Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events

Irene Delgado-Fernandez, Robin Davidson-Arnott
Department of Geography, University of Guelph, Guelph, ON, Canada

Abstract

Observations of aeolian transport in coastal areas have focused on short-term experiments because of limitations imposed by instrumentation. This paper uses a case study at Greenwich Dunes, Prince Edward Island National Park, Canada, to analyze how sediment transport takes place at the beach over periods of weeks to months. A monitoring station provided hourly time series of vegetation cover, shoreline position, fetch distances, surficial moisture content, presence of ice and snow, wind speed and direction and transport processes over nine months. Analysis shows that high wind speeds may not generate any net transport into the dunes because of the limitations imposed by snow/ice cover, moisture, and short fetch distances. Despite extreme winds during intense storms, such events often lead to wave scarping rather than aeolian sediment input to the foredunes. When sediment was transported on the beach, the magnitude was regulated by a combination of factors including: angle of wind approach, fetch distance, moisture content, and duration of the wind event. In particular, angle of wind approach (and therefore fetch distance) may demote a high magnitude wind event with strong transport potential to one with no transport at all, which poses challenges for predicting the effects of individual storms over the course of several months. A significant proportion of sediment delivery to the foredunes was associated with wind events of low to medium magnitude. It is suggested here that large magnitude wind events have low probabilities of resulting in transport towards the foredune because factors such as wave inundation play an increasing role in preventing sediment movement across the beach. This has implications for modelling and management, and highlights differences between the magnitude and frequency of aeolian transport events in the coastal environment compared to those in deserts and to fluvial sediment transport.

Keywords

Meso-scale; Event frequency; Event magnitude; Foredune budget

1. Introduction

As in many other landscapes, coastal dunes evolve as a consequence of both gradual changes in state variables (e.g., vegetation growth or decay) as well as episodic event-based disturbances (e.g., wave scarping) (Pye, 1983 and Psuty, 2005). In particular, sediment input by wind from the beach to the adjacent foredunes is intermittent both at the instantaneous (Stout and Zobeck, 1997) and medium scales (Delgado-Fernandez and Davidson-Arnott, 2009). Knowledge of sand transport by wind is essential for sediment budget calculations because it produces an output of sediment from the beach and constitutes the primary source of sediment supply for building the dune (Svasek and Terwindt, 1974 and Davidson-Arnott et al., 2005). Therefore, understanding the characteristics of aeolian transport events in coastal areas is necessary to predict the evolution of coastal dunes.

The role of transport events and their relation to morphological change has been widely recognized in geomorphology (Higgitt and Lee, 2001). In general terms, magnitude and frequency of events are inversely related. Stronger river flows, for example, which have the potential to carry large sediment loads, tend to occur less frequently. Thus, the significance of high magnitude events in terms of the proportion of ‘geomorphic work’ accomplished may be quite small in comparison to events of intermediate magnitude and frequency that are thought to dominate the fluvial landscape (Wolman and Miller, 1960).

Knowledge about the characteristics of aeolian transport events contributing to the long-term evolution of coastal dunes is surprisingly limited. Time series of sediment transport for river flows are available from a variety of monitoring stations world-wide over long periods of time, but there are no equivalent records for aeolian transport in coastal areas. This poses several challenges for coastal aeolian geomorphology. First, the lack of sediment transport time series at the same time resolution and duration as wind records makes it difficult to assess the relative significance of wind events of different magnitude. Prediction of sediment supply to the foredunes is often based on hourly data of wind speed and direction from meteorological stations along the coast that are incorporated into one of many alternative sediment transport models that presume ideal conditions on the beach (e.g., Chapman, 1990 and Miot da Silva and Hesp, 2010). Sediment transport calculations at meso-scales typically assume a correspondence between applied stress (wind speed) and sediment transport rate, and this may be modified by the cosine of the angle of wind approach in order to account for sediment supply to the foredune per unit distance alongshore (Davidson-Arnott and Law, 1996 and Bauer and Davidson-Arnott, 2003). Second, there is a spectrum of problems associated with ‘up scaling’ results from short-term experiments. The goal of many fieldwork studies is to observe significant events where landform units are modified and forces affecting their evolution can be measured and quantified. But even when a number of geomorphic processes are characterized in detail over the course of a short-term experiment, traditional experimental designs produce knowledge based on ‘snapshots’, and thus miss the transition from one scale to another (Coulthard, 2009). This lack of a comprehensive view on the dynamics of aeolian sediment transport, beyond the duration of short-term experiments, is a major limitation to providing managers and planners with an appropriate set of tools for decision-making (Sherman, 1995).

The recent incorporation of remote sensing techniques to measure aeolian processes at the beach over long periods of time (months to years) has enabled the direct observation of transport rather than relying on inference derived from morphological evidence (e.g.,Lynch et al., 2008 and Delgado-Fernandez et al., 2009). The importance of this type of approach is that it allows matching time series of wind speed and direction with observations and measurements of sediment transport on the beach at the same time-scale.

The main objective of this paper is to characterize the magnitude and frequency of aeolian transport events on the beach and to assess their role in supplying sediment for foredune building using a data set collected with a remote sensing station at Greenwich Dunes, Prince Edward Island National Park (Canada). The questions addressed here are: 1. how do the frequency and magnitude of transport events compare with the frequency and magnitude of the associated wind events?; and 2. what is the effect of limiting factors such as moisture, fetch, snow and ice, and angle of wind approach? If the presence of other variables weakens the relationship between applied stress (wind) and the rate of sand transport, and if this can be generalized to most beach–dune systems, then the conceptual ideas put forward by Wolman and Miller (1960) may need to be adapted to the particular case of aeolian transport in coastal areas. Information about the characteristics of transport events identified in the time series described here can provide a means of enhancing our ability to model meso-scale sand supply to the foredune.

The first part of this paper deals with the characterization of the magnitude and frequency of wind events or, in other words, with the nature of the applied stress at Greenwich. The second part examines the characteristics of the corresponding transport events over the study period.

2. Regional setting

Long-term monitoring of the beach and foredune was carried out at Greenwich Dunes (Fig. 1A), located on the north shore of Prince Edward Island (PEI), Canada. The measurements presented in this paper cover a section of the coast of approximately 1.5 km in length. The foredune ranges in height from 6 to 10 m with a steep stoss slope of 20–25° and the dune crest is aligned roughly east–west. The beach is 30–40 m wide and consists predominantly of quartz sand with a mean grain diameter of 0.26 mm. Marram grass (Amophila breviligulata) covers the foredunes and exhibits considerable seasonal patterns of height and density. Summer months are usually characterized by the development of a vegetated embryo dune which is removed or strongly eroded every two or three years during Fall and Winter storms. Monitoring of 9 profiles spaced along the 6 km-long shoreline of Greenwich Dunes from 2002 to 2009 showed an average net deposition of sand in the foredune of approximately 3500 kg m^{-1} $year^{-1}$ with most deposition taking place during the Fall and early Winter period and very little deposition occurring during the summer months from June to August. Spatially, net deposition was consistently lowest along the eastern end of the shoreline (≈ 1250 kg m^{-1} $year^{-1}$) and highest near the centre (≈ 6700 kg m^{-1} $year^{-1}$). At the study site (white box in Fig. 1B) net deposition rates were close to the average for the whole shoreline. Fig. 1C and D displays net annual changes in deposition measured using a modified bedframe device (Davidson-Arnott and Law, 1990 and Ollerhead et al., 2003) and morphological changes surveyed with DGPS over a profile located within the study site (line W in Fig. 2). During the winters of 2004 and 2008 intense storms resulted in erosion of the embryo dunes and cliffing of the foredune (≈−800 and − 6150 kg m^{-1} $year^{-1}$ respectively). Annual net deposition during the rest of the years was approximately 5111 kg m^{-1}, with a maximum in 2006 (≈ 9700 kg m^{-1}) and a minimum in 2003 (≈ 1280 kg m^{-1}). Net deposition from September 2007 to May 2008 was ≈ 3017 kg m^{-1}. Thus the study site is representative of medium volumetric changes both spatially and temporally and the period of observations presented in this paper is a year of average deposition and storm events.

The coast is microtidal with a mixed semidiurnal regime and a maximum range at spring tides of approximately 1 m. Precipitation at PEI is abundant year-round. Annual average totals are approximately 1000 mm, with peaks from October to January due to the more frequent and more intense storm activity. Wet days number 130 to 160 a year, with snow days accounting for 30% of them. Ice covers much of the Gulf of Saint Lawrence from January to early April, reducing the marine influence and strongly affecting temperatures in PEI which may fall below − 18 °C. Drift ice is often found around the Island as late as May and is subject to rapid movement as a result of changing wind conditions (Environment Canada and Atlantic Climate Center). During the 2007–2008 Winter the cameras at Greenwich recorded the dynamics of sea ice, showing several periods of clearing from the nearshore during offshore winds (sometimes in less than 24 h) and corresponding rapid build-up during periods of onshore winds.

Prevailing winds from the SW and W occur predominantly in summer. These offshore to alongshore winds are generally not competent to transport sediment to the foredune despite their higher frequency (Walker et al., 2006). Fall and Winter months are characterized by intense mid-latitude storms accompanied by strong winds from the NE to the NW. Powerful North Atlantic storms with winds > 100 km h^{-1} have the potential to deliver large volumes of sediment to the dune but they may also be accompanied by heavy rain or snowfall and storm surge. Further information regarding the study site may be found in Walker et al., 2003, Hesp et al., 2005, Davidson-Arnott et al., 2008 and Bauer et al., 2009.

3. Material and methods

3.1. Instrumentation, data collection and processing

The long-term monitoring station at Greenwich permits the acquisition of continuous records of wind and beach characteristics that can be coupled with sand transport measurements over periods of months. The experimental set up is described in detail inDelgado-Fernandez et al. (2009) and only a brief description is given here. Three 8-megapixel digital cameras were mounted on the top of a 6 m-high mast on the crest of the 8 m foredune (Fig. 2A). The cameras were controlled by a Mumford Time Machine™ programmed to take pictures every hour on a continuous basis, with the pictures stored on an internal memory card and downloaded every 2–3 months. The camera looking to the east provided qualitative data on the overall beach, weather and wave conditions over a distance of approximately 1.5 km alongshore.

The offshore- and west-facing cameras covered distances of 40 m and 100 m alongshore, respectively. Wind speed and direction were measured using a Windsonic 2-D sonic anemometer mounted at the top of the mast at a height of approximately 14 m above the beach surface. The wind was sampled at 1 Hz on a HOBO Energy Pro data logger with average values being stored every 2 min.

