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Fetch effect on the developmental process of aeolian sand transport in a wind tunnel postprint

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Abstract

As the sand mass flux increases from zero at the leading edge of a saltating surface to the equilibrium mass flux at the critical fetch length, the wind flow is modified and then the relative contribution of aerodynamic and bombardment entrainment is changed. In the end the velocity, trajectory and mass flux profile will vary simultaneously. But how the transportation of different sand size groups varies with fetch distance is still unclear. Wind tunnel experiments were conducted to investigate the fetch effect on mass flux and its distribution with height of the total sand and each size group in transportation. The mass flux was measured at six fetch length locations (0.5, 1.2, 1.9, 2.6, 3.4 and 4.1 m) and at three free-stream wind velocities (8.8, 12.2 and 14.5 m/s). The results reveal that the total mass flux and the mass flux of each size group with height can be expressed by q=aexp(-bh), where q is the sand mass flux at height h, and a and b are regression coefficients. The coefficient b represents the relative decay rate. Both the relative decay rates of total mass flux and each size group are independent of fetch length after a quick decay over a short fetch. This is much shorter than that of mass flux. The equilibrium of the relative decay rate cannot be regarded as an equilibrium mass flux profile for aeolian sand transport. The mass fluxes of 176.0, 209.3 and 148.0 m size groups increase more quickly than that of other size groups, which indicates strong size-selection of grains exists along the fetch length. The maximal size group in mass flux (176.0 m) is smaller than the maximal size group of the bed grains (209.3 m). The relative contribution of each size group to the total mass flux is not monotonically decreasing with grain size due to the lift-off of some small grains being reduced due to the protection by large grains. The results indicate that there are complex interactions among different size groups in the developmental process of aeolian sand transport and more attention should be focused on the fetch effect because it has different influences on the total mass flux, the mass flux profile and its relative decay rate.

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Full Text

Fetch Effect on the Developmental Process of Aeolian Sand Transport in a Wind Tunnel

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Abstract

As sand mass flux increases from zero at the leading edge of a saltating surface to equilibrium mass flux at the critical fetch length, the wind flow is modified and the relative contributions of aerodynamic and bombardment entrainment change, causing simultaneous variations in velocity, trajectory, and mass flux profile. However, how the transport of different sand size groups varies with fetch distance remains unclear. Wind tunnel experiments were conducted to investigate the fetch effect on mass flux and its height distribution for both total sand and each size group. Mass flux was measured at six fetch locations (0.5, 1.2, 1.9, 2.6, 3.4, and 4.1 m) and at three free-stream wind velocities (8.8, 12.2, and 14.5 m/s). Results reveal that total mass flux and the mass flux of each size group with height can be expressed by $q = a\exp(-bh)$, where q is sand mass flux at height h, and a and b are regression coefficients. The coefficient b represents the relative decay rate. Both the relative decay rates of total mass flux and each size group are independent of fetch length after a rapid decay over a short fetch. This equilibrium length is much shorter than that required for mass flux equilibrium. The equilibrium of the relative decay rate cannot be regarded as representing equilibrium mass flux profile for aeolian sand transport. The mass fluxes of the 176.0, 209.3, and 148.0 m size groups increase more rapidly than other size groups, indicating strong size selection along fetch length. The maximal size group in mass flux (176.0 m) is smaller than the maximal size group in bed grains (209.3 m). The relative contribution of each size group to total mass flux does not decrease monotonically with grain size because lift-off of some small grains is reduced due to protection by large grains. These results indicate complex interactions among different size groups during the developmental process of aeolian sand transport, warranting greater attention to fetch effects because they exert different influences on total mass flux, mass flux profile, and relative decay rate.

Keywords: fetch length; mass flux profile; grain size distribution; sand transport; wind tunnel experiment

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1 Introduction

The fetch effect describes the downwind increase in mass flux with distance from the leading edge of a saltating surface (Stout, 1990; Gillette et al., 1996; Dong et al., 2004a; Delgado-Fernandez, 2010; Lynch et al., 2016). Mass flux measured from areas where fetch distance is shorter than the critical fetch distance underestimates true equilibrium mass flux. Consequently, numerous studies have examined effects of moisture, surface texture, gravel, and other sediment-limited conditions (Gillette et al., 1996; van der Wal, 1998; Dong et al., 2004b; Bauer et al., 2009) and over dry loose sand beds (Shao and Raupach, 1992; Dong et al., 2004a), but most have focused on total mass flux. However, as mass flux increases with fetch distance and wind flow becomes modified, the velocity and trajectory of saltating sand grains and the vertical distribution of mass flux should also vary along fetch distance—parameters that are important in aeolian sand transport models under supply-limited conditions (de Vries et al., 2014; Hoonhout and de Vries, 2016). Furthermore, studies show that mass flux profiles differ substantially among size groups (Arens et al., 2002; Xing, 2007; Li et al., 2008; Tan et al., 2014; Yang et al., 2019). Yet, research on fetch effects on the transport of different size groups during the developmental process of aeolian sand transport remains scarce.

