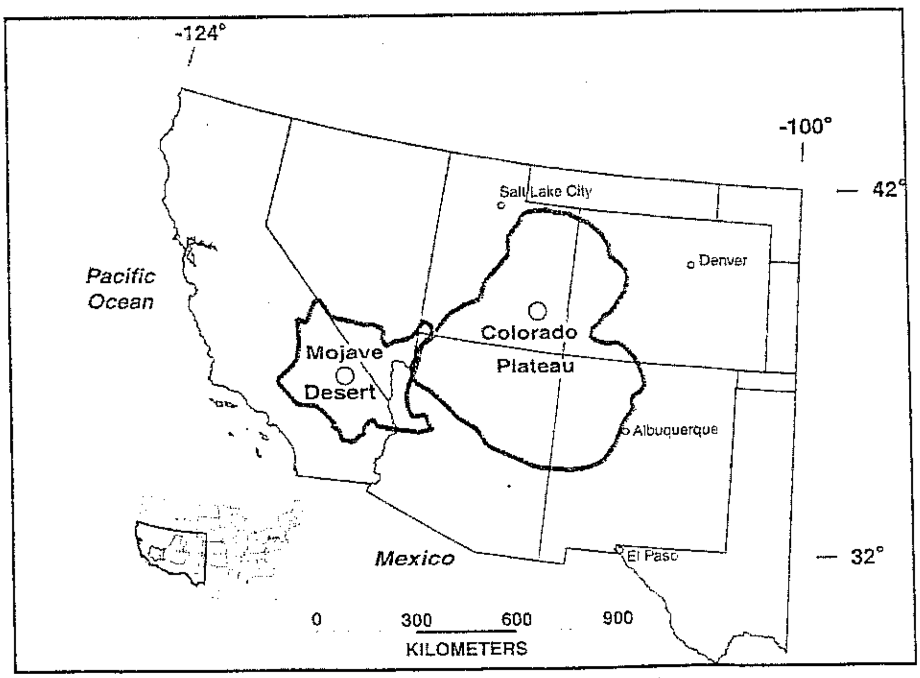

Figure 1 Map of southwestern United States showing extents of the Colorado Plateau and the Mojave Desert, and study sites (open circles; Canyonlands on the Colorado Plateau; Soda Lake-Devil's Playground in the Mojave Desert) discussed in text.

In this paper, we describe the integration of geologic and ecologic studies, meteorological data, remote sensing methods, and modeling techniques to understand dust emission and deposition in the southwestern United States. The methods are designed to (1) determine soil conditions and properties leading to dust emission; (2) detect and track dust events from satellite images; (3) calculate current rates of dust emission and deposition in some ecologically sensitive areas; (4) develop a dynamic wind-erosion model that includes the effects of atmospheric stability; (5) distinguish between mineral-dust haze and industrial/urban pollution at locations far from potential sources; (6) characterize the mineralogy and chemistry of dust and evaluate its roles in ecosystem function, including possible effects on exotic species invasion; (7) detect eolian dust in desert soils, determine dust sources, and estimate past rates of deposition; and (8) model future dust emission and transport under different climatic scenarios.

PHYSICAL SETTING AND CLIMATOLOGY

The southwestern United States is characterized by great variations in topography and climate. Arid and semi-arid, sparsely vegetated land dominates low- to moderate-elevation (less than about 2000 m) terrain. Precipitation in these desert regions is typically less than 250 mm/year, with large seasonal and annual variation that results in corresponding changes in vegetation cover. These changes in vegetation cover have a major influence on dust emissions, with reductions in emissions during wet seasons or years related partly to increased plant cover (Brazel and Nickling, 1987; MacKinnon et al., 1990; Musick, 1999).

Arid lands of the western United States periodically experience strong winds, commonly having annual drift potential >200 vector units (terminology of Fryberger and Dean, 1979). The seasonal timing of dust generation and the downwind areas affected vary depending on prevailing weather systems as well as on geographic and physiographic setting (e.g., Bach et al., 1996; Brazel and Nickling, 1987). Dust emissions may be associated with cold easterly Santa Ana winds over southern California; and with high downdraft winds ahead of mostly southerly convective, monsoonal storms, especially during summer in Arizona and New Mexico (Baudat and Breed, 1999).