Sediment transport and deposition were measured using several different techniques. Two Safire saltation probes which measure the impact of saltating sand grains on a piezoelectric sensor (Baas, 2004) were deployed at foredune toe and at the seaward edge of the embryo dune (Fig. 2B). Output from the Safires was measured at 1 Hz and the average value stored every 2 min. The height of the Safires above the bed was initially set at 5 cm above the bed and was reset during site visits approximately every two months. The sensors were sometimes buried by sand for periods of time and the most seaward one was destroyed by the movement of a large log along the beach during a storm on December 12, 2008 and was replaced on February 20, 2009. Because of their deployment within the field of view of the cameras, the continuity and quality of Safire records could be assessed from the RGB images, which permitted the identification of times when the piezoelectric sensor was buried as well as the height of the sensing area above the sand surface when it was exposed.

Four erosion–deposition (ED) pins were deployed within the field of view of the cameras (Fig. 2B). The ED pins consisted of wooden rods marked at 2 cm intervals driven vertically into the sand surface. Changes in the level of the sand against the rod could be measured with an accuracy of 1 cm on the hourly photographs to give a profile of net change in the sand surface elevation. The volume of sediment deposition along two survey lines across the stoss slope and toe of the foredune was measured every two to three months using a bedframe (Davidson-Arnott and Law, 1990 and Ollerhead et al., 2003). A series of wooden posts were augered into the sand along the profile and levelled forming permanent stations spaced 3–5 m apart. Measurements of the distance to the bed at 12 points within a 1 m × 1 m square were made using a portable bedframe device consisting of an aluminum frame with tabs to locate the measurement points. The bedframe has a square sleeve which allows it to be slotted exactly over the 0.1 m × 0.1 m top of the post and thus permits repeated measurements at each station with a high degree of accuracy. The bedframe is moved from station to station and stored away from the line. Net erosion or deposition at a particular station is determined by averaging the measurements made at the 12 points within the frame.

The images from the north and west cameras were rectified (Fig. 2B) based on a model developed using 40–50 ground control points which were surveyed using a Differential Global Position System (DGPS). The rectified images were then used to derive information on beach surface moisture, snow and ice cover, vegetation cover and the location of the shoreline. Maps of moisture content of the beach sand surface (Fig. 2C) were derived from surface brightness recorded in the photographs using a transfer function derived from in situ correlation between pixel brightness and measurements of surface moisture (McKenna Neuman and Langston, 2006, Darke and McKenna Neuman, 2008 and Darke et al., 2009). Surface brightness measurements were normalized against the brightness of whiteboard located within the field of view of the cameras in order to account for changes in sun angle and cloud cover (Delgado-Fernandez et al., 2009).

Vegetation was extracted from each image using an Unsupervised Classification available as part of the Analysis extension from Leica Systems, which isolated pixels where vegetation was present. The 3D Analyst Tools was used to reclassify the output into NoData values for all classes except the ones containing vegetation. The shoreline was digitized manually for each photograph. Beach width was obtained hourly from the position of the shoreline and the vegetation line. Storm surge, high water levels, or spring tides (often in combination) strongly reduced beach width, which also varied due to seasonal changes in the extent of embryo dune vegetation. Beach width and mean angle of wind approach for a given hour were used to calculate maximum fetch distances (Bauer and Davidson-Arnott, 2003).

Data were processed using a combination of ArcGIS 9.2, PCI Geomatica 9.1 and Excel. A Geodatabase (PEI GDB) built with ArcCatalog was developed to store and manage time series, following the guidelines suggested by Arctur and Zeiler (2004). Seven thematic layers were identified early in the design of the PEI GDB. Each thematic layer is a collection of geographic elements. This partition of geographic information into logical information layers is a key feature for map overlay and data analysis in geographical information systems (GIS) projects. The temporal resolution and spatial representation of the measurements collected for this study are summarized in Table 1. The advantage of the PEI GDB is that it allowed different types of analysis, such as selecting particular time series or showing the evolution of different variables. For the purpose of the analysis presented here, time series were grouped into broad but descriptive categories so events could be classified according to their general characteristics. For example, note that wind measurements were stored with their original temporal resolution (2 min) in the PEI GDB but were averaged to obtain hourly mean values for the purpose of the analysis presented here (Section 3.2). The results presented in this paper cover nine months of data collection from September 2007 to May 2008.

Table 1. Time series of factors stored in the PEI GDB.

RAW data	Used for	Temporal resolution	Spatial representation	Thematic layer
RGB images	Rectified images	1 h	Raster	Surface characteristics
	Moisture maps	1 h	Raster	
	Snow–ice cover	1 h	Tabular data	
	Shoreline position	1 h	Vector	Beach boundaries
	Vegetation cover	1 h	Raster	
	Transport intensity(qualitative)	2 h	Tabular data	Transport measurements
ED pins	Erosion/deposition processes	1 h	Tabular data	
Safires	Transport Intensity	2 min	Tabular data	
Beframe posts	Net deposition	2 months	Tabular data	
2D sonic	Wind speed	2 min	Tabular data	Wind measurements
	Wind direction	2 min	Tabular data	

3.2. Analysis of wind and transport events

A key element of the analysis presented here is the distinction between wind events and transport events. A wind event is defined as a period of time when wind speeds exceed a pre-defined threshold and thus the potential exists for aeolian sediment transport to occur (Section 3.2.1). A transport event is defined as a wind event during which sediment transport on the beach is measured and/or observed in photographs taken by the cameras (Section 3.2.2).

3.2.1. Wind events

The threshold wind speed used to define a wind event was chosen so as to isolate those periods when there was the potential for sediment transport to occur, based on wind speed alone, and to ignore the rest of the record when it was unlikely that transport would occur. Previous experiments by Delgado-Fernandez and Davidson-

Arnott (2009) at Greenwich suggested the use of 6 m s^{-1} as a threshold value. The minimum duration for a wind event to be considered relevant to transport was at least 2 h over the threshold of movement. A summary of the analysis carried out to determine the threshold wind speed and the minimum duration of wind event is given in the appendix.

Events were initially grouped into 7 classes based on the mean wind speed, following a classification adapted from the Beaufort scale (Table 2). The first class, light breeze, contained all winds below the threshold while the remaining six classes ranged from moderate breeze (6–8 m s^{-1}) to fresh gale with winds > 16 m s^{-1}. Several statistics were calculated for every wind event, such as event duration, mean angle of wind approach and range of wind directions.

Table 2. Wind classification used to group events based on the mean wind speed. Note that the Beaufort scale goes up to 12 (hurricanes have wind speeds > 33 m s^{-1}).

Beaufort			PEI classification	
Group	Speed (m s^{-1})	International description	Speed (m s^{-1})	Description
0	0.3	Calm	< 6	Light breeze
1	0.3–1.5	Light air		
2	1.5–3.3	Light breeze		
3	3.3–5.5	Gentle breeze		
4	5.5–8	Moderate breeze	6–8	Moderate breeze
5	8–11	Fresh breeze	8–10	Fresh breeze
6	11–14	Strong breeze	10–12	Strong breeze
			12–14	Very strong breeze
7	14–17	Moderate gale	14–16	Gale
8	17–20	Fresh gale	> 16	Fresh gale

The magnitude of wind events was assessed through calculation of the potential sediment transport using hourly records of mean wind speed and the duration of the wind event. In effect, this provides a measure of the potential sediment transport assuming transport-limited conditions and is thus the starting point for prediction of sediment supply to the foredune. The relationship proposed by Hsu (1974) was adopted because of its simplicity and easy application using hourly wind speed rather than bed shear velocity (U*):

$$q=1.16\times^{10-5}\cdot U^{3} \qquad \text{equation (1)}$$

where U is the mean wind speed in m s^{-1} and q is the instantaneous transport rate in kg m^{-1} s^{-1}. The value of q represents the potential of wind to transport sediment in the direction of the wind vector. In order to obtain a magnitude based on the potential of wind to deliver sediment towards the foredune, q was modified by the angle of wind approach (α) relative to shore normal (Davidson-Arnott and Law, 1996 and Bauer and Davidson-Arnott, 2003):

$$q_n=q\cdot\cos\propto \qquad \text{equation (2)}$$

where qn represents the potential transport into the foredune per unit alongshore distance (kg m^{-1} s^{-1}). Total sediment transport for a wind event (Q) can thus be predicted by summing the potential transport for each hour:

$$Q=\sum_{i=1}^{N} q_i \cdot 3600 \qquad \text{equation (3)}$$

where qi is the predicted instantaneous sediment transport rate for hour i and N is the total number of hours in the event. As is the case for instantaneous transport, the proportion directed towards the foredune (Qn) may be calculated as:

$$Q = \sum_{i=1}^{N} q_i \cdot \cos \propto \cdot 3600 \qquad \text{equation (4)}$$

Wind events were grouped into five classes ranging from very small to very large potential transport based on the criteria outlined in Table 3 for both Q and Qn. It is worth noting that the absolute value for sediment transport predicted by Eq. (1) depends in part on the constant which Hsu developed for the beaches he worked on. According toSherman et al. (1998), Hsu's equation calculates transport rates close to those predicted by Bagnold's (1941) equation which are in the middle range respect to other equations commonly used in aeolian geomorphology. Furthermore, the focus of this study was on the relative magnitude of predicted transport which is controlled primarily by U^3 and the duration of the event. Most models use a cubic relationship between sediment transport rate and wind speed or shear velocity, and in this regard, the approach was consistent with normal practice.

Table 3. Classification used to group events of different magnitudes based on the potential to transport sediment in the direction of the wind vector (Q) or towards the dune (Qn).

Q or Qn (10^2 kg m^{-1})	Magnitude
< 3	Very small
3–9	Small

Q or Qn (10^2 kg m^{-1})	Magnitude
9–27	Medium
27–81	Large
> 81	Very large

3.2.2. Transport events

Measuring sediment transport rates is a challenging task at the meso-scale. Instrumentation needs to be deployed at the beach and left unattended over long periods of time. There are a number of shortcomings associated with different types of deployment, such as instrument failure or periods of low quality data (e.g., ED pins may be removed by waves or Safires buried by sediment accumulation). However, until alternative ways of measuring actual transport rates at the beach over the time frame of months are developed, available instrumentation designed for short-term experiments needed to be adapted. The approach at Greenwich to overcome these adversities consisted of combining the techniques described in Section 3.1 (Table 1): (1) Direct measurement of saltation intensity using Safires permanently deployed at the back beach and embryo dune; (2) Indirect measurement of saltation intensity using RGB image interpretation. Two consecutive snapshots were necessary to observe sediment movement at the beach, shown by the migration of bedforms or dry sand patches. For each event, information was extracted from the offshore-, west-, and east-facing cameras, and compared amongst each other; (3) measurement of erosion or deposition at a point on an hourly basis using the ED pins; and (4) measurement of deposition in the embryo dune/foredune every 2 months along two survey lines using the bedframe technique.

