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The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition

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ABSTRACT

The deposition of aeolian, or windblown, dust is widely recognized as an important physical and chemical flux to ecosystems. Dust deposition adds exogenous mineral and organic material to terrestrial surfaces and can be important for the biogeochemical cycling of nutrients. There have been many studies that characterize the physical and chemical composition of dust. However, few studies have synthesized these observations in order to examine patterns geochemical fluxes. We have compiled observations of dust deposition rates, particle size distributions (PSD), mineralogy and bulk elemental and organic chemistry.
The rates of dust deposition observed across the globe vary from almost 0 to greater than 450 g m^{-2} yr^{-1}. Sites receiving dust deposition can be partitioned into broad categories based on there distance from dust source regions. When compared to global dust models our results suggest some models may underestimate dust deposition rates at the regional and local scales. The distance from the source region that dust is deposited also influences the particle size distributions, mineralogy, and chemical composition of dust; however, more consistent dust sampling and geochemical analyses are needed to better constrain these spatial patterns. On average, the concentrations of most major elements (Si, Al, Fe, Mg, Ca, K) in aeolian dust tend to be similar (±20%) to the composition of the upper continental crust (UCC), but there is substantial variability from sample to sample. In contrast, some elements tend to be depleted (Na) or enriched (Ti) in dust, likely as a result of soil weathering processes prior to dust emissions. Trace elements, especially heavy metals, are consistently enriched in dust relative to the UCC. Ecologically important nutrients, such as N and P, are also present in dust deposition. The geochemical flux attributable to dust deposition can be substantial in ecosystems located proximal to dust source regions. We calculate estimates of elemental flux rates based on the average chemical composition of aeolian dust and varying rates of deposition. These estimated flux rates are useful as a rough gauge of the degree to which dust deposition may influence biogeochemical cycling in terrestrial ecosystems and should be utilized to better constrain deposition estimates of global dust models.

1. Introduction

For centuries scientists have been intrigued by the transport and deposition of windblown particulate matter or "aeolian dust". In 1846, Charles Darwin compiled observations of dust deposited on ships in the Atlantic Ocean, including his own account from the H.M.S Beagle, and concluded that the material likely originated from the African Continent (Darwin, 1846). Darwin's keen observations foreshadowed the future appreciation of dust deposition as an important biogeochemical flux. The dust cycle is now recognized as a global transport mechanism, bridging distant ecosystems and moving large quantities of particles. Windblown dust can travel tens of thousands of kilometers before being deposited (Biscaye et al., 1997; Grousset et al., 2003). Thus, even remote areas located far from source regions receive a regular flux of particulate dust. Furthermore, the accumulation of dust is now accepted as a control of biogeochemical cycling in many ecosystems (Jickells, 1995; Grantz et al., 2003; Derry and Chadwick, 2007). Despite evidence of the ecological importance of dust deposition, we know relatively little about how the chemical composition of dust varies through space and time. To better constrain the composition of dust and to improve estimates of the geochemical flux resulting from its deposition, we have compiled contemporary accounts of dust chemistry, mineralogy, particle size distribution (PSD), and deposition rates. We use the results of this synthesis to examine how dust fluxes vary spatially and to examine the ability of global dust models to predict deposition rates and geochemical fluxes.

The term "aeolian dust" is typically used to refer to mineral particulate matter originating from the wind erosion of soils. The focus of this study is on characteristics of soil-derived dust; however, when considering the geochemical composition of dust deposition, we must also consider other sources of atmospheric particles. Additional sources of organic and inorganic particles to the atmosphere include

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anthropogenic/industrial emissions, volcanic emissions, and biomass burning. The mixing of these particle sources with soil-dust likely increase the overall organic (Mahowald et al., 2005a; Shen et al., 2007) and trace-metal (Gaudichet et al., 1995; Erel et al., 2006) content of the dust that is deposited to terrestrial ecosystems.

Dust-derived element fluxes can influence terrestrial biogeochemistry through several processes. On short time-scales (days to weeks), dust directly affects vegetation (Farmer, 1993), alters the rate and timing of snowmelt (i.e. water availability; Painter et al., 2007), and provides essential elements (nutrients) for plant and microbial productivity. For example, a series of studies performed in Hawaii have shown that small rates of dust accumulation over time exert control over terrestrial productivity through the contribution of rock-derived nutrients (Kennedy et al., 1998; Chadwick et al., 1999). Dust has also been shown to be a source of elements essential for productivity in soils from other tropical (Swap et al., 1992), Mediterranean (Soderberg and Compton, 2007), and arid ecosystems (Reynolds et al., 2006a). In addition, over long timescales dust can be an important factor in the formation and development of soils (Yaalon and Ganor, 1973; Pye, 1995; Simonson, 1995). Dust accumulation in soils can influence texture, element composition, acid neutralizing capacity (Miller et al., 1993; Larssen and Carmichael, 2000; Muhs and Benedict, 2006), and may influence soil weathering fluxes (Porder et al., 2007).

The global dust cycle is a dynamic process and has undergone major changes in the past. Long-term records from ice and sediment cores indicate dust deposition rates were greatest during glacial maxima (Thompson, 2005; Lambert et al., 2008). In addition, shifts from glacial to interglacial periods are correlated with changes in dust source regions (Sun et al., 2001). Past fluctuations in the dust deposition are typically attributed to climate variability (Thompson, 2005; Street-Perrott et al., 2000; Werner et al., 2002; Mahowald et al., 2006). Similarly, contemporary measurements show that periods of drought are correlated with greater dust flux from deserts (Prospero and Nees, 1977; Okin and Reheis, 2002; Prospero and Lamb, 2003). Drought conditions lead to desertification, which increases the extent of dust source areas (Mahowald, 2007). In contrast, one of the main drivers of global warming, atmospheric CO_2, could actually decrease dust emission. The greening of arid and semi-arid regions as a result of CO_2 fertilization is predicted to decrease the extent of dust source regions (Smith et al., 2000; Mahowald, 2007). For example, one modeling study predicts a 60% reduction in dust at CO_2 concentrations double that of pre-industrial levels (Mahowald et al., 2006). These decreases in dust result from an increased extent of vegetation in arid and semi-arid settings (Mahowald et al., 1999; Mahowald and Luo, 2003). In addition to the influence of climate on dust processes, dust may also controls climate through mechanisms including the direct influence of dust on atmospheric albedo and the indirect influence of dust on biogeochemical cycling of elements (Arimoto, 2001).

Changes in dust deposition rates have also been attributed to human activity (Neff et al., 2008). Several studies have examined the impact of contemporary land use on dust emission from arid soils and found that soil disturbances such as grazing and off-road vehicle use destabilize desert pavement making surfaces more prone to wind erosion (Gill, 1996; Marticorena et al., 1997; Belnap and Gillette, 1998; Neff et al., 2005; Hoffmann et al., 2008). For example, over the past 200 years grazing in the American Southwest has led to increases in soil wind erosion (Belnap and Gillette, 1997; Neff et al., 2005). The timing of land use changes, in both North and South America, correspond to observations of increased dust deposition in downwind ecosystems (McConnell et al., 2007; Neff et al., 2008). Similarly, it has been suggested that land use change in the Sahel region of Africa has resulted in increased dust deposition to the tropical Atlantic (Moulin and Chiapello, 2006). At present, agriculture is estimated to contribute between 10–50% of the total global dust emission (Tegen and Fung, 1995; Sokolik and Toon, 1996; Tegen et al., 2004).

It is not yet clear how future changes of both climate and land use will further modify the global dust cycle or how the resulting changes in dust deposition will influence ecosystems (Mahowald and Luo, 2003). Establishing a benchmark of contemporary dust deposition rates and geochemical composition is an important step in evaluating future changes. Many individual observations of dust geochemical and physical characteristics have been reported for various locations around the world. By compiling these measurements of dust deposition chemistry and mineralogy, we hope to generate an estimate of average Aeolian dust composition and to provide a resource for evaluating the chemical flux to ecosystems.

The goals of this study are to synthesize observations of physical and chemical dust fluxes, to evaluate the spatial variability of these fluxes, and to build a framework to examine the importance of dust for terrestrial ecosystems. To achieve these goals we will (1) describe aspects of the global dust cycle that influence the flux of dust, (2) compile observations that characterize the deposition of dust and its physical and chemical properties, (3) evaluate geochemical fluxes resulting from dust deposition and discuss the potential ecological importance of these fluxes for terrestrial ecosystems, and finally (4) compare measured dust deposition rates to model estimates.

2. Background: the global dust cycle

The dust cycle consists of three physical processes: the mobilization or emission of dust from a source area, the transport of those particles through the atmosphere, and the subsequent deposition of dust particles. Each of these processes exerts a control over the physical and chemical flux from dust. First, the mechanisms controlling the emission of particles from the landscape determine the quantity and composition of dust available for transport. Second, atmospheric processes determine the distance that dust is transported and modify the chemical and physical properties of dust. Finally, deposition processes remove dust from the atmosphere resulting in the flux of Aeolian material to downwind ecosystems.

2.1. Source areas and global budget

Contemporary Aeolian dust is most commonly derived from the deflation of surface soils. The emission of dust from soils is a natural process, but anthropogenic disturbances may enhance emission at local and regional scales (Mahowald and Luo, 2003; Tegen et al., 2004). Dust emissions from arid and semi-arid soils are widespread and likely the primary source of dust globally (Simonson, 1995; Herman et al., 1997; Prospero et al., 2002). Arid and semi-arid zones occupy approximately 1/3 of the global land area, however not all dry areas emit dust. Within arid regions, topographic depressions with an abundant source of fine-textured particles are often the most significant dust emitters. For example, playa lakes, floodplains, and areas of alluvial outwash are major dust source areas (Prospero et al., 2002). In addition, other environments exhibiting an abundance of fine-textured material, such as glacial outwash plains, can be important dust source areas.

Dust source regions can be classified by the relative strength of the source and its contribution to the global dust budget. There are three primary dust source regions that dominate global emission and several secondary regions that also contribute appreciable amounts of dust to the atmosphere (Prospero et al., 2002). Using the Total Ozone Mapping Spectrometer, Prospero et al. (2002) identified the dominant (primary) dust source regions as North Africa, the Middle East, and Asia. Each of these regions is situated between 15°N and 45°N, in an area termed the "global dust belt" (Prospero et al., 2002). In addition, several regional (secondary) sources of dust have been identified in North America, Australia, South Africa, and South America (Prospero et al., 2002). From a global perspective, the most significant global dust sources are the Saharan and sub-Saharan (Sahel) areas of

northern Africa and the Gobi–Taklamakan region of Asia (Herman et al., 1997; Prospero et al., 2002).

Estimates of annual global dust emissions range from 50 to 5000 Tg yr^{-1} (Goudie and Middleton, 2006) but the most recent modeling estimates have narrowed this range to between 800 and 2000 Tg yr^{-1} (Cakmur et al., 2006). However, many of these estimates are based on global models, which consider only the emission of clay and small silt-sized particles (Mahowald et al., 1999; Ginoux et al., 2001; Luo et al., 2003; Zender et al., 2003a), or on extrapolations of a limited number of direct observations (Goudie, 1983; Goudie and Middleton, 2001). The rate and temporal variability of dust emission is one of the major sources of uncertainty in global dust cycle.