METEOROLOGICAL STATIONS AND WIND EROSION MONITORING

Wind erosion is monitored at ecologically sensitive sites, using recently installed portable meteorological and geological instrumentation designed to function in remote areas for long periods of time. The stations record soil temperature and moisture, in addition to standard meteorological parameters (wind speed and direction, precipitation, air temperature at 3-m height, temperature gradient between 1 and 3 m heights, relative humidity, as well as incoming and outgoing radiation in the visible to near-infrared (400–1100 nm) spectrum. Wind erosion and particle displacement are determined in several ways. First, an 'erosion sensor', consisting of a piezoelectric crystal mounted 5 cm above the surface, measures the number of sand-particle impacts each hour and the resulting kinetic energy of the particles (Tigges et al., 1999). Total sand and dust movement is monitored over longer time periods by weighing sediment trapped in collectors, which rotate to face the wind, at heights of 0.1, 0.5, and 1.0 m above the surface. Several other similar meteorological stations with erosion sensors and wind-oriented sediment collectors have operated in the southwestern U.S. for nearly 20 years (Breed and Reheis, 1999). Data from these stations have been recently used to test models of dune mobility based on climatic indices (Lancaster and Helm, in press) and to assess the response of sand-transport processes to climatic variability. Initial results of these studies show that sand-transport rates are very sensitive to variations in vegetation cover resulting from changes in annual precipitation.

One set of stations is located in the vicinity of Soda Lake-Devil's Playground in the east-central Mojave Desert of California (Fig. 1), near a Holocene dune field (Kelso Dunes) (Lancaster, 1997). Today, the area commonly experiences dust events, apparently related to both natural and human activity. Combined with vegetation-change analysis and dust-emission monitoring from ground and satellite observations, the stations provide meteorological data to test and validate a wind-erosion model described below.

Another set of stations is located in the Canyonlands district of the central Colorado Plateau in southern Utah (Fig. 1), a high-elevation (>1000 m) semi-arid region. For this area, land-management and scientific issues of ecosystem function and evolution, plant community structure, invasion by noxious weeds and annual grasses, landscape stability, and land-surface vulnerability to wind erosion are considered in the context of prior and current land use as well as climatic variability. Wind-erosion monitoring at these sites exemplifies land-surface responses to weather conditions and land-use that will provide important baselines for the recognition of future changes to the landscape. A comparison of monthly total sand flux (particle impacts) at three stations partly reflects past and current land use as it affects vegetation cover (Fig. 2). Sandy surficial sediment at all sites is similar in particle-size distribution and source. Highest sand

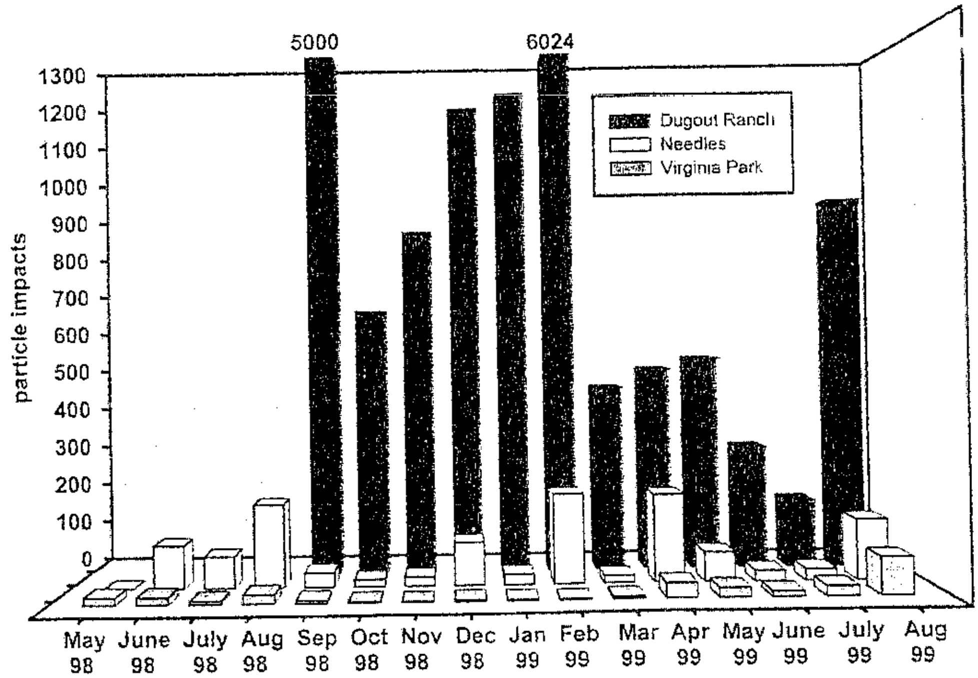

Figure 2 Bar diagram showing sediment-particle impacts (total impacts per month) on wind-erosion monitors at three stations in the Canyonlands area, Utah. The Dugout Ranch station began operation in September 1998.

