Fundamental mismatches between measurements and models in aeolian sediment transport prediction: The role of small-scale variability

Thomas E. Barchyn a,⇑, Raleigh L. Martin b, Jasper F. Kok b, Chris H. Hugenholtz a

a Department of Geography, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2K 3M4, Canada
b Department of Atmospheric and Oceanic Sciences, University of California – Los Angeles, Los Angeles, CA 90095, USA

ARTICLE INFO

Article history:
Received 10 June 2014
Revised 23 July 2014
Accepted 29 July 2014
Available online 19 August 2014

Keywords:
Aeolian sediment transport
Prediction
Measurement
Modeling

ABSTRACT

Predicting aeolian sediment transport is a long-standing and difficult challenge that is important to a variety of scientific disciplines, including geology, geomorphology, agriculture, meteorology, and climatology. Here, we argue that improvements in predictions of aeolian sediment transport are limited by incompatibilities between empirical measurements and mathematical models. We focus on the spatial and temporal variability in transport. Measurements indicate considerable variability on small time (second) and length (meter) scales, yet models are almost ubiquitously based on assumptions of time and space-invariant transport. Mismatches between measurements and models limit summative predictive capacity by reducing the ability to use measured data to test and drive models. We suggest: (i) revising model conceptualizations and evaluating the representativeness of steady state saltation to constrain the realism of existing models, (ii) improving and optimizing measurement technology to produce more reliable and accurate measurements, (iii) explicitly specifying the scale of measurements, and (iv) designing variable matching tests between models and measurements to work around measurement limitations. Continuing with the status quo, where measurements and models are dealt with separately, is likely to erode summative predictive capacity.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

The movement of sediment by wind (“aeolian” sediment transport) is widespread on Earth and other planetary bodies (Greeley and Iversen, 1985). Nonetheless, the prediction of aeolian sediment transport rates remains a fundamental and much-lamented problem that hampers progress in a diversity of scientific disciplines, including geomorphology, geology, agriculture, meteorology, and climatology (Bauer et al., 1996; Baas, 2007, 2008; Kok et al., 2012; Ellis and Sherman, 2013). Models generally have low predictive capacity, differing from measurements and each other (in cases) by over an order of magnitude (Ellis and Sherman, 2013; Sherman et al., 2013; Kok et al., 2014). This situation has driven new research in an effort to improve prediction through increased understanding of the physics of transport (Anderson and Haff, 1988; Kok and Renno, 2009; Durán et al., 2012; Dupont et al., 2013; Pähtz et al., 2013; see also reviews: Durán et al., 2011; Kok et al., 2012).

The goal of improving the prediction of aeolian transport is spurred by two general motivations. First is a desire to understand the process of aeolian transport. Second is a push for providing prediction tools for applications. Transport prediction models are used as components in prediction tools in many areas with major implications for both society and other scientific disciplines. For example, mineral dust aerosols are generated through the impacts of saltating particles on soils (e.g., Gillette et al., 1974; Shao et al., 1993), and can remain suspended in the atmosphere for days to weeks, impacting surface radiation and climate (Mahowald et al., 2011), hydrology (e.g., Skiles et al., 2012), and human health (e.g., O’Hara et al., 2000; Field et al., 2009). The emission of dust and erosion of soil from agricultural fields is also a longstanding problem with widespread economic and societal implications (e.g., Marx et al., 2014). Similarly, changes in vegetation cover in dune fields (“activation” / “stabilization”) are important to understand for predicting future land values and habitability (e.g., Barchyn and Hugenholtz, 2013). In coastal environments, foredunes shelter inland locations from storm surges. Foredunes depend on aeolian transport to maintain their form (e.g., Arens et al., 2013; Durán and Moore, 2013). Finally, the movement of sediment by wind is responsible for major changes to landscapes, as preserved in the stratigraphic record, and is a key geological process on Earth (Livingstone et al., 2007), Mars (Bridges et al., 2014), Titan (Lorenz, 2014), and possibly Venus (Greeley and Iversen, 1985).
Applications of aeolian sediment transport tend to be fed from the same pool of knowledge, known as “aeolian transport research”. The topic of aeolian transport research is often separated into efforts to measure and efforts to model transport, allowing specialization among researchers. We argue here that specialization has also led to a disconnect between those involved in measurement and those involved in modeling. Some disconnection is desirable as it allows focused effort but too much disconnection erodes summative predictive capacity.

