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Temporal and spatial variability of aeolian sand transport: Implications for field measurements

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ABSTRACT

Horizontal variability is often cited as one source of disparity between observed and predicted rates of aeolian mass flux, but few studies have quantified the magnitude of this variability. Two field projects were conducted to evaluate meter-scale spatial and temporal in the saltation field. In Shoalhaven Heads, NSW, Australia a horizontal array of passive-style sand traps were deployed on a beach for 600 or 1200 s across a horizontal span of 0.80 m. In Jericoacoara, Brazil, traps spanning 4 m were deployed for 180 and 240 s. Five saltation sensors (miniphones) spaced 1 m apart were also deployed at Jericoacoara. Spatial variation in aeolian transport rates over small spatial and short temporal scales was substantial. The measured transport rates (Q) obtained from the passive traps ranged from 0.70 to 32.63 g/m/s. When considering all traps, the coefficient of variation (*CoV*) values ranged from 16.6% to 67.8%, and minimum and maximum range of variation coefficient (*RVC*) values were 106.1% to 152.5% and 75.1% to 90.8%, respectively. The miniphone Q and *CoV* averaged 47.1% and 4.1% for the 1260 s data series, which was subsequently sub-sampled at 60–630 s intervals to simulate shorter deployment times. A statistically significant ($p < 0.002$), inverselinear relationship was found between sample duration and *CoV* and between Q and *CoV*, the latter relationship also considering data from previous studies.

1. Introduction

Field observations of aeolian saltation frequently refer to the presence of sand streamers, the most obvious visual manifestation of horizontal variation in transport rates. In the several studies designed to quantify horizontal transport rate variability, large differences have been measured over small temporal and spatial scales (Bauer et al., 1996; Gares et al., 1996; Davidson-Arnott et al., 1997; Baas and Sherman, 2005; Jackson et al., 2006). The purpose of this paper is to present results from two field experiments to extend our understanding of the magnitude of meter-scale horizontal variability, compare our results to those from other studies, and discuss the implications of our findings for sampling protocols for field measurements of aeolian sand transport.

The ability to predict sand transport rates is critical to researchers and environmental managers. It has been 75 years since Bagnold (1936) first presented his sediment transport model, yet we still do not have a complete understanding of the fundamental physical relationships comprising the aeolian system. Even though there have been many important advances in understanding the grain-scale physics of sand transport, efforts to scale up that understanding to describe the complex interactions between wind and sand in prototype environments has lagged. Substantial inconsistencies exist between field-based measurements and models predicting sediment transport rates (Sherman et al., 1998). Commonly employed models, such as those of Bagnold (1937) or Lettau and Lettau (1978), are based upon ideal (uniform and steady) behavior of the fluid and sediment systems, which rarely occur, and presume that sand and wind systems are equilibrated. It is common to have a moist sand surface (Namikas and Sherman, 1995; Jackson and Nordstrom, 1998; Cornelis and Gabriels, 2003; McKenna Neuman, 2003; Wiggs et al., 2004), surface crusting (Leys and Eldridge, 1991; Rice and McEwan, 2001), topographic variability (Iversen and Rasmussen, 1994; Hesp et al., 2005), or vegetation present (Hesp, 1981; Lancaster and Baas, 1998; Kuriyama et al., 2005) that can inadvertently impact the 'ideal' conditions. Transport rates are also influenced by turbulence in the wind field (Williams et al., 1994; Sterk et al., 1996; Bauer et al., 1998; Ellis, 2006), intermittency (Stout and Zobeck, 1997; Schonfeldt, 2004; Wiggs et al., 2004; Davidson-Arnott and Bauer, 2009), and variations in fetch length (Nordstrom and Jackson, 1992; Jackson and Cooper, 1999; Bauer and Davidson-Arnott, 2003; Dong et al., 2004; Delgado-Fernandez, 2010), yet the models are not constructed to adequately address these. The horizontal variability occurring across the transport field has been attributed to changes

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in the wind field (non-uniform, unsteady conditions), surface (e.g., texture, moisture, or vegetation), sampling methodologies (e.g., trap efficiency, sample duration, or fetch effect), or combinations of any of the former.

The literature suggests several explanations for the spatial and temporal horizontal variability in the saltation field, all related to physical features of the wind field and the unconsolidated and mobile sediment surface. In particular, Jackson et al. (2006) group these explanations according to the temporal scale at which a particular factor is most influential or relevant: short (seconds to minutes), intermediate (tens of minutes), and long (hours to days). Short or small-scale variability has been related to the presence and location of streamers (Baas and Sherman, 2005), surface moisture (Namikas and Sherman, 1995; Cornelis et al., 2004; Wiggs et al., 2004; Udo et al., 2008; Nield et al., 2010), turbulence and coherent structures (Sterk et al., 1996; Ellis, 2006), wind direction, fetch length (Bauer and Davidson-Arnott, 2003; Bauer et al., 2009), and differences in the upwind sand source (Lee, 1987; Wiggs et al., 2004). For example, transport rates may change 5–10% per 0.1 mm change in grain size using Kawamura's (1951) sand transport equation (Baas, 2003). Butterfield (1993), Stout and Zobeck (1997), Bauer et al. (1998), McKenna Neuman et al. (2000), and Davidson-Arnott et al. (2005) have all described the inherent nature of wind unsteadiness and the implications for applying existing steady saltation transport models to a consistently unsteady and highly variable transport system. Sampling duration is also a consideration, as the measurement period needs to be long enough to measure the largest turbulent eddies characterizing the fluid flow, but short enough to not be influenced by larger patterns of variability (Sterk et al., 1996; van Boxel et al., 2004; Leenders et al., 2005). Finally, at short time scales, topographic parameters affecting transport include changes in relative height, slope, vegetation and fetch, all of which influence wind speed and directionality that result in potential spanwise transport variability. At intermediate time scales, Jackson et al. (2006) identify microtopographic obstacles and modal wind conditions as the most relevant controls. At longer time scales, weather and regional wind patterns dominate and are the first order controls on transport patterns (Tsoar, 2002; Arens et al., 2004; Levin et al., 2006).