flux is at the Dugout Ranch site (1545 m), which has been grazed by cattle since the 1880s and is currently grazed by 150–200 cattle for 2–3 weeks during the spring. Vegetation at the site is mainly exotic, weedy annual plants that provide incomplete ground cover. The site lacks significant biologic soil crust (cyanobacteria, lichen, or moss). Intermediate sand flux is at the Needles site (1512 m), which was intensively grazed until about 25 years ago. Invasive annual grass dominates the site, which also has a thin cyanobacterial soils crust characteristic of moderately disturbed areas. Lowest sand flux over the study period is at Virginia Park (1725 m), one of the few grassland areas in the region that was never grazed due to inaccessibility to livestock. Native perennial grasses dominate, with spaces between plants commonly occupied by well-developed biologic soil crust (mostly cyanobacteria, lichens, and mosses). We conclude that sand-flux variability at these three sites may at least partially reflect the history of grazing. The different sand flux values at the sites, however, also correspond to different degrees of exposure to wind. The Dugout Ranch site has the greatest wind exposure (wind speeds sometimes in the range 6–10 m/sec), being located at the mouth of a drainage basin aligned with prevailing southwesterly winds. Such wind speeds, however, likely cannot solely account for the much larger sand fluxes at the site. The Virginia Park setting, with wind speeds mostly <6 m/sec, is partly protected from the wind by rock walls. Wind speeds at the Needles site rarely exceed 8 m/sec, and thus sand flux differences between this site and Virginia Park appear strongly related to differences in the cover of plants and biologic soil crust.

REMOTE SENSING TO DETECT DUST STORMS, MAP VEGETATION CHANGES, AND MONITOR LAND USE

Monitoring ecosystems requires a capability to map surface features and to detect surface change. Surface soil types and vegetation cover are important parameters that control the vulnerability of ecosystems to climate change and land-use patterns, particularly as they enhance or retard wind erosion. Surface sampling and instrumentation can provide detailed temporal information at a given site, but the spatial resolution is usually inadequate for regional or global studies and monitoring. In contrast, remotely sensed satellite imagery has good spatial resolution compared to ground-based instruments and can be used both to monitor surface features and their changes over large areas and to expand ground-based data to regional and global scales. Satellite images can also show how different parts of an ecosystem respond to climate and other environmental changes (Chavez and MacKinnon, 1994).

Satellite imagery from the southwestern U.S. has recently been used to (1) detect dust storms; (2) map

Figure 3 Print showing the spatial extent and transport direction of the dust during a major wind event in April, 1997, southern California. The image was collected by the GOES satellite and has approximately 1 km resolution. Note that the dust plumes define a regional pattern going from approximately the center of the image to the right (eastward).

vegetation changes over seasonal-to-decadal scales; and (3) identify areas vulnerable to wind erosion related to natural conditions and land use. The high temporal resolution (every 15 minutes) of the GOES (geostationary satellite) data permits imaging of the beginning, growth, and demise of dust storms. Records of regional wind speed are used to select these images; change-detection methods are applied to images taken both during a windy day and during a clear, calm day a few days before or after. The relatively high spatial resolution (30 meters) of the Landsat Thematic Mapper (TM) enables (1) detection of change in local and regional vegetation cover and (2) mapping areas vulnerable to wind erosion (Chavez and MacKinnon, 1994). The latter can be obtained by analyzing imagery during wet and dry seasons or wet and dry years selected on the basis of regional rainfall records. We have also examined images collected by the Landsat Multispectral Scanner (MSS; see also Crowley and Bowers, 1999), the WiFS system on board IRS-1C, and SeaWiFS for monitoring environmental change. Advantages and disadvantages of data from each system, along with examples of images, are given by Chavez and MacKinnon (1999).