In this commentary, we discuss how measurements and models must function in concert in aeolian transport research. We focus on a particularly acute area of measurement-model mismatch: spatial and temporal variability in transport. We discuss how empirical observations indicate that aeolian transport is highly variable on second-meter scales (e.g., Baas and Sherman, 2005), yet most models consider transport to be uniform (Kok et al., 2012). Conversely, measurements are quite limited in capacity to measure sediment flux. We make a case that this mismatch is limiting progress in improving predictions. We present actionable suggestions to accelerate commensurability between models and measurements. For primers on the topics discussed here refer to reviews by Durán et al. (2011) and Kok et al. (2012).

2. Measurements and models are inseparable

To begin, we first clarify the roles of measurements and models within aeolian transport prediction (see also general discussion: Harvey, 1969; Bauer et al., 1996; Rhoads and Thorn, 1996 and chapters therein; Phillips, 2004; Kleinhans, 2010; Kleinhans et al., 2010). We define measurement as the link between the synthetic mathematical world and the real world. Measurement is the process of quantifying physical reality. Measurements are combined with observations and physical reasoning to create mathematical representations of transport systems, known as models. In aeolian transport research, most models relate a series of input variables (e.g., wind shear stress, sediment properties, and environmental conditions) to resultant sediment flux. We define ‘prediction’ as using models to create estimates of sediment transport for physical conditions not represented by measurements. Predictions can be made in time (forwards or backwards) and in space (for locations lacking measurements). We focus strictly on the use of mathematical models for prediction. Measurements and models commonly integrate in (at least) three ways:

(i) Measurements of input variables are required to feed models (e.g., wind speed, sediment properties, environmental conditions) (refer to reviews by Durán et al., 2011; Kok et al., 2012; Ellis and Sherman, 2013). In some cases when aeolian transport models are components in larger models, input measurements are replaced by other models (e.g., reanalysis meteorological data: Ashkenazy et al., 2012).

(ii) Measurements of both input and output variables are often required during model development to parameterize empirical components. Many models do not (or cannot) fully represent the underlying physics of sediment transport, and hence require empirical components to match reality (Ellis and Sherman, 2013).

(iii) Measurements of both input and output variables are required during model development to assess model functioning. Regardless of the level of empiricism present, the reliability of models needs to be assessed. Commonly this is done with an independent dataset, which is compared with model predictions. We advocate for a more rigorous evaluation of models based on confidence, where the level of confidence in model predictions depends on the accuracy of the model in representing physical processes, the reliability of empirical input parameters, the sensitivity of the model to these parameters, and the statistical uncertainty inherent in modeled processes (especially when dealing with chaotic phenomena like turbulence) (see Oreskes et al., 1994). Blindly comparing or parameterizing a model based on one or two reference dataset presents the danger of generalizing overly broadly about modeled processes based on measurements that may only represent special cases.

These interactions stress the inseparability of measurements and models. For example, regardless of the sophistication of the mathematical models, if the models cannot be tested with present measurement technology, users will have poor confidence in the predictions. Conversely, models that depend on empirical parameters that are impossible to measure offer limited utility.

