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High-frequency measurements of aeolian saltation flux: Field-based methodology and applications

Raleigh L. Martin[a,*], Jasper F. Kok[a], Chris H. Hugenholtz[b], Thomas E. Barchyn[b], Marcelo Chamecki[a], Jean T. Ellis[c]

[a] *Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095, USA*
[b] *Department of Geography, University of Calgary, Calgary, AB, Canada*
[c] *Department of Geography and School of Earth, Ocean and Environment, University of South Carolina, Columbia, SC 29208, USA*

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ABSTRACT

Aeolian transport of sand and dust is driven by turbulent winds that fluctuate over a broad range of temporal and spatial scales. However, commonly used aeolian transport models do not explicitly account for such fluctuations, likely contributing to substantial discrepancies between models and measurements. Underlying this problem is the absence of accurate sand flux measurements at the short time scales at which wind speed fluctuates. Here, we draw on extensive field measurements of aeolian saltation to develop a methodology for generating high-frequency (up to 25 Hz) time series of total (vertically-integrated) saltation flux, namely by calibrating high-frequency (HF) particle counts to low-frequency (LF) flux measurements. The methodology follows four steps: (1) fit exponential curves to vertical profiles of saltation flux from LF saltation traps, (2) determine empirical calibration factors through comparison of LF exponential fits to HF number counts over concurrent time intervals, (3) apply these calibration factors to subsamples of the saltation count time series to obtain HF height-specific saltation fluxes, and (4) aggregate the calibrated HF height-specific saltation fluxes into estimates of total saltation fluxes. When coupled to high-frequency measurements of wind velocity, this methodology offers new opportunities for understanding how aeolian saltation dynamics respond to variability in driving winds over time scales from tens of milliseconds to days.

1. Introduction

Wind-blown (aeolian) transport of sand shapes a variety of desert, coastal, and planetary landscapes (e.g., Lancaster, 1988; Bridges et al., 2012; Durán and Moore, 2013). Saltation, the ballistic hopping motion of wind-blown sand grains, drives the bulk of aeolian sand flux (Bagnold, 1941), abrades bedrock (Perkins et al., 2015), erodes soil (Chepil, 1945), and generates airborne dust through impacts with the soil surface (Gillette et al., 1974; Shao et al., 1993; Marticorena and Bergametti, 1995; Kok et al., 2014). Studies of landscape evolution and dust generation require models that accurately relate wind speed, surface conditions, and the resulting sand flux (e.g., Kok et al., 2012).

Unfortunately, aeolian saltation models often do a poor job of predicting rates of sand transport in natural environments (e.g., Kok et al., 2012; Sherman and Li, 2012; Sherman et al., 2013; Barchyn et al., 2014b). Most existing aeolian saltation models are based on the assumption of a steady-state momentum balance (e.g., Ungar and Haff, 1987; Andreotti, 2004), but saltation in natural environments is driven by widely-varying turbulence spectra, which produce broad spatial and temporal variations in the saltation flux (e.g., Baas, 2006; Durán et al., 2011). Though wind-tunnel experiments can capture some of this turbulent variability (e.g., Li and McKenna Neuman, 2012, 2014), such experimental settings differ substantially from natural environments in their ability to capture saltation-wind interactions (e.g., Sherman and Farrell, 2008), producing broad unexplained discrepancies between field and laboratory measurements (Barchyn et al., 2014b; Martin and Kok, 2017a). In addition, sedimentological factors like soil moisture (Arens, 1996; Davidson-Arnott et al., 2008), surface crusting (Gillette et al., 1982), sediment availability (Webb et al., 2016a), electrification (e.g., Kok and Renno, 2008), mid-air particle collisions (e.g., Sørensen and McEwan, 1996; Carneiro et al., 2013), and surface grain-size distributions (Iversen and Rasmussen, 1999), cause further differences among models, wind tunnel experiments, and field measurements. Though recent studies have sought to understand each individual factor governing aeolian saltation dynamics separately, our ability to model how this constellation of atmospheric and sedimentological factors

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* Corresponding author.
E-mail address: raleighmartin@gmail.com (R.L. Martin).

