Journal of Coastal Research	12	3	664–672	Fort Lauderdale, Florida	Summer 1996

Offshore Aeolian Transport Across a Beach: Carrick Finn Strand, Ireland

K.F. Nordstrom[†], B.O. Bauer[‡], R.G.D. Davidson-Arnott , P.A. Gares[§], R.W.G. Carter[*], D.W.T. Jackson', and D J. Sherman[‡]

[†]Institute of Marine and Coastal Sciences
Rutgers University
New Brunswick, NJ 08903, USA

[‡]Department of Geography
University of Southern California
Los Angeles, CA 90089, USA

'Department of Geography
University of Guelph
Guelph, Ontario N1G 2W1, Canada

[§]Department of Geography and Planning
East Carolina University
Greenville, NC 27858, USA

[*]Deceased

'University of Ulster
Coleraine, Co. Londonderry
Northern Ireland BT52 1SA, UK

ABSTRACT

NORDSTROM, K.F.; BAUER, B.O.; DAVIDSON-ARNOTT, R.G.D.; GARES, P.A.; CARTER, R.W.G.; JACKSON, D.W.T., and SHERMAN, D.J., 1996. Offshore aeolian transport across a beach: Carrick Finn Strand, Ireland *Journal of Coastal Research*, 12(3), 664–672. Fort Lauderdale (Florida), ISSN 0749-0208.

This study examined cross-shore differences in wind speed and aeolian sediment transport rate in relation to beach surface conditions in the lee of a 6 m high dune during 2 days of offshore winds at Carrick Finn Strand, Ireland. Near-surface wind speed, surface moisture, carbonate content and mean grain size increased in the offshore direction; sediment sorting became slightly poorer. The rate of sediment transport was small from the dune toe out to a distance of about 20 m and then increased rapidly to about 40 m seaward of the dune. The rate decreased seaward of this location early each day due to a great increase in surface moisture content. Greater rates of transport occurred seaward of this location later in the day and are attributed to drying of the beach surface and increased wind speeds. Rates of offshore aeolian transport on the beach in the lee of the dune are affected by shore-parallel zones differing in wind speed, surface moisture and sediment characteristics that change in location through time. These zones include a Lee-of-Dune Zone, where no aeolian entrainment occurs because of low wind speeds; an Erosion Zone, located sufficiently far from the dune that wind is effective in entraining and removing sediments; a Transport Zone where erosional losses are replaced by inputs from upwind; and an Accretion Zone on the moist portion of the foreshore.

ADDITIONAL INDEX WORDS: *Wind speed, aeolian transport, beach, dune, sand size, sediment traps, surface moisture, Carrick Finn Strand, Ireland.*

INTRODUCTION

Offshore winds dominate over onshore winds in magnitude and frequency along some coasts (GUTMAN 1978; HENNIGAR 1979; NORDSTROM *et al.* 1986; GARES *et al.* 1993). Offshore winds may result in locally high rates of sediment transport to the beach or nearshore (ROSEN 1979; SO 1982; AUGUSTINUS *et al.* 1990; GARES 1990; 1992; DINGLER *et al.* 1992; MCLACHLAN and BURNS 1992) and may create pronounced topographic changes in the dunes or just landward of them (TAYLOR and FROBEL 1990; HUNTER *et al.* 1983; GARES 1992). Despite the potential importance of offshore winds in the coastal sediment budget, there are few detailed studies of both wind velocity and aeolian transport on the beach in the lee of dunes.

The focus of field studies of aeolian transport in coastal environments is usually on onshore transport because of the large number of coasts where onshore winds prevail and the significance of onshore winds to the growth and maintenance of foredunes. When data on offshore aeolian transport are gathered on the beach, the data may not be analyzed in detail because of the interest in sediment input to the dune (SVASEK and TERWINDT 1974; SARRE 1989a; ARENS 1994). Studies that do provide quantitative estimates of offshore transport often focus on changes within the dune zone, and the field data may be gathered no farther seaward than the beach/dune contact or seaward limit of vegetation (ROSEN 1979; MCCLUSKEY *et al.* 1983; NORDSTROM *et al.* 1986; GARES 1992; GOLDSMITH *et al.* 1990). Previous field studies that examine rates of transport from the dune to the beach reveal large rates of transport at gaps in the dune, such as walkways, mouths of blowouts and overwash fans (ROSEN 1979; MCCLUSKEY *et al.* 1983; GARES 1992), but these transport rates only quantify movement from the dune to the backbeach and ignore sediment movement across the beach to the water.

Studies by SO (1982), DINGLER *et al.* (1992), and WAL and MCMANUS (1993) ascribe differences in aeolian erosion and deposition to local sources and sinks within shore-parallel

95136 received 10 June 1994; accepted in revision 12 July 1995.

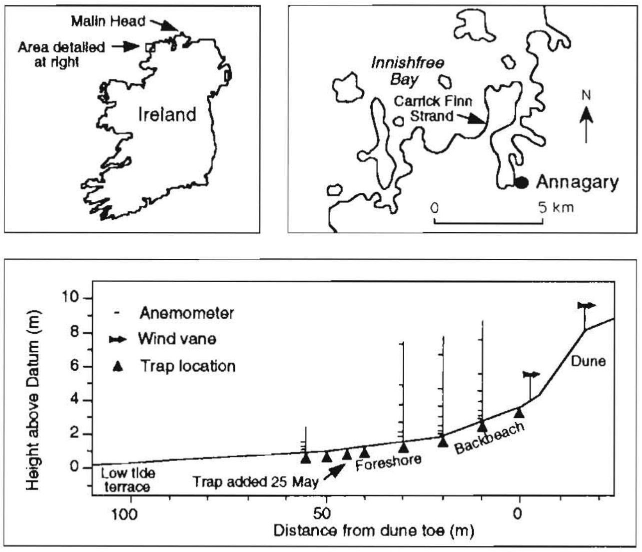

Figure 1. Site location and position of traps and meteorological instruments on sampling line. Topography is from field surveys conducted May 1992.

