Small-Scale Spatial Variations in Aeolian Sediment Transport on a Fine-Sand Beach

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ABSTRACT

Variability in sediment transport is evaluated over a wind-normal span of four meters. Transport rates were determined from 5 vertical cylindrical sand traps emplaced at 1-m intervals during 4 different wind conditions on a sand beach in Ocean City, New Jersey, USA. Mean wind speeds ranged from 6.1 to 7.1 m s⁻¹. Winds blew at a slight angle to shore-parallel on all days, resulting in slight differences in the distances of each trap from adjacent beach sub-environments (intertidal zone, backshore), where surface roughness and moisture content characteristics differed. Variation in trapping rates was greatest on the backshore where wind speeds were most variable. Comparison of trapping rates across the array indicates that sand volumes trapped at individual locations commonly varied by 20% from the mean rate. Differences between the largest and smallest volumes trapped commonly exceeded 150%. These results suggest that not only should great care be taken in the location of individual traps, even in geomorphically simple environments, but the results obtained with one trap should be interpreted with caution.

ADDITIONAL INDEX WORDS: Backshore, grain size statistics, intertidal zone, New Jersey, aeolian sand transport, sand trapping rates, wind direction, wind speed.

INTRODUCTION

Understanding the spatial variability of sand movement by aeolian transport is important for identifying sources of uncertainty in relating transport rates and wind characteristics monitored in the field to predictive equations. Sediment transport rarely occurs in optimum conditions in beach environments due to a variety of spatial and temporal factors. Spatial variability of transport rates is influenced by local variations in wind speed, direction and turbulence, surface moisture, topography, textural properties of sediment, and small-scale roughness elements (e.g., litter and bedforms) (Jackson and Nordstrom, 1998; Hesp, 1999). Potential transport rates commonly depart from actual rates (SHERMAN et al., 1998), particularly when the transport is across complex backshore and intertidal sub-environments. Estimating the rate of aeolian sediment transport is often based on the quantity of sediment that is trapped at fixed locations, using a single trap to represent transport conditions over distances of meters. The focus of this paper is to examine local variability in transport rates at multiple sampling locations within a sub-environment over a 4-m interval. Most studies of spatial variations in aeolian transport focus on cross-shore transport from the beach to the dune or the dune to the beach (BAUER et al., 1990; WAL and MCMANUS, 1993; NORDSTROM et al., 1996; NAMIKAS et al., 2003). Spatial variability is normally addressed in terms of large-scale differences (Davidson-Arnott and Law, 1990; Goldsmith et al., 1990), but Gares et al. (1996) evaluated small scale (0 to 5 m) variations along the beach (shore-parallel trapping line) during an offshore wind. This study is complementary to Gares et al. (1996) in that it evaluates small-scale differences but across the beach (shore-perpendicular trapping line) during longshore winds.

Winds blowing at an oblique angle to the shoreline can increase the fetch and supply of sediment available for transport (ARENES et al., 1995; BAUER and DAVIDSON-ARNOTT, 2003) but cut across several distinctive shore-parallel sub-environments, each of which has different topography and moisture levels (WAL and MCMANUS, 1993). The implication is that the rate of sand transported within one of the shore-parallel sub-environments (wetted foreshore, foreshore, dry intertidal storm foreshore, wind-reworked backshore) will vary depending on cross-shore location. Winds blowing parallel to the shoreline should result in less spatial variability in transport where upwind sediment source characteristics are similar and fetch distances are great enough to allow for a saturated transport condition to occur.

Roughness elements that affect small-scale differences in transport (Figure 1) vary in the cross-shore zones depending on frequency of surface reworking by waves and winds. The upper beach just seaward of the dune is reworked by storm waves that can deposit large amounts of vegetative debris at the uppermost wrack line and in subsequent litter lines formed by swash during falling water levels. Aeolian processes rework this backshore over time, creating local zones of scour and deposition (Figure 1a). The frequent reworking of non-storm waves on the foreshore below the storm berm during subsequent tidal cycles removes litter and aeolian forms and creates a surface that is relatively free of roughness elements (Figure 1b). The removal of roughness elements from the regularly reworked intertidal foreshore should result in greater similarity in spatial samples of sediment transported by wind from this environment. At the same time, the different degrees of inundation of the foreshore by waves and tides also sets up a sediment moisture controlled gradient in transport potential.