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interact to control the aeolian saltation flux remains limited. Coupled high-frequency (HF) field measurements of wind and saltation offer the potential to improve our understanding of some of the atmospheric factors affecting saltation flux variability, and they can also help to constrain the role of sedimentological factors (e.g., Martin and Kok, 2017a).

Until recently, field-based observations of aeolian saltation have been limited to low-frequency (LF) measurements with saltation traps (i.e., sampling interval $\geqslant \sim 1$ min. These traps generally provide reliable measures of the saltation mass flux over time scales of minutes to days (e.g., Greeley et al., 1996; Sherman et al., 1998; Namikas, 2003), though comparative studies reveal variations in trap accuracy that depend on wind speed and airborne grain sizes (e.g., Goossens et al., 2000). Assuming that saltation traps do indeed provide reliable measures of the saltation flux, LF studies are useful for relating saltation flux and vertical saltation profile characteristics (Greeley et al., 1996; Namikas, 2003; Farrell et al., 2012) to time-averaged wind speeds (Sherman et al., 1998; Sherman and Li, 2012). However, such LF studies are unable to resolve the HF spatial and temporal variability in saltation flux (i.e., $\leqslant \sim 1$ min) resulting from wind turbulence in the atmospheric boundary layer (e.g., Baas and Sherman, 2005). Such variability is thought to produce much of the disagreement between measurements and models of aeolian saltation flux (Barchyn et al., 2014b).

To better resolve turbulence-induced saltation fluctuations, a variety of new HF sensors have been deployed in field studies over the past two decades (e.g., Baas, 2004; Barchyn and Hugenholtz, 2010; Sherman et al., 2011). HF measurements typically register individual sand grains, using sensors with optical gates (e.g., Hugenholtz and Barchyn, 2011; Etyemezian et al., 2017), piezoelectric impact plates (e.g., Barchyn and Hugenholtz, 2010; Sherman et al., 2011), or acoustic microphones (e.g., Spaan and van den Abeele, 1991; Ellis et al., 2009b). Such sensors are capable of recording measurements at time scales ranging from tens of milliseconds to seconds (e.g., Sterk et al., 1998; Baas, 2008; Martin et al., 2013), much faster than the most rapid automated saltation trap sampling techniques (Bauer and Namikas, 1998; Butterfield, 1991; Namikas, 2002; Ridge et al., 2011).

HF saltation sensors have been used in recent years to address a variety of questions in aeolian research. Recent field studies deploying HF saltation sensors, in tandem with HF anemometer wind observations, have quantified the frequently observed spatial and temporal patterns of alternating high and low saltation flux known as "aeolian streamers" (Baas and Sherman, 2005; Weaver and Wiggs, 2011). Other HF field deployments have offered further insight on the temporal variability of saltation flux (Sterk et al., 1998; Schonfeldt and von Lowis, 2003; Baas, 2006; Martin et al., 2013), across complex topography (Bauer et al., 2015, 2012; Davidson-Arnott et al., 2012; Hoonhout and de Vries, 2017) and around vegetation (Barrineau and Ellis, 2013; Chapman et al., 2013). HF sensors are also vital for describing saltation intermittency and thresholds (Stout and Zobeck, 1997; Schönfeldt, 2004; Wiggs et al., 2004a; Barchyn and Hugenholtz, 2011; Poortinga et al., 2015; Webb et al., 2016a) and the effects of humidity and soil moisture on these thresholds (Arens, 1996; Wiggs et al., 2004b; Delgado-Fernandez et al., 2012). Optical HF sensors have also been used extensively for the measurement of wind-driven snow transport (Leonard et al., 2011; Bellot et al., 2013; Maggioni et al., 2013; Trujillo et al., 2016).