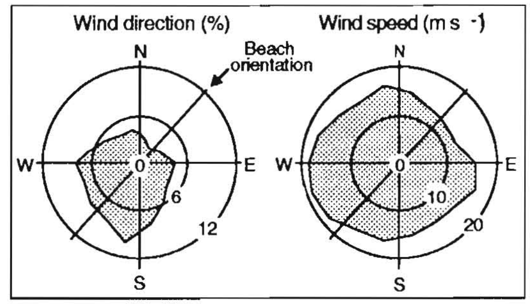

Figure 2. Wind data from Malin Head 1983–1993. Source: Irish Meteorological Office Records.

zone's across the beach. These studies call attention to the need to relate differences in rates of transport to differences in both spatially-varying flow fields and surface conditions (source widths, sediment characteristics, moisture) across beaches. The wind conditions that occurred during our study provide an opportunity to examine these relationships during offshore winds. These data, and results of previous studies are then used to develop a conceptual model of wind speed, sediment transport and surface elevation changes in the lee of a high dune under offshore winds.

Field data were gathered on a sand beach at Carrick Finn Strand, County Donegal, Ireland (Figure 1) during the period 12 to 27 May 1992 as part of the multi-experiment Aeolus Project (SHERMAN *et al.* 1994). The overall objectives of the field study were to examine cross shore variations in wind speed, cross-shore and longshore variations in source width and sediment transport. The cross-shore variations are the focus of this paper, whereas the longshore variations are described in detail in a companion paper by GARES *et al.* (this volume).

STUDY SITE

The study site (Plate 1) is located near the mid point of a beach in Innishfree Bay (Figure 1). Shoreline orientation is 42/222 deg; winds from an azimuth of 132 deg blow directly offshore. At the time of initiation of the study, the beach had a broad, low-tide terrace, a 45 m wide upper foreshore, with a slope of 4.3 deg and a 22 m wide backbeach, with a slope of 5.5 deg. The upper limit of swash just prior to deployment of equipment was only 22 m from the dune toe (about 2.5 m above the elevation of the low tide terrace), but high-water levels were considerably lower during the time sand traps were used to monitor transport. The backbeach near the dune toe was sparsely vegetated and was about 4.0 m above the level of the low tide terrace. The crest of the dune averaged about 6.0 m above the backbeach at the toe. The dune had a dense vegetation cover, consisting principally of *Ammophila arenaria*.

Carrick Finn was selected because it was thought that the strong winds common to this region (Figure 2) would enhance the probability that sand-moving events would occur during the period dedicated to field monitoring. Winds from the southwest to west (obliquely onshore at the field site) blow at the highest speeds, but offshore winds from the south are common and of relatively high speed.

METHODS

Wind speeds were monitored using 23 rotating-cup anemometers. These were placed on three 6-m high masts located on the beach at distances of 10, 20 and 30 m from the toe of the dune and on one portable 1.5-m high mast located 55 m from the toe of the dune, near the high water line. Data on wind direction were collected using 2 wind vanes placed on top of two 1.5-m high masts located between the dune crest and the toe of the dune (Figure 1, Plate 1). The masts located 10 and 20 m from the toe of the dune had anemometers 0.15, 0.3, 0.6, 1.2, 1.8, 2.8 and 4.8 m above the beach surface. The mast located 30 m from the toe of the dune had anemometers 0.3, 0.6, 1.2, 2.2, 3.4 and 5.8 m above the surface. The mast at 55 m had anemometers 0.15, 0.3 and 0.6 m above the surface. Data were sampled at 1.0 Hertz and recorded over 15 min, a common averaging interval using cup anemometers (WOLFE and NICKLING 1993). Data from the wind vanes were used to determine mean wind direction relative to shore normal.

Aeolian transport was measured using vertical cylindrical traps (ROSEN 1979) and V traps (GARES *et al.* this volume). Comparative data from both types of traps are discussed in GARES *et al.* (this volume). Only the data from the cylindrical traps are discussed here because more of these traps were deployed across the shore for a greater number of sampling records. These traps were each 0.4 m high, with a 40 mm wide opening. The advantages and drawbacks associated with vertical traps are discussed in JONES and WILLETTS (1979), ILLENBERGER and RUST (1986) and SHERMAN

Plate 1. Study site during field deployment. Anemometers on the masts with wind vanes in the foreground did not function properly during the experiment.

(1990a). Efficiency of these traps is reported to be 70% (MARSTON 1986). Sampling inefficiencies are related to back pressure and scour. These effects are assumed to have greater significance when relating rates of transport gathered in the field to predicted rates than when comparing relative rates measured by the same means, as is the case in this study.

Offshore wind speeds were sufficiently great to move sediment on 24 and 25 May. Five 15-min sediment-sampling runs were conducted on 24 May; four 15-min sediment-sampling runs were conducted on 25 May. Traps were placed at 10 m intervals across the backbeach along the instrument transect on 24 May, extending seaward from the toe of the dune. An additional trap was placed 55 m seaward of the toe of the dune, just landward of the swash limit during the previous high tide. An eighth trap was placed 45 m seaward of the dune toe on 25 May, at a location where data from the previous day indicated that there was a notable change in rate of trapping. The traps next to the anemometer masts were offset 0.5 m at right angles to the wind direction to avoid interference. The 15-min sampling period for traps was considered long enough to obtain a sample of sufficient size for lab analysis but short enough to minimize effects of scour at the mouth of the traps. Visual estimates revealed that scour depths were <5.0 mm for any sampling run. Traps were oriented toward the direction from which the wind was blowing at the beginning of each sampling run.