2.2. Emission

Saltation and sandblasting are the basic mechanisms leading to particle entrainment and dust generation from soils (Shao and Raupach 1993; Grini and Zender, 2004). Saltation occurs when wind velocities are sufficient that sand sized soil particles are transported horizontally and the movement of these particles across the soil surface entrains other particles (Shao and Raupach, 1993). The bombardment of soil surfaces by moving sand particles (sandblasting) can dislodge smaller silt and clay sized particles (Grini and Zender, 2004; Okin, 2005). Silt and clay sized particles are difficult to mobilize through the action of wind alone because they are bound tightly together by cohesive forces. Thus the saltation and sandblasting mechanisms are critical for fine textured dust entrainment. The size and energy of the saltating particles as well as the strength of the surface that is bombarded can influence the amount particles emitted from soil (Grini and Zender, 2004) and also determine the PSD of dust that is transported away from the source region.

Local factors controlling the emission of dust include the PSD of soils, surface roughness, and climate (Marticorena et al., 1997). In order to be a substantial source of dust, a soil must also have an adequate supply of both sand particles to initiate the saltation process and fine textured silts and clays that can be suspended for long-distance transport (Gillette, 1988; Grini and Zender, 2004). Surface roughness mutes the force exerted by winds and can be increased by landscape position (Zender et al., 2003b), vegetation composition, and both abiotic and biotic crusts (Marticorena et al., 1997; Belnap and Gillette, 1997). Therefore, the presence of vegetation and/or soil crusts reduces a soils susceptibility to wind erosion and dust emission. Dry soils with large areas of bare ground (lower surface roughness) tend to be largest emitter of dust (Okin and Gillette, 2001). Even within vegetated regions, dust "hot spots" or areas of high surface erodability can dominate the emission of dust from soils (Gillette and Hanson, 1989; Okin, 2005). The dominant climatic factors controlling the emission of dust from soils are wind speed and soil moisture content (Gillette, 1988). Dust emission most often occurs in regions where strong winds can initiate saltation and sandblasting. Higher levels of precipitation result in increased soil moisture, which can act to stabilize soils by forming physical rain crusts that protect soils from wind erosion (Marticorena et al., 1997). However, in some arid regions, seasonal precipitation may actually increase salt emissions by increasing rates of evaporite formation (Reynolds et al., 2007).

2.3. Transport

Once a soil particle is entrained in the atmosphere, it is transported away from the source area by advection and atmospheric circulation. Aeolian dust particles can be transported for thousands of kilometers before they are deposited. For example, Grousset et al. (2003) used a combination of techniques to show that Asian dust had been transported ~20,000 km before it was deposited on the snowpack of the French Alps. The distance that dust is transported depends on the energy of the air-mass (Rea and Hovan, 1995; Arimoto et al., 1997), the removal of particles by gravitational settling and scavenging (Arimoto et al., 1997), and the size of the emitted particles (Tegen and Fung, 1994). Large particles have a tendency to be deposited closer to their source region as a result of their greater mass and settling velocities (Rea and Hovan, 1995), while small particles can be transported thousands of kilometers (Tegen and Fung, 1994; Schulz et al., 1998). However, there have been accounts of very large dust particles (>100 μm in diameter) transported considerable distances before being deposited (Betzer et al., 1988). Free troposphere transport of dust is one mechanism through which dust particles may be transported substantially further than predicted based on particles size (VanCuren and Cahill, 2002; VanCuren et al., 2005). These transport dynamics lead to variability in the dust deposition rates (and possibly chemical fluxes) across the landscape.

2.4. Deposition

During transport, dust particles are continuously removed from the atmosphere by processes of dry and/or wet deposition. The relative importance of these different mechanisms varies both temporally (Guerzoni et al., 1997) and spatially (Ginoux et al., 2004) and several factors can influence which mechanism of dust deposition dominates. These factors include the seasonal timing of dust storms (Tegen et al., 2002), the PSD of the dust being transported (Tegen and Fung, 1994), and local climate conditions. Dry deposition proceeds via gravitational settling and turbulent mixing of particles out of the atmosphere and is the dominant mechanism removing sand and large silt-sized particles (Tegen and Fung, 1994). In contrast, wet deposition results from the scavenging of particles by rain or snow and therefore is dependent on total amount of precipitation as well as the vertical distribution of rain or snow in the atmosphere. Wet deposition is the dominant mechanism removing clay-sized particles from the atmosphere (Tegen and Fung, 1994). The deposition of silt-sized particles occurs as a result of both dry and wet deposition processes. There is evidence that the chemical composition of dust may be related to the mechanisms (dry vs. wet) of deposition (Kocak et al., 2005; Al-Momani et al., 2008).

Rates of dust deposition depend on several factors including the concentration of dust in the atmosphere, the energy of the winds transporting the dust, as well as orographic and surface features of the depositional environment (Goossens, 2000). The influence of surface features on dust deposition rates vary seasonally in response to the structure and composition of surface vegetation. For example, vegetation exhibits a wide variety of morphologies, some of which are more effective at trapping atmospheric particles. As a result, vegetation species composition affects dust deposition rates (Tegen et al., 2002) and changes in vegetation composition leads to changes in deposition rates (Hoffmann et al., 2008). Landscape position is another physical factor that influences dust deposition. A study by Hoffmann et al. (2008) found that rates of deposition were higher on leeward slopes then on windward slopes, summits, or planes. However, these field measurements are contrasted by wind tunnel and modeling studies, which predict deposition to be highest on windward slopes (Goossens, 1988; Zufall et al., 1999). Landscape position may also influence the particle size distribution of deposited dust, the results of wind tunnel experiments suggest there is a reduction in the in the grain-size of dust deposited on leeward slopes compared to windward slopes (Goossens, 2006). The results of the studies described above show that dust deposition rates are highly variable at the local and regional scales. Despite this heterogeneity there are clear spatial patterns in deposition rates.

Ecosystems located in close proximity to large source regions experience the most frequent events and greatest rates of deposition. The mass flux from dust is greatest near source areas because the large sand- and silt-sized particles are quickly removed by gravitational settling. As the suspended mass of dust particles is transported away from the source region, the abundance of large, heavy particles, decrease. For example, a study of deposition at 8 sites along a transect from the Hexi Corridor across the Loess Plateau, in the Gansu Province

of China, found that the mean size of dust particles deposited decreases with distance downwind of the source region (Derbyshire et al., 1998). A similar pattern of has also been observed in the Southwestern, United States (Goldstein et al., 2008).

2.5. Dust geochemical characteristics

The chemical and mineralogical composition of soil-dust yields information about its provenance (Grousset and Biscaye, 2005; Painter et al., 2007; Yang et al., 2007), influence on climate forcing (Sokolik et al., 1998; Sokolik and Toon, 1999), and its potential implications for human and ecological health (Shinn et al., 2003; Erel et al., 2006). From an ecological perspective, the deposition of nutrients and other essential elements can be important for ecosystem productivity (Swap et al., 1992; Kennedy et al., 1998; Chadwick et al., 1999; Reynolds et al., 2006a; Soderberg and Compton, 2007). In contrast, the deposition of heavy metals and other contaminants may be deleterious to ecosystem health (Holmes and Miller, 2004; Graney et al., 2004). Dust also transports microorganisms and potential pathogens and the influence of these organisms on terrestrial ecosystems is not well known (Shinn et al., 2003; Kellogg and Griffin, 2006; Griffin et al., 2007).

In general, the chemical and mineralogical characteristics of dust should be similar to the source soil. However, the physical fractionation of soil during dust emission can alter dust chemistry relative to source soils. For example, wind erosion preferentially removes fine-textured soil particles, which are often enriched in trace elements relative to other portions of the soil (Li et al., 2008). Furthermore, each step of the dust cycle may fractionate and/or alter physical and chemical characteristics of dust. Thus the particle size, mineralogy, and chemistry of dust deposition are dependent on many of the processes described above including emission from soils, transport through the atmosphere, and deposition. By synthesizing many observations of dust deposition rates and geochemical characteristics, we hope to better constrain the range of geochemical fluxes associated with dust deposition.

3. Methods

3.1. Dust deposition rates

To improve our understanding of the spatial distribution of dust deposition rates, we have compiled a dataset of contemporary observations, assembled from the peer-reviewed literature. This study is unique in that we focus primarily on direct measurements of dust deposition, which are typically made by passive sampling techniques. The most commonly used passive sampling techniques collect dust using a non-reactive collection pan filled with glass marbles, which serve as the depositional surface (Goossens and Offer, 1994; Reheis and Kihl, 1995). Other passive techniques estimate deposition rates from the accumulation of dust on snow/ice (e.g. Painter et al., 2007) or soil surfaces (e.g. Muhs and Benedict, 2006). We have excluded estimates of deposition rates determined from soil and sediment chemistry, these methods typically integrate deposition over decades or longer and are confounded by the weathering processes. We have included in our analyses several estimates of dust deposition rates generated from active sampling techniques. These estimates of dust deposition are commonly used to validate model simulations (i.e. Ginoux et al., 2001) and provide a useful benchmark. Active sampling collects dust particles using air filtration at or near ground level (Prospero et al., 1987). Estimates of deposition from active sampling are contingent upon the ability to accurately convert atmospheric dust concentration to rates of deposition (Wesely and Hicks, 2000) and my not account for wet deposition. Where we have included active sampling estimates of deposition rates, we rely on the conversion to deposition rates reported in the original study. The deposition rate units reported in the compiled observations vary from study to study. For ease of comparison, we have converted all reported rates to units of $g\,m^{-2}\,yr^{-1}$. In cases where multiple measurements of deposition rates have been made over several years we use the mean rate. In cases where several observations were made at different spatial locations, if the observations were made in the same region, then the mean of those observations was used. Conversely, if the observations were made in different regions, then individual regional observations were used.

To examine if dust fluxes are related to the proximity to source areas, we classified each observation based on the estimated distance to the closest known primary or secondary dust source (from Prospero et al., 2002). Observations were classified as "local", "regional", or "global" if they were located between 0–10 km, 10–1000 km, and >1000 km from a primary or secondary dust source region, respectively. After classifying the deposition type of each observation, we ranked the observations by the measured (or estimated) annual deposition rate and then evaluated whether our imposed deposition types grouped together.

3.2. Dust chemistry, mineralogy, and particle size

In addition to deposition rates, we also compiled observations of dust physical and chemical properties. Specifically, we compiled measurements of dust particle-size, mineralogy, bulk elemental composition, total organic matter, and organic carbon. Because atmospheric dust may be fractionated during deposition processes, we have focused our synthesis on the characteristics of dust collected by passive sampling techniques and have excluded measurements of dust chemical and physical characteristics made from active sampling techniques. All measurements of dust chemistry have been converted to units of % or *ppm* for individual elements (not oxides). Furthermore, all elemental concentrations reported reflect both inorganic and organic sources except where stated otherwise. In regard to dust mineralogy, we have compiled quantitative and semi-quantitative estimates. In most cases, dust chemistry and mineralogy was reported for a specific particle size range, unfortunately the size ranges used for chemical and mineralogical analyses often varied from study to study. As a result, we have not explicitly examined variations in chemistry or mineralogy related to particle size, though we do evaluate evidence for these patterns in our discussion of the results.