In order to integrate this diverse information a qualitative scale was developed, based primarily on the hourly photographic record, describing the intensity of transport at the beach (Table 4). This classified transport into 6 codes ranging from 0 for no transport observed or measured, to 5 with large quantities of sand being transported across the entire beach. Events were associated with a transport code that reflected the peak of transport intensity (in any direction) observed during the event, together with the number of hours when transport was observed. In order to obtain a qualitative approximation of how much sand was moved towards the foredune, the transport code identified in Table 3was modified by cos α to produce a $code_n$ which is equivalent to q_n predicted by Eq. (2). Thus for example, a code 4 condition with strong transport on the beach could be reduced to a $code_n$ 1 for highly oblique winds.

Table 4. Criteria used to classify transport events into different classes of transport intensity.

Transport code	Description
0 — No transport	
1 — Trace	Small gusts generating some traces of transport. Safires may or may not record transport, ED pins show no change. Subtle movement, just over threshold.
2 — Isolated	Visible streamers limited to a small portion of the beach, generally close to the shoreline. Small intensity transport, highly intermittent in Safires.
3 — Medium	Medium intensity transport. Streamers generalized to more than one section of the beach. May be some bedform migration of a few centimetres. ED pins may record small changes.
4 — Strong	Streamers generalized over entire beach. Visible bedform migration of more than 0.5 m. Strong transport; “stormy weather” to the eye. Continuous records in Safires, and changes of two to few cm in ED pins.
5 — Large scale	Overall beach modification due to aeolian processes. Major deposition at embryo dune/dune toe area. Largest changes of tens of cm in ED pins. Vegetation burial.

3.3. Supply-limiting conditions and fetch distances

Moisture maps were stored with a 0.05 m spatial resolution. Moisture content exhibited very complicated patterns and its relation to sediment transport and wind is worthy of detailed investigation beyond the scope of this paper. For the purpose of the analysis reported here the spatial distribution of moisture values was simplified into three broad categories: 1) 'dry', with at least 90% of beach surface containing ≤ 2% of moisture; 2) 'threshold-changing', with moisture of 2–10% covering the beach surface; and 3) 'wet', when transport was completely shut down because of rainfall or melting of snow/ice (moisture > 10% over the entire beach). The goal was to differentiate clearly between moments when large values for moisture content ('wet') yielded no transport (Davidson-Arnott et al., 2008) while acknowledging that with smaller values of surface moisture ('threshold-changing') wind gusts and drying may create a diversity of transport situations (Wiggs et al., 2004 and Davidson-Arnott and Bauer, 2009).

Percentages of snow/ice cover were calculated from rectified RGB images. A mean value was obtained for each event and used for the classification outlined in Table 5. This relatively simple classification permitted isolation of periods of time when the beach was significantly covered by snow/ice (> 60%). An average fetch distance was calculated for each event, given relatively constant conditions on beach dimensions (e.g., frozen shoreline) and angle of wind approach. Hourly details were included in the analysis when strong variations of wind direction or shoreline position resulted in significantly varying fetch distances.

Table 5. Classification of snow/ice cover.

Snow–ice cover	Class
Complete	> 80%

Snow–ice cover	Class
High	60–80%
Medium	40–60%
Low	20–40%
“Patches”	< 20%

4. Magnitude and frequency of wind events

4.1. Wind events and potential transport in all directions

A total of 184 wind events were detected from September 1, 2007 to May 31, 2008 (Fig. 3). These encompass all the potential sediment transport events and thus the starting point for prediction of sediment transport to the foredune. As expected (e.g.Mathew, 2006) the frequency of events decreased with increasing values of the mean wind speed class (Fig. 3A). Approximately half of wind events were ‘moderate breezes’ with mean wind speeds of 6–8 m s^{-1}, 30% were ‘fresh breezes’ and 13.5% were ‘strong breezes’. The remaining 10 events ranged from ‘very strong breezes’ (6 events) to a single ‘fresh gale’ with a mean wind speed exceeding 16 m s^{-1}. In general event duration was greater with increasing mean wind speed (Fig. 3A, bar graph) with most of the highest mean wind speed events lasting more than 24 h. Because of the direct relationship between event duration and mean wind speed, and the fact that aeolian sand transport scales with U^3 rather than U, the mean wind speed did not provide a good measure of the magnitude of the event. The potential transport associated with each wind event was calculated using Eqs. (3) and (4) and this value was used as a measure of the magnitude of the event for total transport and for the proportion directed towards the foredune respectively (Section 3). Fig. 3B shows the frequency of wind events by magnitude class as defined in Table 3. Table 6 contains the relation between events magnitudes and mean wind speeds. Approximately 60% (109 events) of all wind events fell into the very small magnitude class ($Q < 3$ □ 10^2 kg m^{-1}) as a result of short durations and/or very low wind speeds (83% of events of very small magnitude were moderate breezes). There were 11 large magnitude wind events ($27 \leq Q < 81$ □ 10^2 kg m^{-1}) and 4 very large magnitude wind events with the potential to transport more than 8.1 □ 10^3 kg m^{-1}.

Table 6. Percentages of wind event magnitudes (Q, Eq. (3)) in relation with mean wind speeds.

	Event magnitude (Q)				
Mean wind speed (m s^{-1})	Very small	Small	Medium	Large	Very large
6–8	83%	12%			
8–10	15%	73%	48%	9%	
10–12	2%	12%	52%	45%	
12–14		3%		27%	50%
14–16				18%	25%
> 16					25%
Number of events	109	33	27	11	4

The monthly distribution of all wind events is displayed in Fig. 4A. Winter was the season with the highest potential sediment transport at Greenwich, followed by Fall, with the lowest potential (not presented here) in the Summer. January was the month with the greatest number of wind events, and December contained the strongest ones. The pie graph in Fig. 4A shows the percent of sediment potentially carried by events of different magnitudes ($Qm_{\%}$), which may be calculated following the expression suggested byWolman and Miller (1960):

$$Q_{m\%} = \frac{(Q_i \times F)}{Q_{tot}} \cdot 100 \qquad \text{equation (5)}$$

where Qi is the sediment carried by a given magnitude wind event, F is the frequency of a given event, and Qtot is the total sediment transport predicted over the study period. Despite their lower frequency, very large magnitude wind events (one in November and three in December) accounted for a quarter of the total potential sediment transport over the 9 months of the study. Very low magnitude events, on the other hand, were rather inefficient in terms of potential transport; 109 events accounted for only 8% of the total potential sediment transport. Medium and high magnitude events carried 30% and 27% of the total potential transport. Because event duration increased with mean wind speed, the potential to transport sediment (event magnitude) during very strong breezes and gales was enhanced, which increased their significance for the total predicted transport despite their lower frequencies. This has implications for modelling aeolian events in coastal areas (Section 7.2).

4.2. Wind events and potential transport toward the foredune

The formation of coastal dunes requires onshore winds capable of moving sediment landward (Pye, 1983 and Davidson-Arnott and Law, 1990). Offshore events accounted for almost half of the total events recorded at Greenwich (90 out of 184). If offshore wind events are eliminated the total predicted transport decreases to 71% of the original amount. As winds with an onshore component approach the beach at an increasingly oblique angle, the cosine effect drastically reduces the amount of sand delivered to the foredunes per unit distance alongshore (Bauer and Davidson-Arnott, 2003). The reduction in potential transport due to the cosine effect decreased the predicted amount delivered to the foredune to approximately 41% of the total potential transport. Fig. 4B displays alongshore to onshore wind events which magnitude was reduced according to how much the wind direction departed from onshore perpendicular (Qn). Despite an overall decrease in the number and magnitude of events, the percent of sediment potentially carried by onshore wind events remained essentially the same as that for all wind events (compare pie graphs in Fig. 4A and B).

5. Magnitude and frequency of transport events

The previous section examined wind events and the potential sediment transport that would be predicted by an analysis using standard aeolian transport formulae. This section examines only those events, defined as transport events, where actual sediment transport was observed and/or measured. It is assumed that in all other cases transport was inhibited as a result of the presence of one or more of the transport-limiting factors that act to increase the threshold for sediment entrainment or shelter the beach from wind action. Note that the transport events may be, indeed often are, of shorter duration than the wind event within which they are embedded, or they may occupy several periods within the event because of the effect of transport-limiting factors during a portion of the wind event.

5.1. Transport in all directions

Only 66 wind events produced observed transport (Fig. 5A), 40 of which had only trace movement or isolated transport (codes 1 and 2, respectively; Table 4). The remaining 26 events ranged from medium to very strong transport, and these may have significant geomorphological and sediment budget implications.

There was only one very strong transport event resulting from a very large magnitude wind event (mean speed of 12–14 m s^{-1}, duration 90 h) starting on November 9 (discussed in detail in Section 6.2). There were 6 strong and 18 medium transport events, which were primarily associated with medium and large magnitude wind events (mean wind speeds between 8 and 12 m s^{-1}; Table 6). Only 2 out of 18 medium transport events resulted from wind events with mean speeds < 8 m s^{-1}. The first occurred on March 26, 2008 with constant alongshore winds of 7.25 m s^{-1} blowing over 24 h; the second developed on April 30, with offshore winds of 7.8 m s^{-1} blowing dry sand from the dune and blowouts to the beach.

The number of hours over which transport was observed increased with the transport code. Fig. 5B shows that transport events with lower codes (trace and low transport) tended to last 5 h or less, while the mean duration of strong and very strong transport events was over 25 h (note that there was only 1 very strong transport event). The Fall was the most active season for aeolian sediment transport (Fig. 5C). November contained the only event coded as 5 (very strong transport) and the majority of code 4 (strong transport) events. Very few transport events were recorded in the winter months of December, January and February, but transport events became more frequent early in the spring and continued through May. Section 6 compares transport events in Fig. 5C with wind events in Fig. 4A and examines the effects of supply-limiting factors.