Sediment samples, weighing approximately 70–90 g were collected from the top 10 mm of the beach surface on 23 May and placed in air-tight containers. Sampling was carried out across the beach at 5 m intervals from the toe of the dune to the location of the seaward-most trap. Gravimetric moisture content of each sample was determined in the laboratory by subtracting the weight of air-dried samples from the original weight. Settling-velocity distribution of a 5–10 g split of each sample was determined using a settling tube with a diameter of 204 mm and a fall distance of 2.0 m. Arithmetic transformation of settling velocities was carried out using the Chi statistic (MAY 1981). Mean and standard deviation (sorting) of these distributions were determined by the method of moments using a class interval of 0.1. The sedimentation diameter equivalent to the mean was determined using the equation of GIBBS *et al.* (1971). Carbonate content of beach samples collected 23 May and trap samples from 24 May was determined by comparing dry weights of the original samples with weights after treatment with dilute hydrochloric acid. This analysis was done because the proportion of shell fragments varied considerably across the beach.

Topography was measured using a transit and stadia rod placed at representative breaks in slope on the dune, backbeach and low tide terrace as well as at the masts. Changes in beach surface elevations were measured on 25 May using 6.4 mm diameter steel pins, emplaced 0.5 m downwind of all traps at 10:15. Elevations at the pins were measured before the first trap deployment, after the first two deployments, and after the last deployment. Accuracy of readings is estimated at ± 0.5 mm.

RESULTS

Data on surface characteristics gathered 23 May (Figure 3) reveal that the values of several variables increase across the

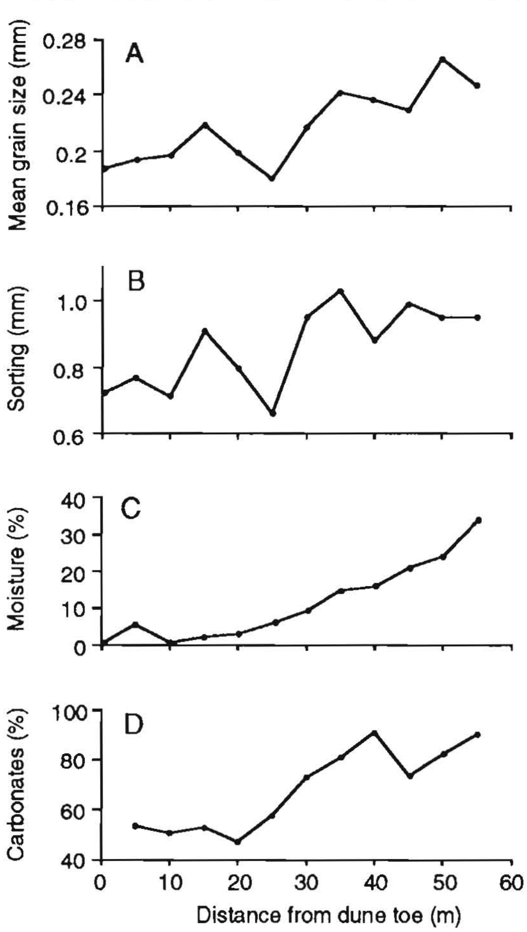

Figure 3. Mean grain size (A), sorting (B) surface moisture (C) and carbonate content (D) of the beach surface sampled 23 May.

beach in the offshore direction, including mean grain size (0.19 mm to 0.27 mm), surface moisture (0.2% to 34.0%) and carbonate content (53.5% to 90.4%). The increase in surface moisture and carbonate content is considerable, beginning near the location of the contact between the backbeach and the foreshore at the beginning of the field deployment (22 m from the toe of the dune). Sediment on the foreshore is more poorly sorted than on the backbeach.

Mean wind direction on the lee slope of the dune, just seaward of the crest, varied from a minimum of 1.5 deg north of shore-normal (almost directly offshore) for the record beginning at 12:45 on 24 May to a maximum of 37.6 deg south of shore-normal for the record beginning at 18:30 on 25 May. Except for the record beginning at 15:15 on 24 May, wind direction was always closer to shore-normal on 24 May than on 25 May.

Wind-velocity profiles across the beach for offshore flows are strongly influenced by the presence of the blocking dune. Figure 4 shows two representative velocity profiles measured 30 m from the foredune toe on 24 and 25 May. The uppermost anemometer is separated from the lower anemometers by an intermediate zone of streamline divergence and ex-

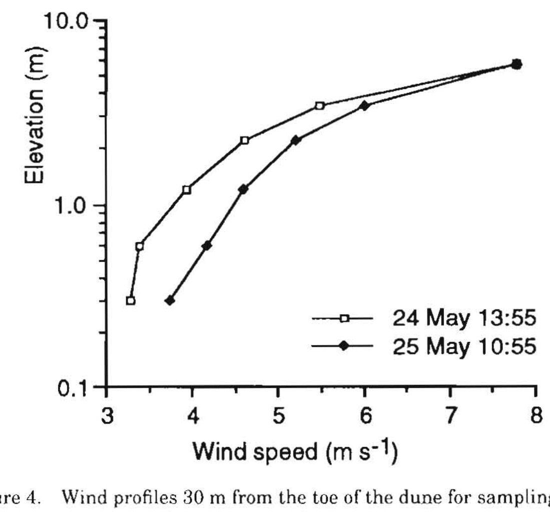

Figure 4. Wind profiles 30 m from the toe of the dune for sampling runs at 13:55 on 24 May and 10:55 on 25 May.

treme shear (between about 1.5 m to 5 m elevation) associated with vigorous downward flux of horizontal momentum. The departure from a log-linear profile is expected on a sloping beach near a dune. The non-logarithmic shapes of the wind-velocity profiles imply that standard regression-based estimates of shear velocity (BAUER *et al.* 1992) using all the anemometers on each mast would yield erroneous results. Using data from the lowest anemometers (0.15 and 0.30 m) to estimate shear velocities yields values that are generally below the threshold for initiation of motion (about 0.2 m s^{-1}) of the finer grain sizes on the beach (about 0.2 mm); the estimated shear velocities actually decrease in the seaward direction on 25 May.