Natural sand surfaces typically contain mixed grain size groups, with each group exhibiting different transport behavior. For example, Li et al. (2008) found that mass flux profiles for 90–355 m size groups follow an exponential function, while those for 355–1000 m groups follow a power function. Tan et al. (2014) reported that mass flux profiles for fine sand groups (63–800 m) can be expressed by a Gaussian peak function, while coarse groups (800–2000 m) follow an exponential function. Yang et al. (2019) observed that fine sand mass flux decreases slightly with height above the sand bed at wind velocities <18 m/s, increases slightly at >18 m/s, then shows rapid exponential decrease, whereas medium and coarse sand decrease exponentially with height. They also found that contributions of medium and coarse sand to total mass flux increase with wind velocity. These different mass flux profiles and contributions obviously influence the total mass flux profile, which represents the weighted superposition of all size group profiles and likely explains different total mass flux profile forms such as exponential (Nickling, 1983; Nalpanis et al., 1993; Rasmussen and Sørensen, 2008), power (Sterk and Raats, 1996), and Gaussian peak functions (Dong et al., 2004b). This also affects parameters including mean size, sorting, skewness, and kurtosis (Arens et al., 2002; Farrell et al., 2012; Tan et al., 2014).

The developmental stage may also exert influence. At the very early stage of aeolian sand transport, aerodynamic entrainment dominates saltation dynamics, transporting more small than large grains. As more grains become entrained, wind flow becomes significantly modified and bombardment entrainment quickly dominates aerodynamic entrainment (Shao and Raupach, 1992; Bauer and Davidson-Arnott, 2003; Delgado-Fernandez, 2010). Meanwhile, sand grains absorb more momentum from wind flow and impact the sand bed at much greater velocities, ejecting more large grains into the airflow. Consequently, dislodgment rates and mass flux profiles of different size groups vary until true equilibrium is reached. Shao and Raupach (1992) found that their 14.5 m long sand bed did not meet criteria for saltation stabilization. Dong et al. (2004a) also observed total mass flux increasing within their 16 m long sand bed. Therefore, wind tunnels in most studies were probably insufficiently long to observe complete aeolian sand transport development, suggesting that many wind tunnel results were likely derived from specific stages of the developmental process.

This study aims to investigate the fetch effect on the developmental process of aeolian sand transport by analyzing changes in mass flux and its relative decay rate for total sand transport, and the relative importance of each size group along fetch distance.

2 Materials and Methods

All experiments were conducted in a blow-type non-circulating wind tunnel at the School of Geography and Tourism, Shaanxi Normal University, China. The wind tunnel has a total length of 16.5 m, with a working section 7.0 m long, 0.5 m wide, and 0.6 m high. Roughness elements (78 wood blocks measuring 0.02 m × 0.04 m × 0.04 m) were placed before the working section to produce a thick boundary layer. Free-stream wind velocity can be continuously varied from 3 to 35 m/s. Boundary layer thickness in the working section is approximately 0.12 m. Figure 1 [Figure 1: see original paper] shows the instrumentation layout.

Test sand was obtained from the Tengger Desert, China, with mean size 0.19 mm and standard deviation 0.41. Critical aerodynamic entrainment wind velocity is approximately 6 m/s. In experiments, a 0.029 m thick sand layer was evenly spread on a sand tray along the wind tunnel bed. The segmented sand sampler of Dong et al. (2004c) measured sand mass flux profile. This trap is 0.30 m high with 15 collection chambers (0.01 m wide and 0.02 m high). The sampler was positioned at six fetch locations: 0.5, 1.2, 1.9, 2.6, 3.4, and 4.1 m downwind from the leading edge (locations A–F in Figure 1). Locations are unevenly distributed due to immovable supporting structures. Three free-stream wind velocities (8.8, 12.2, and 14.5 m/s) were used to measure mass flux profiles.

Sampling durations were 1200, 420, and 300 s, determined primarily by sand bed depletion because upwind sand grains are blown away, exposing the bed floor after prolonged experiments. Each experiment was terminated before bed floor exposure to ensure fetch distance remained unchanged. Warm-up and cessation periods lasted only a few seconds—much shorter than total experimental duration—making their contributions to total mass flux negligible. For each fetch length and wind velocity combination, three replicates were conducted to obtain mean values.