To evaluate spatial patterns in the chemical and physical properties of dust deposition, we attempted to compare each of the three deposition types (local, regional, and global). However, in most cases these comparisons were difficult due the small number of observations available in the literature and limited overlap in the chemical analyses reported by each study. As a result, we were forced to speculate on how the characteristics of dust deposited may change with distance from source areas. However, we were able to compare the chemical characteristics of dust emitted from three different source regions including Africa, Asia, and North America.

To assess the relative elemental composition of Aeolian dust, we compare individual measurements of dust element composition with the average chemical composition of the upper continental crust (UCC) from Wedepohl (1995). Ideally, the chemical composition of dust should be compared to soil chemistry because most dust is formed from soils that have undergone some degree of chemical weathering not reflected in the chemistry of the UCC. However, there are several factors that made comparing dust chemistry to soils difficult. One challenge is that, at present, there are no easily available databases of global soil geochemistry. In addition, soils exhibit a high degree of spatial heterogeneity in their chemical composition (especially in vegetated areas). Finally, some soils are formed primarily from dust (Pye, 1995; Reynolds et al., 2006b), complicating comparisons to dust chemistry. In response to these issues, Schütz and Rahn (1982) examined the elemental concentration of different soil particle size classes and determined that bulk crustal rock was a

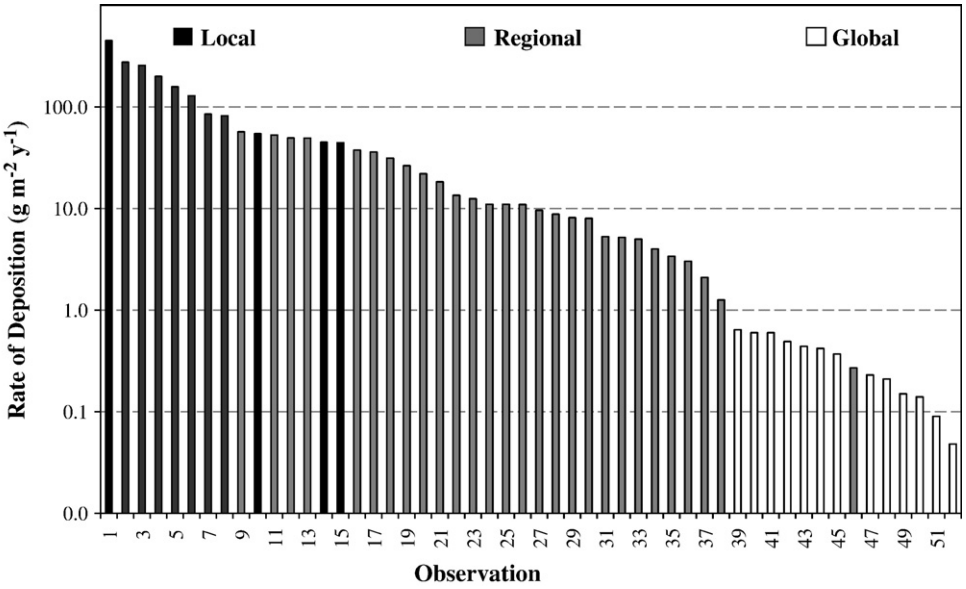

Fig. 1. *Synthesized observations of dust deposition rates.* The mean annual deposition rates for 52 different locations throughout the world (g m^{-2} yr^{-1}) are plotted on a logarithmic scale. Each observation is shaded based on its estimated distance from the source region. Black bars show observations made from 0–10 km from the dust source (local), dark grey bars show observations made from 10–1000 km from the dust source (regional), and light grey bars show observations made greater than 1000 km from the dust source area (global). In most cases the 3 spatially defined class group together reflecting a relationship between the rate of deposition and the distance from the dust source region. The *x*-axis reflects the rank order of the observations. Information about the location of each observation and the original source of the data is located in Table 1.

suitable, if not ideal, reference material for evaluating the chemical composition of dust.

To interpret our comparison of dust chemistry to the UCC we must keep in mind that the composition of dust is likely to deviate from that of average UCC values for a number of reasons. First, dust is produced from soils formed from crustal material through the processes of physical and chemical weathering. These processes lead to differential losses of elements that are easily weathered, resulting in soils that are depleted in mobile elements and enriched in immobile elements relative to the average UCC composition (Schütz and Rahn, 1982). Second, surface soils tend to accumulate organic matter and consequentially dust emitted from soils may also contain a substantial organic component (e.g. Ramsperger et al., 1998), which is not represented in composition of the UCC. Finally, the fractionation of soil particle sizes during dust emission and transport may lead to changes in the bulk chemical composition of dust.

4. Results

4.1. Rates of deposition

Dust deposition rates, spanning several orders of magnitude, have been observed throughout the world (Fig. 1). In the studies we have compiled, dust deposition ranges from 0.05 g m^{-2} yr^{-1} on Penny Ice Cap in Northern Canada (Zdanowicz et al., 1998) to 450 g m^{-2} yr^{-1} in the Taklimakan desert of China (Zhang et al., 1998). When we ranked these observations by deposition rate, there is a relationship between deposition rate and distance to source region. In Fig. 1, the ranked observations of mean annual dust deposition rates (Table 1) group together based on the assigned spatial classes (local, regional, global) and thus each deposition class exhibits a characteristic range of dust deposition rates (Table 2). Sites, located more than 1000 km from any primary or secondary source regions (global), receive between 0.05 and 1.00 g m^{-2} of dust/year. This range of dust inputs likely represents the background rate of dust deposition, such that all sites throughout the world receive, at minimum, this range dust deposition each year. Sites located between 10 and 1000 km from source areas (regional) experience dust inputs that range from 1.0 to 50 g m^{-2} yr^{-1}. Based on Fig. 1, locations experiencing regional rates of deposition are further subdivided into sites located near primary source regions (20–50 g m^{-2} yr^{-1}) and those located near secondary source regions (1.0–20 g m^{-2} yr^{-1}). Finally, sites located within or very near to active source areas (local) receive greater than 50 g dust m^{-2} yr^{-1}. Local dust deposition rates may also differ substantially between primary and secondary source regions but we were not able to quantify this distinction.

4.2. Particle size distribution

For the purpose of this study, we utilized a particle size classification scheme including clay (<2 μm), fine silt (2–20 μm), coarse silt (20–50 μm), fine sand (50–125 μm), and medium sand (125–250 μm). Local deposition is characterized by a substantial portion of coarse silts and/or fine sands with between 10–60% of the total mass made up of particle greater than 20 μm in diameter (Table 2). Fine silts are also abundant in local dust, contributing between 25–60% of the total deposition mass, while clay particles account for 10–40%. In contrast, regional dust has a smaller proportion of coarse silts and fine sands, a larger proportion of fine silts, and clay content similar to local deposition. Finally, global deposition is composed entirely of silts and clays; however, the split between these two size-fractions is not clear from the compiled data. Overall, the compiled observations reflect a general trend of decreasing particle size with increasing distance from the source region. Furthermore, these data suggest that silt-sized particles are the optimal size for atmospheric transport and highlight the importance of relatively large particles (>10 μm).

4.3. Mineralogy

The mineralogy of dust varies systematically across local, regional, and global deposition types (Table 3). Local-type deposition has a higher proportion of coarse and fine sands and as a result is often dominated by quartz minerals. Specifically, quartz accounts for 50% or more of the total mineral mass of local deposition. In addition to quartz, many local-dust samples also contain phyllosilicate (5–30%), feldspar (10–30%), and carbonate (0–25%) minerals. In comparison, regional-dust samples exhibit a higher proportion of feldspars and phyllosilcates but often still contain appreciable amounts of quartz and carbonates. The mineral composition of global-dust is dominated by phyllosilicates (20–60%), most commonly illite and kaolinite.

Table 1
Dust deposition observations and sources ranked by the mean annual rate of dust input.

Rank	Location	Lat	Long	Class	Deposition	Duration	Source
1	Desert regions, China	40	85	Local	450	1	Zhang et al. (1998)
2	Central Libya, North Africa	28.5	16.25	Local	276	1	O'Hara et al. (2006)
3	Lake Tekapo, New Zealand	−43.9	170.5	Local	257	1/2	McGowan et al. (1996)
4	Niger, West Africa	13	2	Local	200	7	Drees et al. (1993)
5	Northern Nigeria, Africa	12.1	8.5	Local	159	NA	McTainsh and Walker (1982)
6	North Libya, North Africa	32	13	Local	129	1	O'Hara et al., 2006
7	Northern Nigeria, Africa	12	8	Local	85.0	1	Moberg et al. (1991)
8	South Libya, North Africa	27.25	14	Local	82.0	1	O'Hara et al. (2006)
9	Argentinean Pampa	−36.5	−64.25	Regional	57.0	3	Ramsperger et al. (1998)
10	Phoenix, AZ	33.44	−112.07	Local	54.5	1	Pewe (1981)
11	Hexi Corridor/Loess Plateau, China	36.5	105	Regional	53.0	4	Derbyshire et al. (1998)
12	NE Subtropical Atlantic	18.5	−21	Regional	49.5	2	Bory et al. (2002b)
13	German Alps	47.5	11.08	Regional	49.3	2	Kufmann (2006)
14	Negev Dessert, Israel	34.8	30.8	Regional	45.0	1/3	Goossens (2000)
15	Dead Sea, Israel	31.5	35.4	Local	44.5	3	Singer et al. (2003)
16	New South Wales, Australia	−30	146	Regional	37.6	10	McTainsh and Lynch (1996)
17	Mesa Verde, CO	37.2	−108.5	Regional	36.0	2	Arrhenius and Bonatti (1965)
18	Namoi Valley, Australia	−30.3	150	Regional	31.4	6	Cattle et al. (2002)
19	South Island, New Zealand	−43	170	Regional	26.4	1	Marx and McGowan (2005)
20	Ghana, Gulf of Guinea	7.5	−34	Regional	22.0	2	Resch et al. (2008)
21	Mediterranean Basin	35.88	14.5	Regional	18.3	NA	Guerzoni et al. (1999)
22	Mallorca Island, Mediterranean	40	−7	Regional	13.5	6	Fiol et al. (2005)
23	San Juan Range, CO	37.9	−107.7	Regional	12.5	5	Lawrence, unpublished
24	Tel Aviv, Israel	32	34.5	Regional	11.0	1	Ganor and Mamane (1982)
25	Mojave Dessert, NV and CA	37	−116	Regional	11.0	16	Reheis (2006)
26	Coast Mountains, BC, Canada	50.4	−122.9	Regional	10.9	1	Owens and Slaymaker (1997)
27	Karakoram Mountains	36	75.7	Regional	9.60	3	Wake et al. (1994)
28	NE Subtropical Atlantic	21	−31	Regional	8.80	2	Bory et al. (2002b)
29	Pamir Mountains, Tajikistan	38.2	75.1	Regional	8.14	2	Wake et al. (1994)
30	Cote d'Ivoire, Africa	7.3	5.9	Regional	8.00	1/6	Stoorvogel et al. (1997)
31	Spain	41.8	2.3	Regional	5.30	3	Avila et al. (1997)
32	Sapporo, Japan	43.1	141.3	Regional	5.20	1	Uematsu et al. (2003)
33	Front Range, CO	40	−105.5	Regional	5.00	1	Ley et al. (2004)
34	Wind River Range, WY	43	−109.5	Regional	4.00	2	Dahms and Rawlins (1996)
35	So. Tibetan Plateau, China	28.5	87.5	Regional	3.39	1	Wake et al. (1994)
36	Tanggula Shan Mountains	33.4	91.1	Regional	3.02	2	Wake et al. (1994)
37	French Alps	45.5	6.5	Regional	2.10	30	Deangelis and Gaudichet (1991)
38	Miami, Florida	25.75	−80.25	Regional	1.26	2	Prospero et al. (1987)
39	Norfolk Island, Australia	−29.08	167.98	Global	0.64	5	Prospero et al. (1989)
40	Midway Atoll	28.2	−177.35	Global	0.60	7	Prospero et al. (1989)
41	Shemya, Aleutian Islands	52.92	174.06	Global	0.60	7	Prospero et al. (1989)
42	McMurdo Valley, Antarctica	−77.6	163.8	Global	0.49	5	Lancaster (2002)
43	Enewetak, Marshall Islands	11.3	162.3	Global	0.44	7	Prospero et al. (1989)
44	Oahu, HI	21.3	−157.6	Global	0.42	7	Prospero et al. (1989)
45	New Caledonia	−22.15	167	Global	0.37	3	Prospero et al. (1989)
46	Himalaya (S. Slope)	28	86.7	Regional	0.27	1	Wake et al. (1994)
47	Nauru, South Pacific	−0.53	166.95	Global	0.23	7	Prospero et al. (1989)
48	Rarotonga, Cook Islands	−21.25	−159.75	Global	0.21	7	Prospero et al. (1989)
49	Samoa, Samoan Islands	−14.25	−170.6	Global	0.15	1	Arimoto et al. (1987)
50	North Island, New Zealand	−34.5	172.75	Global	0.14	1	Arimoto et al. (1990)
51	Fanning, Line Islands	3.9	−159.3	Global	0.09	7	Prospero et al. (1989)
52	Penny Ice Cap, Canada	67	65	Global	0.05	7	Zdanowicz et al. (1998)