The near-surface flow field in the lee of the dune, revealed in data from the anemometers placed 0.15 m above the surface (Figure 5), increased from small velocities at the toe of the dune to greater velocities farther seaward in response to the momentum transfer coupled to the fast-flowing upper air stream. The slowest winds that caused aeolian transport on the two days occurred during the record of 10:25 on 24 May (Figure 5) when mean speed was 3.2 m s^{-1} at the location 55 m seaward of the dune toe. The plots of wind speeds show an increase with distance from the dune, although at different speeds. The slopes of the plots differ for different wind records because the angle the wind blows, relative to the orientation of the dune, affects the wind-speed gradient in the lee of the dune.

The rates of sand trapped (Figures 6 and 7) generally conform to the increases in wind speed. The rates are small from the toe of the dune to a distance of about 20 m and then increase in the offshore direction. The rates on 24 May decrease on the foreshore at about 40 m early in the day under the slowest winds. Comparison of sampling records begining at 12:45, 13:55 and 16:30 on 24 May indicates higher rates of transport farther out on the beach later in the day for nearly the same wind speeds, implying a change in surface conditions favoring transport. This may be due to drying of the

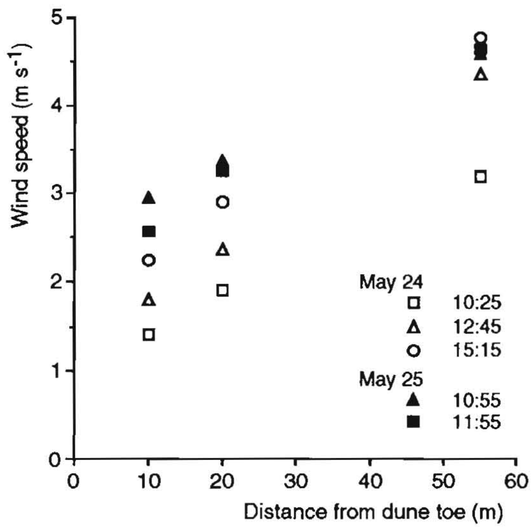

Figure 5. Wind speed at 0.15 m elevation for selected sampling runs on 24 May (open symbols) and 25 May (closed symbols).

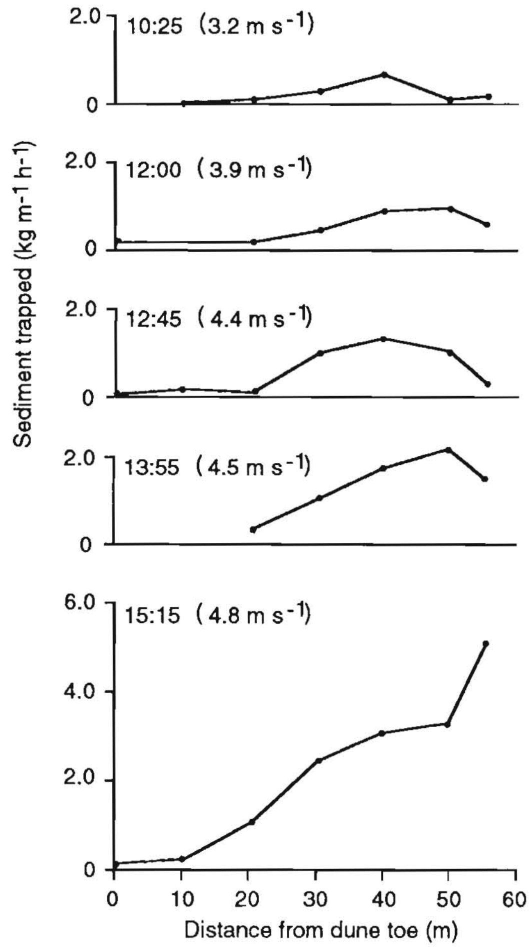

Figure 6. Rates of sediment trapped on 24 May. Time indicates start of 15 min sampling run. Wind speed in parenthesis is the mean value for the anemometer 0.15 m above the beach surface 55 m from the dune toe.

beach surface at that location or the cumulative effect of movement of the more mobile drier sediment populations downwind, where they provide a better source for the traps farther from the dune. Transport rates on 24 May are greatest during the record beginning at 15:15, when wind speeds were relatively high (Figure 5). The departure of wind direction from shore-normal was greater during this sampling period than all others during the experiment, resulting in the greatest source widths for each trap. The width of the source area upwind of the trap 55 m seaward of the dune toe was 86 m at 15:15, in contrast to the 55, 57 and 66 m source widths for the records beginning at 12:45, 13:55 and 16:30 respectively.

Data for the first 2 sampling runs on 25 May (Figure 7) indicate a higher rate of trapping near the toe of the dune than occured on 24 May. Wind speeds were greater close to the dune on 25 May (Figure 5), presumably because of the more oblique angle of wind approach. Light rain occurred periodically after 14:00 on 25 May. The heaviest rain occurred after 16:00; rain ceased about 17:00. Low trapping rates during the period beginning at 18:30 is attributed to both the light rain and lower wind speeds. Wind speeds during the record beginning at 19:55 were the highest of all runs during the experiment. Mean speed at 0.15 m elevation was 3.7 m s^{-1} 10 m seaward of the dune and 5.6 m s^{-1} 55 m seaward of the dune (when mean speed at the 5.8 m high anemometer 30 m from the dune toe was 8.7 m s^{-1}). Rates of trapping are thus relatively high, even at the the trap farthest out on the foreshore. We cannot account for the anomolously low amount of sediment trapped 45 m from the dune toe during the record. It could be due to chance spatial variation in sand transport. Spatial variations in the longshore direction can be about this order of magnitude, as discussed by GARES *et al.* (this volume).