GOES (Geostationary Operational Environmental Satellite) images collected during several major wind events have been analyzed to track the evolution of dust storms. A movie has been produced using GOES images at 15-minute intervals for several hours during a large dust storm across southern California in April, 1997 (Chavez and MacKinnon, 1999). One of the images collected during this dust storm is shown in Figure 3. Mapped extents and directions of dust plumes reveal dust transport over several hundred kilometers, from the Mojave Desert of California (some plumes originating in the study area indicated on Figure 1) to Grand Canyon National Park, Arizona, and the central part of the Colorado Plateau, Utah.

Detailed vegetation-change analysis of Landsat TM images yields a digital mosaic/image map contrasting the southwestern United States between a wet period (spring, 1992) and a dry period (summer, 1997). Geometric and radiometric processing is applied to the image data; the radiometric processing includes, when needed, a correction for atmospheric effects (Chavez, 1996). The Landsat TM images are also used to generate wind-erosion vulnerability image maps using a procedure that identifies areas of high reflectance and low vegetation density (Chavez and MacKinnon, 1997). The digital vegetation-change image reveals (1) regional patterns of landscape change, some of which appear related to land use, as well as areas having increased levels of wind-erosion vulnerability from 1992 to 1997 and (2) detailed local vegetation dynamics. Results from the latter analysis can be linked to possible sources of fine-grained sediment.

CHARACTERISTICS OF DUST, SOUTHWESTERN UNITED STATES

Dust plays an important role in global climate and biogeochemical cycling, because dust pathways transcend topographic and even oceanic barriers. Current modeling suggests that modern dust in the atmosphere may either moderate (Li et al., 1996) or enhance (Tegen et al., 1996) the temperature effects of greenhouse-gas emissions. Dust is a major component of soils in both arid and humid areas (e.g., Reheis et al., 1995). Dust incorporated into soils provides suitable textures and nutrients for plant growth (Swap et al., 1992; Drees et al., 1993), influences hydrology by altering soil texture, and may partly control the invasion patterns of exotic plants such as *Bromus tectorum* L. (cheatgrass) (Hanson, 1999). Dust generation in arid and semi-arid regions may be partly the results of climatic change as well as human impacts, such as urban construction (e.g., Wilshire, 1980). Dust from disturbed desert soils carries the fungus responsible for coccidiodomycosis (valley fever). Inhalation of excessive amounts of silicate dust can cause health problems (Ross et al., 1993), and dust enriched in toxic metals, such as antimony, arsenic, cadmium, and lead, is potentially even more deleterious to health. These important effects of dust highlight the need to understand the deposition rates and composition of desert dust and how dust sources may change with climate and land use.

We use a combination of passive-type collectors (marble-filled pans), aerodynamically designed, passive airfoil devices ('Frisbee' samplers; Wu et al., 1992), and snow accumulations to sample dusts in the southwestern U.S. The dust-collection devices provide samples that tend to represent locally derived dusts (1–10 km) admixed with regionally derived (10–100s of km) and far-traveled atmospheric dusts (100s–1000s of km); these can be obtained seasonally or integrated throughout a year. In contrast, dust from snow pack at high altitudes represents only winter and early spring dustfall, largely from regional sources. Samples from the marble pans are analyzed for salt and carbonate contents and particle size; bulk major and trace element concentrations are determined using instrumental neutron activation analysis and (or) induction coupled plasma (ICP) techniques on selected samples. Dust trapped both in snow and on airfoil collectors at low elevations is analyzed in minute quantities by microbeam methods and ICP-mass spectrometry. Source studies of mineral dusts are planned using Sr-, Pb-, and Nd-isotopic analyses. Information on sources of aerosolic sulfates and nitrates may come from $\delta^{17}O$ and $\delta^{18}O$ analyses (Huiming Bao, University of California, San Diego, pers. comm).

Collections at low-altitude sites in Canyonlands National Park (Utah) on airfoil samplers by dry deposition record dust flux at about 0.5 to 2 $g/m^2/yr$. Collections in seasonal snow packs at high-altitude sites indicate that dust flux is about 0.5 to 10 $g/m^2/yr$ (extrapolated to whole years from winter dustfall; Hinkley et al., 1999a). The fluxes vary strongly, between both sub-annual and annual periods. These results are similar in quantity and in seasonal and annual variability to those measured from the marble pans (Reheis and Kihl, 1995; Reheis, 1997).