The specific location or region of the observations is reported along with the geographic coordinates. We list the exact latitude and longitude of each observation when that information was reported in the original publication, otherwise we list estimated coordinates based on the described location of the study. We have also listed the expected deposition class of each observation that was determined based on estimates of the distance from observation to the assumed source region. The average annual deposition rate is reported in units of g m^{-2} yr^{-1}. The study duration is reported in years and labeled "NA" when that information was not available.

Global deposition likely contains large amounts of phyllosilicate minerals as a result of decreases in amount of quartz. However, quartz and feldspars still account for up to 20% of global-dust. The observed variations in the three proposed deposition types are likely related to differences in particle size distribution (i.e. Leinen et al., 1994; Merrill et al., 1994).

4.4. Dust chemistry

The concentrations of most major elements are generally similar to the average upper-continental crust (Table 4, Fig. 2). Specifically, the concentrations of the elements Si, Al, Fe, Ca, K, Mg, and Mg in dust are within a factor of ±0.2 of UCC concentrations. Several major elements do differ from UCC concentrations. Specifically, P and Ti are exhibit mean concentrations that are 1.6 and 1.7 times that of the UCC respectively, while the mean Na concentrations of dust are 0.5 times that of the UCC. Trace elements, particularly heavy metals such as Cr, Co, Pb, Cu, and Ni tend to be enriched relative to UCC values. On average, dust exhibits concentrations 4.8, 3.2, and 3.2 times the concentrations in UCC, for elements Pb, Cu, and Ni respectively. Fig. 3 shows the mean and range of enrichment observed for each element considered. We found very few observations of the organic composition of dust. However from the limited number of observations ($n=3$), the total organic composition of dust is usually between 8–10% of the total dust mass. Carbon is the dominant element represented in the organic fraction, representing between 2–6% of the total dust mass (data not shown). Total nitrogen accounts for between 0.4–0.8% of the total dust mass (Table 4).

The overall variability in dust chemistry and enrichment relative to the UCC is relatively small for major elements despite the fact that the

Table 2
General physical characteristics of three distinct classes of Aeolian deposition: local, regional, and global.

Deposition class	*n*	Distance from source	Deposition rate	Particle size
		km	g m^{-2} yr^{-1} (mean)	% clay, silt, sand
Local	11	0–10	50 – 500 (200)	20, 50, 30
Regional	28	10–1000	1 – 50 (20)	25, 60, 15
Primary			25 – 50	
Secondary			1 – 25	
Global	13	>1000	0 – 1 (0.4)	30, 70, 0

The deposition range of the regional class is further divided by source region strength (primary or secondary). Data compiled from observations listed in Table 1.

observations are compiled from around the globe (Fig. 2). The standard errors of major element concentrations are typically within 20% of the mean values (Table 4). Of the major elements compiled, Ca is the most variable, likely as a result of the wide range of calcite abundance found in surface soils. The concentrations of trace elements in dust, especially the heavy metals, are much more variable than the concentration of major elements. Of the trace elements compiled Pb, Ni, and Co are the most variable. Similarly, when observations are partitioned based on the assumed source areas, trace elements exhibited the greatest regional variability (Fig. 3). In particular, the trace element composition of dust from North American source regions is distinct from Asian and African dust. However, more observations of dust from these regions are needed to perform adequate statistical evolutions of these patterns.

5. Discussion

5.1. Deposition rate

The spatial distribution of dust deposition observations provides a useful framework for evaluating geochemical flux from dust. The compiled data reveal that annual dust deposition can be as high as 450 g m^{-2} yr^{-1} in areas located within or immediately adjacent to dust source regions (Zhang et al., 1998). In general, deposition rates decrease with distance from source regions, yet deposition rates in areas regionally proximal to primary or secondary dust sources can be as high as 50 g m^{-2} yr^{-1}. In contrast, rates of global-deposition are consistently less than 1 g m^{-2} yr^{-1}.

The timescales of the compiled observations range from several months to several decades, but 90% of observations span a year or more (Table 1). Although we believe this compilation of observations provides a meaningful examination of dust deposition rates, it is likely that the annual rate of deposition at any single location is highly variable though time. For example, there is abundant evidence that the rate of dust deposition varies seasonally in many ecosystems (Bory et al., 2002a; Prospero and Lamb, 2003; O'Hara et al., 2006) and several modeling studies have shown that dust emission is highly sensitive to seasonal parameters such as the extent of precipitation, vegetation, meteorology, and land use (Werner et al., 2002; Mahowald et al., 2002; Mahowald et al., 2007). Furthermore, evidence suggests in some settings, a large portion of the total annual dust flux occurs during a relatively small number of very dusty days (Avila et al., 1997). These observations bring into question the frequency and duration of sampling used to estimate dust deposition rates. Areas receiving local-deposition may be characterized by more frequent deposition events, while the dust flux to areas receiving regional or global-deposition are more likely to be dominated by infrequent deposition events. As a result, accurately measuring dust deposition in areas of regional or global-deposition requires continuous and long-term measurements. Studies focusing on the dust flux to a particular location should consider seasonal factors controlling both the emission of dust from likely source regions as well as local factors that may influence the deposition process.

When the compiled deposition rates are mapped, the spatial relationships between the three deposition types are clearly visible (Fig. 4). With few exceptions, areas receiving local-deposition are located in or very near to primary or secondary dust source regions. In contrast, areas of regional-deposition rates are typically located around the perimeter of dust source regions, while areas of global-deposition are located far from known sources of dust. Overall, these results fit our expectations for the spatial patterns of dust deposition intensity in relation to source areas. Exceptions to these patterns may be a result of local, tertiary, dust source regions producing in higher than expected

Table 3
The range of mineral abundances observed for dust of different deposition types (as defined in text).

Deposition type	Quartz	Feldspars	Carbonates	Phyllosilicates	Other
Local	50–60+%	5–30%	0–25%	5–30%	0–12%
Regional	30–50%	5–35%	0–25%	5–40%	0–12%
Global	15–30%	20–40%	0–25%	20–60%	0–12%

Mineral content is presented in units of % and broken down into 4 major mineral groups. The phyllosilicates includes most clay minerals but is typically dominated by illite and kaolinite. Data compiled from Wilke et al. (1984), Moberg et al. (1991), Leinen et al. (1994), Alastuey et al. (2005), Fiol et al. (2005), Zdanowicz et al. (2006) and Jeong (2008).

Table 4
Elemental concentrations observed in Aeolian dust deposition.

Element	*n*	Min	Max	Mean	Mean enrichment
Si (%)	12	22.4	35.7	28.5 ± 0.8	0.9
Al (%)	12	3.7	12.7	7.1 ± 0.7	0.9
Fe (%)	14	1.3	7.8	3.6 ± 0.4	1.2
Ca (%)	12	1.0	10.2	3.6 ± 0.8	1.2
Mg (%)	12	0.5	2.3	1.2 ± 0.2	0.9
K (%)	14	1.2	4.6	2.3 ± 0.2	0.8
Na (%)	13	0.4	2.5	1.2 ± 0.2	0.5
Ti (ppm)	13	2000	10000	5000 ± 1000	1.7
Mn (ppm)	10	280.0	1239.2	637.5 ± 87	1.2
P (ppm)	10	654.6	2007.4	1086.6 ± 137	1.6
Cu (ppm)	6	11.7	112.0	45.3 ± 16	3.2
Ni (ppm)	8	12.7	225.9	58.6 ± 26	3.2
Co (ppm)	6	5.0	99.9	23.9 ± 17	2.1
Cr (ppm)	8	39.0	131.0	78.9 ± 12	2.3
Pb (ppm)	7	20.7	236.0	80.8 ± 33	4.8

The mean enrichment (or depletion) factor is calculated relative to the average elemental concentrations in the upper continental crust (from Wedepohl, 1995). Data compiled from Wilke et al. (1984), Reheis and Kihl (1995), Stoorvogel et al. (1997), Zhang et al. (1998), Yadav and Rajamani (2004), Goudie and Middleton, 2006, Moreno et al. (2006), Jeong (2008), and Lawrence, unpublished.

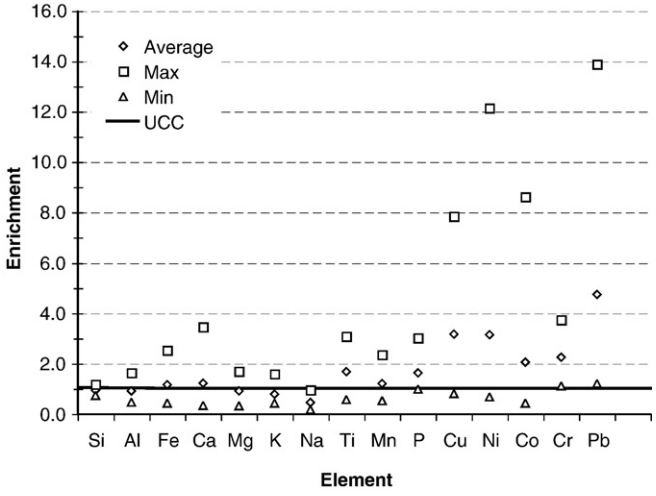

Fig. 2. *Enrichment factors of aeolian dust relative to the Upper Continental Crust (UCC).* Enrichment factors are calculated for each element relative to average concentrations of the UCC from Wedepole, 1995. The enrichment factors for the minimum (triangles), maximum (squares), and mean (diamonds) of the synthesized observations are shown relative to the average UCC (black line).

