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Ice core record of dust sources in the western United States over the last 300 years

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A B S T R A C T

Over the past ~5000 years, amplified dust generation and deposition in the American West has been linked to human activity. In recent decades, intensified rates of agriculture and livestock grazing have been correlated with greater dust production detected on seasonal to annual timescales. The combination of land use intensification and climate change (i.e. increased drought frequency) in North America highlights the importance of characterizing the sources of dust both before and after the influence of anthropogenic activity. We apply high-precision geochemical and isotopic (Sr and Nd isotopes) techniques to an ice core from the Upper Fremont Glacier (Wyoming, USA) to produce the first glacial dataset from the American West. Our Sr-Nd isotopic composition data indicates the evolving dust provenance to the Upper Fremont Glacier (UFG) from a long-range transport of mineral dust to a local source. This increasing input of dust from a local source is supported by a rise in average dust particle diameter combined with greater average dust concentration throughout the record. The greater presence of dust particles smaller than 2.5 μm in the most recent samples from UFG ice core record support existing satellite and sediment core data regarding the effects of anthropogenic activity upon dust sources and pathways in the American West. Although the Sr-Nd isotope database in North America needs be expanded, our results provide a survey of windborne dust through the past 270 years.

1. Introduction

1.1. Background and motivation

Ice cores provide a continuous record of climate history and can capture a longer time period than modern, in-situ measurements and, when compared to lake sediments, ice cores are not contaminated with local sedimentary input derived from rivers (i.e. lake sediment studies). Midlatitude alpine glaciers are regional archives of climate providing insight into paleoclimate and paleoenvironmental conditions. The high accumulation rates preserve anthropogenic pollutant input at high temporal resolution (Schuster et al., 2002; Uglietti et al., 2015). Physical measurements of impurities (such as mineral dust) in the ice can provide insight into the regional and global climate conditions through time (Delmonte et al., 2004a; Fischer et al., 2007; Wolff et al., 2006). In addition to particle size distribution, determining the sources and transport pathways of dust involves detailed studies of the mineralogy, elemental compositions, and radiogenic isotopic composition of dust entrained within ice and potential source areas (PSAs) (Delmonte et al., 2004a; Lupker et al., 2010; Thevenon et al., 2009). Here, we attempt to isolate the contributions of different sources of dust deposited on the midlatitude Upper Fremont Glacier (Fig. 1) in North America during the time period of 1720 CE to 1974 CE to document changes in the dust cycle throughout the increasing agricultural and industrial activity in the American West.

Dust deposition can impact terrestrial ecosystems by: (1) contributing to phosphorus deposition in the western US, leading to eutrophication of inland waters (Ballantyne et al., 2011), (2) altering the energy balance in mountain environments by accelerating melting rates of snow packs and alpine glaciers (Painter et al., 2007), and (3) shift regional hydrological cycles due to earlier melting (Painter et al., 2007).

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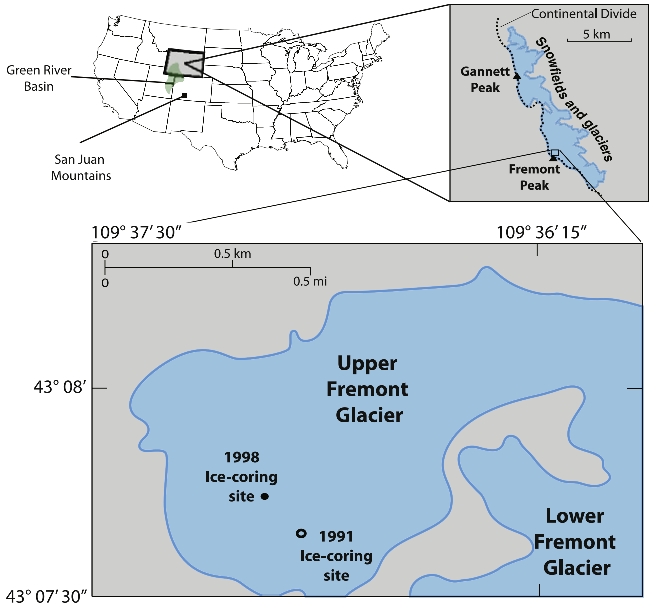

Fig. 1. Upper Fremont Glacier (UFG) location map with 1998 CE ice coring site (samples measured in this study) depicted by black circle and 1991 CE ice coring site depicted by open circle. Ice coring site is located within the Wind River Range, WY, east of the continental divide. Locations of potential source areas of dust from San Juan Mountains, Colorado (black square) and Green River Basin (green shaded area) are also noted.

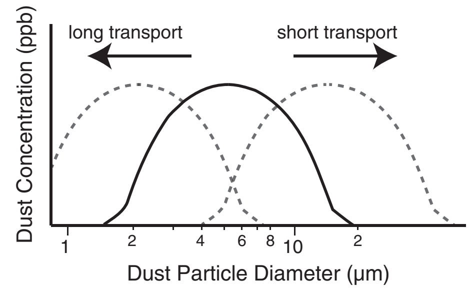

Fig. 2. Schematic of dust particle size distribution as an indicator of transport distance. Note that smaller (larger) dust particle diameters are indicative of long (short) transport distance.