3. Spatial and temporal variability in transport as a case example

Considerable spatial and temporal variability in transport exists at high-resolution spatial (meter) and temporal (second) scales (Lee, 1987; Butterfield, 1991; Stout and Zobeck, 1997; Sterk et al., 1998; Baas and Sherman, 2005; Bauer and Davidson-Arnott, 2014; Fig. 1). This variability is not incorporated into most models (Kok et al., 2012). There is strong rationale for addressing variability in aeolian transport. First, the dominant driving variable, wind shear stress, is highly variable on a variety of scales due to boundary layer turbulence and synoptic forcing (Martin et al., 2013). Second, there is a non-linear relation between sediment flux and wind shear stress, thus mathematically the predicted sediment transport will depend on the time-averaging of wind shear stress (Bauer et al., 1998, 2013; Spies and McEwan, 2000; Spies et al., 2000). Third, the temporal scale of turbulence variability overlaps the response time scale of sediment flux, suggesting that sediment flux may consistently lag the wind (e.g., Butterfield, 1998; Schönfeldt and von Lowis, 2003; Baas, 2006; Martin et al., 2013). Together, these points suggest variability is an important component of natural sediment transport that needs to be carefully parameterized into models and incorporated into measurement strategies. With the increasing reliability and complexity of analytical and numerical models (e.g., Andreotti, 2004; Kok and Renno, 2009; Pätzl et al., 2012; Durán et al., 2012; Carneiro et al., 2011) and increased resolution of field measurement techniques (e.g., Baas, 2008; Sherman et al., 2011; Hugenholtz and Barchyn, 2011), accounting for the variability of aeolian transport should thus be a research priority.

3.1. The challenges of field measurement: producing high-resolution spatio-temporal data

While quantitative data showing spatio-temporal variability have been presented (e.g., Baas and Sherman, 2005, see Fig. 1), reliably measuring variability in transport and driving variables through space and time is a major technical challenge. There are several reasons why only a small portion of transport can be quantified.

First, instruments used to measure sediment transport and related driving variables need to be directly placed within the saltation layer (e.g., Hugenholtz and Barchyn, 2011). This has the following implications: (i) the density and size of the instruments is limited (too dense of an array will affect transport), (ii) some portions of the saltation cloud are difficult to measure (e.g., creep and reptation close to the bed), and (iii) some instruments are sensitive to saltator impacts, limiting the height at which they can be placed.
has therefore served as the primary explanatory variable therefore partially neglect the role of these challenges may have future solutions.

Second, as instruments are designed to be physically small (to not interfere with saltation), they tend to have small sampling areas (e.g., Ellis et al., 2009). Such small measurements effectively amount to point timeseries at one specific $x$, $y$, $z$ location. However, the large spatial variability of sand transport (e.g., Baas and Sherman, 2005) makes it desirable to obtain a more detailed 3D representation of saltation streamers and relevant variables. Doing so requires both a sufficient number of instruments and some understanding of the spatial and temporal autocorrelation structure of variables to fill in the gaps in coverage. The few datasets of spatial and temporal variability in transport (e.g., Baas and Sherman, 2005) have revealed some aspects of the autocorrelation structure of natural transport, providing some guidance on the necessary sampling strategy, but more needs to be done.

A third limitation on assessment of spatial and temporal variability is the lack of calibration for high-resolution sediment flux instruments (e.g., Nickling and McKenna Neuman, 1997). Indeed, many high-resolution instruments produce only unitless particle counts (e.g., Baas, 2004; Hugenholtz and Barchyn, 2011; Barchyn et al., 2014). Relative measurements of sediment flux are useful for some work (e.g., Barchyn and Hugenholtz, 2011), but reliably calibrated sediment flux measurements are required to guide and evaluate models. Note that this difficulty applies primarily to sediment flux measurement; most other instruments (e.g., anemometers) are well calibrated and reliable as they have much larger user bases and commercial support.

In addition to sampling issues for capturing variability in sediment flux, parameterizing the turbulent shear stress from wind forcing is also a critical challenge. Anemometers are well calibrated and understood, but wind speed is not equal to the wind shear stress, $\tau$. Most aeolian transport models extending back to Bagnold (1941) consider the dependence of transport flux on shear velocity, defined as $u_* = \sqrt{\tau/\rho_a}$, where $\rho_a$ is the air density. As compared to other variables describing the wind, shear velocity offers two big advantages. For observationalists, $u_*$ is relatively straightforward to measure based on the law-of-the-wall vertical profile of horizontal wind velocities (Bagnold, 1941):

$$U(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right)$$

where $U(z)$ is time-averaged horizontal (streamwise) wind velocity at height $z$, $\kappa$ is Von Karman’s constant (typically $\kappa = 0.4$), and $z_0$ is the aerodynamic roughness height. For theorists, $u_*$ directly relates to the downward flux of horizontal fluid momentum in the surface layer, offering physical grounding to models. Due to its universal convenience, $u_*$ has therefore served as the primary explanatory variable for comparing measurements and models (e.g., Kok et al., 2012).