Though helpful for advancing the understanding of saltation dynamics, HF measurements typically provide only relative, not absolute, measures of the aeolian saltation flux (e.g., Barchyn et al., 2014a). Typically, these HF sensors produce data in counts per second. Such count rates are only internally relative and require a conversion to physically meaningful quantities, which may not be as simple as one grain per count (Barchyn et al., 2014a). For certain research purposes, these relative HF saltation measurements are sufficient, such as for studies of saltation intermittency and thresholds at a single point (e.g., Stout and Zobeck, 1997; Martin and Kok, 2017b). However, to understand the relationship between turbulence structures and saltation flux variability in space and time, absolute HF measurements of saltation flux are needed (e.g., Martin et al., 2013; Bauer et al., 2015; Hoonhout and de Vries, 2017).

To address the need for reliable HF saltation flux measurements, studies have compared the performance of different HF sensors (e.g., Davidson-Arnott et al., 2009; Leonard et al., 2011; Massey, 2013) and assessed the comparability of HF particle counts to LF trap saltation fluxes (e.g., Sterk et al., 1998; Goossens et al., 2000; Sherman et al., 2011). Though these studies generally reveal linear relationships among particle counts from different sensors (e.g., Barchyn et al., 2014a), they also indicate substantial differences in sensitivity between sensors of the same type (Baas, 2008) or among sensors of different types (Hugenholtz and Barchyn, 2011). HF saltation sensors are potentially subject to "saturation" effects – i.e., reaching a maximum saltation flux above which measured particle counts no longer increase (Hugenholtz and Barchyn, 2011; Sherman et al., 2011). HF sensors may also have response sensitivities to momentum or particle size (Barchyn et al., 2014a). Additionally, HF sensors may display "drift", or variation in their performance through time, due to environmental conditions causing sensor degradation (Hugenholtz and Barchyn, 2011; Bauer et al., 2012; Barchyn et al., 2014a).

A fundamental issue with most HF measurements is that, whereas traps and sensors typically provide only height-specific values for the saltation flux, models of aeolian saltation consider total (vertically-integrated) saltation fluxes (e.g., Bagnold, 1941; Owen, 1964; Ungar and Haff, 1987; Andreotti, 2004). To facilitate direct comparisons of these height-specific saltation measurements to the total vertically-integrated saltation fluxes considered in numerical (e.g., Dupont et al., 2013), analytical (e.g., Pähtz et al., 2013), and wind-tunnel (e.g., Li and McKenna Neuman, 2014) studies of HF saltation variability, measurements from sensors at multiple heights must be combined to provide estimates of the total saltation flux. Turbulent variability and counting uncertainties may hinder the convergence of these profiles to expected exponential (Ellis et al., 2009a; Fryrear and Saleh, 1993; Namikas, 2003; Dong et al., 2012) or other (Zobeck and Fryrear, 1986; Dong et al., 2011) profile shapes over short time scales (e.g., Bauer and Davidson-Arnott, 2014). Thus, existing studies of high-frequency saltation flux variability are limited to examination of relative or height-specific saltation fluxes (e.g., Baas, 2008).

In short, LF trap and HF sensor measurement techniques each have distinctive advantages and disadvantages for determining saltation flux. LF measurements can accurately measure horizontal and vertical profiles of mass flux and sediment size, but they can detect only the broadest fluctuations of saltation mass flux associated with the passage of large-scale turbulent structures (McKenna Neuman et al., 2000). HF sensors can resolve saltation responses to turbulence, but their ability to provide absolute mass fluxes is questionable (Hugenholtz and Barchyn, 2011). Ideally, the respective advantages of LF and HF measurements could be combined to provide HF time series of absolute saltation flux.

In this paper, we describe a new methodology to generate reliable high-resolution time series of the total (vertically-integrated) saltation mass flux. Specifically, we do so by using absolute LF measurements from sediment traps to calibrate relative HF measurements from optical particle counters. Though such calibration has been performed in the past (e.g., Martin et al., 2013; Haustein et al., 2015), we provide here a much more systematic development, testing, and explanation for a calibration-based methodology to obtain HF time series of vertical saltation profiles and total saltation fluxes. To do so, we first describe the three field sites at which we collected LF and HF saltation measurements (Section 2) and the instrumentation involved in these measurements (Section 3). In Section 4 we describe the sequence of steps for obtaining calibrated, high-frequency measurements of the total saltation flux, and we present some illustrative results. In the Discussion (Section 5), we outline the advances and limitations of the HF saltation