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Review Article

The geologic records of dust in the Quaternary

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ABSTRACT

Study of geologic records of dust composition, sources and deposition rates is important for understanding the role of dust in the overall planetary radiation balance, fertilization of organisms in the world's oceans, nutrient additions to the terrestrial biosphere and soils, and for paleoclimatic reconstructions. Both glacial and non-glacial processes produce fine-grained particles that can be transported by the wind. Geologic records of dust flux occur in a number of depositional archives for sediments: (1) loess deposits; (2) lake sediments; (3) soils; (4) deep-ocean basins; and (5) ice sheets and smaller glaciers. These archives have several characteristics that make them highly suitable for understanding the dynamics of dust entrainment, transport, and deposition. First, they are often distributed over wide geographic areas, which permits reconstruction of spatial variation of dust flux. Second, a number of dating methods can be applied to sediment archives, which allows identification of specific periods of greater or lesser dust flux. Third, aeolian sediment particle size and composition can be determined so that dust source areas can be ascertained and dust transport pathways can be reconstructed. Over much of the Earth's surface, dust deposition rates were greater during the last glacial period than during the present interglacial period. A dustier Earth during glacial periods is likely due to increased source areas, greater aridity, less vegetation, lower soil moisture, possibly stronger winds, a decreased intensity of the hydrologic cycle, and greater production of dust-sized particles from expanded ice sheets and glaciers.

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"I wish those dusty Santa Ana winds would come and carry me out to sea..."

–from "Santa Ana Winds," written by Steve Goodman, Mary Gaffney and Mike Jordan, published by Big Ears Music, Inc. o/b/o itself & Red Pajamas Music (ASCAP).

1. Introduction

There has been an increasing awareness of the significance of mineral dust in the Earth's physical systems and biosphere. This new interest in dust is highly interdisciplinary, spanning the fields of geology, biology, and atmospheric sciences, and even integrating work from the extraterrestrial scientific community. In recent reviews, Kohfeld and Harrison (2000, 2001), Harrison et al. (2001), Tegen (2003), Goudie and Middleton (2006), Kohfeld and Tegen (2007), Maher et al. (2010) and Shao et al. (2011) summarize a number of important impacts of mineral dust on the Earth-atmosphere system. Because dust can have high concentrations in the atmosphere, it can change the overall planetary radiation balance through direct effects on radiation at both solar (shortwave) and terrestrial (longwave) portions of the electromagnetic spectrum (Tegen, 2003). Authors of the 2007 IPCC report specifically identify dust as an important component in the global radiation balance (Forster et al., 2007). Fine-grained dust can be a significant carrier of Fe and phytoplankton blooms can occur in the ocean after dust-derived Fe fertilization (Falkowski et al., 1998; Jickells et al., 2005; Mahowald et al., 2009). Such blooms can result in significant carbon dioxide drawdown from the atmosphere, thus altering the planetary carbon balance. An often-overlooked process is that dust can have important effects on the biogeochemical cycle of terrestrial ecosystems, adding nutrients to soils and the vegetation they support. Numerous studies now document evidence for far-traveled dust additions to soils (Rex et al., 1969; Jackson et al., 1971; Birkeland, 1999; Kurtz et al., 2001; Reynolds et al., 2001; Muhs et al., 2007a, 2007b, 2010). Finally, dust can have tremendous importance in paleoclimate studies. Because dust is entrained and transported by wind, geologic records of dust are some of the few direct indicators we have of atmospheric circulation in the past. Thus, dust records of the past are of considerable importance in testing general circulation models (GCMs) (Mahowald et al., 1999, 2006).

This review summarizes some of what is known about geologic records of dust. Dust monitoring and dust trapping programs have given us valuable records of modern dust flux. Some of the longer dust monitoring and trapping programs include those on Barbados and in Florida (Prospero, 1999; Prospero and Nees, 1977, 1986; Prospero and Lamb, 2003) and those in the southwestern United States (Gile and Grossman, 1979; Reheis, 2003, 2006; Reheis and Kihl, 1995). Nevertheless, although these programs constitute some of the longer direct measurement records we have, the length of such records is on a timescale of decades. In order to understand the links between dust flux and major climate changes of the Quaternary, it is necessary to examine geologic records of fine-grained particle deposition by the wind.

In this paper, the use of the word *dust* follows that of Pye (1987), who defines dust as a suspension of solid particles in a gaseous medium. A corollary to this is that the term dust also refers to *deposits* of such particles. Crucial in this definition is the term *suspension*, which refers to the mode of transport in the atmosphere. Dust particles are those that have been entrained by the wind and are transported horizontally without contact with the ground surface. Suspension requires a vertical component of wind flow, such that grains are kept aloft as long as the vertical component of the wind exceeds the particle settling velocity (Pye, 1987). This distinguishes dust particles from larger grains, such as sand, that can also be transported by the wind. Sand-sized particles, when transported by the wind, do so largely by saltation, a bouncing type of particle motion with periodic contact with the ground surface, or by surface creep, where there is constant contact with the ground surface during horizontal transport. Pye (1987) distinguishes between *short-term suspension*, which is that experienced by particles that have diameters of ~70 μm to ~20 μm and *long-term suspension*, which is that experienced primarily by particles with diameters <20 μm. Thus, grains larger than ~20 μm tend to be deposited within ~30 km of their source, whereas grains <20 μm and particularly those <10 μm are capable of *long-range transport* (LRT), up to thousands of kilometers away from their source.

There are important exceptions to these theoretical concepts about dust particle sizes and distance of transport in long-term suspension. Betzer et al. (1988) document the presence of mineral particles >75 μm diameter that have been transported to the Pacific Ocean, more than 10,000 km from their sources in Asia. Off the west coast of Africa, from studies of dust traps that are ~300–450 km from the closest possible coastal sources, Ratmeyer et al. (1999) report that mean particle sizes range from ~10 to ~20 μm, but particles as large as ~55 μm were also found. Stuut et al. (2005) made shipboard dust collections, also off the coast of western Africa, and report modal particle sizes of 8–42 μm, but also find a significant number of particles with diameters >100 μm.

The term *aerosol* is sometimes used when referring to dust, particularly LRT dust, commonly those particles with diameters <10 μm. In its broadest sense, aerosol refers to a suspension of fine liquid and/or solid particles dispersed within a gaseous medium (Prospero et al., 1983). Thus, aerosols can be mineral particles, but also include volcanic glass particles, sea salt, hydrocarbons, smoke, mist, fumes and fog. Aerosols that are not mineral particles are not included in this review.

There is often some confusion about the term "dust" and the term "loess." Loess is defined as silt-dominated sediment that has been entrained, transported, and deposited by the wind (see reviews by Pye (1987, 1995) and Muhs (2007, in press)). Loess can be recognized in the field as a distinctive, terrestrial sedimentary body and can be mapped as a geologic unit. Its thickness, however, is highly variable and can range from a few centimeters to several hundred meters. Loess occupies an intermediate position in a continuum of aeolian sediments (from sand to LRT dust), with a mean particle size that is smaller than windblown sand (2–0.05 mm), but coarser than LRT dust (typically < 10–20 μm).