While convenient, $u_*$ is a measure of the average turbulent downward flux of horizontal fluid momentum, and is therefore only meaningful over sufficiently long averaging periods of ~5–30 min (Namikas, 2003), such that the contribution of the broad range of individual eddies present in the surface layer is captured (e.g., Stull, 1988; Kaimal and Finnigan, 1994; Van Boxel et al., 2004). The use of $u_*$ to describe sand transport, with its pronounced variability on second timescales, therefore creates some fundamental problems. Indeed, the existence of so-called “aeolian streamers” (Baas and Sherman, 2005), indicates that sand transport responds to the high-frequency fluctuations of turbulent eddies. In part because of this reason, field measurements of transport rates are strongly dependent on the time period over which $u_*$ is averaged (Martin et al., 2013). Models dependent on $u_*$ as the explanatory variable therefore partially neglect the role of these
turbulent fluctuations. Additionally, the definition of saltation, which is poorly defined in situations without logarithmic wind profiles, occurs within areas of significant topography such as dunes (Wiggs et al., 1996) and with roughness elements such as vegetation (e.g., King et al., 2006).

Here, we have raised issues primarily in measuring spatially and temporally variable sand transport and wind stress. These issues are meant to be illustrative, but other measurement issues exist. These include quantifying the variability in soil moisture (e.g., Edwards and Namikas, 2009; Wiggs et al., 2004b), soil structure (e.g., Jerolmack et al., 2011), surface roughness (e.g., Hugenholtz et al., 2013; Nield et al., 2013), and thresholds for initiation and cessation of transport (e.g., Barchyn and Hugenholtz, 2011).

3.2. Model structure: equilibrium between forcing and transport?

A large number of analytical and numerical models of aeolian sand transport have been presented over the past decades. Nearly all assume equilibrium of some sort between wind forcing and transport. The most straightforward of these are the classical semi-empirical analytical models, starting with the work of Bagnold (1941) (see Table 1 in Kok et al., 2012; Ellis and Sherman, 2013). Over the past decade or so, analytical models have been developed that account for more of the detailed mechanics of sand transport, resulting in more complex relations for the sand flux (Sauermann et al., 2001; Andreotti, 2004; Sørensen, 2004; Durán and Herrmann, 2006; Lämmel et al., 2012; Pähtz et al., 2012). The wide availability of computational resources has also allowed development of numerical transport models, starting with the critical works of Anderson and Haff (1988, 1991). These models include simulations of saltation in equilibrium (Werner, 1990; Kok and Renno, 2008, 2009) as well as numerical models that simulate saltation from inception to steady state (e.g., Anderson and Haff, 1988, 1991; Ma and Zheng, 2011; Durán et al., 2012; Carneiro et al., 2011). With increasing computational resources, as well as improved understanding of the relevant processes, new models are trending towards a more physics-based description of transport (e.g., Anderson and Haff, 1991; Durán et al., 2011; Kok et al., 2012).

Despite these advances, two structural aspects of the present generation of analytical and numerical models do not match field observations. First is the simplification that saltation is driven by a constant downward flux of horizontal fluid momentum. Second is the assumption that sediment transport rate is in equilibrium with the driving wind flow. These assumptions clearly do not match the field observation that sand transport often occurs in streamers, rather than in a spatially- and temporally-homogeneous manner (Baas and Sherman, 2005; Sherman et al., 2013). A constant momentum flux and constant flux response are powerful in distilling the basic physics of saltation (see Durán et al., 2011; Kok et al., 2012), but these simplifications do not match the reality in the field (Sherman et al., 1998; Delgado-Fernandez and Davidson-Arnott, 2011; Martin et al., 2013).

This noted, the response time of transport to wind speed fluctuations is fast and equilibrium saltation may be present (but ephemeral). Both measurements and models suggest that transport rates respond to changes in wind speed with a characteristic time scale of \( \sim 1.0 \text{s} \) (Anderson and Haff, 1991; McEwan and Willetts, 1993; Butterfield, 1991; Jackson and McCloskey, 1997; Wiggs et al., 2004a; Ma and Zheng, 2011). As a result, saltation could be close to steady state within individual aeolian streamers. Further evidence supporting this notion includes the relative invariance of saltation layer height and particle speed with wind speed (Namikas, 2003), and the occurrence of a focusing of wind profiles for different wind speeds known as the Bagnold focus (Bagnold, 1936) (see Kok et al., 2012 for a more detailed discussion).