Many of the factors that affect the spatial variation in aeolian transport rates are relevant at all time scales, but some are more influential within a given time interval. At intervals of seconds to minutes, when the distribution of sediment in transport is closely related to the path of individual sand streamers, factors such as surface drying, gustiness and short-term changes in wind direction that alter the duration and direction of streamers become important. At intermediate time scales (tens of minutes)
the short-term variability of streamers affecting each trap should be smoothed spatially. Modal wind conditions may then be critical, causing sediment distribution to be influenced largely by microtopographic obstacles that create shadow zones and by winds that blow at an angle to traps, creating different lengths of sand sources in different shore-parallel environments. At long time scales, when weather systems change over hours to days, regional wind direction shifts will cause more pronounced changes in the exposure to source areas in adjacent environments. In general, greater convergence of the distribution of trapping rates should occur with increased time if wind conditions are fairly uniform and if the upwind surface characteristics are similar. The purpose of this paper is to identify small-scale variability in sediment transport with winds nearly parallel to the shoreline orientation. The study was conducted on a sand beach at Ocean City, New Jersey, a site characterized by little variation in sediment grain size and beach slope across and alongshore, thus reducing the influence of these factors on spatial variation in transport.

METHODS

Transport rates were determined from sets of 5 sand traps emplaced at 1-m intervals during 4 different wind conditions on 26 February and 13 and 18 March (Figure 2). The site is a nourished sand beach backed by a protective dune that varies in height from 2 to 3 m above backshore elevation. The width of beach from the toe of the dune to the upper limit of swash at low water is over 60 m. Beach sediments are fine sands. Data on wind speed were gathered on the beach using a low mast with 3 Gill anemometers placed 0.3, 0.6 and 0.9 m above the surface. Mean wind direction was measured with a compass by sighting on a micravane placed 1.65 m above the ground surface on the incipient foredune. A probe measuring temperature and relative humidity was placed at 1.6 m elevation 15 m landward of the wind vane. All instruments were recorded at 1 Hz on a Campbell data logger. Data reported are means of conditions occurring during the entire elapsed times when trap samples were taken. Shear velocities were estimated from mean wind speed over 10-min intervals for each monitoring period and compared to the critical threshold velocity (Bagnold, 1941) determined from surface sediment samples gathered on 14 March. Percent of instantaneous wind speeds exceeding the critical threshold velocity was determined for each monitoring period to assess the role of variability of wind speed on transport.

Sediment in transport was gathered using vertical cylindrical traps (Leatherman, 1979) that are 0.37 m high and have an opening of 43.0 mm. Traps were emplaced and monitored by 2-person teams and remained in place from 25 min to 1 hr, depending on how soon transport conditions began to change due to onset of precipitation (26 February) or significant change in wind velocity or direction (13, 18 March). The experiment on 26 February used 10 traps in two cross-shore lines on the upper backshore (Figure 2). Short-term trapping rates were determined using a measuring stick inserted into trap reservoirs at intervals of 10 min. Measurements were estimated to the nearest 10 mm, resulting in a potential measurement error of 1.45 kg m⁻¹ hr⁻¹ or 5% of the mean trapping rate of all traps. Trapping rates for 13 and 18 March were determined from the dry weight of total volumes caught in the traps, so minor differences in trapping could be accurately evaluated. The experiment conducted the morning of 18 March used traps placed at the same location as 13 March, but this portion of the former backshore had been reworked by swash during the previous high tide and was relatively free of macro-roughness elements (similar to conditions depicted in Figure 1b). A second set of 5 traps was then placed on the backshore that had not been reworked by swash (similar to conditions depicted in Figure 1a).

Visual estimates of the types and approximate dimensions of roughness elements in the three zones were obtained on 14 March to help evaluate the reason for differences in trapping rates. Spatial variation in trapping rates is evaluated using the coefficient of variation for small samples (Sokal and Rohlf, 1981) for sets of traps along a transect. Ranges in variation were also determined by dividing the mean trapping rate by the minimum and maximum trapping rate, and the maximum rate by the minimum rate for a monitoring period. These statistics were calculated so results could be compared to results in Gares, et al. (1996), and so that the maximum potential variation could be normalized to a percent difference. Grain size characteristics of sediments caught in selected traps and on the surface were analyzed for mean and sorting using moment measures (Folk and Ward, 1957).