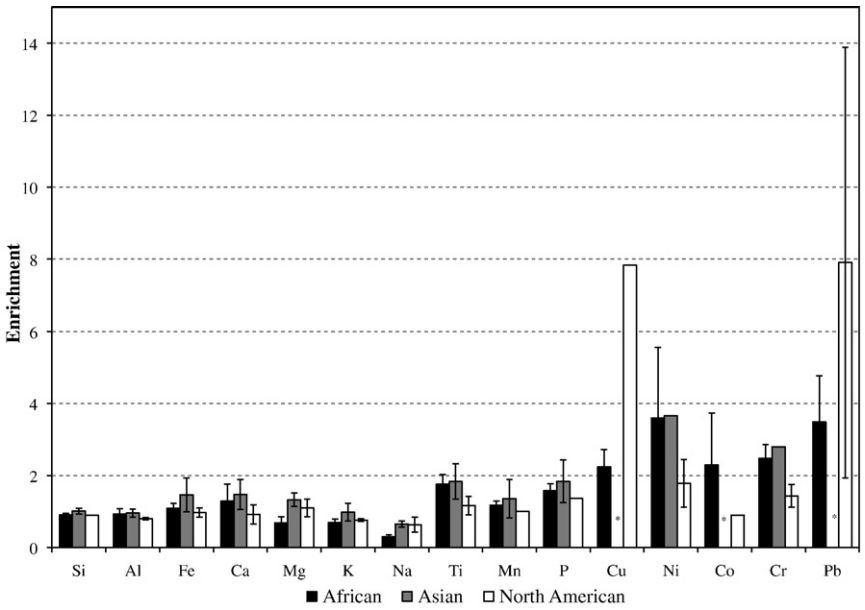

Fig. 3. *Enrichment factors of dust from different source regions relative to the Upper Continental Crust (UCC).* Synthesized observations of dust chemical composition are partitioned and compared by source region. All chemical concentrations are presented as enrichment factors relative to the upper continental crust for ease of viewing.

deposition rates in some areas (for example McGowan et al., 1996) or geographic barriers limiting the deposition of dust in areas located near to major source regions (for example, south slope of the Himalaya, Wake et al., 1994).

With the exception of several widely cited estimates of dust deposition from active sampling (i.e. Ginoux et al., 2001), we have limited our synthesis to direct observations of deposition. Direct measurements of dust deposition by passive collection methods are advantageous in that they do not require the detailed site characterization to calculate deposition rates from atmospheric dust concentrations. However, there are several limitations associated with passive measurements of dust deposition. For one, artificial collection surfaces used in passive measurement of dust deposition are often not representative of natural surfaces. In addition, collections need to be made at several different heights above the ground in order to characterize the vertical deposition profile and to accurately calculate ground level deposition fluxes (Sow et al., 2006). Finally, the collection efficiency of passive collectors is also known to decrease with elevated wind speeds (Sow et al., 2006). As a result of these problems, deposition rates measured by passive collection may not represent true deposition rates (Goossens and Offer, 1994; Goossens and Rajot, 2008). In general, passive measurements of dust deposition often underestimate deposition rates (Sow et al., 2006). Another issue with passive dust collectors is that they are prone to contamination by local organic matter as well as by birds and insects (Reheis and Kihl, 1995). This local contamination of samples may also influence the measured physical and chemical composition of the dust. Many recent studies using passive collection protocols attempt to prevent local contamination by elevating passive samplers some distance above the ground and by incorporating bird and insect deterrents into the sampler design (Reheis and Kihl, 1995; Zaady et al., 2001). Active sampling protocols are also susceptible to local contamination. In addition, active sampling estimates of deposition and require the quantification of particle size, wind velocity, and surface characteristics in order to convert filtered dust masses to dry deposition rates (Wesely and Hicks, 2000; Goossens and Rajot, 2008), additional calculations are also required to determine wet deposition rates. Finally, both methods for the direct measurement of dust deposition may not accurately reflect the actual accumulation of dust. For instance, Ewing et al. (2006) measured contemporary dust deposition with passive collectors in arid and hyperarid sites of the Atacama Desert, Chile and compared these to estimates of deposition based on the accumulation of salts in the soil profile. The results of this comparison suggest that passive collections may have overestimated deposition rates, or more likely, that the accumulation of dust in some soils is limited by presence of physical soil crusts (Ewing et al., 2006).

5.2. Particle size

Theory suggests that at some distance from a dust source region the PSD reaches equilibrium (Rea and Hovan, 1995), where the relative abundance of different sized particles stabilizes. Dust that has reached this PSD threshold has been referred to as "background" (Prospero et al., 1983) and in the deposition framework we have proposed above, it is equivalent to global-type deposition. Similarly, local- and regional-type deposition exhibit predictable dust particles size patterns. Specifically, local deposition has higher abundances of coarse particles while regional deposition has intermediate abundances of sands and large-silts. Even though the relative abundance of fine-textured particles is lower in regional and local-deposition, the overall flux of fine-textured particles is much greater than the flux from global-deposition (Table 2).

We report our best estimate for the average PSD for each of the three deposition types, which reflect the observed decrease in the relative abundance of large particles with increasing distance from dust source regions. However, we were not able to determine a characteristic PSD for each of our proposed deposition types. The actual PSD of dust deposition was quite variable even when observations are partitioned in classes based on distance from source region. Several factors blur the relationship between particle size and source distance including wind speed, topography, and the PSD of the source region. Additionally, in areas where multiple dust source regions may contribute to the overall dust flux, the PSD of dust deposited may exhibit multiple particle size modes. For example, a study of dust in Mali, West Africa found dust deposited there exhibited a bi-modal PSD during deposition events consisting of both local and regional sources (McTainsh et al., 1997).

Overall, the synthesized data reveal that each class of deposition (local, regional, global) exhibited distinct particle size distributions (Table 2). In other words, the particle size distribution of dust inputs did appear to vary systematically with distance from the source region. However, because many of the compiled studies reported partial or no particle size data, our interpretation of differences between dust

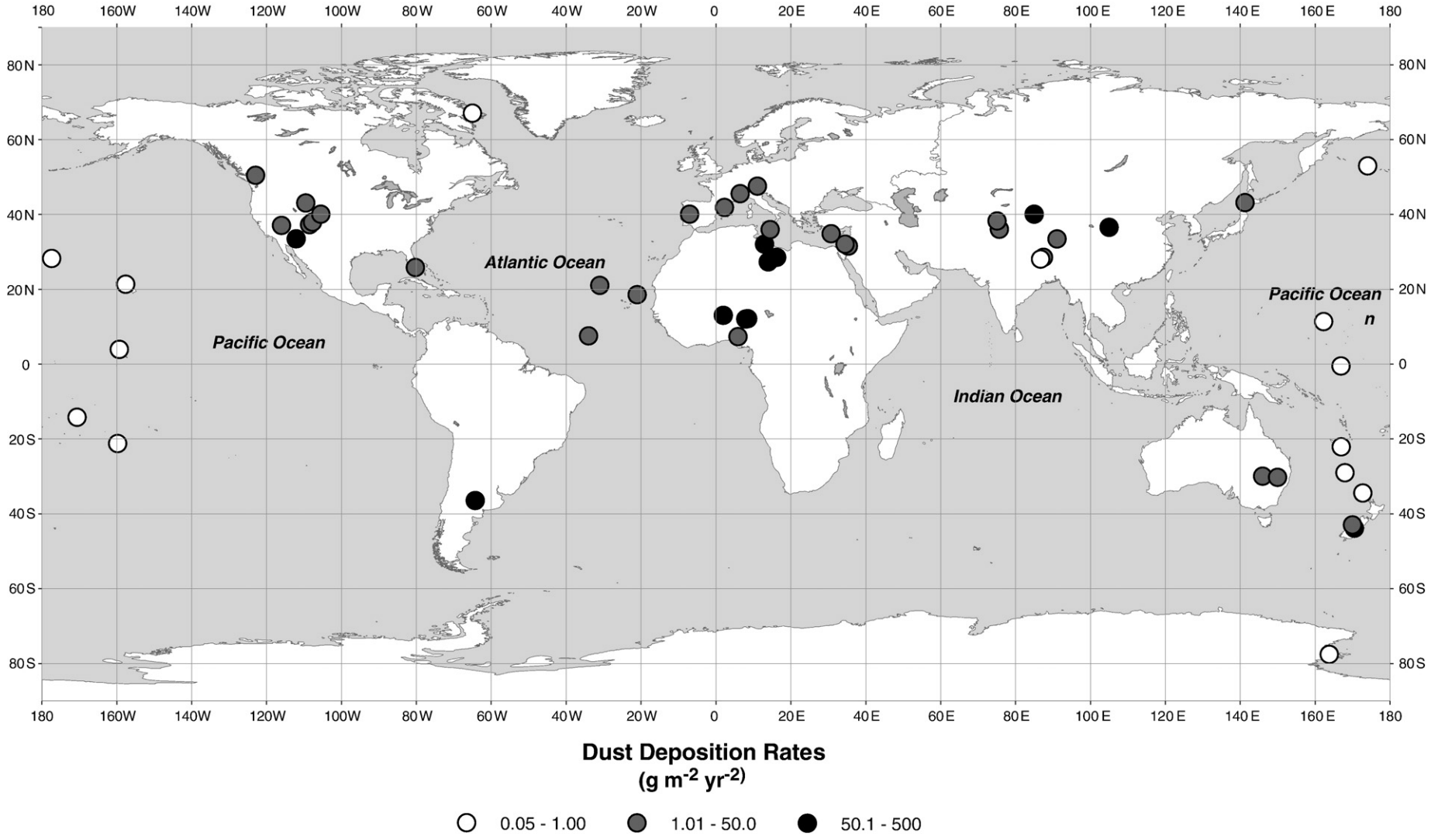

Fig. 4. *Spatial map dust deposition rates partitioned into three spatial classes.* The synthesized observations of dust deposition ($g\ m^{-2}\ yr^{-1}$) are projected as one of three classes based on deposition rate. When the observations are mapped, the proposed relationship between the rate of dust deposition and proximity to source regions appears to hold true. Major primary and secondary source regions are located in north central Africa, central Asia, the southwestern United States, central Australia, and South America.

deposition and class particle size characteristics remains qualitative at best.

5.3. Mineralogy

Previous research has shown that silicate minerals including quartz, feldspars, and phyllosilicates dominate Aeolian dust (Schütz and Sebert, 1987). Our results are consistent with these observations. The phyllosilicates present in dust include illite, kaolinite, smectite, and montmorillonite clays, chlorite, and in some cases micas. Dusts may also contain substantial amounts of carbonates, oxides, sulfates, and/or halites but quantity of these minerals is quite variable in space and time. For example, a multi-year study of dust deposition in the Mojave Desert of southern Nevada and California found that carbonates ranged from 8–30%, gypsum ranged from 0.1–6.6%, and total soluble salts ranged from 4–18% of the organic-free dust mass (Reheis and Kihl, 1995).