In order to obtain an approximation of the relative proportion of sand moved by transport events of different magnitude, a simple calculation multiplying the transport intensity code by the duration of transport event was computed (Fig. 5D) and the procedure described in Section 4.1 was applied. It is assumed here that the transport classes are exponential rather than linear to account for the relationship with U^3. In other words, the increase in transport is larger when going from medium to strong than from trace to low. Almost 40% of the total sediment was carried during medium transport events (of medium frequency and duration according to Fig. 5A and B). Approximately 33% of the sediment was moved during strong transport events of low frequency, followed in percentage by low intensity but frequent events (17%) and a single very strong transport event (8%). Very small (trace) transport events were insignificant in terms of the amount of sediment they carried (2.5%). Thus, medium and strong transport events were most important from the perspective of aeolian sediment movement at Greenwich but how much of this sediment played a role in building the foredune? What controls beach and dune sediment exchange and sand input to the foredune?

5.2. Transport toward the foredune

Fig. 6 shows the transport events according to the predominant wind direction during the event. Note that there was almost no transport associated with wind directions alongshore from the east, and that the majority of transport was developed during westerly winds. Most transport periods coded as 4 (strong) were associated with alongshore and offshore wind angles. Alongshore winds blowing over long fetch distances along the beach were able to accumulate and build-up dry sand patches quickly even in the presence of high surficial moisture content. These sand bedforms progressively migrated over the moist surface, ‘sliding’ over the beach. Fig. 7 shows two examples of typical alongshore wind events with strong transport and sediment moving over a moist or a frozen surface. Topographic steering might result in some sediment going into the foredune with alongshore or even offshore winds (Lynch et al., 2008). However, the existence and strength of recirculating eddies producing onshore transport during offshore winds still needs to be explored and is likely related to factors such as dune height, wind direction, and wind speed. In agreement with previous observations at Greenwich (Walker et al., 2006) the net quantity delivered to the dune during offshore flows was found to be insignificant compared to the total transport during the event.

In order to obtain an approximation of the amount of sand actually delivered to the foredune the coden was calculated as explained in Section 3.2.2. Out of a total of 66 events, 32 had a negative qn and visible offshore transport and 7 were alongshore withqn ≈ 0; thus they have been excluded from the following analysis. Fig. 8A shows the remaining 27 transport events with a coden > 0, thus indicating that some proportion of the sediment transport was directed towards the foredune. Sediment input to the foredune represented approximately 27% of the total observed transport. Interestingly, the only very strong transport event (code = 5) occurred during oblique onshore winds and thus a large proportion of sediment moved toward the foredune (coden = 5). However, there were no coden = 4 transport events and only 2 medium (coden = 3) and 5 low (coden = 2) were identified. The remaining 19 onshore events were associated with trace amounts of sediment movement (coden = 1). Three events were responsible for approximately 75% of the total sediment input to the foredune (Fig. 8C). These occurred on November 11, March 17 and May 10 (Fig. 8B) and their characteristics are listed inTable 7. Numerical values for these three events need to be compared with actual deposition on the dune to allow a proper quantification of their significance. However, in general terms, the isolation of the type of events likely contributing to foredune building has important implications both for what needs to be considered and what needs to be excluded for future modelling (Section 7).

6. The role of limiting factors

The comparison between applied stress (wind events) and transport processes observed at Greenwich leads to several questions. The first question is why so many of the observed wind events did not result in any transport, despite having the potential to do so based on theoretical considerations. In particular, there is a need to assess the conditions regulating the strongest wind events at the beach because of their extraordinary potential to move large amounts of sediment ($> 27 \times 10^2$ kg m^{-1} per event). The windiest season (Winter) is the least effective season for transport (compare Fig. 4A and B with Fig. 5 and Fig. 8, respectively). While extensive snow/ice cover was responsible for preventing many transport events during the winter, the comparison between Fig. 4 and Fig. 8 suggests that there were other factors limiting the development of transport over the entire study period. There is a need to clearly identify the role of fetch distances and moisture content, and in what type of situations they play a significant role in shutting down sediment transport.

The second question is what are the key factors limiting the development of strong transport (coden = 4) toward the dunes at Greenwich. The comparison of Fig. 5 and Fig. 8suggests that the angle of wind approach introduces a significant limitation but there is a need to specify in what situations this is the primary control. Finally, there is a need to clarify the characteristics surrounding the only very strong onshore transport event because of its significance over the study period (29% of total sediment input to the foredune, Fig. 8C).

The following sections deal with the role of limiting factors in preventing transport over entire wind events (Section 6.1), decreasing the portion of time over which sediment movement occurs (duration of transport event) and reducing the magnitude of transport when it develops (Section 6.2).

6.1. Inhibition of sediment transport during wind events

About 65% (119) of all wind events did not produce any transport (Fig. 5A). Many of these (84) were associated with very small wind event magnitudes, mostly because of short duration and/or with winds just above threshold. At least a quarter were moderate breezes blowing over a dry surface, pointing to the relevance of the fluid entrainment threshold. Because potential sediment transport associated with these wind events was small, they would not make a large contribution to the error in predicting actual sediment supply to the dune. However, there were 35 wind events with wind speeds clearly above the threshold (> 8 m s^{-1}) that did not result in any transport, including 3 out of the 4 very large magnitude wind events and 7 out of 11 large magnitude events. Table 8summarizes the main characteristics of these 10 wind events, which include the only fresh gale observed at Greenwich over the course of nine months (December 3), 3 gales (December 1, 12, and 15), and several very strong breezes. Together these 10 events accounted for 37% of the total predicted sediment transport (Q) and 45% of the total predicted sediment input to the foredune (Qn). The overall result was rather different though: not only was there no sediment input from the beach to the dunes, but instead sand was eroded from the foredunes because of wave scarping due to storm surge and wave run-up.

Table 8. Characteristics of 10 large magnitude wind events resulting in no transport (code = 0). Symbols are defined in Table 7. Snow is expressed in % of surface covered.

Date	U	U_{max}	WD	α	Q	Qn	Snow	Limiting factors
03/12/07	18.4	30.3	32	ob E	11,230	8259	> 80	Snow/ice; storm surge and foredune scarping despite ice foot
01/12/07	15.3	23.1	46	ob W	8354	5938	15	Fetch extremely limited (wave run-up)
04/10/07	10.2	14.9	119	ob W	6457	4491	0	Rain (moisture)
14/01/08	9.9	15.8	74	ob E	3705	3160	20	Storm surge and short fetch distance during wind peak hours (ice foot acts as barrier to erosion); snow melting (moisture) prevents transport during rest of event
02/01/08	11.9	19.4	38	ob W	3300	2010	> 80	Snow/ice
23/09/07	12.6	14.9	40	on/ob W	3666	1918	0	Wave run-up and partial embryo dune scarping during onshore winds (ED pin at the back beach lost 4 cm of sand due to wave action); intense rain during oblique winds
12/12/07	15.2	23.6	30	ob W	5689	1440	> 80	Snow/ice
15/12/07	14.5	24.8	28	ob W	4622	1193	> 80	Snow/ice
08/12/07	12.5	19.4	31	ob W	2993	555	> 80	Snow/ice
16/12/07	13.2	26.1	65	off W	8860	− 3066	> 80	Snow/ice
Total predicted					58,876	28,964		
Percent of predicted Q or Qn in 9 months					37%	45%		

The most important limiting factor was the presence of snow and ice over the beach surface during the winter months. This factor shut down sediment transport during 6 of the 10 events listed in Table 8. Included in this group is the fresh gale on December 3, 2007, with the highest potential sand transport of the study period. In this instance transport would also have been shut down for a large portion of the event by storm surge and wave run-up, as wave action resulted in significant erosion of the embryo dune. The gales on December 12 and 15 presented similar conditions, with 80–90% of the surface covered by snow/ice (Fig. 9A and B). Storm surge and wave run-up were the key factor preventing sediment transport during the third gale on December 1 as well as wind events on October 29, 2007 and January 14, 2008. The gale lasted 46 h but no sediment movement was recorded despite an oblique onshore wind direction from the west, because of beach inundation due to wave run-up (Fig. 9C and D). Rain was a primary factor preventing sediment transport alone (event on October 4, 2007) or in combination with other factors (event on September 23, 2007) (Table 8).

Snow/ice covering at least 80% of the beach surface prevented sediment movement in 16 of the remaining 25 low to medium magnitude wind events for which no transport was observed. Snow patches or moderate to large values of surface moisture due to snow melting or rain prevented sediment entrainment in the remaining 9 wind events.

The exclusion of offshore wind events decreased the amount of total predicted sediment transport (Q) to 71% of its original amount. The reduction in potential transport due to the cosine effect for those winds with an onshore component was of 41% respect to the transport predicted in all directions (Qn respect Q). Limiting factors preventing sediment entrainment during entire onshore wind events further decreased the potential input to the foredune to 16% of the original amount.

Furthermore, when transport was observed, limiting factors often reduced its magnitude due to complex relationships between wind speed, event duration, angle of wind approach and fetch distance. This will be discussed in the next section.

6.2. ‘Time limited’ and ‘magnitude limited’ events

All transport events at Greenwich were ‘time limited’ i.e., with transport being developed only over a portion of the wind event. On average, the duration of wind events was approximately 25 h, while the average duration of transport events was only 8 h. The majority of transport events were also ‘magnitude limited’, i.e., the magnitude of the transport event was smaller than the magnitude of the wind event and generally not predictable from it. For example, none of the large magnitude wind events in September (Fig. 4A) resulted in strong transport (Fig. 5C). Similarly, only 1 of the 6 strong transport (code = 4) events resulted from a large magnitude wind event. Some of this complexity can be seen in Table 7, where a complex relationship between wind speed, thresholds, wind direction and limiting factors regulates sediment input to the foredune within the three events.

In order to show some these interactions it is instructive to focus on the detailed time series recorded during the only very strong transport event on November 9–13, 2007 (Fig. 10). This event led to burial of vegetation of the embryo dune due to deposition of approximately 25 cm of sand. Despite of strong winds exceeding the threshold for sand movement for 90 h, transport was only recorded by the Safires on the upper beach for approximately 28 h. High surface moisture content due to rainfall prevented transport during the first 20 h of the storm. An increase of wind speed on the morning of November 10 (blowing obliquely from the NE and therefore yielding a relatively long fetch distance) favoured sediment movement during the second portion of the storm, though the magnitude of transport was limited due to intermittent rain. A subsequent increase of wind speed coinciding with low tide (and therefore a wide beach and long fetch distance) generated intense instantaneous transport on the back beach. The wind direction changed from oblique to nearly shore perpendicular on the morning of November 11, producing a storm surge which, coupled with a rising tide, led to inundation of the beach during the final portion of the storm. This resulted in a complete shut down of the aeolian transport system and partial erosion of the embryo dunes.