The mismatches between conceptualizations used in models and those represented by field situations have been recognized by some authors. Dupont et al. (2013, 2014) developed a model of saltation transience, incorporating an artificial turbulence generator and numerically simulating the spatial and temporal evolution of saltation. The majority of models, however, still conceptualize saltation as time and place-invariant, or simply do not consider space and time.

4. Solutions

Despite incompatibilities between measurements and models that severely limit the ability to quantify spatial and temporal variability in aeolian sediment transport, there are possible solutions. We present some of these below.

4.1. Revise model conceptualizations and evaluate representativeness

First, to better describe natural saltation, models should be adapted to address spatial and temporal variability in wind stresses driving transport. For example, an exemplary study was completed by Dupont et al. (2013), which couples a saltation model to a three-dimensional large eddy simulation over a flat erodible surface. We expect new models will need to be developed to simulate saltation over more complex natural topography, especially as there is evidence that aeolian processes are substantially enhanced in the presence of topography (Rosenberg et al., 2014). Second, as substantial effort has been invested in understanding equilibrium saltation, we should evaluate to what degree naturally-occurring saltation is indeed in equilibrium with the driving wind flow (Baas, 2006). Understanding the statistics of steady state saltation would help constrain the representativeness of this substantial legacy of work. Additionally, this would help constrain the representativeness of experimental data, which, because of constrained wind tunnel geometry, are obtained under a turbulence spectrum that is truncated compared to that occurring naturally in the atmosphere (e.g., Li and McKenna Neuman, 2012; Bauer et al., 2013). Comparisons between wind tunnel and field measurements show that there are substantial differences between their properties (Farrell and Sherman, 2006; Sherman and Farrell, 2008; Kok, 2011). Understanding the limits of wind tunnel data is necessary for determining how experiments can and cannot be applied to informing and parameterizing sediment transport models. These tests will require careful field studies measuring transverse and streamwise spatial changes in sediment flux and could be accomplished with a spatial arrays of low profile flux sensors such as the Wenglor optical transport sensors (Hugenholtz and Barchyn, 2011). The spatial gradient in flux associated with saltation adjustment toward equilibrium is widely thought to set the minimal length over which dunes can be stable (see review: Kok et al., 2012) and the effects are observable over simple topography (e.g., Elbelhiti et al., 2005). Further field studies of flux adjustment over more complex dune topography are needed (Weaver and Wiggs, 2011; Wiggs and Weaver, 2012).

4.2. Improve and optimize measurement technology

Clearly, improving measurement technology is necessary. For example, understanding how particle counts translate into sediment flux is important (Baas, 2004; Mikami et al., 2005; Hugenholtz and Barchyn, 2011; Barchyn et al., 2014). Further, precision calibration is necessary for all sediment transport sensors to gain confidence in the reliability of sensors, particularly as sensor
response can vary with grain size and saltation intensity (Goossens et al., 2000; Barchyn et al., 2014). Standardized approaches to field data collection (Barchyn et al., 2011) may help improve data quality in an interim manner, until commensurability between different measurement technologies can be more concretely assessed. New technology for sediment transport remote sensing needs to be further developed and is among the most promising new approaches for quantifying flux (e.g., image based analysis, Baas and Van den Berg, 2010; Sherman et al., 2013). Consumer camera technology is improving quickly and new platforms such as unmanned aerial vehicles are becoming more accessible (Hugenholtz et al., 2012). Adaptation of wind tunnel passive sensing techniques (such as laser Doppler anemometry: see Li and McLennan, 2012) to field settings is another possible avenue for progress. Remote sensing could offer the synoptic perspective that is necessary to more accurately model spatial and temporal variability in transport.