RESULTS

Wind Conditions

Mean wind speeds ranged from 6.10 to 7.07 m s⁻¹ during the four monitoring periods (Table 1). Variability of wind speed was greatest on the afternoon of 18 March. Shear velocities, calculated over 10-minute intervals for each monitoring period, were above the threshold of entrainment for clean, dry sediments on the backshore \( (d = 0.208 \text{ mm}; u_c = 0.21 \text{ m s}^{-1}) \) and on the foreshore \( (d = 0.237 \text{ mm}; u_c = 0.22 \text{ m s}^{-1}) \) during the four
monitoring periods. The percent frequency that the winds exceeded the threshold velocity ranged from 77% on 13 March to 100% on 26 February (Table 1). However, these results do not account for the influences of sediment moisture or ice content in the calculations of the threshold conditions.

Surface Characteristics

Winds blew at a slight angle to shore-parallel on all days (Figure 2) resulting in slight differences in the distances of each trap from adjacent environments where surface conditions differed. Inspection of conditions on 26 February indicated that the upwind surface was nearly flat with few obstructions. The only apparent differences were some patches of relatively dry sand that had been deposited in the wakes of streamers. The more comprehensive inventory of surface characteristics conducted on 14 March revealed that the backshore below the upper storm wrack line contained mounds of vegetative litter with average heights of about 40 mm and average widths of about 0.25 m, along with bits of broken shell up to 5 mm high (Figure 1). Ripples up to 5 mm high and aeolian bedforms up to the height of the vegetative litter coexisted with shallow depressions created by aeolian scour. The lower backshore (where data were gathered 13 March) contained isolated shells up to 80 mm high, shell fractions averaging 5 mm high and spaced about 0.23 m apart, small accumulations of vegetation up to 15 mm high, and accumulations of windblown sand 10 mm high with small ripples superimposed. The regularly reworked foreshore below this zone (Figure 1b) was similar to conditions the morning of 18 March when the upper swash limit was landward of the trap locations. The surface had only shell hash, with pieces no higher than 3 mm and separated by distances >0.7 m, with no aeolian bedforms.

Sediment Trapping

Mean grain size of sediments trapped ranged from 0.195 to 0.212 mm during the monitoring periods. Variation in trapping rates is greatest on the backshore, as revealed in the greater coefficient of variation for 26 February and the afternoon of 18 March when monitoring occurred on the backshore. Trapping rates on 26 February (Table 1) reveal that there is an increase in the quantity of sediment trapped from the swash limit toward the toe of the dune (Traps A-E) but this trend is reversed at the traps 35 m downwind (Traps F-J). One way ANOVA reveals that there is no significant difference in mean trapping rates between the two transects but there is greater variability among individual traps along the transect. Variation between traps for a given monitoring period were estimated from the coefficient of variation for sets of traps (ie, ABC, CDE, BCD, and ACE) along a given transect (Table 2). On 13 March the upwind source area was composed of dry sand. Coefficient of variation for Traps ABC was lower (23%) than for Traps CDE (29%) but the variation at a 2-m interval (Traps ACE) was the lowest (19%). On the morning of 18 March traps were deployed in the same location as 13 March, but the upwind source area had been reworked by waves and was characterized by dry sand moving across the intertidal beach. Coefficient of variation for Traps ABC was the lowest (5%) compared to Traps CDE (22%) or ACE (27%). These results suggest that the degree of variability between sets of traps is lower when data are gathered across the intertidal beach.

The range in variation reported in Table 2 provides an estimate of the degree of departure of individual traps from the mean value. The range in variation is greatest during the afternoon of 18 March when winds were more variable. The range for the other monitoring periods are similar suggesting that individual traps can depart an average 20% of the mean depending on where they are located. More dramatic are the differences between the maximum and minimum volumes trapped along each array (Table 2). In four of the five cases, the range in sediment trapping exceeded 150% of the minimum.
rate. For the afternoon of 18 March, the range was 242%.

**DISCUSSION**

Errors in estimating transport from single point measurements of spatially variable environments can result in poor predictive capability of sediment transport models. BAUER et al. (1996) analyzed spatial variation in onshore sediment flux along the backshore when mean onshore wind speeds were 6.8 to 8.8 m s\(^{-1}\) and found high coefficients of variation (51–78%) in sediment trapped. Their study differs from ours because winds were shore-perpendicular and the topographic and moisture characteristics were more complex. GARES et al. (1996) found that variation in alongshore (0–5 m) sediment trapping during offshore winds was ±20% of the mean. The results of our investigation of trapping over the same distance reveal that trapping rates averaged ±25% of the mean. The slightly greater variation in our results is due to the variation in trapping on the afternoon of 18 March. Results from our investigation show that backshore variation in trapping is higher than on the intertidal beach, suggesting that more traps may be required to better estimate actual transport landward of the intertidal zone. Most sets of trapping rates reveal greater values at either end of the array, implying that trap position within a cross-shore sub-environment may be important when winds blow at an angle across sub-environments.