In summary, transport was only detected during 28 h (time limited) and its intensity was reduced at least over 15 h (magnitude limited). Furthermore, the peak in wind speed did not coincide with the peak in aeolian transport, but rather with sediment output from the dune because of wave scarping. This suggests that in this system the strongest stresses may not yield the greatest amount of geomorphic work. These results are in-line with observations on the importance of oblique angles of wind approach (long fetch distances) and their relation with increases in sediment transport rates on narrow beaches (Nordstrom and Jackson, 1993 and Bauer et al., 2009).

7. Discussion

7.1. Characteristics of wind events delivering sediment to the foredunes

Three events at Greenwich accounted for approximately 75% of the total transport delivered to the foredune over the 9 month study period and the remainder was accounted for by a small number of events of lesser magnitude (Section 5.2). Fig. 11displays transport events toward the foredune (coden) with respect to wind event magnitude. For the purpose of generalizing the discussion to other locations, wind events blowing over a surface significantly covered by snow/ice are not included (total of 48). Observed transport (continuous line) was calculated by adding the total transport for all events within each of the graph bars. The total transport for each event is a relative value based on the intensity transport code (coden) and duration of transport event (Section 5.1). This allows for an estimation of the type of wind events that were responsible for sediment input to Greenwich dunes over the period.

Initially, as the magnitude of wind events increased so did the proportion of wind events resulting in transport, and the magnitude of transport associated with them (Fig. 11). For example, there were 6 out of 20 medium magnitude wind events generating transport, and their intensity (coden) was generally larger compared to very small wind events. As a result of this, the peak of aeolian transport (continuous line) was centered between small and medium magnitude wind events generating low to medium magnitude transport. Beyond this a further increase of wind event magnitude was associated with a decrease in total sand transport. Only 3 out of 7 large magnitude wind events inputted small amounts of sediment to the dune (coden = 1; traces). This is because other environmental factors, such as short fetch distances and large surface moisture content, tended to limit or shut down sand transport. The pattern of decreasing transport with increasing wind magnitude is complicated by the existence of a single strong transport event (solid dot in Fig. 11) generated by a large magnitude wind event (November 9–13, 2007), but it is difficult to assess its significance without a much longer time series to provide a statistically robust analysis. This event is a reminder that, given an appropriate combination of factors, such as tidal stage, increasing beach width and oblique angle of wind approach, a single storm may result in the transport of large amounts of sediment.

However, transport during this event was both time and magnitude limited (Section 6.2). More importantly, it should be contextualized with respect to the rest of large magnitude wind events, as only this one out of 9 resulted in strong transport toward the foredune.

7.2. Conceptual model for aeolian sediment input to foredunes

Fig. 12 shows (A) the original graph by Wolman and Miller (1960) of the significance of events of different frequency and magnitude associated with fluvial sediment transport; (B) similar curves derived from the nine-month study at Greenwich Dunes; and (C) comparison between observed wind events and resulting transport as explained throughout this paper. Note that only wind events with mean wind speeds above 6 m s^{-1}were included in the analysis at Greenwich and thus Fig. 12B and C lack of information below this threshold. Both the frequency of wind events (curve b) and the associated mean transport rate (curve a) at Greenwich (Fig. 12B) followed the conceptual ideas proposed by Wolman and Miller (curves b and a respectively in Fig. 12A). However, the introduction of the duration of the wind event (curve c in Fig. 12B) as a factor regulating the amount of “work” done by events of different magnitude has the effect of modifying the shape of the potential transport with respect to the one proposed by Wolman and Miller (compare curves d in Fig. 12A and B). As explained in Section 4.1, high wind speeds seldom appeared isolated but rather grouped in events of long duration, which increased the potential transport associated with infrequent but large magnitude wind events. In other words, the amount of “work” expected from strong breezes and gales was greater not only because of the larger magnitude, but also because of the high positive correlation between mean wind speed and mean duration. However, the actual “work” performed by most of these large magnitude wind events was insignificant and this was the primary source of over-prediction of sediment input to the foredune at the site.

Fig. 12C compares predicted and observed transport at Greenwich based on the results of this study. Curve d is repeated from Fig. 12B and represents the predicted sediment transport in any direction, and curve e represents the predicted sediment transport toward the foredunes (these are equivalent to Q and Qn in the pie graphs of Fig. 4A and B, respectively). As discussed in Section 4.2, the predicted sediment transport towards the foredune was approximately 41% of the total potential transport but the percent of sediment potentially carried by different magnitude wind events remained essentially the same despite introducing the cosine effect. Curve f is repeated from Fig. 11 and represents observed transport at Greenwich. This curve summarizes, conceptually, results discussed in Section 6: sediment input to Greenwich dunes was both time and magnitude limited and decreased with increasing wind magnitude because of the role imposed by limiting factors such as moisture or fetch distances. Gales and very strong breezes blowing over snow-free surfaces resulted in storm surge and even wave scarping (Section 6.1), and thus were associated with sediment removal from the foredune rather than sediment input through aeolian processes. Thus, the probability of large magnitude wind events producing correspondingly large magnitude transport events decreases as the mean wind speed of the event increases. While the high wind speeds associated with low frequency, high magnitude events are important in calculating sediment erosion and transport in desert environments and agricultural fields, these may be completely counterbalanced in coastal areas by processes related to nearshore dynamics and beach–dune interaction (Psuty, 1988 and Sherman and Bauer, 1993).

7.3. Implications for numerical modelling

Meso-scale modelling approaches based on hourly measurements of wind speed and direction (e.g. Fryberger and Dean, 1979) calculate sediment transport based on U^3 and thus magnify the potential of strong (and long) wind events that, in the coastal zone, have a very low probability of resulting in any significant sand movement. Over-prediction of sediment input to the foredune on a time-scale of a year is thus likely due primarily to the inclusion of large magnitude wind events during which transport either does not occur or is significantly reduced, rather than to uncertainty associated with estimates of the threshold value for sand movement or simplifications of sediment characteristics at the beach surface (e.g., grain size). There are two primary problems in attempting prediction of sediment inputs to coastal dunes over periods of weeks to years: 1) determining an appropriate set of equations that incorporate complexities such as surface moisture content, beach width and fetch distances; and 2) securing quantitative data on these variables for input into a model at time scales of weeks to months. Although an exact prediction of dune development over years may not be possible using deterministic equations, such simulations could aid in our understanding of the most likely scenarios (Sherman, 1995). Probabilistic approaches such as those commonly used in meteorological modelling may improve meso-scale sediment transport predictions in coastal areas, and measuring their quality may be more critical than measuring their absolute accuracy (Sutherland et al., 2004).

Finally, predictions of sediment supply to the foredune at the meso-scale should be based on factors that can be measured or estimated rapidly and at minimal expense (Davidson-Arnott and Law, 1990). Most meteorological stations along the coast contain hourly data sets of wind speed and direction, precipitation (both snow and rain), water levels, temperature and other variables. Additionally, beach width can be predicted by combining tide data and storm surge predictions based on standard meteorological data. The time series at Greenwich are currently being used to determine how factors such as surficial moisture content and fetch distances may be estimated in this way and to assess the reliability of such predictions.

8. Conclusions

Some of the scale-dependent issues hampering our ability to predict dune development can be addressed with a systematic identification of key controls and synoptic measurement of the processes and responses involved (Sherman, 1995). By analyzing when and how transport takes place at the beach, this paper identified fundamental tradeoffs between key factors regulating sediment supply to the foredunes. Results from the long-term monitoring at Greenwich suggest that a large portion of the total sediment flux over nine months may be carried by a few small to medium wind events (8–12 m s^{-1}), and that the angle of wind approach and fetch distance may be more important than having a very strong wind. The overall role of frequent but short duration periods of moderate breezes (6–8 m s^{-1}) is insignificant because more than 70% were not able to transport sand. Only 1 of 15 large magnitude wind events delivered large quantities of sediment to the embryo dune. Furthermore, the strongest wind events did not result in aeolian transport at all but, rather, yielded wave scarping and foredune erosion. The windiest season (Winter) was the least important for aeolian sediment transport because of the effect of snow/ice cover on this beach. At least 60% of the largest magnitude wind events encountered a surface protected by a frozen beach.

There are a number of methodological and conceptual limitations that this paper does not consider but are of potential relevance. Topographic adjustments were not quantified during wind events (and for extended periods of time) due to instrumental limitations and access to the site. Also, methods to measure sediment transport over long time periods require improvement. Furthermore there is a need to compare qualitative observations of transport processes with actual measures of deposition at the embryo dune and foredune over several months, and to incorporate the ideas explained in this paper in new modelling approaches. The study site at Greenwich Dunes is representative of many beaches in the Gulf of Saint Lawrence, east coast of Canada and the Great Lakes. While the details of beach–dune systems in other areas will be different because of different wave, tidal and climate regimes, and thus result in changes in the efficiency of different magnitude wind events (e.g., skews in the transport curve) the conceptual approach described here may be universally applicable. Also, although the objective of this paper was to identify general patterns and the role of a few key parameters future studies should explore the details of many events individually (such as possible niveo-aeolian activity during two winter events, sublimation processes, and relations between bedform shape and rate of migration under different wind and surface conditions).

Finally, monitoring stations such as the one deployed at Greenwich should be maintained for periods of years to assess seasonal and inter-annual variability.

Although key factors controlling sediment dynamics will likely vary depending on the geographical location and beach dimensions, the contribution of this paper was to demonstrate that the largest transport rates do not necessarily occur during periods when wind speeds are at their greatest. This is linked to the essential characteristics of aeolian transport on coastal areas, which yield tradeoffs between beach geometry, angle of wind approach and fetch distance. These critical interrelationships reinforce the uniqueness of coastal dunes.

Acknowledgments

We thank Parks Canada for granting permission to carry out work at Greenwich Dunes and personnel at Greenwich Dunes for their support in the field. Special thanks to Roger Steadman and Allan Doyle for help with transporting equipment to and from the research site. Financial support for the study has been provided through a Natural Sciences and Engineering Research Council of Canada Discovery Grant to RD-A, through a research grant from Parks Canada to RD-A, Ian Walker and Jeff Ollerhead, and through a University of Guelph Lattornell Travel grant to ID-F. ID-F also acknowledges support provided by the Ontario Graduate Scholarship Program. Jeff Ollerhead provided help with many of the aspects related to data collection and monitoring. Mario Finoro and Sandy McLean provided technical support for the construction of the station at Greenwich, and Adam Bonnycastle aided in the development of scripts to process the data. A number of people have been involved in the fieldwork and we would particularly like to thank Bernie Bauer, Ian Walker, Hosahng Rew, Rosie Smit, Kathryn Powel, and Gavin Manson. We would like to thank the thoughtful suggestions by Bernie Bauer, which greatly improved the paper, as well as detailed reviews by Bill Nickling and Ray Kostaschuck. We are grateful to the feedback and comments provided by two anonymous reviewers.