Sand samples from chambers were weighed using a high-accuracy electronic scale

(0.001 g accuracy), and grain size distributions were analyzed with a Microtrac-S3500 grain size analyzer (Microtrac Inc., USA). Because mass flux at 8.8 m/s wind velocity was very small, relative decay rates for each size group were not calculated.

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3 Results

3.1 Mass Flux Profile of All Size Groups and Total Mass Flux Figure 2 [Figure 2: see original paper] shows mass flux profiles for all size groups across fetch lengths and wind velocities. At 8.8 m/s, mass flux decays exponentially across the entire vertical region for all six fetch lengths (Fig. 2a). At 12.2 m/s, mass flux generally decays with height but shows small negative deviation below 0.03 m (Fig. 2b). At 14.5 m/s, the 0.5 m fetch profile resembles Figure 2b, but the other five fetch lengths show mass flux increasing with height above the sand bed then rapidly decreasing (Fig. 2c). This aligns with some previous studies (Dong et al., 2004a; Tan et al., 2014) but differs from other positive deviation results (Butterfield, 1999; Namikas, 2003; Li et al., 2008; Kang et al., 2016). Disagreement partly arises because intrusive samplers have difficulty collecting all saltating and creeping grains in the near-bed region where mass flux concentration is densest, though this does not affect the mass flux profile above the reversal height.

The vertical distribution of sand mass flux above 0.03 m can be described by the exponential function:

$$q = a\exp(-bh)$$

where q is sand mass flux ($\mathrm{kg/(m^2 \cdot s)}$) of all size groups at height h (m), and a and b are regression coefficients. Coefficient b represents the relative decay rate of sand mass flux with height. Using least-squares curve fitting, relative decay rate b was calculated and shown in Figure 3 [Figure 3: see original paper].

Figure 3 shows variation of total mass flux and relative decay rate with fetch length. Total sand flux generally increases with fetch length, with this tendency strengthening at higher wind velocities. At 8.8 m/s, after rapid growth and an overshooting stage, total mass flux decreases to a constant, apparently approaching the equilibrium stage noted by Shao and Raupach (1992). For this study’ s short working section, the complete tendency of total mass flux at 12.2 and 14.5 m/s could not be observed.

Both wind velocity and fetch length affect relative decay rate. In Figure 3, relative decay rate b decreases with wind velocity because sand grains absorb more momentum from stronger wind flow, achieve greater lift-off velocity, and reach higher elevations. Figure 3 also shows b decreasing rapidly at short fetch lengths (approximately 2.6 m), then decaying much more slowly and becoming nearly constant at a certain fetch length much shorter than that required for total mass flux equilibrium. This agrees with experimental results of Dong et al. (2004a) and numerical results of Xiao et al. (2013). Dong et al. (2004a) argued that mass flux profile reached equilibrium with a stable probability distribution of lift-off velocity. However, this contradicted their further investigations showing average saltation height increased throughout their experimental fetch length, implying lift-off velocity continued increasing, grains moved to higher elevations, and mass flux profile did not reach true equilibrium.

3.2 Mass Flux Profile and Total Mass Flux of Each Size Group Mass flux for each sand size group can be calculated by:

$$q_i = q \cdot f_h(d_i)$$

where q_i and q are sand mass flux ($\mathrm{kg/(m^2 \cdot s)}$) of grain size group d_i and total mass flux of all size groups at height h (m) (Fig. 2), d_i is diameter (m) of size group i, and $f_h(d_i)$ is mass fraction of d_i at height h analyzed by the Microtrac-S3500 grain size analyzer.

Mass flux profiles for four size groups appear in Figure 4 [Figure 4: see original paper]. At low wind velocities and/or short fetch lengths, mass flux decays exponentially across the entire height region, consistent with studies of loose sandy surfaces (Dong et al., 2003; Namikas, 2003) and some gravel surfaces at low wind velocity (Tan et al., 2016). As wind velocity and/or fetch length increase, mass flux profiles gradually deviate from sandy surface behavior. A peak mass flux appears at 0.03 m height, then decreases with height, presenting the classic unimodal curve over gravel surfaces (Dong et al., 2004b). However, mass flux above 0.03 m for each size group still follows the exponential function of Equation 1.