Annual collection and analysis from passive pan samplers at numerous sites in southern Nevada and California since 1984, combined with soil and weather data, shed light on: (1) the genesis of soils formed under arid conditions (Reheis et al., 1995); (2) the relation between dust storms and climate; (3) natural dust sources; (4) Owens (dry) Lake as a source for a significant part of deposited dust as much as 400 km downwind (Reheis, 1997); and (5) human disturbances in the desert, revealed by signatures of agricultural and construction dust. One finding is that high dust flux follows periods of high precipitation, because floods deposit fine-grained sediment susceptible to deflation. Another finding documents the greater importance of alluvial vs. playa sources (Gillette et al., 1982). Results from a sampling transect along Death Valley show that the modern playa contributes salt- and carbonate-rich dust, but the wide plain of the Amargosa is a more important source of silt and clay (Reheis and Kihl, 1995). In addition, a significant part of the elevated amounts of As, Sb, and especially Zn in dusts from the study area is likely contributed by Owens (dry) Lake and nearby mining and milling spoil in Owens Valley (Fig. 4). Current work emphasizes the identification of dust sources by comparing elemental (and in the future, isotopic) compositions of modern dust with those of potential source sediments.

The dust from snow packs provides a record of regional background composition and flux, and it is strongly enriched in certain trace elements (e.g., Cu, Zn, As, Ag, Cd, and Pb) relative to an average crustal rock composition (Table 1). Similar enrichments (As, Bi, Cd, Sb, Se, Zn, Pb, and Cu) are seen in dust collected by dry deposition on airfoil devices (Table 1). For these potentially toxic trace elements, snow with low

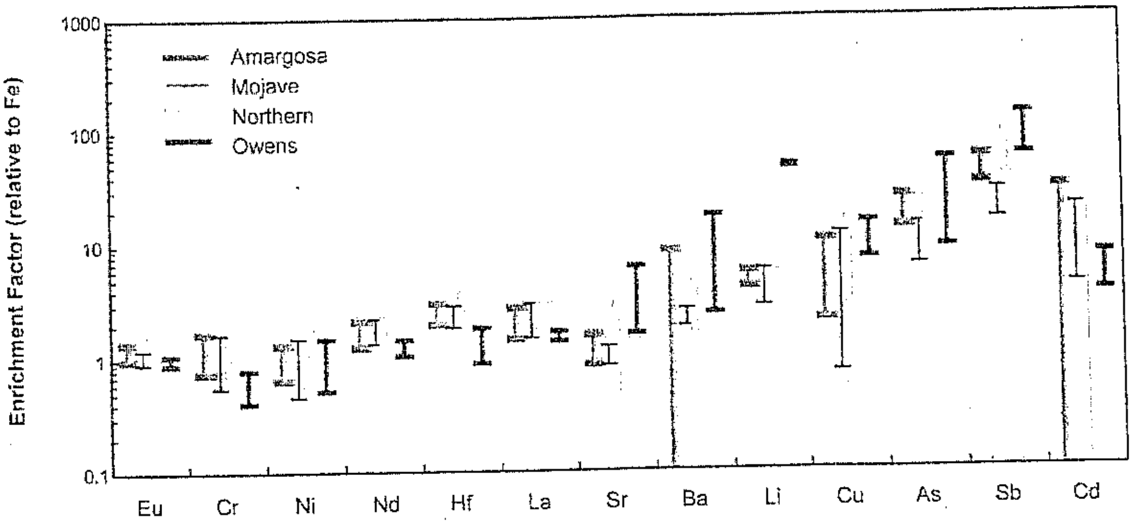

Figure 4 Elemental enrichment factors for <50-micrometer dust samples collected in marble-pan samplers. Averages are calculated for geographic groups of sites. Bars show range of one standard deviation about the mean. Averages are calculated for geographic groups of sites in southern Nevada and California.

Table 1 Trace element enrichment in dusts collected on airfoil samples and in snowpack, with comparison to dust in pre-industrial Antarctic ice.