In addition to the frequently cited reasons for spatial variability, Jackson et al. (2006) suggest a possible linkage between lower wind speeds and higher variability because sand is not able to pass over small topographic obstacles. They also suggest that closely co-located traps can create an edge effect that is otherwise not observed, and widely spaced traps will eliminate this issue. Lastly, they state that horizontal variability in the transport field might depend on the duration of study. Assuming similar wind conditions, the longer sampling durations should yield less variability compared to shorter durations (Jackson et al., 2006). This is intuitive and commonly observed in the field because transport patterns such as streamers migrate laterally, on the order of meters, across the wind field. Therefore, the implication is that short-term variability (at sub-meter and second to minute scale) is removed with longer sampling durations.

Sediment transport rates in laboratory and field experiments typically use measurements from one location to represent sand flux. Many recognize (McEwan and Willetts, 1993; Davidson-Arnott and Bauer, 2009), but few measure, horizontal variability of the transport field. To the best of our knowledge, only five field-based studies have been designed to quantify horizontal transport variability: Bauer et al. (1996), Gares et al. (1996), Davidson-Arnott et al. (1997), Jackson et al. (2006), and Baas and Sherman (2005). The former four studies deployed Leatherman (1978) and/or Guelph-Trent sand wedge traps (Nickling and McKenna Neuman, 1997) for durations of 10–60 min. Specifically, Bauer et al. (1996) deployed 12 traps spaced 13–20 m apart; Davidson-Arnott et al. (1997) used two trap pairs 2.5 m apart; and Gares et al. (1996) deployed three Guelph-Trent sand wedge traps placed 1 m apart for three runs, two for 900 s, and one for 1800 s. The latter study also included five runs using Leatherman-style (1978) traps placed 1 m apart, four of which lasted 900 s and one lasting 1800 s. Jackson et al. (2006) deployed one or two groups of five Leatherman-style traps spaced at 1 m for four runs lasting 600 s. Rather than employing passive traps, Baas and Sherman (2005) deployed 35 piezoelectric-based Safires, spaced 0.1 m apart, to identify and characterize streamers with spatial scales (streamer widths) averaging 0.2 m and with time scales of a few seconds.

1.1. Approaches to quantify spatial variability in transport

Variability in the saltation field has been quantified using multiple expressions to represent the magnitude of change. For example, Bauer et al. (1996) employ the coefficient of variation (incorrectly referred in their paper as "coefficient of variability"):

$$CoV_{\mathrm{B}} = (Q_{\mathrm{std}}/Q_{\mathrm{avg}})100 \tag{1}$$

where Q_{std} is the standard deviation of the measured transport rates, Q, from a set of traps, and Q_{avg} is the average Q for all traps. Jackson et al. (2006) employed a modified coefficient of variation to adjust for small sample sizes (n), based on the research of Sokal and Rohlf (1981):

$$CoV_{\mathrm{SR}} = \left[\left(\frac{Q_{\mathrm{std}}}{Q_{\mathrm{avg}}}\right)100\right] + \left(1 + \frac{1}{4n}\right) \tag{2}$$

Table 1
CoV values from Gares et al. (1996) and Jackson et al. (2006) using Eq. (3). The values in parentheses after the run number correspond with the run numbers used in Fig. 6.

Run number	Run duration (min)	Traps	CoV (%)
Gares et al. (1996)			
6 (G6G-T trap)	30	3 × Guelph-Trent	51.4
7 (G7 G-T trap)	15	3 × Guelph-Trent	9.5
8 (G8 G-T trap)	15	3 × Guelph-Trent	38.9
6 (G6 L trap)	30	5 × Leatherman	20.3
7 (G7 L trap)	15	5 × Leatherman	42.9
8 (G8 L trap)	15	5 × Leatherman	78.3
9 (G9 L trap)	15	5 × Leatherman	67.4
10 (G10 L trap)	15	5 × Leatherman	34.0
Jackson et al. (2006)			
26 Feb (J26FebA–E)	10	Leatherman Traps A–E	54.1
26 Feb (J26FebF–J)	10	Leatherman Traps F–J	50.8
13 Mar (J13Mar)	10	Leatherman Traps A–E	41.0
18 Mar AM (J18MarAM)	10	Leatherman Traps A–E	28.4
18 Mar PM (J18MarPM)	10	Leatherman Traps A–E	98.9