Comparison of sediments in the traps with sediments gathered on the beach on 23 May (Figure 8) reveals higher percentages of carbonates in the fraction moved by winds, implying that the shell hash is more easily transported than the other fractions. The high proportion of carbonates on this beach may partially account for the relatively large transport rates for the wind velocities monitored.

Readings at the pins used to measure changes in surface elevation on 25 May (Figure 9) reveal that scour occurred on the lower backbeach and highest part of the upper foreshore. The seaward portion of the upper foreshore appears to have been a transport surface characterized by little erosion or deposition. Sediment removed from the higher beach appears to have nourished locations downwind of the seaward-most pin.

DISCUSSION

Conventionally, aeolian transport rates are modelled on the basis of shear velocity (e.g. BAGNOLD 1941; HSU 1987), but even under relatively simple field and lab conditions, the

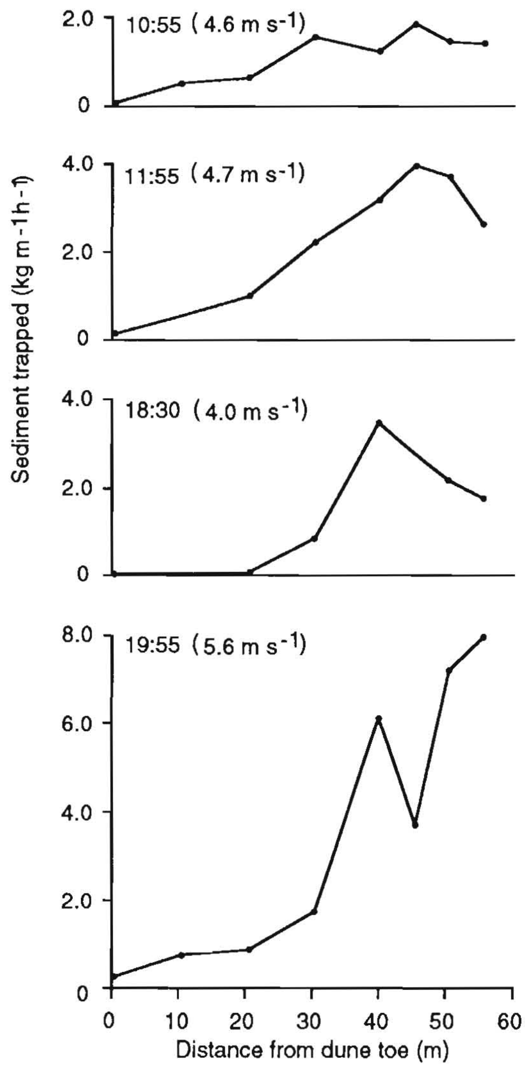

Figure 7. Rates of sediment trapped on 25 May. Time indicates start of 15 min sampling run. Wind speed is for anemometer 0.15 m above the beach surface 55 m from the dune toe.

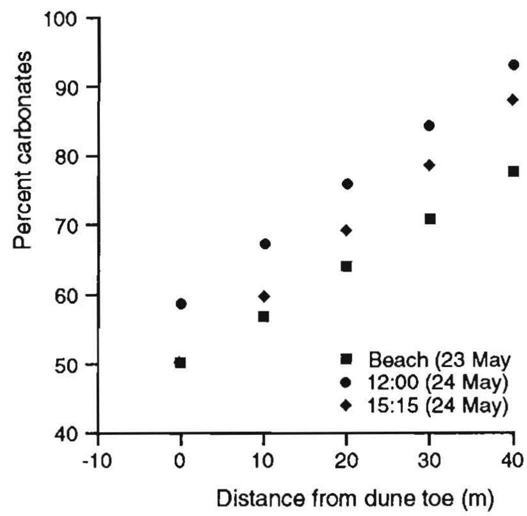

Figure 8. Comparison of relative amount of carbonates in samples from beach traps for representative times on 24 May with samples gathered on the beach at similar distances from the dune toe on 23 May .

relationship between the wind velocity profile, shear velocity and sediment transport can be uncertain (SVASEK and TERWINDT 1974; BAUER *et al.* 1990; WAL and MCMANUS 1993; MCKENNA NEUMAN and NICKLING 1994). The decrease in estimated shear velocities in the seaward direction on 25 May are contrary to measurements of sediment transport on both days (Figures 6 and 7). Estimates of shear velocity using the lowest anemometers are not robust. We conclude that near-surface mean wind speed is a better indicator of transport potential as suggested by LANCASTER (1987) until more is understood about the character of boundary-layer development and shear-velocity distributions in non-uniform flow fields in the lee of dunes.

Transport rate distributions in the cross-shore direction are complicated but explainable in the context of differences in wind speed as affected by beach moisture, sediment sizes, source widths and carbonate content. Transport rate distributions are different through both time and space because of changes in these variables.

Surface moisture decreases the amount of sediment moved for a given wind speed by increasing the shear velocity required to initiate motion and by trapping sediment delivered from upwind sources. Previous investigations indicate that there is a discrepancy in the effects of specific values of moisture content in reducing aeolian transport, especially at high moisture levels (NAMIKAS and SHERMAN, in press). Moisture in the portion of the beach characterized by high percentages of calcium carbonate exceeds the levels for completely-saturated sand reported by SHERMAN (1990b) and is attributed to a greater percentage of pore space within the carbonate fragments (GARES *et al.* this volume; SHERMAN *et al.* 1994). There is no precedent in the literature for quantitative evaluation of the effect of moisture levels this high, but there is no debate that the considerable increases in moisture in the offshore direction (Figure 3) would tend to decrease downwind rates of erosion, contributing to reduced rates of transport (Figures 6 and 7).