Locality	Type	Time	Al	As	Bi	Cd	Cu	Pb	Sb	Zn
Canyonlands 1	Airfoil	Autumn 98	0.99	4.7	1.8	6.4	2.2	2.9	3.6	3.2
Canyonlands 2	Airfoil	Summer 99	1.12	8.4	8.1	3.0	4.2	5.2	12	3.8
White Mountains	Snowpack	Mid-winter 99	1.00	8.0	9.0	6.0	1.2	4.0	18	7.0
La Sal Mountains	Snowpack	Spring 98	0.74	11	NA	84	11	35	84	43
Antarctica	Ice	Pre-industrial	NA	NA	NA	>100	NA	~25	NA	NA

Enrichment factors are ratios of observed concentration of selected elements in representative single samples of dust to average crustal rock (Wedepohl, 1969). Locality, sample collection sites. Canyonlands National Park, Utah, site 1, Virginia Park, latitude (lat) = 38° 05.58′N; longitude (long) = 109° 50.40′W; site 2, Needles, lat = 38° 09.70′N; long = 109° 45.35′W. White Mountains, California, snowpack (lat = 37° 23.17′N; long = 118° 11.00′W) had high concentrations of dust. La Sal Mountains, Utah, snowpack (lat = 38° 34.15′N; long = 109° 16.28′W) had low concentrations of dust. Time, season and year of collection. NA = not analyzed. Pre-industrial ice samples are from Taylor Dome, west Antarctica.

concentrations of dust has larger enrichment factors than snow with higher dust concentrations. Snow-pack dust in low concentrations appears to represent far-transported material that resided for a long time in the atmosphere and thereby became enriched in trace elements (Duce et al., 1975; Weiss et al., 1978). Snow-pack dust in high concentrations is typically less enriched in trace element content and appears to represent more directly transported, local or regional dust.

Industrial pollution may account for the high abundance of many trace metals in atmospheric load. The amounts of trace elements present in pre-industrial Antarctic ice, however, are much greater than can be attributed to mineral dust and ocean salt present in the ice. Volcanic emissions appear to account for the bulk of pre-industrial enrichment (Hinkley et al., 1999b). Excluding dust samples derived directly from the region of Owens lake, the elevated concentrations of trace elements (above normal crustal values) in the southwestern U.S. dust may be caused by a combination of modern industrial fallout and the natural trace-element elevation of the background atmospheric load, perhaps related to quiescent worldwide volcanic emissions.

There is a natural atmospheric background component of eolian dust (Hinkley et al., 1997), identified in snow from Antarctica, Greenland, Alaska (high coastal mountains), and high Central Asia (at times of local widespread snow cover). This dust has chemical proportions within restricted ranges (e.g., K/Ca = 0.2–0.5; Ca/Ba = 70–130; Ca/Sr = 100–200). Some of the high-altitude snow samples from the southwestern U.S. have this background composition (Table 1), especially those that do not appear to have high concentrations of dust from nearby sources. This observation suggests that fine dusts falling in the southwestern U.S. are largely natural atmospheric background dust from far-distant sources. High-flux dusts of local origin in the southwest have other compositions, distinct from this background dust.

RECOGNITION OF EOLIAN DUST IN ARID-LAND SOILS AND APPLICATIONS TO ECOSYSTEM STUDIES

The presence of eolian dust in arid-land surficial deposits and soils underscores the vulnerability of these deposits to future wind erosion and the consequent loss of their nutrients. Many techniques have been used to detect the presence of eolian dust in soils (e.g., Jackson, 1981; Muhs, 1983; Reheis, 1990; McDonald et al., 1995; McFadden et al., 1987; Wells et al., 1987), but we still lack rapid, quantitative ways to test for such dust over large areas. A new combination of magnetic and petrologic methods has been developed to identify the presence of eolian dust over the central part of the geologically simple Colorado Plateau (Fig. 1) so that the roles of such dust can be evaluated for ecosystem function and vulnerability. These methods have also been applied in the geologically and magnetically complex eastern Mojave Desert to confirm an eolian origin for much of the silt in Pleistocene and Holocene alluvial surfaces and on nearby peaks (see McDonald et al., 1995; McFadden et al., 1987; Wells et al., 1987). The methods involve the rapid measurement of magnetic-mineral type, abundance, and magnetic grain size (domain state) to establish quantitative contrasts between surficial sediment/soil and rock substrate. Petrographic identification of magnetic Fe-Ti oxide minerals and magnetic measurements sensitive to ultrafine-grained magnetite or maghemite distinguish between detrital and in-situ pedogenic origins for the magnetic signals. On the central Colorado Plateau, evidence for eolian dust comes from the combination of (1) the presence of titanomagnetite, which originated in igneous rocks, responsible for moderately high magnetic susceptibility (MS; typically $1 \times 10^{-7} m^3/kg$) of upland soil and surficial deposits and (2) the absence of such magnetic minerals in the host sedimentary rocks ($MS < 1 \times 10^{-8} m^3/kg$) of the region (Fig. 5).