Figure 4 also shows grain size strongly affects mass flux profiles. Small sand size groups tend toward unimodal curves, while large groups show exponential decrease with height. Dong et al. (2004a, b) found peak mass flux height increased with both wind velocity and sand surface fetch length, but in our experiment peak mass flux height remains constant (0.03 m), possibly due to larger wind velocities and fetch lengths in their study. With increasing wind velocity, critical grain size for direct aerodynamic entrainment and velocity of entrained sand grains increase, enabling more large grains to reach higher elevations.

Relative decay rate b for each size group was calculated and shown in Figure 5 [Figure 5: see original paper]. At any fetch location, b appears to decrease with increasing grain size, indicating mass flux of large size groups decays more quickly with height than small groups. This agrees with Li et al. (2008), though their size groups ($d > 355$ m) followed a negative power law. In our experiments, mass fraction of $d > 355$ m in bed grains is less than 5%, and mass flux profiles for these groups were not analyzed. b also decreases quickly within the first

1.4 m fetch length, then approaches a constant value, similar to total mass flux relative decay rate in Figure 3 but differing by grain size. b for small size groups (e.g., 88.0 and 140.7 m) decays more quickly than large groups at short fetch lengths.

Figure 5 also shows b for total mass flux deviates significantly from b of the maximal bed grain size group (209.3 m) and b of the main transport size group (176.0 m; Fig. 6 [Figure 6: see original paper]), but is close to some small size groups. At 12.2 m/s, b for total mass flux nearly equals b for the 148.0 m size group. At 14.5 m/s, b for total mass flux is also close to b for the 148.0 m group when fetch length is less than 2.6 m, but then approaches the 176.0 m group. Meanwhile, b variation amplitude changes with grain size, as curves for 124.5, 148.0, 176.0, and 209.3 m appear smoother than others. This is attributable to different mass fraction contributions of each size group to total mass flux. Larger deviations in measured q_i for less-transported size groups cause relatively greater fluctuations in b.

Figure 6 shows total mass flux of different size groups Q_i with fetch length, where Q_i is calculated by integrating mass flux with height according to mass flux profiles for different size groups. First, Q_i for the 176.0, 209.3, and 148.0 m size groups constitute the main components of total mass flux Q, but Q_i for the 176.0 m group exceeds Q_i for the 209.3 m group (maximal size group in bed grains). Second, increasing rates of these three size groups with fetch length exceed those of other groups whose contributions are small but not negligible. Total mass flux Q represents the weighted superposition of Q_i for all grain size groups, as does the total mass flux profile. Different increasing rates for each size group with fetch also show that the ratio of mass flux for each size group at different fetch lengths varies significantly. This contradicts Yang et al. (2019), who found weight percentage of each size group in transport matches weight percentage in bed grains, probably because their four size groups (very fine, fine, medium, and coarse) masked detailed information compared to our eight size groups.

These results contradict the independence assumption of Shao et al. (1996), who assumed different size groups transport independently and mass flux of each group is unaffected by others. These results also indicate that median or mean grain size of bed grains is unsuitable for representing all grain size groups in transport.

3.3 Mean Grain Size Profile Mean grain size profile is an important parameter for validating aeolian sand transport models and reflects grain trajectory and lift-off velocity. Figure 7 [Figure 7: see original paper] shows mean grain size d_m decreases with height in each experiment and shows weak increasing trend with fetch, agreeing with widely accepted conclusions. Jensen and Sørensen (1986) and Rice et al. (1995) found large grains launch at lower speeds and angles than small grains in wind tunnel experiments. Xiao et al. (2012) also found mean horizontal velocity of small size groups exceeds that of large groups at any height in numerical simulation. Apparently, mean lift-off velocity of saltating sand grains decreases with grain size, reducing probability of reaching higher elevations as evidenced by grain-size distributions in Figure 8 [Figure 8: see original paper]. This disagrees with Tan et al. (2014) and Yang et al. (2019), who found d_m decreases with height initially then increases, with reversal point height increasing with wind velocity. This difference may result from different mass flux measurement heights and different bed grain size distributions. Maximum height was 0.60 m in Tan et al. (2014) and 0.50 m in Yang et al. (2019), whereas it ranges between 0.05 and 0.25 m in this study depending on fetch length and wind velocity. Test sands in Tan et al. (2014) and Yang et al. (2019) contained more medium sand (250–500 m) and coarse sand (500–1000 m), making sand transport more similar to gravel sand surfaces.