Spatial variation in trapping rates is attributed to spatial differences in upwind source characteristics, fetch and variation in wind conditions (DAVIDSON-ARNOTT and LAW, 1990; BAUER et al., 1996; GARES et al., 1996). Transport on 26 February should have the lowest variation in trapping of the four monitoring periods. Winds were less variable, instantaneous speeds were above the threshold velocity and the upwind source area had little variation in roughness because waves had recently reworked the beach just seaward (upwind) of the traps. The coefficient of variation for the five traps was the second highest behind the afternoon of 18 March. The more variable rates on the afternoon of 18 March may be because much of the sand transported during the lower wind speeds was not able to pass the small obstacles as efficiently as during the longer time that had elapsed since storm wave inundation. Roughness elements can reduce transport, be a location of deposition for transported sediments and provide a source of sediment for subsequent entrainment and transport (BLUMBERG and GREELEY, 1993; GARES et al., 1996; VAN DER WAL, 1998).

The threshold for sediment entrainment is most sensitive to changes in surface topography (0.1–1.0 mm) particularly for sediment sizes greater than 0.2 mm (Blumberg and Greeley, 1993). The location of the isolated roughness elements on the backshore (Figure 1a) on 13 March and the afternoon of 18 March could account for the higher coefficient of variation and the greater range in variation of trapping (Table 2).

**CONCLUSIONS**

Numerous factors can cause small scale spatial differences in aeolian sediment transport rates. The results of this investigation suggest that spatial variation exceeding 200% over a four meter span can occur even when wind and upwind source characteristics are relatively uniform. The results indicate that multiple trap arrays may be required to better estimate transport landward of the intertidal zone, where surfaces are less uniform. If a single trap is used, placement in the middle of a distinctive shore-parallel zone may reduce edge effects and provide the best estimate of mean transport conditions.

**ACKNOWLEDGEMENTS**

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**LITERATURE CITED**


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**Table 1. Wind and atmospheric characteristics and trapping rates for period traps were deployed in locations identified in Figure 1.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Temp. °C</th>
<th>RH %</th>
<th>(U_{10}(\text{m} \text{s}^{-1})) (m s(^{-1}))</th>
<th>(U_{crit}(\text{m} \text{s}^{-1})) (m s(^{-1}))</th>
<th>Trapping rate (kg m(^{-1}) hr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RH (%)</td>
<td>Mean   Std Dev.</td>
<td>Mean   % &gt; (U_{crit}) Trap</td>
<td>Trap</td>
</tr>
<tr>
<td>26 Feb. (A-E)</td>
<td>-2.5</td>
<td>65</td>
<td>7.07   0.82</td>
<td>3.09   100</td>
<td>33.3</td>
</tr>
<tr>
<td>(F-J)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 March</td>
<td>6.1</td>
<td>80</td>
<td>5.58   1.01</td>
<td>4.23   77</td>
<td>6.4</td>
</tr>
<tr>
<td>18 March (AM)</td>
<td>13.0</td>
<td>69</td>
<td>7.50   1.06</td>
<td>5.54   83</td>
<td>34.4</td>
</tr>
<tr>
<td>18 March (PM)</td>
<td>11.0</td>
<td>74</td>
<td>6.10   1.30</td>
<td>4.40   80</td>
<td>3.3</td>
</tr>
</tbody>
</table>

RH - Relative humidity; \(U_{10}\) - Wind speed; \(U_{crit}\) - Critical threshold velocity

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**Table 2. Coefficients of variation and range of variation in trapping rates for sets of traps.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Coefficient of Variation (%)</th>
<th>Range in Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traps</td>
<td>Traps</td>
</tr>
<tr>
<td>26 Feb. (A-E)</td>
<td>ABCDE</td>
<td>(FGHIJ)</td>
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<tr>
<td>(F-J)</td>
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<td>46</td>
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<tr>
<td>13 March</td>
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<tr>
<td>18 March (PM)</td>
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<td>23</td>
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