4.3. Specification of scale

If spatial and temporal variability in transport is to be considered within models, all numbers require specification of scale. This applies to both measurements and models. Numbers describing wind, saltation, and other aeolian transport variables represent finite windows of space and time. In part because of the fundamental sensitivity of sediment transport measurements involving $u_t$ to the averaging interval (e.g., Martin et al., 2013), numbers have different representations when the scale is changed. For example, $u_t$ calculated from a daily average wind profile may indicate $u_t < u_{t,5}$, where $u_{t,5}$ is the threshold shear velocity, and therefore no transport. On that same day, 15 min wind profiles would predict $u_t > u_{t,5}$ and sediment transport during a brief afternoon storm surrounded by otherwise placid conditions with $u_t < u_{t,5}$. In this example the daily average shear velocity, while presented with the same units as the 15 min shear velocity, is a different quantification of wind. Strictly speaking, the two shear velocity measurements cannot be meaningfully compared. A further problem is that the threshold value $u_t$ itself is likely dependent on the averaging timescale over which it is obtained (Martin et al., 2013). Therefore, measurements and models should compare variables at equivalent length and time scales. Alternatively, scaling relationships could be derived to estimate relationships between different scale-dependent quantities. Global circulation models for climate studies offer promising examples of downscaling and subgrid scale parameterizations (e.g., Wilby and Wigley, 1997) that could be applied to aeolian transport models.

Many studies include specification of spatial and temporal scale, but this is often hidden deep within the methods section of the study. If spatial and temporal variability is to be treated within new aeolian transport models, all numbers will require explicit qualification of the space and time which is represented.

4.4. Variable matching between models and measurements

The technical limitations of measurements discussed above are unlikely to be solved immediately. This creates a problem whereby models can be developed from extension of physical principles that cannot be easily tested (e.g., Dupont et al., 2013, 2014). While it may not be possible to test every aspect of complex physics-based models of saltation, we may be able test select aspects of these models through careful matching of variables. For example, it could be possible to output synthetic transport timeseries from models that are designed to correspond to the type of measurements which can be collected reliably. Expected measurements for sediment flux at certain heights above the bed, for certain timeframes, could be produced and directly compared to field measurements.

Note that such efforts do not constitute model ‘verification’, rather they simply increase the confidence we have in models. Ideally, models would be informed by perfect information about all aspects of the system for which they are making predictions. Lacking full omniscience, we can at least utilize the snapshots provided by measurements to test and improve our confidence in models. Large uncertainties revealed in models can inform the most urgently needed measurements and improvements in measurement technology, which in turn can help to fill model gaps. Such model development should be informed by comparisons to aeolian saltation observed at multiple measurement sites, each of which will reveal model sensitivities to different site parameters.

5. Summary

Here we have identified problems with aeolian sediment transport prediction that we believe deserve community consideration. Measurements and models are part of an integrated system: measurements are required to translate the real, natural world into numbers; models are required to manipulate those numbers to develop informed predictions. As a result of the integration, mismatches between measurements and models can limit the reliability of prediction tools, with important consequences for other disciplines and applications.

We use the example of variability in transport to highlight particularly acute areas of measurement-model mismatches. Variability in transport is widely acknowledged, yet not addressed within most transport models. Grounding transport models in physics allows models to advance beyond technological limitations in transport measurement. To help address measurement-model mismatch we propose several suggestions: (i) revising model conceptualizations to incorporate spatial and temporal variability, (ii) improving measurement technology, (iii) explicitly specifying the scale of all numbers used within measurements and models, and (iv) using understanding of what variables can be collected to produce matched variables between models and measurements. These suggestions will not immediately make models and measurements commensurate, but they will help improve the situation. We believe improvements will have tangible effects on prediction tools that other disciplines and applications rely upon.

7. Role of funding sources

This study was funded by the University of Calgary, National Science and Engineering Research Council of Canada, Alberta Innovates, Cenovus Energy, and the U.S. National Science Foundation. Funders had no role in the study design, data collection, analysis, interpretation, report preparation, or the decision to submit the paper for publication.

Acknowledgements

We acknowledge financial support for this project from the University of Calgary, National Science and Engineering Research Council of Canada, Alberta Innovates, Cenovus Energy, and the U.S. National Science Foundation (NSF) under award number AGS-1358621 and EAR Postdoctoral Fellowship award number 1249918.

References