Relative to host bedrock, the sediment is enriched in many elements, including P, Mg, Na, Zn, and Al, as well as Ca at sites where bedrock lacks calcite cement. Although these methods do not identify specific source areas, geologic and geochemical considerations of the closest likely sources suggest dust transport over many tens to hundreds of kilometers. Moreover, detailed particle-size analysis indicates that a high proportion of the silt-sizes particles in the surficial sediment is concentrated in the 2–20 μm fraction. This pattern, which differs greatly from the particle-size distribution of silt in nearby bedrock, is expected for long-range transport.

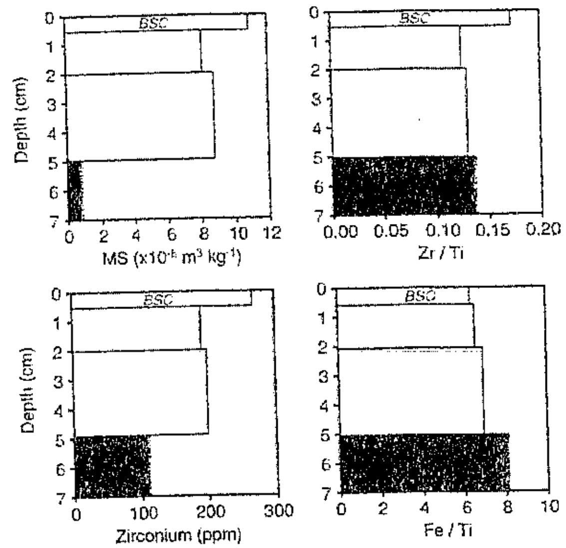

Figure 5 Plots of magnetic susceptibility (MS) and geochemical results, averaged from sites associated with sandstone substrates, against depth. BSC, biologic soil crust. Solid pattern represents bedrock.

The biologic soil crust, which stabilizes much of the surficial mantle, is a natural dust trap and may document a change in dust source over the past several decades. Relative to underlying sediment, this crust layer has more magnetite, higher Zr, higher Zr/Ti, and nearly constant Fe/Ti (Fig. 5). These shifts in magnetic and chemical properties are consistent with increased eolian input from desert regions (much underlain by granitic and rhyolitic rocks) west and southwest of the Colorado Plateau. The magnetic and chemical shifts recorded in the biologic soil crust may reflect recent, intensive human disturbance of arid lands off the Colorado Plateau.

Recognition of eolian dust in the surficial sediment mantle on Colorado Plateau underscores the vulnerability of this land surface to wind erosion. In the Canyonlands area, such dust also provides an important substrate for biologic soil crusts, which stabilize arid-land surfaces. These results thus may influence decisions about certain land-use practices to ensure minimal disturbance of the surface in sensitive areas. The results also indicate the need to monitor areas for loss of vegetation and sand movement that together would promote dust emission.

DEVELOPMENT OF A NEW WIND EROSION MODEL

The modeling component of our project includes development of a wind erosion model based on wind speed, atmospheric shear stress (frictional force) on the surface, and atmospheric stability (Fig. 6). This