Appendix

This research makes use of hourly wind speed recorded at 14 m height over the beach surface. Thus, there is a need to justify the use of both the wind velocity and the minimum velocity to keep sand in saltation at 14 m as a surrogate for drag velocity and threshold shear velocity. According to Fryberger and Dean (1979, p. 146) one may use hourly wind speed data at 10 m height over the beach surface to predict transport by making several simplifying assumptions. If shear velocity is proportional to the wind velocity at any given height then the Lettau and Lettau (1977) equation may be modified as follows:

$$q \propto U^{*2}(U^{*} - U_{t}^{*}) \qquad \text{equation (6)}$$

into:

$$q \propto U^{2}(U - U_{t}) \cdot t \qquad \text{equation (7)}$$

where U* and U*t are the shear velocity and impact threshold shear velocity respectively (Eq. (6)), U is wind velocity, Ut is the impact threshold wind velocity (both at an average height of 10 m) and t is the time wind blew (Eq. (7)). Fryberger and Dean assumed that (1) the surface consists of loose quartz sand grains with an average diameter 0.25–0.3 mm; (2) the surface is dry, unvegetated and free of bedforms larger than ripples, and; (3) the threshold wind velocity may be extrapolated using Bagnold's equation (1941, p. 104):

$$U_{t(z)} = 5.75U_t^* \log(^{z}/_{z'}) + U_t' \qquad \text{equation (8)}$$

where z′ is the roughness surface factor and U′t is the threshold wind velocity at a height z′. Fryberger and Dean derived the following values from work by Belly (1964) for a sand surface of 0.3 mm average:

$$z' = 3.05 \times 10^{-3}\,\mathrm{m}$$
$$U_t' = 2.74\ \mathrm{ms}^{-1}$$
$$U_t^* = 0.16\ \mathrm{ms}^{-1}$$

The resulting wind impact threshold wind velocity at Greenwich following Fryberger and Dean's approach is $Ut_{(14\ m)} = 6.11$ m s^{-1}, which is similar to the one used in this study based on calculations by Delgado-Fernandez and Davidson-Arnott (2009) after a short-term experiment at Greenwich beach. These authors compared mean values of wind speed at 0.25 m and 14 m height over the beach surface extracted from 20 10-minute runs (Fig. 13) and suggested an approximate correlation factor of 0.66. Previous research by Davidson-Arnott et al. (2008) involving the use of cup anemometers and saltation probes at the same study site suggested a minimum wind speed of 4.2 m s^{-1} at 0.3 m high for measuring transport (average value for cup anemometer at the foreshore).Delgado-Fernandez and Davidson-Arnott (2009) decreased this threshold to 4 m s^{-1} to ensure that no transport periods were lost during a filtering procedure. Thus, a wind of 4 m s^{-1} at 0.25 m high corresponds to 6.1 m s^{-1} at 14 m.

Finally, Bagnold (1941, p. 101) suggests that the threshold velocity at any height z may be calculated as follows:

$$U_{t(z)} = 5.75A\sqrt{\frac{\sigma-\rho}{\rho}gd}\cdot log\left(^{z}/_{k}\right) \qquad \text{equation (9)}$$

where A = 0.1, σ is the density of grain material (2650 kg m^{-3}), ρ is the density of air (1.22 kg m^{-3}), d is the grain diameter (0.26 mm at Greenwich beach), k is the roughness factor (z′ = 3.05 × 10^{-3} m), and z = 14 m. Under these conditions,$Ut_{(14\ m)}$ = 4.99 m s^{-1}, which is significantly lower that the values predicted previously.

The use of one threshold value for wind speed over months contradicts many findings about the high variability of thresholds for sand movement at the instantaneous scale (e.g., Wiggs et al., 2004 and Davidson-Arnott and Bauer, 2009). Furthermore, any of the methods above require several assumptions regarding sediment and flow characteristics, which introduce uncertainties in calculations (e.g., an increment of z′ from 0.0018 to 0.01 decreases $Ut_{(14\ m)}$ from 6.55 to 5.63 m s^{-1} in Eq. (8)). Variations in sediment size and sorting, packing and surface characteristics will introduce large variations in the critical shear stress and hence will have significant effects on transport. However, one may assume a low enough wind threshold for dry sand under which transport is not likely to occur. Sediment transport rates around this threshold are also likely to be small, so the effect should be insignificant in predicting total sediment transport over a period of months. Analysis in this study suggest that the refinement of the wind threshold for dry sand may not be a first order priority if this is used to isolate moments where transport has the potential to occur (wind events). There was only one transport event of less than 6 m s^{-1} over nine months at Greenwich (mean wind speed = 5.1 m s^{-1}, duration of wind event = 10 h; transport code = 1-traces; duration of transport = 2 h). Events with wind speeds from 6 to 8 m s^{-1} were responsible of only 2.5% of the total transport in all directions. Wind events driving the majority of sediment to the foredunes presented higher wind speeds.

Two images were necessary to observe evidences of sediment movement from bedform migration or ED pins records and thus this dictated the minimum duration of an event. Isolated hourly records of wind speeds over 6 m s^{-1} did take place in the time series but were ignored in the analysis, which was also supported by the lack of transport evidences from the Safires records during those particular short time periods. Even if transport may have occurred this was negligible over the long-term because isolated records of wind speed tended to be of very low magnitude. There were 83 isolated hourly values of wind speeds > 6 m s^{-1} and 78 (94%) of them were < 8 m s^{-1}.

References

Arctur, D. and Zeiler, M., 2004. Designing geodatabases: case studies in GIS data modeling. ESRI, Redlands, California, 393 pp.

Baas, A.C.W., 2007. Complex systems in aeolian geomorphology. In: Murray, A.B. and Fonstand, M.A. (Eds.), Proceedings of the 38^{th} Binghamton Geomorphology Symposium, Duke University, October 5-7. Geomorphology 91 SI, 311-331.

Bauer, B.O. and Davidson-Arnott, R.G.D., 2003. A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry and fetch effects. Geomorphology 49, 89-108.

Bauer, B.O., Davidson-Arnott, R.G.D., Hesp, P.A., Namikas, S.L., Ollerhead, J., Walker, I.J., 2009. Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport. Geomorphology 105, 106-116.

Chapman, D.M., 1990. Aeolian sand transport - an optimized model. Earth Surface Processes and Landforms, 15, 751-760.

Christiansen, M.B. and Davidson-Arnott, R.G.D., 2004. Rates for landward sand transport over the foredune at Skallingen, Denmark and the role of dune ramps. Geografisk Tidsskrift, Danish Journal of Geography 104, 27-36.

Coulthard, T.J., 2009. Numerical models of catchment scale sediment transfer: progress, problems and potential, Eos Trans. AGU 90, Jt. Assem. Suppl., Abstract H74B-02

Darke, I., Davidson-Arnott, R.G.D. and Ollerhead, J., 2009. Measurement of beach surface moisture using surface brightness. Journal of Coastal Research 25, 248-256.

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., (Eds.), Coastal Dunes: Form and Processes, John Wiley & Sons Ltd., 177-20.

Davidson-Arnott, R. G. D. and Law, M. N. 1996. Measurement and prediction of long-term sediment supply to coastal foredunes. Journal of Coastal Research 12, 654-663.

Davidson-Arnott, R.G.D., MacQuarrie, K. and Aagaard, T., 2005. The effect of wind gusts, moisture content and fetch length on sand transport on a beach. Geomorphology 63, 115-129.

Davidson-Arnott, R.G.D., Yang, Y., Ollerhead, J., Hesp, P.A. and Walker, I.J., 2008. The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. Earth Surface Processes and Landforms 33, 55 – 74.

Davidson-Arnott, R.G.D. and Bauer, B.O., 2009. Aeolian sediment transport on a beach: Thresholds, intermittency, and high frequency variability. Geomorphology 105, 117-126.

Delgado-Fernandez, I. and Davidson-Arnott, R.G.D., 2009. Sediment input to foredunes: description and frequency of transport events at Greenwich Dunes, Prince Edward Island, Canada. Journal of Coastal Research, SI 56, Proceedings of the 10th International Coastal Symposium, Lisbon, Portugal, 302-306, v1.

Delgado-Fernandez, I., Davidson-Arnott, R.G.D. and Ollerhead, J., 2009. Application of a remote sensing technique to the study of coastal dunes. Journal of Coastal Research 25, 1160-1167.

Fryberger, S. G. and Dean, D., 1979. Dune forms and wind regime. In: McKee, E. D. (Ed.), A Study of Global Sand Seas. U. S. Geological Survey Professional Paper 1052. Chapter F., 141-151

Hesp, P.A., Davidson-Arnott, R.G.D., Walker, I.J. and Ollerhead, J., 2005. Flow dynamics over a foredune at Prince Edward Island, Canada. Geomorphology 65, 71-84.

Higgitt, D.L., and Lee, M.E., 2001. Geomorphological processes and landscape change: Britain in the last 1000 years, Wiley-Blackwell, 320 pp.

Hsu, 1974. Computing eolian sand transport from routine weather data. Proceedings of the 14th Conference on Coastal Engineering, ASCE, New York, 1619-1626.

Lynch, K., Jackson, D.W.T. and Cooper, A.G., 2008. Aeolian fetch distance and secondary airflow effects: the influence of micro-scale variables on meso-scale foredune development. Earth Surface Processes and Landforms 33, 991-1005.

Mathew, S., 2006. Wind Energy. Fundamentals, Resource Analysis and Economics, Springer, xii+246 pp.

Miot da Silva, G., Hesp, P.A., and Dillenburg, S.R. (in press). Coastline orientation, aeolian sediment transport and foredune and dunefield dynamics of Moçambique Beach, southern Brazil. Earth Surface Processes and Landforms.

Nordstrom, K.F., Jackson, N.L., Bruno, M.S. and de Butts, H.A., 2002. Municipal initiatives for managing dunes in coastal residential areas: a case study of Avalon, New Jersey, USA. Geomorphology 47, 137-152.