Because the impacts of dust on ecosystems depend on the chemical compositions and thus source of the dust, understanding the dust sources and pathways in the American West is important to determine how both ecosystems and surface energy mass balance have evolved throughout time.

1.1.1. Global versus local inputs of dust

Dust fluxes are derived from both global (thousands of kilometers from the sink) and regional (tens to hundreds of kilometers) sources. Global sources (e.g. important deserts) are large places up to millions of square kilometers in area, generally arid, have an abundance of small particles and are subject to strong winds. The amount and impact of regional 'local' dust originating from anthropogenic activity (e.g. agriculture) is location-dependent and, in general, is believed to be less than the global contribution (Tegen et al., 2004), although this belief is not well quantified. Modern global dust emissions and corresponding source areas are observable via satellite (Ginoux et al., 2012; Prospero et al., 2002); major dust sources are the largest northern hemisphere deserts (North Africa, Middle East, and the high deserts of Asia). Dust is carried out of Asia eastward, with dust storm peaks in the spring (Prospero et al., 2002 and references therein).

Distinguishing between global (arid) and regional local dust is important due to ongoing land-use and climate change that will likely have a larger impact on local versus global dust transport and deposition. Increasing agriculture or aridity due to land-use change may create new sources of local dust, however the effects of climate change should dominate future dust emissions from well-characterized global dust sources (e.g. the Sahara, Gobi and Atacama deserts) (Tegen et al., 2004).

Shifts in average particle diameters can distinguish local from global dust. Far-traveled dust is typically < 10 μm due to the effects of gravitational settling, and regionally sourced dust is typically > 10 μm (Fig. 2) (Delmonte et al., 2004a; Mahowald et al., 2005). Glaciers at high altitudes and low latitudes can have deposited local/regional dust particles ranging from 3 to 12 μm (Uglietti et al., 2014). The lifetime of dust particles in the atmosphere is dependent on particle size, ranging from a few hours for particles larger than 10 μm, up to several weeks for submicrometer-sized particles (Mahowald et al., 2005). The threshold friction velocity, or the friction velocity a particle must pass before movement via saltation, increases with grain size due to gravity, but also increases for smaller particles due to particle cohesion, which results in an optimum particle size of ~60–80 μm at which the threshold friction velocity is at a minimum (Mahowald et al., 2005). Dust particles with sizes of ~70 μm are picked up most easily by winds, however, the dust transported thousands of kilometers has a modal diameter of ~2 μm (Mahowald et al., 2005; Schulz et al., 1998). Although long-range transported dust is typically small, larger dust particles (>100 μm) have been recorded to travel long distances to remote oceanic regions (Betzer et al., 1988). Increases in dust concentration and average particle diameter may result from land use changes (Fig. 3), increased drought frequency, and higher than average wind speed, all of which culminate in greater dust emission and deposition (Ballantyne et al., 2011; Belnap and Gillette, 1997; Neff et al., 2008; Reheis and Urban, 2011).

To address the issue of increasing dust deposition related to anthropogenic activity in the western United States, several studies utilize dust particles in lake sediment cores and mountain snowpack (Brahney et al., 2014; Brahney et al., 2013; Doebbert et al., 2014; Neff et al., 2008). Dust particles in lake sediment cores are operationally defined as up to 65 μm in diameter, while dust in ice cores is generally smaller (Brahney et al., 2014, 2013; Doebbert et al., 2014; Neff et al., 2008). The primary method of distinguishing between long range transported dust to a locally derived source is particle size distribution. Neff et al. (2008) defined a 37–63 μm grain size fraction as eolian derived and the > 250 μm as locally eroded bedrock. Additionally, Neff et al. (2008), measured particle-size distribution for modern dust for 5 different dust deposition events, with the results showing that 40% of dust mass collected occurs in the 10–37 μm class, 26% in the 37–63 μm class, and 17% in the 63–180 μm class. The authors speculated that the relatively large proportion of particles > 37 μm is evidence for particles that have been transported hundreds rather than thousands of kilometers (Middleton et al., 2001; Neff et al., 2008). Similarly, Ballantyne et al. (2011) studied lake sediments in two size classes: 37–60 μm and > 250 μm. The smaller size class most closely resembled the particle size distribution of eolian dust, whereas the larger size class was most likely locally derived sediment (Ballantyne et al., 2011). In order to discern changes in finer dust particles from regional sources (>10 μm) versus globally sourced dust (<10 μm), we utilize the Upper Fremont Glacier ice core as a paleoclimate record that is relatively pristine and does not contain sediment input from bedrock weathering.

Regionally, the largest modern, documented dust sources in North America lie between the Sierra Nevada Mountains to the west, and the Rocky Mountains to the east (Prospero et al., 2002). There is seasonal variability in the export of dust from these regions, with dust transport generally highest from April through September. Human activity can result in greater dust availability over time, and studies show that the number and magnitude of dust sources in the American West region has increased as a result of anthropogenic activities (Grayson, 1993;