The slight increase in mean grain size in the offshore direction would tend to decrease rates of transport downwind during low wind speeds. Slightly poorer sorting (BAGNOLD 1941) and increases in source width would tend to increase rates of transport, as would increases in carbonate content, because shell particles are more likely to be entrained and moved that terrigenous sediments in the same matrix (SARRE 1989). The significance of beach width as a source of sediment for aeolian transport has been observed in several studies examining onshore transport (SVASEK and TERWINDT 1974; BAUER 1991; DAVIDSON-ARNOTT and LAW 1990; NORDSTROM and JACKSON 1992), but the effect of this variable is obscured in studies of offshore transport because both source width and wind speed increase in the offshore direction. The

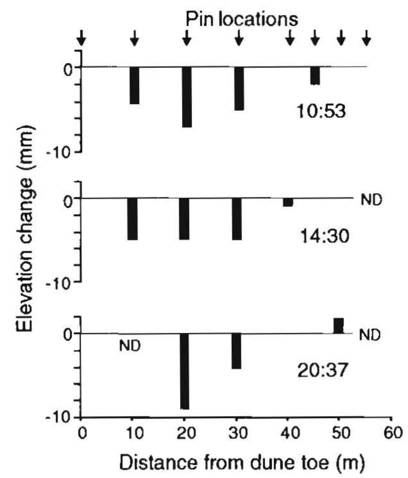

Figure 9. Surface elevation changes measured at erosion pins. Data for each time period represent cumulative change relative to initial surface at 10:15. Lack of a vertical bar at pin represents no change. There are no data 55 m from the toe of the dune after 10:53 (indicated by ND) because the pin was inundated by swash uprush.

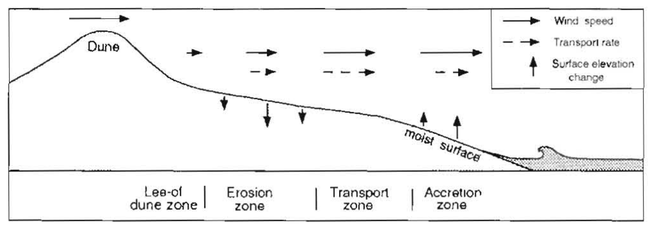

Figure 10. Conceptual model relating wind speed to aeolian transport and surface elevation changes across a beach during offshore winds. The figure ignores the contribution of sand from dune to beach because the prototype dune at Carrick Finn is well vegetated, and wind speeds during the experiment were not high enough to overcome the associated reduction in transport potential.

combined effects of spatial increases in wind speed and source width (along with effects of sediment sorting and carbonate content) appear to overcome the effects of increasing moisture at higher wind speeds, but conditions near the moist foreshore reduce rates of transport during low wind speeds. ARENS (1994) reports a general increase in transport rates with distance offshore of a dune of similar height during offshore winds, with a slight, but conspicuous, reduction in transport rate on moist portions of the beach. WAL and MCMANUS (1993) also show a decrease in rate of sand transport on the beach face near the water due to moist conditions. The increased rates of transport through time on the moister portions of the beach at Carrick Finn Strand (Figure 6) are attributed to drying of surface sediments. The significance of evaporation rate and speed of drying to prediction of aeolian transport is underscored by (HOTTA 1984) and (SHERMAN 1990b).

Data from the pins used to determine changes in surface elevation (Figure 9) indicate that sediment losses through aeolian transport may be compensated by delivery of sediment from upwind sources. The upper beach can be a source of sediments for the lower beach (WAL and MCMANUS 1993; DINGLER *et al.* 1992). Our data also indicate that shore-parallel zones of sources and sinks occur, although we did not monitor surface elevation changes seaward of the last sand trap, so we cannot specify the width of the zone where deposition occurred or quantify deposition at specific locations.

The relatively great height of the dune and the high moisture and carbonate content of the sediments on the beach at Carrick Finn Strand prohibit meaningful comparison of specific values of important variables with those reported in previous studies, but results can be used to develop a conceptual spatial model of offshore transport using relative values of wind speed, sediment transport and elevation changes. This model (Figure 10) shows changes across the beach in the lee of a high dune; wind speeds on coasts where dunes are low or do not exist (AUGUSTINUS *et al.* 1992; DINGLER *et al.* 1992) remain great across the beach, and transport may be limited more by source characteristics than by the transport capacity of the wind.

The Lee-of-Dune Zone (Figure 10) is characterized by dry sediments, but little entrainment occurs when winds are of low or moderate speed because wind speeds are below threshold values. The surface of the backbeach and upper foreshore above the swash limit is also dry. This area is far enough from the dune that wind is effective in entraining sediments. Transport rates may be small here because of limited source widths and relatively low wind speeds, but this is a zone of net sediment loss by deflation during offshore winds because sediment losses are not replaced from upwind sources. Sediments removed from this Erosion Zone replace losses from the beach downwind of it, creating a Transport Zone with little net change. The mid foreshore is a zone of sediment accumulation when moist and when offshore winds are gentle. The Accretion Zone (Figure 10) may be located here early in the day or just after tidal fall, although it may be displaced downwind later in the day due to drying of the beach surface (Figure 6).

High wind speeds overcome restrictions to sediment transport caused by factors such as atmospheric humidity, vegetation and surface moisture (SARRE 1989b; ARENS 1994) and will result in a downwind displacement of the Erosion Zone, Transport Zone and Accretion Zone as well as an increase in rates of transport, erosion and accretion. For example, the upper foreshore can be a zone of transport during increased wind speeds (Figure 7; WAL and MCMANUS 1993), and the Accretion Zone under those conditions may be displaced all the way to the active swash or (at low tide) to the water ponded on the low tide terrace. Data from ARENS (1994) indicate that strong offshore winds increase rates of transport near the dune; this can displace the boundary between the Lee-of Dune Zone and the Erosion Zone upwind.