Ollerhead, J., Johnson, P., Davidson-Arnott, R.G.D., Walker, I. and Hesp, P.A., 2003. Sediment supply to coastal foredunes, Greenwich Dunes, Proceedings of the Canadian Coastal Conference. CCSEA, Kingston, Ontario, pp. 12.

Psuty, N.P., 2005. The Evolving Paradigm of Coastal Geomorphology Inquiry. In: Sanjaume, E. and Mateu., J. (Eds.), Geomorfologia Litoral i Quaternari, Homenatge al professor V.M. Rossello i Verger. Universitat de Valencia, Spain, 373-382.

Pye, K., 1983. Coastal Dunes. Progress in Physical Geography 7, 531-597.

Sherman, D.J., 1995. Problems of scale in the modeling and interpretation of coastal dunes. Marine Geology 124(1-4): 339-349.

Stout, J.E. and Zobeck, T.M., 1997. Intermittent saltation, Sedimentology 44, 959-970.

Sutherland, J., Peet, A. H. , and Soulsby, R.L., 2004. Evaluating the performance of morphological models. Coastal Engineering 51, 917-939.

Svasek, J. N. and Terwindt, J. H. J., 1974. Measurement of sand transport by wind on a natural beach, Sedimentology 21, 311-322.

Walker, I.J., Hesp, P.A., Davidson-Arnott, R.G.D. and Ollerhead, J., 2003. Topographic effects on airflow over a vegetated foredune: Greenwich Dunes, Prince Edward Island, Canada. Proceedings Coastal Sediments '03. ASCE, New York, pp. 15.

Walker, I. J., Hesp, P.A., Davidson-Arnott, R.G.D., and Ollerhead, J., 2006. Topographic Steering of Alongshore Airflow over a Vegetated Foredune: Greenwich Dunes, Prince Edward Island, Canada. Journal of Coastal Research 22, 1278-1291.

Wiggs, G.F.S., Atherton, R.J. and Baird, A.J., 2004. Thresholds of aeolian sand transport: establishing suitable values. Sedimentology 51, 95-108.

Wolman, M.G. & W.P Miller. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68, 54-74.

References Online:

1. Environment Canada, Atlantic Climate Center
http://atlantic-web1.ns.ec.gc.ca/climatecentre/default.asp?lang=En&n=CACEE433-1
[Consult : July 30, 2009]

List of Figures

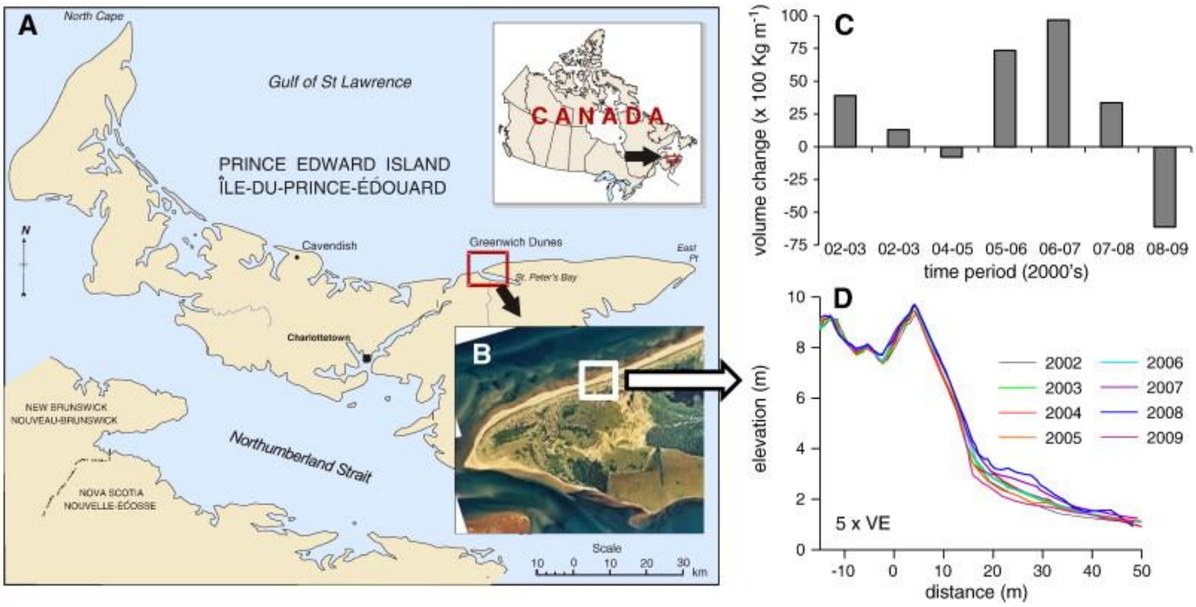

Fig. 1. A) Location of study area; B) Close up on Greenwich Dunes and location of the study site (white box); C) Net volume changes measured by the bedframe technique at line W located within the study site during the decade of the 2000s (see relative location in Fig. 2); D) DGPS surveys of line W reflecting the focus of changes occurring at the embryo dune and foredune toe.

1054

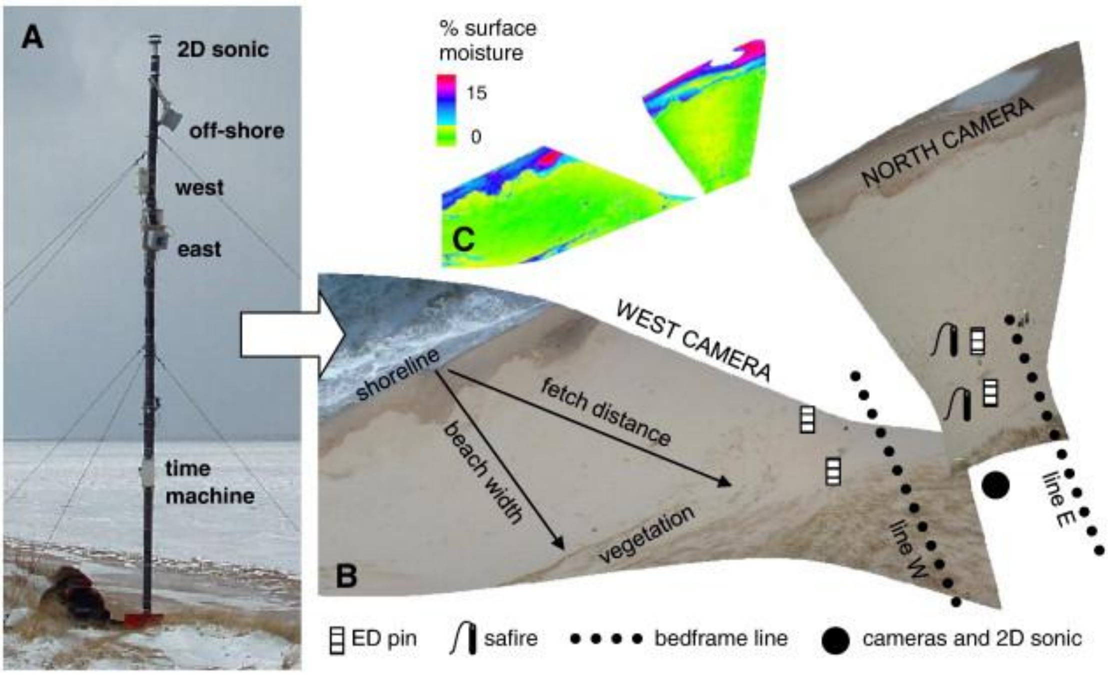

Fig. 2. A) Principal components of the long-term monitoring station. A 2-D sonic anemometer was located at the top of the mast, with three digital cameras below it; B) Example of rectified images for the offshore (north facing) and west-facing cameras and instruments deployment; C) example of moisture map produced from rectified RGB images (after Delgado-Fernandez et al., 2009).

1055

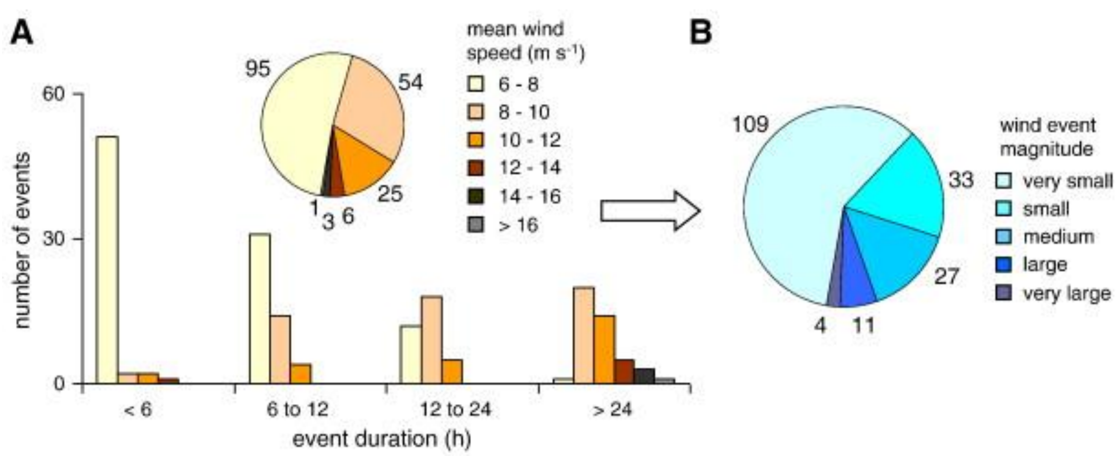

Fig. 3. A) Percentage and duration of wind events with different mean wind speeds. In general, the number of events decreased and the event duration increased with increasing mean wind speed; B) Magnitude of wind events based on potential sediment transport Q (kg m^{-1}) calculated using hourly wind speed and event duration (Eq. (3)). Table 6 contains the relation between events magnitudes and mean wind speeds. Note that 60% of all events (109) had very low magnitudes and only 2% (4 events) fell into the very large magnitude class. The values outside of the pie chart indicate the number of events.