Many of the variable characteristics of dust mineral composition may be explained by differences in the geologic composition of the source regions (Claquin et al., 1999). On the global scale, mineralogical difference in source soils should be large enough to distinguish between dust generated from different primary and secondary source areas (Krueger et al., 2005). On the regional scale, variations in the mineral composition of dust can be subtle (Schütz and Sebert, 1987) but in some cases variations may be great enough to identify the source areas. For instance, Caquineau et al. (1998) determined that the ratio of kaolinite to illite in clay fractions of dust deposited in the Caribbean could be used to determine its source region in Africa. In another example, Kufmann (2006) observed seasonal shifts in the mineral composition of dust deposited in the Alps and concluded that seasonal snow cover regulates the relative contribution of dust from local versus regional source areas.

Our results suggest there are several predictable trends in dust mineral composition based on distance from its source region. With increasing distance from the source region, minerals associated with clay- and silt-sized particles make up a greater proportion of the dust mass. More specifically, dust deposited further from its source area tends to have greater proportions of phyllosilicates and lower proportions of quartz and feldspar (Table 3). This is consistent with other research that has focused on the transport of dust-derived minerals (Leinen et al., 1994; Merrill et al., 1994; Arnold et al., 1998). For example, Arnold et al. (1998) showed that the mineral content of dust is fractionated with increased transport time through the atmosphere, the relative abundance of primary minerals decreased while the abundance of secondary phyllosilicates increased.

5.4. Chemistry

The concentration of most major elements in dust is, on average, similar to the concentrations of the average UCC, though there is substantial variability in the concentration of most elements (Table 4, Fig. 2). In many cases, the similarities and differences between the chemical composition of dust and the UCC can be explained in light of the weathering process. For example, Na is an element that is often depleted in dust relative to the UCC; on average, the concentration of Na in dust is 50% less than UCC concentrations (Table 4, Fig. 2). During the weathering of crust material to form soils, Na is leached from soil profiles, likely resulting in the consistent depletion of Na in fine textured soils and dust (Schütz and Rahn, 1982). Conversely, immobile elements such as Ti are often enriched in dust. Immobile elements become enriched in soils (and subsequently dust) as mobile elements are leached away and the overall volume of the soil changes. Other weathering resistant elements such as Zr and Hf also exhibit similar enrichments in fine textured soils and in dust (Schütz and Rahn, 1982; Castillo et al., 2008).

The weathering derived enrichment of immobile elements in fine soils and dust has implications for the interpretation of the concentrations of other more mobile elements. If the observed enrichment of immobile elements are a result of weathering derived changes in the volume of soil prior to dust emission and not as a result of an additional source of those immobile elements to dust, the concentration of other more reactive elements will also have been influenced by the volume changes. As a result of these processes the measured depletion of a mobile element in dust relative to the UCC may underestimate the actual depletion. Similarly, the enrichment of immobile elements maybe overestimated if weathering losses are not taken into account. Changes in concentrations of elements resulting from weathering derived volume losses can be accounted for by normalizing to the concentration of an element that is known to be immobile. However, this approach is only viable for dust samples if the dust material originates from a single source soil. Because this assumption is very difficult to test and rather unlikely, the best approach is to use caution when interpreting comparisons to the UCC. The concentration of immobile elements in dust is also an important factor for studies of soil profile development that use these elements as immobile tracers of volume loss in soils. If dust deposition adds particles, which are enriched or depleted in these elements relative to local bedrock and/or soil, calculations of weathering intensity and mass loss based on immobile element ratios may be skewed.

Our results also confirm that trace elements are consistently enriched in dust relative to the UCC (Fig. 2, Table 3). Many other researchers have noted the enrichment of trace elements in dust (Reheis et al., 2002; Yadav and Rajamani, 2004; Erel et al., 2006; Zdanowicz et al., 2006; Yang et al., 2007; Castillo et al., 2008) and this enrichment is not unexpected given that the silt- and clay-size fractions of soils often exhibit high concentrations of trace elements relative to other soil size fractions (Schütz and Rahn, 1982; Hardy and Cornu, 2006; Castillo et al., 2008). For example, Schütz and Rahn (1982) examined the relationship between trace element concentrations and particle size in desert soils from Africa and North America and showed several general patterns of particle size dependent enrichment of elements. Most notably, metals, including Cu, Zn, Ag, Au, and As are highly enriched in soil particles less than 10 μm (Schütz and Rahn, 1982). Similarly, Castillo et al. (2008) reported enrichments of Zn, Cu, Ni Cr, Mo, and Pb in both African fine soils fractions and dust. In addition, because dust emission preferentially removes the silt- and clay-sized particles, dust will likely become further enriched in the concentrations of trace elements relative to both soils and UCC. Furthermore, size dependent fractionation of dust during deposition may lead to increased trace element enrichment with increasing distance from dust source areas. Unfortunately, trends in dust elemental composition based on particle size were difficult to identify in the compiled data because of overlap in the particle size of the compiled chemical data.

There are several mechanisms that can lead to the enrichment of trace-elements in fine textured soil and subsequently dust; among them, the reduction of the quartz dilution effect (Hardy and Cornu, 2006), the natural enrichment of trace elements in weathering resistant secondary clay minerals, the retention of trace-elements in secondary weathering products, and weathering derived changes in volume. In addition to these physical and chemical mechanisms associated with soil development, chemical transformations and mixing with other aerosol sources during atmospheric transport of soil-dust may also contribute to trace element enrichments (Chester and Murphy, 1986; Holmes and Miller, 2004; Erel et al., 2006).

Castillo et al. (2008) point out that natural geochemical processes alone do not easily explain the enrichments of transition metals such as Pb, Zn, and Cd. Instead, the enrichments of metals in dust are attributed to anthropogenic (Castillo et al., 2008), volcanic emissions (Hinkley et al., 1999), and/or biomass burning (Gaudichet et al., 1995). Atmospheric chemical reactions involving dust and other aerosols can alter the chemical characteristics of dust before it is deposited (Dentener et al., 1996) and pollutants may bind directly to dust particle surfaces (Erel et al., 2006). The reactions of soil-dust particles with other aerosols

are influenced by dust mineral composition (Krueger et al., 2005). For example, Sullivan et al. (2007) showed that high levels of nitrate accumulate on calcite-rich dust while high levels of sulfate accumulate on aluminosilicate-rich dust. Furthermore, some dust minerals may dissolve during atmospheric transport (Spokes et al., 1994; Spokes and Jickells, 1996). As an example, studies of dust to the Bay of Japan have suggested that a large portion of dust calcite completely dissolves in the atmosphere during transport (Jacobson and Holmden, 2006).

Overall, the chemical composition of Aeolian dust collected from around the globe exhibit many similarities, yet subtle differences do exist. One factor that leads to variations in dust chemistry is heterogeneity in composition of the source region (Moreno et al., 2006). In fact, the compiled observations of dust chemistry suggest that the dust emitted from different primary or secondary source regions are distinct (Fig. 3). Specifically, dust deposited in North America appears to be more enriched in trace-metals relative to both African and Asian dusts. Similarly, comparisons of the chemical composition of Asian (VanCuren and Cahill, 2002) and African (Perry et al., 1997) dust particles with North American dust found source regions can sometimes be distinguished based on element composition. These chemical differences could be a result of variations in source soil geology, local or regional anthropogenic emissions, or it may reflect a change in dust composition during long-range transport (VanCuren and Cahill, 2002). For example, concentrations of elements including Al, Fe, Ti, and Mg are likely related to the abundance of phyllosilicate minerals, while Ca variability may be related the abundance of soil carbonates. However, because of inconsistencies in the collection methods and the timing of the synthesized chemical observations, it is difficult to place much confidence in the observed variations in the chemical composition of dust from different sources regions. Moreover, without a better spatial distribution of direct measurements of dust chemistry it seems most appropriate to use a globally averaged value of dust composition to estimate the elemental flux from dust.

Aeolian dust, although typically dominated by mineral material may also contain a significant organic component. Several researchers have reported the total organic content of dust deposition to be within 5–8% of the total mass (Ramsperger et al., 1998; Ley et al., 2004). However, dust can exhibit exceedingly high organic matter contents. For example, Boon et al. (1998) found that dust deposited in Australia contained organic matter contents as high as 91% of the total mass. Li et al. (2008) found evidence that soil organic matter is the first component of soils to be eroded and redistributed by winds. This suggests that the organic content of dust emitted from specific source regions may decrease through time. However, the emission of particles during biomass burning may elevate the organic content of dust from some regions (Mahowald et al., 2005a). Overall, the organic fraction of dust may be an important source of biologically cycled nutrients including N and P.

Nitrogen is not a major component of rock or soil minerals, yet dust may still be an important source of both organic and inorganic nitrogen. In general, organic N deposition is an underestimated component of the nitrogen cycle and organic N input from dust may be an important contributor to this global flux of N (Neff et al., 2002). The reported range of total nitrogen content in dust is 40–80 mg N g^{-1}. These values are relatively high when compared to the N content of arid soils. For example, arid soils in the southwestern US typically contain less than 3 mg N g^{-1} (Fernandez et al., 2006). One mechanism that could account for the enrichment of N in dust relative to source soils is the binding of inorganic N compounds with dust mineral surfaces during atmospheric transport (Krueger et al., 2005). Alternatively, arid soils may exhibit low N content specifically as a result of dust emission (Neff et al., 2005). While the importance of N fluxes to ecosystems has been widely studied, the role of dust as a source and sink of nitrogen in terrestrial ecosystems may be underappreciated.

The enrichment of phosphorus in Aeolian dust is ecologically important because P is often a limiting or co-limiting nutrient for biologic processes in many different ecosystems (e.g. Schindler, 1977; Peterson et al., 1993; Wu et al., 2000; Cleveland et al., 2002). Phosphorus concentrations of atmospheric deposition are often measured either as total (TP) or soluble P (usually measured as PO_4). The measurements of TP compiled here include both inorganic and organic P. Thus, the relatively high concentrations of P in dust compared to the UCC may be a result of substantial organic P. If we assume that inorganic P concentrations in dust are equal to UCC values and that any enrichment in P is a result of organic P content, we estimate that organic P may account for up to 50% of the total dust P in some cases. These estimates are supported by several studies, which point out the input of organic P to the atmosphere from biomass burning (Gaudichet et al., 1995; Ferek et al., 1998; Artaxo et al., 2002) and biogenic particles including pollen, spores, and microbial cells (Graham et al., 2003). In a study of dust in the Amazon Basin, Mahowald et al. (2005a) combined direct measurements of aerosol chemistry and atmospheric modeling to estimate that biomass burning and biogenic particles accounted for over 90% dust P. The study by Mahowald et al. (2005a) concluded that the Amazon region was a net source of P, largely as a result of human disturbance. These results show that human interactions with the dust cycle are important controls of P deposition. To what extent natural and human-caused changes in the dust cycle influence the future flux of P to ecosystems is an important area of future research. The ecological importance of P deposition to terrestrial ecosystems depends not only on rate of P input, but also on the size of soil P reservoirs and the rate of P turnover (Okin et al., 2004). More detailed analyses of dust P chemistry are warranted to better constrain the source and to determine the availability of P once it is deposited.

5.5. Rates of chemical flux

Based on the average chemical composition of dust, the characteristic deposition rate, and the PSD, we can estimate the potential element flux for each of the three dust deposition types. Specifically, we have calculated individual element fluxes by multiplying the mean concentration (see Table 4) of each element by the minimum and maximum rate of deposition for each deposition type. Table 5 shows the calculated range of potential flux for several elements. We use the mean elemental concentrations from observations of dust chemistry as a way of roughly capturing temporal variability in dust deposition chemistry (space for time). The average chemical concentrations used may be biased toward the chemical composition of dust from primary dust source areas because there have been more observations of dust chemistry from those regions. However, these estimates represent the best approximation of the chemical flux resulting from dust deposition available for areas where dust chemical content has not been directly measured.