Long-term wind data for the study area (Figure 2) indicate that offshore winds, particularly southerly winds, can occur with high frequency and speed. The potential for offshore transport is thus greater than indicated by the data gathered for this study, but the net effect of these offshore winds in transporting sand across the beach will be low relative to onshore winds because of the reduction in near-surface flows caused by the high dune. The large amount of offshore transport reported in studies of shorelines where dunes are low or there are gaps in the dunes (ROSEN 1979; MCCLUSKEY *et al.* 1983; DINGLER *et al.* 1992) may not occur in the lee of high dunes, underscoring the role of the dunes in modifying the local sediment budget and increasing the relative geomorphic impact of onshore winds.

CONCLUSIONS

We conclude that, under offshore wind conditions, beaches in the lee of moderate to high dunes are a spatially constrained aeolian transport system with rapid transitions in wind speed, sediment characteristics and moisture conditions. Results of this study support results of previous experiments that indicate that offshore transport by aeolian processes is affected by spatial compartmentation in shore-parallel zones. Our results show how the boundaries of the zones can change under short time scales, but the complexity of wind flow, temporal differences in surface characteristics and the simultaneous effect of several variables influencing aeolian transport in the offshore direction prevent specification of the contribution of each factor.

ACKNOWLEDGEMENTS

Support for this project was provided by the National Geographic Society (P.A. Gares, Principal Investigator) and the North Atlantic Treaty Organization (D.J. Sherman, Principal Investigator). We are grateful to Julian Orford and Nuno Gomes for assistance in the field. The project is part of the Aeolus Program. This is Contribution Number 94-22 of the Rutgers University Institute of Marine and Coastal Sciences.

LITERATURE CITED

ARENS, S.M., 1994. *Aeolian Processes in the Dutch Foredunes.* Academisch Proefschrift University of Amsterdam.

AUGUSTINUS, P.G.E.F., LAEVEN, M.P., RUWE, J. and DEVRIES, J.B., 1990. Dune formation and dune degradation in the Camargue, France. *Littoral 1990.* Association EUROCOAST, pp. 115–119.

BAGNOLD, R.A., 1941. *The Physics of Blown Sand and Desert Dunes.* London: Methuen.

BAUER, B.O., 1991. Aeolian decoupling of beach sediments. *Annals of the Association of American Geographers.* 81, 290–303.

BAUER, B.O., SHERMAN, D.J., NORDSTROM, K.F. and GARES, P.A., 1990. Aeolian transport measurement and prediction across a beach and dune at Castroville California. *In:* NORDSTROM, K.F., PSUTY, N.P., and CARTER, R.W.G. (editors), *Coastal Dunes: Form and Process.* Chichester: Wiley, pp. 39–55.

BAUER, B.O., SHERMAN, D.J. and WOLCOTT, J.F., 1992. Sources of uncertainty in shear stress and roughness length estimates derived from velocity profiles. *Professional Geographer.* 44, 453–464.

BAUER, B.O., DAVIDSON-ARNOTT, NORDSTROM, K.F., OLLERHEAD, J. and JACKSON, N.L., Indeterminacy in aeolian sediment transport across beaches. *Journal of Coastal Research.* this volume.

DAVIDSON-ARNOTT, R.G.D. and LAW, M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. *In:* NORDSTROM, K.F., PSUTY, N.P., AND CARTER, R.W.G. (editors), *Coastal Dunes: Form and Process.* Chichester: Wiley, pp. 177–200.

DINGLER, J.R., HSU, S.A. and REISS, T.E., 1992. Theoretical and measured aeolian sand trasport on a barrier island, Louisiana, USA. *Sedimentology.* 39, 1031–1043.

GARES, P.A., 1990. Eolian processes and dune changes at developed and undeveloped sites, Island Beach, New Jersey. *In:* NORDSTROM, K.F., PSUTY, N.P., and CARTER, R.W.G. (editors), *Coastal Dunes: Form and Process.* Chichester: Wiley, pp. 361–380.

GARES, P.A., 1992. Topographic changes associated with coastal dune blowouts at Island Beach State Park, New Jersey. *Earth Surface Processes and Landforms,* 17: 589–604.

GARES, P.A., NORDSTROM, K.F., SHERMAN, D.J., BAUER, B.O., DAVIDSON-ARNOTT, R.G.D., CARTER, R.W.G., JACKSON, D. and GOMES, N., 1993. Aeolian sediment transport under offshore wind conditions: implications for aeolian sediment budget calculations. *In:* HILDEBRAND, L.P. (editor) *Coastlines of Canada.* New York: American Society of Civil Engineers, pp. 59–72.

GARES, P.A., DAVIDSON-ARNOTT, R.G.D., BAUER, B.O., SHERMAN, D.J., CARTER, R.W.G., JACKSON, D. and NORDSTROM, K.F., 1994. Longshore variations in aeolian sediment transport, sediment size and moisture at Carrick Finn Strand, Republic of Ireland. *Journal of Coastal Research.* this volume.

GIBBS, R.J., MATTHEWS, M.D. and LINK, D.A., 1971. The relationship between shear size and settling velocity. *Journal of Sedimentary Petrology,* 41, 7–18.

GOLDSMITH, V., ROSEN, P. and GERTNER, Y., 1990. Eolian transport measurements, winds, and comparison with theoretical transport in Israeli coastal dunes. *In:* NORDSTROM, K.F., PSUTY, N.P., AND CARTER, R.W.G. (editors), *Coastal Dunes: Form and Process.* Chichester: Wiley, pp. 79–101.

GUTMAN, A., 1978. The interaction of eolian sand transport, vegetation, and dune geomorphology, Currituck Spit, Virginia-North Carolina. Unpublished M.A. Thesis. Williamsburg, VA: College of William and Mary.

