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The temporal variability of centimeter-scale surface roughness in a playa dust source: Synthetic aperture radar investigation of playa surface dynamics

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ABSTRACT

Emission of mineral dust aerosols is highly dynamic, in part due to variability in surface erodibility. Investigation of the variations of surfaces within dust source regions has the potential to elucidate the processes that control erodibility and to improve model representations of dust emission. In this study, we investigate surface temporal variability in the Black Rock playa (Nevada, USA) using synthetic aperture radar (SAR) satellite data from between 2004 and 2010. The SAR backscatter (σ_0) observations of the playa surface are compared to weather station observations and temporally-resolved measurements of water inundation derived from multi-spectral MODIS satellite data. The data illustrate that centimeter-scale surface roughness on the playa is surprisingly heterogeneous over multi-meter length scales and evolves dynamically on annual time scales. Interannual changes in surface roughness on the playa are quite large compared to the variability of surface roughness during the summer months (July–September), suggesting that summer anthropogenic and aeolian processes are substantially less important than water-related processes for controlling the evolution of the playa surface. Playa median σ_0 is relatively low in years with high annual precipitation (>140 mm), suggesting that surface water controls centimeter-scale surface roughness and, potentially, erodibility. Spatially, there is a relationship between σ_0 and the time of year at which a surface dries. Areas drying in July have significantly higher σ_0 than surfaces that dry earlier in the year, suggesting that spatial heterogeneity in σ_0 is controlled by cycles of wetting and drying at the edge of the playa lake. The implications in the Black Rock playa, and potentially more broadly, are that water is a critical factor controlling playa surface evolution, and the annual time scale is crucial for investigations of playa erodibility.

1. Introduction

Atmospheric mineral dust is important to the Earth system for various reasons. In the atmosphere, dust has a significant influence on atmospheric radiative transfer and, thus, directly influences climate (e.g., Arimoto, 2001; Boucher et al., 2013; Mahowald et al., 2010). Dust particles entrained in the atmosphere also affect climate indirectly by acting as nuclei for ice and cloud formation (Sassen, DeMott, Prospero, & Poellot, 2003) and, potentially, enhancing the marine biological pump via iron fertilization (Jickells et al., 2005; Martin et al., 1994). Globally and regionally, dust is an important component of soils and can influence not only pedogenesis (Lawrence & Neff, 2009; Reheis et al., 1995) but also the biogeochemistry of terrestrial ecosystems via nutrient input (e.g., Muhs, Budahn, Prospero, & Carey, 2007; Okin, Mahowald, Chadwick, & Artaxo, 2004; Reynolds, Neff, Reheis, & Lamothe, 2006).

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The flux of dust from the continents to the global ocean impacts the global geochemical cycles of a variety of elements and is therefore critical to the evolution of the surface Earth (e.g., Fung et al., 2000; Mahowald et al., 2005; Martin, 1991). The mass flux of dust emitted to the atmosphere is significant (~1000–3000 Tg/a; Huneeus et al., 2011) relative to the riverine flux of dissolved solutes to the global ocean (~3500 Tg/a; Stone, 1956), and may have been two to three times higher in the past (Mahowald et al., 2009). Thus, knowledge of the amount and timing of dust transport through the atmosphere is vital for an understanding of the Earth's surface evolution.

Given dust's short residence time (<two weeks) in the atmosphere, accurate predictions of dust transport and deposition require constraints on both dust emission mass fluxes and the location of dust sources (Engelstaedter & Washington, 2007). Predicting mass fluxes from a given dust source depends on the accurate identification of areas within a given source that actively emit dust. Though dust producers may appear uniform, significant spatial heterogeneities exist within dust source regions (Okin, Gillette, & Herrick, 2006). An important, but poorly constrained, factor that may contribute to such heterogeneities is the susceptibility of the soil surface to wind erosion

(i.e., erodibility; Zender, Miller, & Tegen, 2004; Webb & Strong, 2011). Shifts over time in erodibility can affect dust fluxes, but the time scales over which surface erodibility evolves are not well established (Chappell, Strong, McTainsh, & Leys, 2007). An improved understanding of the appropriate time scale of variability in erodibility would improve model predictions of dust emission, help assess those processes that are most important for controlling erodibility, and provide a mechanistic means of coupling climate and dust models.

Surface roughness determined over centimeter length scales is a crucial component of erodibility. In model predictions of dust emission, surface roughness is important because it affects the friction velocity and shelters portions of the soil surface from wind erosion (Raupach & Lu, 2004; Shao, 2008). Centimeter-scale roughness is influenced by the inter-particle cohesive forces that resist ablation, particularly when the surface is composed of crusts or aggregates (Macpherson, Nickling, Gillies, & Etyemezian, 2008; Zobeck & Onstad, 1987). As a result, changes in roughness imply changes in erodibility, although erodibility and roughness are not necessarily directly proportional.

One of the difficulties in studying surface roughness and erodibility in dust source regions is that field observations are relatively localized in space and time, and do not necessarily observe the conditions most conducive for dust emission. This limitation can be overcome to some extent using remote sensing, which produces observations with substantially higher spatial and temporal resolutions than field-based approaches. For example, multispectral and hyperspectral data have been used to investigate the relationship between erodibility and surface properties such as crusting (de Jong, Addink, van Beek, & Duijsings, 2011; Katra & Lancaster, 2008). Synthetic aperture radar (SAR) instruments are particularly appropriate for investigating the evolution of erodibility, as they provide a relatively direct measurement of surface roughness on length scales on the order of the wavelength of the radiation (i.e., centimeters). Previous studies have documented a relationship between radar backscatter coefficient (σ_0) and the aerodynamic roughness length (a key parameter in dust emission models; Greeley et al., 1997; Marticorena et al., 2006), and radar roughness measurements have been used to improve the parameterization of dust emission models (Prigent, Tegen, Aires, Marticorena, & Zribi, 2005). Most importantly, σ_0 has been found to correlate with surface roughness (measured as the standard deviation of surface height) in an arid playa system (Wadge & Archer, 2002).