Our crude estimates of elemental flux rates generally agree with model predictions in locations characterized by low rates of dust deposition. However, in areas of local and regional deposition our flux estimates may be substantially larger than those predicted by models. For instance, if we use an average rate of total dust deposition to the world's ocean of 2.0 g m^{-2} yr^{-1}, we arrive at annual flux estimates of Si, Al, Fe, P, Cu, and Pb, which are within 25% of those estimated by Duce et al. (1991). Similarly, our estimates of regional and global-deposition of Ca are in good agreement with measurements of Ca fluxes to the Mediterranean region of Spain (Pulido-Villena et al., 2006) and to the North Eastern, United States (Likens et al., 1998), respectively. For the entire range of observed deposition rates our estimates of total P flux (0.0003–0.5 g m^{-2} yr^{-1}) are slightly less than the range predicted by Okin et al. (2004). However, in general, we expect our estimates of element fluxes to ecosystems located in or near dust source regions will be higher than those calculated using modeled estimates of deposition. This is because global dust models tend to underestimate deposition rates in areas proximal to dust source regions (see discussion of deposition modeling below).

Table 5
Estimated annual fluxes of several elements in units of g m^{-2} yr^{-1}.

Type	Global			Regional			Local		
Dep. rate	0.25	0.5	1.0	10	25	50	75	100	500
Si	0.071	0.142	0.285	2.849	7.121	14.243	21.364	28.485	142.427
Al	0.018	0.035	0.071	0.707	1.768	3.537	5.305	7.074	35.369
Fe	0.009	0.018	0.036	0.361	0.902	1.804	2.706	3.609	18.043
Ca	0.009	0.018	0.036	0.361	0.902	1.804	2.706	3.608	18.042
Mg	0.003	0.006	0.012	0.123	0.308	0.616	0.924	1.233	6.163
K	0.006	0.011	0.023	0.226	0.565	1.130	1.695	2.260	11.301
Na	0.003	0.006	0.012	0.117	0.293	0.587	0.880	1.174	5.869
Ti	1.3E-03	0.003	0.005	0.053	0.132	0.263	0.395	0.526	2.631
Mn	1.6E-04	3.2E-04	6.4E-04	0.006	0.016	0.032	0.048	0.064	0.319
TP	2.7E-04	5.4E-04	1.1E-03	0.011	0.027	0.054	0.081	0.109	0.543
Org P	1.6E-04	0.000	0.001	0.007	0.016	0.033	0.049	0.065	0.325
TN	0.010	0.020	0.040	0.400	1.000	2.000	3.000	4.000	20.000
Org C	0.001	0.003	0.006	0.059	0.148	0.295	0.443	0.590	2.950
Cu	1.1E-05	2.3E-05	4.5E-05	4.5E-04	1.1E-03	0.002	0.003	0.005	0.023
Ni	1.5E-05	2.9E-05	5.9E-05	5.9E-04	1.5E-03	0.003	0.004	0.006	0.029
Co	6.0E-06	1.2E-05	2.4E-05	2.4E-04	6.0E-04	1.2E-03	0.002	0.002	0.012
Cr	2.0E-05	3.9E-05	7.9E-05	7.9E-04	0.002	0.004	0.006	0.008	0.039
Pb	5.9E-05	1.2E-04	2.4E-04	0.002	0.006	0.012	0.018	0.024	0.118

Estimates are provided for 3 different dust deposition rates corresponding to each of the 3 deposition types including local, regional, and global (see text for description).

The deposition of dust may represents an important source of nutrients to many terrestrial ecosystems. The potential role of dust fluxes to biological systems can be better demonstrated by comparison to plant nutrient demand. For example, based on the elemental stoichiometry and productivity estimates for a temperate forest (i.e. Schlesinger, 1997), a dust deposition at a rate of 10 g m^{-2} yr^{-1} (regional deposition) could supply 0.5, 0.9, 5.8, 8.4, and 13% of the annual demand for N, P, K, Ca, and Mg respectively. In comparison, global rates of deposition could supply an order of magnitude less of the temperate forest nutrient demands, while local rates of dust deposition could supply an order of magnitude more of these essential elements (Table 6). The potential importance of dust deposition as a nutrient source is greater in ecosystems with lower rates of annual productivity (lower nutrient demand). If we assume the nutrient stoichiometry for other terrestrial ecosystems is similar to that of temperate forests and we scale the demand for each nutrient by the net primary productivity, we find that regional rates of dust deposition can contribute 5x and 8x more of each of the required nutrients in tundra and desert ecosystems compared with the temperate forest estimates. Thus arid, semi-arid, and/or alpine tundra ecosystems, located on the margins of dust source regions, are the most likely to be influenced by dust fluxes (e.g. Johnston, 2001; Muhs and Benedict, 2006; Reynolds et al., 2006a,b). Although, it may seem counterintuitive to imagine dust deposition as factor controlling primary productivity in arid and semi-arid regions (local-deposition), evidence suggests that dust deposition is important for the redistribution of nutrients in these areas (Okin and Gillette, 2001; Reynolds et al., 2006b; Li et al., 2008).

It is important to note that this simple comparison of the supply of nutrients from dust with the biological demand does not prove the importance dust. These comparisons merely show the potential for dust to be significant contributor to biological nutrient demand. It is much more challenging to measure the actual contribution of dust-derived nutrients to ecosystem productivity. To better constrain the role of dust for sustaining productivity many other factors must be considered including the endogenous supplies of nutrients from soil and bedrock weathering, the internal cycling of nutrients, or annual losses from the system. While these calculations are beyond the scope of this paper, several studies have shown the importance of dust as supply of nutrients in terrestrial ecosystems (Graustein and Armstrong, 1983; Swap et al., 1992; Chadwick et al., 1999).

The influence of dust deposition on biogeochemical cycling of elements is in some ways controlled by the relative availability for uptake by biological organisms of each element of interest. Within the dust, many elements occur in multiple geochemical forms, which vary in their biological availability. Elements that are soluble and/or exchangeable may quickly become available for biological uptake, chemical reactions, or export. Delmas et al. (1996) studied the chemistry of snow cover and melt-waters in France and found that Saharan dust that had accumulated in the snowpack quickly weathered releasing base cations, which raised the pH of the melt-waters. Similarly, surveys of snowpack and precipitation chemistry in the Rocky Mountains revealed patterns in snowpack solute chemistry and alkalinity attributable to dust inputs (Turk et al., 2001; Clow et al., 2002), which may influence stream chemistry in this region (Campbell et al., 1995; Clow et al., 1997).

Weathering resistant portions of dust are less readily available for biological uptake or export and are more likely to accumulate in soils or sediments. Over long timescales the accumulation of insoluble dust particles may influence the overall chemical composition of soils (Simonson, 1995; Johnston, 2001; Kurtz et al., 2001; Ewing et al., 2006; Muhs and Benedict, 2006) and aquatic sediments (Kohfeld and Harrison, 2003; Neff et al., 2008). Loess soils have been formed primarily from Aeolian dust deposition and typically retain chemical and textural properties shaped by the dust from which they were formed (Pye, 1995). Furthermore, the long-term weathering of dust that has accumulated in soils and sediments can also be an important control on the dissolved elemental flux to these soils and sediments. Porder et al. (2007) found that in older Hawaiian soils, the accumulation of dust is comparable to the weathering flux. Future studies of dust chemistry, in addition to quantifying the bulk chemical content, should also consider the form and availability of ecologically relevant elements.

5.6. Modeling dust depositions

Mathematical modeling is a valuable tool for understanding and predicting rates of dust deposition and geochemical fluxes (Okin et al.,

Table 6
The potential contribution of Aeolian dust to the annual biological demand for essential elements in a temperate forest ecosystem varies widely depending on the total input of dust.

Temperate forest		Global		Regional		Local	
	Demand (g m^{-2} yr^{-1})	0.5	1	10	25	50	100
N	11.54	0.03	0.05	0.51	1.28	2.56	5.11
P	1.23	0.04	0.09	0.88	2.21	4.42	8.83
Ca	6.22	0.29	0.58	5.80	14.50	29.01	58.01
Mg	0.95	0.65	1.30	12.98	32.44	64.88	129.75
K	6.69	0.17	0.34	3.38	8.45	16.89	33.78

Element demand and deposition rates are reported in units of g m^{-2} yr^{-1} while the proportions filled by dust inputs are reported as the % of the total demand that could be supplied by dust deposition.

2004; Luo et al., 2008). Models provide one of the few tools that can be used to evaluate dust deposition on a global scale. In models, mechanisms of dust emission, transport, and deposition are coupled with spatial distributions of potential dust source regions and atmospheric circulation models to simulate the global dynamics of the dust cycle (Tegen and Fung, 1994; Mahowald et al., 1999; Ginoux et al., 2001; Tegen et al., 2002; Zender et al., 2003a; Luo et al., 2003; Tegen et al., 2004). There are many assumptions that go into building a model of the global dust cycle and these models are often very sensitive to input parameters. For example, Lunt and Valdes (2002) found that their model of dust was very sensitive to several poorly constrained parameters and variations in these parameters resulted in changes in local dust concentrations of up to a factor of 90. Furthermore, global dust models are often parameterized to predict the long-range transport of fine-textured dust particles. Thus, care should be taken when evaluating the applicability of these models for predicting dust geochemical fluxes at different spatial scales.

Most dust models are optimized using either estimates or observations of dust emissions from a particular region (Cakmur et al., 2006). Typically emissions from primary source regions are used to optimize global dust loads. This technique allows models to capture the dominant global dust dynamics driven by the largest source regions. However, the quality and timescale of the data used to optimize these models may influence the ability of the models to accurately simulate dust deposition. Simulated rates of dust deposition are validated through comparisons with direct observations. The number and distribution of dust observations used to validate models set the boundaries of model uncertainty. If a model is optimized using data from the primary dust source regions and then validated against separate observations, the quality of model simulations are well constrained in the region where the observations were made. However, the ability of the model to accurately simulate dust processes is uncertain in regions where the model has not been validated. Many models utilize a limited number of observations to validate model simulations of dust deposition. For example, continental sites are sometimes excluded during the validation process because deposition there is influenced by regional processes such as anthropogenic land-use, wind born organic matter, and industrial pollutants, which are not included in most models (Tegen et al., 2002). Thus, global models often appear to accurately simulate dust deposition, but in some cases these models have not tested against the full range of dust deposition observations.

When global models are tested in continental settings, they tend to underestimate rates of deposition. The GOCART model (Ginoux et al., 2001) compares simulated deposition to observed deposition at 16 sites. The model adequately captures a range of deposition values spanning several orders of magnitude but tends to overestimate the lowest and underestimate the highest observed rates of deposition (Ginoux et al., 2001). Similar results have been obtained in other dust models (Zender et al., 2003a). The underestimation of high rates of deposition is attributed to the lack of large particles in the models (Ginoux et al., 2001).