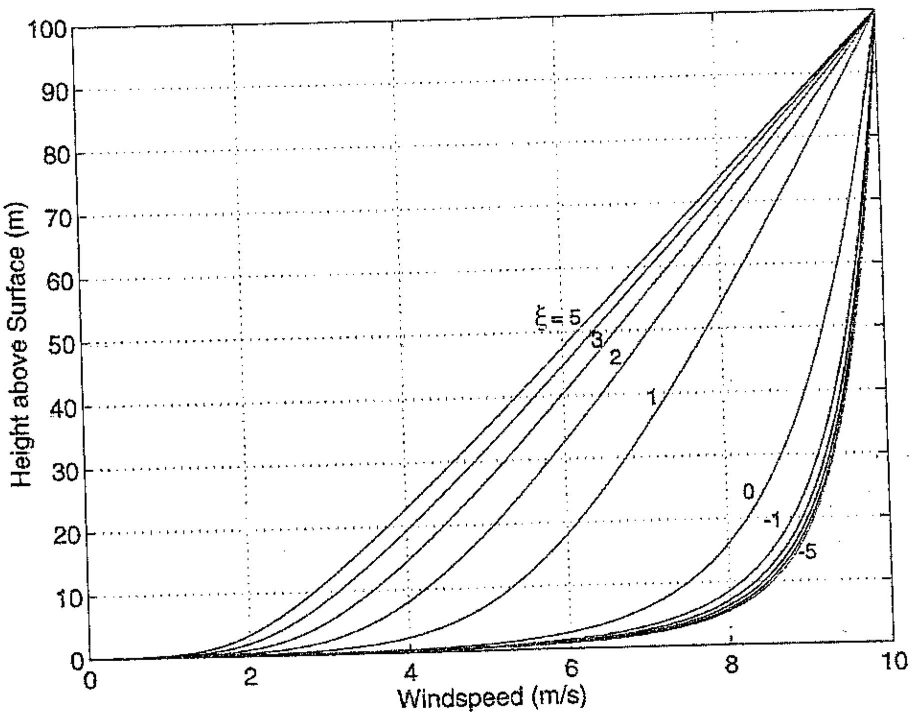

Figure 6 Plot showing the dependence of wind-speed increase with height to atmospheric stability (ξ) for the case where wind speed is 10 m/s at 100-m height above the surface. The shear stress on the surface depends on the rate at which the wind speed increases with height above the surface.

atmospheric boundary layer (ABL) model will calculate the frictional force for atmospheric conditions experienced in southwestern United States. The frictional force depends mainly on the wind speed and the degree of atmospheric stability, and secondarily on surface roughness. For any given surface, the model determines (1) whether the frictional force exceeds that needed to set surface materials in motion and (2) the flux at which materials are transported by the wind.

This modeling extends work by others (e.g., Gillette et al., 1982; Gillette and Passi, 1988; Marticorena et al., 1997) by including the effects of atmospheric stability on atmospheric shear stress. The model is being tested in the Soda Lake-Devil's Playground area of the Mojave Desert, California, using meteorological data, supplemented by soil properties, satellite and ground observations of dust emission, particle flux measurements, and determination of vegetation cover and type. Extrapolation of the site-specific results to the American Southwest will be attempted using mapped and remotely sensed characterizations of surface properties (geology, soil, vegetation) to identify areas vulnerable to wind erosion under current climatic conditions. Away from sites where meteorological measurements are available, the ABL model requires input of wind speed at the top of the boundary layer to calculate the frictional force and particle fluxes. A regional climate model will be used to reconstruct upper-level wind speeds between meteorological stations for specific dates. These wind speeds will then be fed into the ABL model to identify those areas where wind erosion and particle transport should have occurred.

A DUSTIER OR CLEARER FUTURE FOR SOUTHWESTERN UNITED STATES?

The wind erosion model will be linked with a regional climate model and an interactive vegetation package to forecast how critical wind speeds required to move surface materials change with various climatic and land-use scenarios. We will attempt to answer the following questions: How does wind strength vary with natural climate cycles on decadal and century time scales? Wind strength during the spring may be sensitive to changes in the jet stream. How has this natural variability affected the wind's capacity to erode and transport surface material? If climate changes as a result of human activities, to what extent will winds become stronger or weaker? How have soil moisture and vegetation changes affected wind erosion in the past? What can we expect in the future? As an example, $2 \times CO_2$ projections for the southwestern U.S. suggest a decrease in soil moisture, especially during the winter, which could lead to enhanced wind erosion. Wind erosion may also change when surface roughness and low-level mixing are altered by changes in vegetation type and distribution. The models will employ a range of climatic conditions that existed in the past and that are anticipated for the future. Examples include conditions of drought (dust bowl years of the 1930s; decades-long drought like that of AD 1570–1598), Little Ice Age (about AD 1670–1920) conditions of cooler and wetter climate in the northern hemisphere, more frequent El Niño-La Niña cycles, and global warming conditions with doubled CO_2 over pre-industrial levels.

SUMMARY

The potential for future wind erosion/dust generation depends on numerous, sometimes competing, factors. In some semi-arid lands, increased overall aridity or longer periods of drought will likely result in loss of soil moisture and vegetation, leading to enhanced soil erosion via wind. Even wetter conditions in certain arid-land settings may lead to increased dust generation. For example, higher and more frequent runoff events deliver fine-grained sediment to the toes of unvegetated alluvial fans; such sediment, upon drying, can then be entrained by strong winds. Understanding eolian processes is important for ecosystem health and function, landscape visibility as conditioned by air quality, and human health in populated areas, or areas under urbanization, intensive recreation, or industrialization.

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