Figure 8 shows $f_{h,i}/f_{bed,i}$ trends at different heights at 14.5 m/s wind velocity and 4.1 m fetch length, where $f_{h,i}/f_{bed,i}$ is the ratio of mass fraction of size group d_i in transport ($f_{h,i}$) to that in bed grains ($f_{bed,i}$). Higher $f_{h,i}/f_{bed,i}$ values indicate greater relative contribution to mass flux. Relative contribution of small size groups increases with height (Fig. 8), showing mean grain size decreases with height as in Figure 7.

Figure 8 also shows $f_{h,i}/f_{bed,i}$ does not decrease monotonically with grain size. At 0.01 m height, $f_{h,i}/f_{bed,i}$ values for 124.5, 148.0, 176.0, and 209.3 m groups exceed 1 (red line; Fig. 8), while values are less than 1 for other groups, especially 88.0 and 104.7 m groups. At 0.03–0.09 m, maximum $f_{h,i}/f_{bed,i}$ occurs at the 104.7 m group, then drops to the 88.0 m group at 0.11 and 0.13 m heights. This likely results from shielding effects of large grains and reduced wind speed near the bed rather than cohesive forces, which are only important for grains smaller than 70 m, increasing threshold wind velocity (Greeley and Iversen, 1985). Large grains protect underlying grains from bombardment by impacting sand grains and direct wind entrainment, similar to gravel effects on sand transport (Dong et al., 2004b; Gillies et al., 2007).

Wind velocity affects interactions among size groups similarly to fetch length. Critical grain size for direct aerodynamic entrainment and velocity of entrained sand grains increase with wind velocity, enabling more large grains to enter the airflow. Strong size selection indicates complex interactions among different size groups at least during the developmental process of aeolian sand transport, even though relative decay rates of total mass flux and each size group have reached constant values.

Wind tunnel dimensional constraints affect aeolian sand transport. Tunnel dimensions are critical factors determining whether accurate saltation modeling is achieved. If choked saltation occurs, wind tunnel constraints alter wind flow and mass flux profile. Owen and Gillette (1985) investigated wind tunnel size constraints on saltation development and suggested Froude number should be less than 20, defined as $Fr = U^2/(gH)$, where U is free-stream wind speed, g is gravitational acceleration, and H is wind tunnel height. White and Mounla (1991) suggested a more conservative Froude number of 10 to ensure accurate saltation simulation, based on analyzing friction velocity variations downstream in a wind tunnel using walnut shells as test grains. The low density of walnut shells greatly reduces critical entrainment wind velocity and critical Froude number. However, meeting Froude number criteria seems difficult or impossible. According to Owen and Gillette (1985) and White and Mounla (1991), our wind tunnel' s free-stream velocity should be less than 10.8 and 7.7 m/s, respectively—only slightly exceeding critical aerodynamic entrainment wind velocity of our test sands. Additionally, critical aerodynamic entrainment wind velocities for some coarser sands exceed suggested critical wind velocity. Therefore, further study is needed to investigate wind tunnel constraint effects, though this is beyond our current scope.

Our results demonstrate that fetch effects exert different influences on total mass flux and mass flux profile of each size group along fetch distance. Moreover, dimensional constraint effects likely differ for each wind tunnel. Therefore, caution is warranted in wind tunnel experiments. If research focuses on mass flux profile decay rate, short fetch distance suffices. However, if focusing on transport during developmental or equilibrium stages, the working section must exceed critical fetch length.

4 Conclusions

Changes in mass flux and relative decay rate of total sand flux, and changes in each size group during aeolian transport development were examined in a wind tunnel. Main findings are:

1. Relative decay rates of total sand flux and each size group decrease quickly with fetch length when fetch is short, then reach equilibrium. The equilibrium fetch length for relative decay rate is much shorter than that for mass flux, indicating equilibrium of relative decay rate cannot represent equilibrium mass flux profile or aeolian sand transport. Mass flux of large size groups decreases more quickly than small groups in all experiments.
2. Mass flux of each size group increases asynchronously with fetch length. Mass fluxes of the 176.0, 209.3, and 148.0 m size groups increase more rapidly than other groups.
3. Mean grain size decreases with height and increases slightly with fetch length.
4. The maximal size group in transport (176.0 m) is smaller than the maximal size group in bed grains (209.3 m). Relative contribution to total mass flux does not increase with decreasing sand size. Protection effects of large grains on small grains reduce their lift-off probability from the sand bed.

These findings may deepen understanding of interactions among different grain size groups and fetch effects on aeolian sand transport. However, our wind tunnel' s short working section prevented both total mass flux and sand mass flux profile from reaching equilibrium, limiting our inferences about the complete developmental process. Caution is warranted in wind tunnel experiments due to different influences of fetch effects on total mass flux, mass flux profile, and relative decay rate.

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