Models vary widely in their representation of dust particle sizes (e.g. Tegen et al., 2002). For example, several models simulate only particles less than ~10 μm in diameter while others consider particles as large as 1000 μm. The logic for using a small particle size distribution in global dust models is that large particles are removed by gravitational settling very quickly relative to small particles and thus larger particles are not a major component of the global dust cycle. In addition, the smallest particles have the largest contribution to the radiative forcing of dust in the atmosphere (Tegen and Lacis, 1996). However, global-scale dust models often underestimate the particle size of dust deposition resulting in a bias toward small particles in the models (Zender et al., 2004). For example, Ginoux et al. (2001) compared modeled particle size distributions estimated by with Aerosol Robotics Network (AERONET) measurements (Dubovik and King, 2000). These comparisons were only possible at a small number of sites, but in general the GOCART model overestimates small particles and underestimates large particles (Ginoux et al., 2001). Other dust models produce similar results (Tegen et al., 2002; Luo et al., 2003).

The limited particle size distributions used in global dust models may result in the under estimation of deposition rates. In a modeling study where a broad range of particle sizes were simulated, the global emission of the smallest sized particles (<1 μm) accounted for 13% of the total mass of dust emitted, while particle larger than 25 μm accounted for 22% and silt-sized particles (1–25 μm) contributed 65% of dust mass (Tegen and Fung, 1994). Models that use a limited range of dust particle sizes may produce results that are biased in one of two ways. First, if the model is parameterized so that it captures the observed rates of total particle emission (including large particles), then it will overestimate the amount of small particles at the expense of larger ones (see Hand et al., 2004). This bias will result in underestimates of regional deposition but overestimates of far-traveled fine particles. Second, if models using a limited PSD are parameterized to accurately match the emission of PSD of which they simulate, they will have completely ignored the larger size distributions and will underestimate local and regional deposition but will accurately capture the globally distributed fine-textured particles. For example, Bory et al. (2002b) compared model estimates of deposition to the Northeast tropical Atlantic Ocean with observations from water column sediment traps and found the model generally underestimated deposition, they attributed this to a misrepresentation of the particle size distributions used in the model (Bory et al., 2002b).

To better evaluate the ability of global dust models to simulate deposition rates across a range of spatial scales, we compared our compiled observations to modeled estimates of deposition. In a review of the deposition of iron to the oceans, Mahowald et al. (2005b) generated estimates of soil-dust deposition from the average of three reanalysis based models (Luo et al., 2003; Ginoux et al., 2004; Tegen et al., 2004). In Fig. 5 we compare the model-based best estimates of dust deposition, from Mahowald et al. (2005b), with our compiled direct observations of deposition. This comparison reveals several systematic differences between averaged model estimates and observations. The main distinctions are that the models consistently underestimate local deposition (Fig. 5, diamonds) and overestimate background deposition (Fig. 5, triangles). This result is not unexpected, as global models are often tuned to capture the central tendency and consequently they sometimes fail to simulate the extremes. Models underestimate local deposition rates possibly as a result of the exclusion of large particle sizes. In comparison, the overestimation of deposition in areas dominated by long-range transport of dust could result from an over compensation in the modeled abundance of fine-textured particles in order to simulate the observed atmospheric dust burden without the inclusion of relatively large particles. The agreement between modeled estimates of deposition and observations for areas receiving intermediate amounts of dust inputs (regional deposition) are varied (Fig. 5, squares).

The comparison of direct measurements of dust deposition with estimates from global dust models emphasizes the limitations of using global scale models for predicting the chemical flux from dust in many regions. Regional- or local-scale models of dust may provide more realistic estimates of deposition at scales relevant to ecologists (see Pelletier and Cook, 2005); however, these types of models are not be available for many regions. Remote sensing measurements of dust deposition provide a useful alternative to model derived estimates. Remote sensing instruments such as the Total Ozone Mapping Spectrometer (TOMS) as well as satellite imagery have been previously used to observe the emission and transport of dust (Herman et al., 1997; Prospero et al., 2002; Zender et al., 2003a; Massie et al., 2004). These technologies may be used for estimating rates of deposition across large geographic areas (e.g. Jurado et al., 2004), however these methods should be tested against direct measurements of deposition such as those compiled here. In addition, the geochemical composition of dust must be considered in order to accurately predict element flux rates. We find that globally averaged dust chemistry is a reasonable

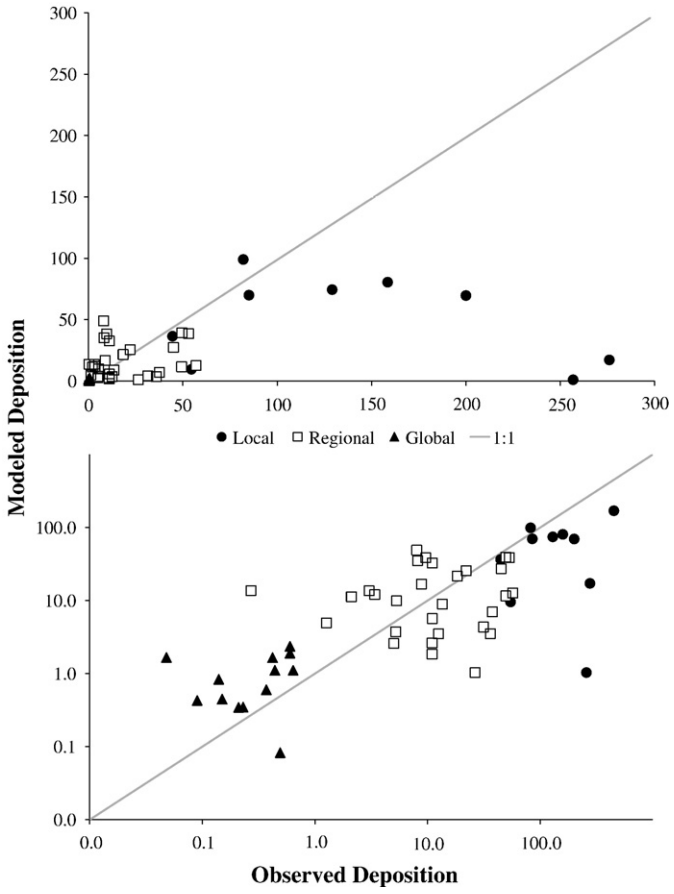

Fig. 5 *A comparison of observed and modeled dust deposition rates.* The synthesized observations of dust deposition rates (g m^{-2} yr^{-1}) are plotted against model estimates for the corresponding geographic region. The upper panel shows this comparison on a log–log scale, while the lower panel shows the same comparison plotted on a linear scale. On both panels points are divided into three deposition classes (local, regional, and global). This comparison shows that model estimates tend to under estimate global and some regional observations and may overestimate global observations. Model estimates where taken from the average of three reanalysis based models (i.e. Mahowald et al., 2005b).

approximation, when direct measurements of dust geochemistry are not available at a specific location.

6. Conclusions

The deposition of Aeolian (wind-blown) dust has important implications for ecosystem biogeochemistry. To best understand the dynamic role of dust in ecosystems, it is important to constrain the contemporary rates of dust deposition rates as well as its physical and chemical composition. Interpreting patterns of the physical and chemical properties of dust requires an understanding of the processes controlling dust emission, transport, and deposition.

To advance our understanding of the spatial variability of dust fluxes, we have synthesized a number of observations of dust deposition rates and the physical and chemical properties of dust. Our results indicate, consistent with the work of others, that dust deposition rates are highly dependant on the distance from source regions. We partitioned the complied observations of deposition rates into three broad classes including global-, regional-, and local-deposition, which are characterized by deposition rates of 0–1 g m^{-2} yr^{-1}, 1–50 g m^{-2} yr^{-1}, and 50–500 g m^{-2} yr^{-1} respectively. In addition, the data we have compiled also supports the notion that the PSD and mineral composition of dust deposited varies predictably across these spatial scales.

Unfortunately, were not able to quantify patterns in the chemical composition of dust deposition in relation to the distance from source areas. This is likely a result of the limited number of high quality observations of dust chemistry. From the observations of dust geochemistry that we were able to compile, the elemental composition of Aeolian dust appears to be relatively consistent. While there is some evidence to suggest there are regional difference in dust chemistry, the globally averaged composition appears to be a good approximation of dust deposited in most regions. On average, the geochemical composition of dust resembles the composition of the upper continental crust for most major elements except Na and sometimes Ca. These patterns reflect the weathering of UCC material to form soil, which is the dominant source of dust. Caution must be used when interpreting the relative enrichment or depletion of dust relative to the UCC because the weathering process leads to volume driven changes in element concentrations. Overall, most trace elements are enriched in dust relative to the UCC, similar to what is observed in the fine-textured size classes of arid soils (Schultz and Rahn, 1982). In addition, many heavy metals are enriched in dust beyond what can be explained by natural processes, these enrichments are often attributed to human sources (Chester and Murphy, 1986; Holmes and Miller, 2004; Erel et al., 2006).

Based on the large variation of dust deposition rates, the geochemical flux from dust spans several orders of magnitude. In the case of global- or background-deposition, our estimates are similar to those reported by Duce et al. (1991). In contrast, our estimates of local and regional elemental flux estimates may be greater than those that would be calculated using modeled estimates of deposition rates. This result suggests more attention should be paid to accurately capturing the true particle size distribution of dust in global models in order to construct reasonable estimates of the geochemical flux resulting from dust deposition.

The potential ecological role of dust geochemical fluxes must be evaluated in light of several factors. First the timing of deposition, the chemical availability of elements in dust, and the ecological element demand must be considered. In addition, the fate of Aeolian dust deposition, whether it accumulates or is remobilized and exported, must also be determined. Finally, the legacy of past dust inputs may also influence the contemporary role of dust in ecosystems.

The utility of global models for predicting the flux of dust on local and regional scales is limited by the emphasis in most models of capturing the dominant global patterns and the primary focus on physical rather than biological processes. Because dust models are often designed to simulate global patterns, they focus on modeling fine textured particles with long atmospheric residence times. As a result, these models likely underestimate deposition in areas where larger sized particles comprise a substantial portion of the dust that is deposited (Bory et al., 2002b). Furthermore, many models are not adequately tested against deposition observations in continental settings. Although the reasoning for the exclusion of continental validation sites is justified, this approach limits the utility of these models for predicting Aeolian fluxes to continental settings.

Global models should be used cautiously when estimating rates of dust deposition and subsequent chemical fluxes. A systematic evaluation of the PSD of dust deposited at different distances from source regions is critical to evaluating model predictions and estimating actual chemical fluxes across different spatial scales. Because model estimates of dust input are used to calculate chemical flux estimates (for example Okin et al., 2004), and models tend to underestimate deposition in areas where larger sized particles account for a substantial proportion of the mass deposited, the flux of elements will likely be underestimated in areas experiencing local and regional deposition. Local and regional scale models and/or remote sensing tools provide an alternative to estimating dust fluxes from global scale models.

The results of our synthesis of dust deposition data from the literature provide a comprehensive evaluation of deposition rates as well as the geochemical composition of dust. This information is useful for estimating the dust derived element flux to ecosystems. However, our conclusions are limited by the wide variety of collection methods and

lack of overlap in chemical and mineralogical analyses in the compiled studies. The implementation of standardized protocols for collecting and quantifying deposition the physical and chemical properties of dust will dramatically improve understanding of contemporary dust fluxes and how they may change in the future.

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