Arid playas are recognized to be significant dust producers regionally, yet the controls on dust emission in such environments are not entirely clear (e.g., Bryant, Bigg, Mahowald, Eckardt, & Ross, 2007; Buck, King, & Etyemezian, 2011; Cahill, Gill, Reid, Gearhart, & Gillette, 1996; Liu, Abuduwaili, Lei, Wu, & Gui, 2011; Prospero, Ginoux, Torres, Nicholson, & Gill, 2002; Reynolds, Bogle, Vogel, Goldstein, & Yount, 2009; Tegen et al., 2002). Playas are particularly useful targets for studies investigating the links between surface roughness and dust emission due to their limited vegetation cover and lack of topography. A number of mechanisms have been proposed to be important for controlling the erodibility of playa surfaces. One potential factor is ephemeral inundation. Previous work proposed that dust emission is affected by previous playa inundation events due to the delivery of fresh, unconsolidated sediment and/or the disruption of stable surface crusts (Bryant et al., 2007; Mahowald, Bryant, del Corral, & Steinberger, 2003). Cycles of wetting and drying have also been suggested to disrupt and roughen soil surfaces, while deposition of fine particles has been proposed as a means of smoothing playa surfaces (Figueira, 1984; Valentin & Bresson, 1992). Groundwater is important to the development of playa surfaces, as evaporating groundwater precipitates evaporite minerals, disrupting playa surface crusts (Reynolds et al., 2007). Aeolian sandblasting, anthropogenic disturbance, and freeze/thaw processes have also been suggested to be important crust disruption processes (Adams & Sada, 2010; Gillette, Niemeyer, & Helm, 2001). Evaluating the relative importance of such mechanisms is critical for incorporating dust emission in climate models at a mechanistic level.

The current study presents observations of centimeter-scale, SAR-derived surface roughness in a playa system through time (2004–2010), with the goals of characterizing the time scales over which erodibility changes and elucidating the processes that control erodibility. This study represents, to our knowledge, the first comprehensive study of the temporal evolution of surface roughness in a playa system. We compare SAR data to the time and location of playa inundation and drying, as well as the timing of precipitation, in order to ascertain which of these processes are important for controlling playa surface variability. Establishing the time scales and processes that regulate the surface structure of the playa will aid in understanding and modeling dust emission. The ultimate goal of identifying dust source regions and understanding the controls on dust emission is to predict dust fluxes in the past and future utilizing a process-based framework.

2. Data and methods

2.1. Study site

The field location for the current study is the Black Rock Desert, in northwestern Nevada, USA (Fig. 1). The Black Rock Desert is a hydrologically closed basin located in a north-south trending normal fault bounded graben in the Basin and Range. The Black Rock playa is a flat (relief < few meters) area in the center of the Black Rock Desert (Sinclair, 1963), on which vegetation is essentially absent. The playa lies at an elevation of 1190 m above sea level (Gesch et al., 2002). In this study, we define the playa proper to be all surfaces below 1192 m, which encompasses 350 km^2. The playa is comprised of silt- and clay-sized lake deposits, which can extend to a depth of 2400 m (Welch & Preissler, 1990). Satellite observations, specifically visible imagery and optical aerosol index, show the Black Rock Desert to be a dust source (Fantle, Tollerud, Eisenhauer, & Holmden, 2012; Lewis et al., 2011). Anthropogenic activity is significant on the Black Rock playa, mainly in the form of vehicular traffic, and is particularly common on the southern end of the playa close to Gerlach (Adams & Sada, 2010). From a hydrologic perspective, the Black Rock playa is fed from the northeast by the ephemeral Quinn River. Streamflow data from the Quinn River at 41°46′30″N 117°48′15″W (site 10353500, waterdata.usgs.gov) demonstrates that the Quinn River experiences limited overland flow (<1 m^3/s) from July to January but in many years flows from February to June. Peak discharge is typically in April or May.

During field campaigns to the Black Rock Desert in 2007 and 2010, we observed a variety of playa surfaces characterized by qualitative differences in roughness. Typical surfaces contained mud cracks, and either were smooth or had features a few millimeters to tens of centimeters in size (Fig. 2). Smooth mud-cracked surfaces (Fig. 2d) were generally strong (when dry), based on their resistance to deformation by vehicles. Rougher surfaces (Fig. 2c) varied in the amount of force required to break the surface; they generally were disrupted by vehicle traffic, and often but not always by foot traffic. Rough surface crusts, on the order of centimeters in thickness, were often underlain by unconsolidated, uncemented sediments. Regions with similar surface types were sometimes large (order of kilometers across). Transitions between surface types at times occurred abruptly, on the scale of meters. The processes controlling transitions between surface types were not immediately obvious on the ground.

2.2. Meteorological data

In this study, meteorological data from the National Climatic Data Center's Gerlach, NV station were utilized (www.ncdc.noaa.gov). Missing precipitation data (2 full months and 16 days scattered through the 2004–2010 study period) were estimated by averaging precipitation recorded at the nearby Lovelock, Lovelock Derby Field, Imlay, Rye Patch Dam, Winnemucca Airport, and Winnemucca meteorological stations.