HENNIGAR, H.F., 1979. Historical evolution of coastal sand dunes on Currituck Spit Virginia/North Carolina. Unpublished M.A. Thesis. Williamsburg, VA: College of William and Mary.

HOTTA, S., 1984. Wind blown sand on beaches. Unpublished Ph.D. thesis, University of Tokyo.

HSU, S.A., 1987. Structure of airflow over sand dunes and its effect on eolian sand transport in coastal regions. *Coastal Sediments 87.* New York: American Society of Civil Engineers, pp. 188–201.

HUNTER, R., RICHMOND, B. and ALPHA, T., 1983. Storm-controlled oblique dunes of the Oregon coast. *Bulletin of the Geological Society of America,* 94, 1450–1465.

ILLENBERGER, W.K. and RUST, I.C., 1986. Venturi-compensated eolian sand trap for field use. *Journal of Sedimentary Petrology,* 56, 541–543.

JONES, J.R. and WILLETTS, B.B., 1979. Erosion in measuring uniform aeolian sand flow by means of an adjustable trap. *Sedimentology,* 26, 463–468.

LANCASTER, N., 1987. Reply. *Sedimentology.* 34, 516–520.

MARSTON, R.A., 1986. Maneuver-caused wind erosion impacts, south central New Mexico. *In:* NICKLING, W.G. (editor) *Aeolian Geomorphology,* Boston: Allen and Unwin, pp. 273–290.

MAY, J.P., 1981. CHI(x): a proposed standard parameter for settling tube analysis of sediments. *Journal of Sedimentary Petrology,* 51, 607–610.

MCCLUSKEY, J.M., NORDSTROM, K.F. and ROSEN, P.S., 1983. An Eolian Sediment Budget for the South Shore of Long Island. Rutgers University Center for Coastal and Environmental Studies/ National Park Service Cooperative Research Unit Technical Report , New Brunswick, NJ.

MCKENNA NEUMAN, C. and NICKLING, W.G. 1994. Momentum extraction with saltation: implications for experimental evaluation of wind profile parameters. *Boundary Layer Meteorology,* 68, 35–50.

MCLACHLAN, A., and BURNS, M., 1992. Headland bypass dunes on the South African coast: 100 years of (mis)management. *In:* CARTER, R.W.G., CURTIS, T.G.F., and SHEEHEY-SKEFFINGTON, M.J. (eds.), *Coastal Dunes: Geomorphology, Ecology and Management for Conservation.* Balkema: Rotterdam, pp. 71–79.

NAMIKAS, S.L. and SHERMAN, D.J., in press. A review of the effects of surface moisture content on aeolian sand transport. *In:* TCHAKARIAN, V. (ed.), *Desert Aeolian Processes.* Chapman Hall.

NORDSTROM, K.F and JACKSON, N.L., 1992. Effect of source width and tidal elevation changes on aeolian transport on an estuarine beach. *Sedimentology,* 39, 769–778.

NORDSTROM, K.F., MCCLUSKEY, J.M. and ROSEN, P.S., 1986. Aeolian processes and dune characteristics of a developed shoreline: Westhampton Beach, New York. *In:* NICKLING, W.G. (editor) *Aeolian Geomorphology,* Boston: Allen and Unwin, pp. 131–147.

ROSEN, P.S., 1979. Eolian dynamics of a barrier island system. *In:* LEATHERMAN, S.P. (editor), *Barrier Islands,* Academic, New York, pp. 81–98.

SARRE, R., 1989a. Aeolian sand drift from the intertidal zone on a temperate beach: potential and actual rates, *Earth Surface Processes and Landforms,* 14, 247–258.

SARRE, R., 1989b. The morphological significance of vegetation and relief on coastal foredune processes *Zeitschrift für Geomorphologie,* Supplement-Band 73, pp 17–31.

SHERMAN, D.J., 1990a. A method for measuring aeolian sediment transport rates. *In:* DAVIDSON-ARNOTT, R.G.D. (editor), *Proceedings of the Symposium on Coastal Sand Dunes.* Ottawa, National Research Council Canada, pp. 37–47.

SHERMAN, D.J., 1990b. Evaluation of aeolian sand transport equations using intertidal-zone measurements, Saunton Sands, England. *Sedimentology,* 37, 385–388.

SHERMAN, D.J., BAUER, B.O., CARTER, R.W.G., JACKSON, D., MCCLOSKY, J., DAVIDSON-ARNOTT, R.G.D., GARES, P.A., JACKSON, N.L., and NORDSTROM, K.F. 1994. The Aeolus Project: measuring coastal wind and sediment systems. *Coastal Dynamics 94.* New York: American Society of Civil Engineers, in press.

SO, C.L., 1982. Wind-induced movement of beach sand at Portsea, Victoria. *Proceedings of the Royal Society of Victoria,* 94, 61–68.

SVASEK, J.N. and TERWINDT, J.H.J., 1974. Measurements of sand transport by wind on a natural beach. *Sedimentology,* 21, 311–322.

TAYLOR, R.B. and FROBEL, D., 1990. Approaches and results of a coastal dune restoration program on Sable Island, Nova Scotia. *In:* DAVIDSON-ARNOTT, R.G.D. (editor), *Proceedings of the Symposium on Coastal Dunes,* Ottawa: National Research Council, pp. 405–431.

WAL, A and MCMANUS, J., 1993. Wind regime and sand transport on a coastal beach-dune complex, Tentsmuir, eastern Scotland. *In:* PYE, K. (editor), *The Dynamics and Environmental Context of Aeolian Sedimentary Systems.* London: The Geological Society, pp. 159–171.

WOLFE, S.A. and NICKLING, W.G., 1993. The protective role of sparse vegetation in wind erosion. *Progress in Physical Geography,* 17, 50–68.