1056

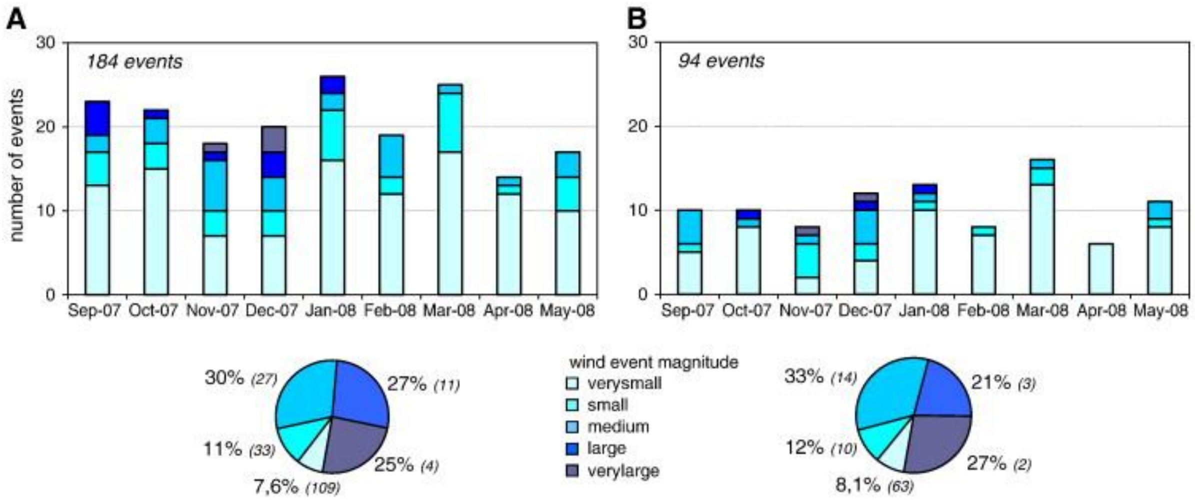

Fig. 4. A) Monthly distribution of all wind events (all directions), with magnitudes based on Q (kg m^{-1}); B) Monthly distribution of wind events potentially delivering sediment to the dune (onshore to alongshore), with magnitudes based on Qn (kg m^{-1}). Offshore events make up approximately half of the total number of wind events (90 out of 184). The exclusion of offshore events and modification of transport by the cosine of the angle of wind approach reduced the total amount of sediment potentially transported to the foredunes to 41% of the total Q. The associated pie diagrams show the percent of potential sediment carried by events of different magnitude (Section 4.1). The numbers outside of the pie charts indicate the percentage and corresponding number of events (in brackets). Despite the decrease in potential sediment transport toward the foredune the proportion of wind events with different magnitudes remained essentially the same.

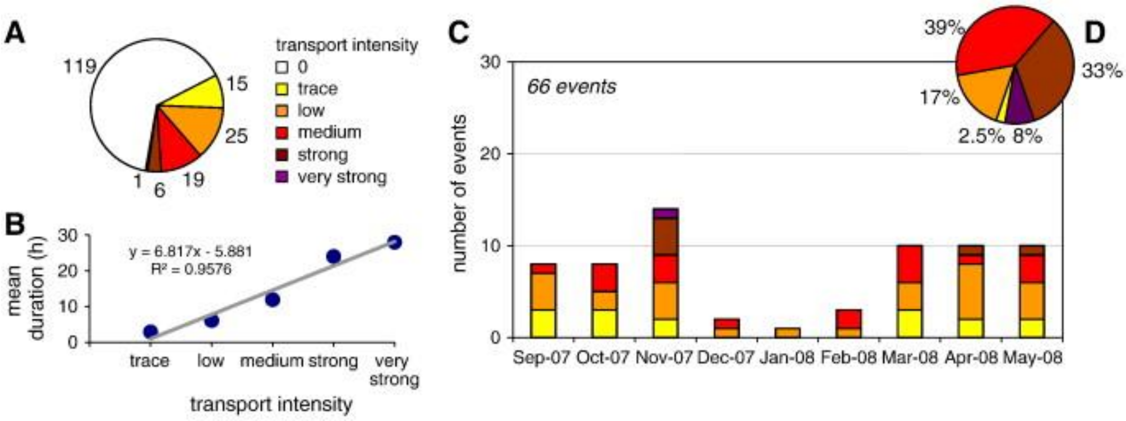

Fig. 5. Observed transport from all directions, based on the qualitative transport code assigned to each event (Table 4). A) Frequency of transport events. Values on the outside of the pie chart indicate the number of events with different transport intensities. The total number of transport events was 65; B) Relation between transport event intensity and transport event duration; C) Monthly distribution of transport events. Note that the strongest and the largest number of events occurred in November; this graph may be compared with the monthly distribution of wind events from all directions in Fig. 4A; D) Percent of total sediment carried by transport events of different magnitudes (Section 5.1). Values on the outside of the pie chart specify the actual percentage value.

1058

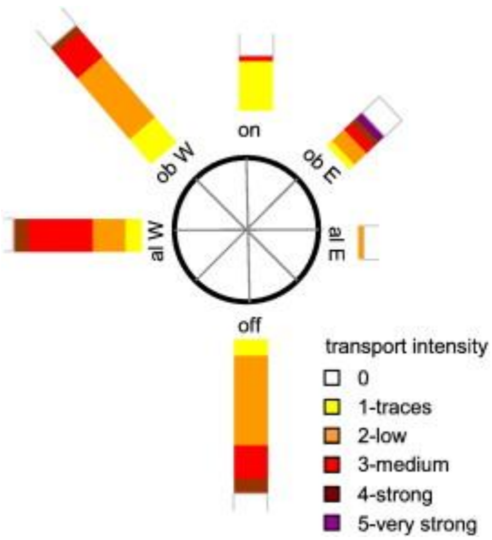

Fig. 6. Grouping of transport events at Greenwich Dunes based on the predominant wind direction for each event; “on” = onshore; “ob” = oblique; “off” = offshore. Note that a large percentage of the observed transport was associated with either offshore or alongshore wind directions which are assumed to deliver little or no sediment to the foredune.

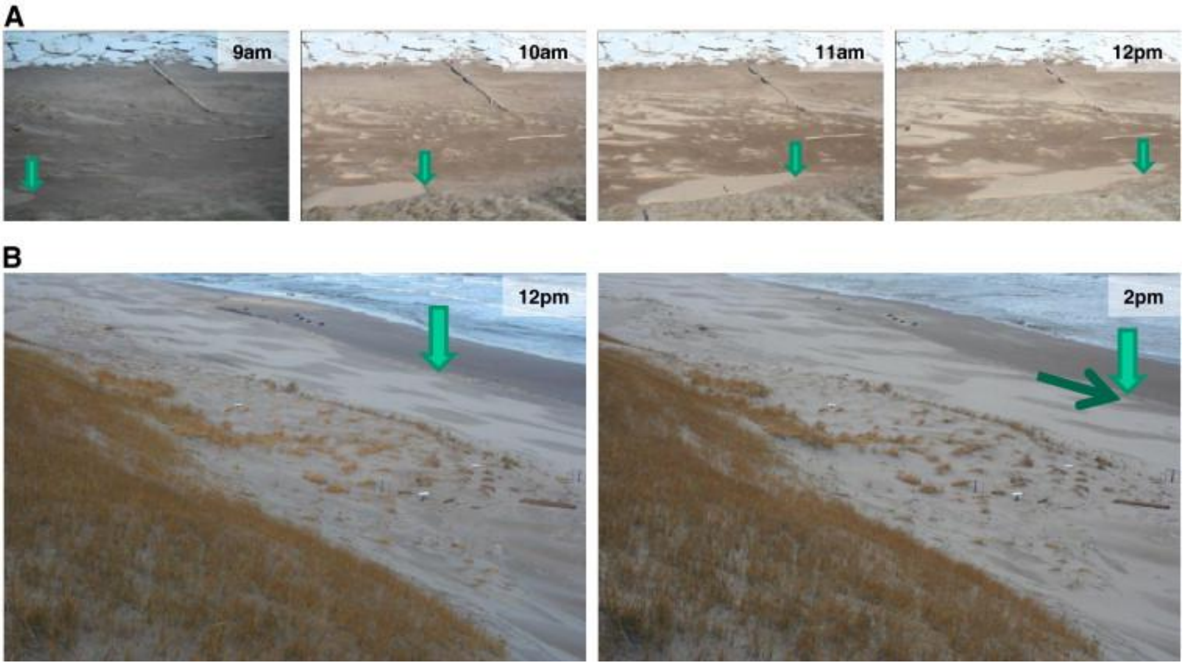

Fig. 7. A) Time series of images taken by the onshore camera during an alongshore transport event on April 3, 2008. Note that the shoreline is frozen and that dry sand transported by the wind seems to “slide” over the beach surface. The arrow points to the beginning of the sand patch as it enters into the field of view of the camera (9 am) and subsequently moves along the dune toe driven by the wind; B) Snapshots from the west-facing camera during an alongshore event on November 17, 2007. The first image (12 pm) was taken close to the beginning of the wind event, with patches of dry sand being formed over the wet surface. The second image was taken 2 h later, with alongshore sediment transport fully developed.

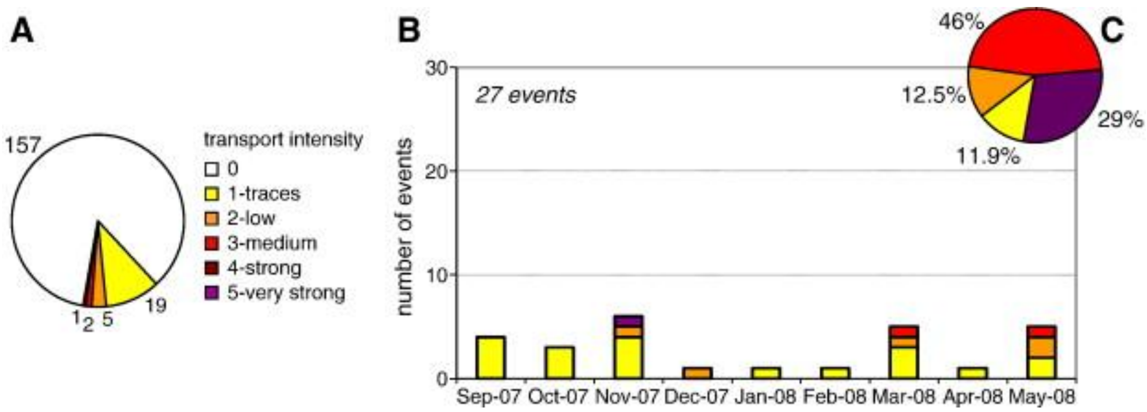

Fig. 8. Observed total transport modified by the angle of wind approach (coden — Section 5.2). A) Frequency of transport events delivering sediment to the foredune. Values on the outside of the pie chart specify the absolute number of events with different transport intensities. The total number of events was 27. Note that there were no strong transport events toward the foredunes; B) Monthly distribution of transport events toward the foredune. Note that November contained the only very strong transport event, while the two medium events occurred March and April. This graph may be compared with the monthly distribution of wind events toward the foredune in Fig. 4B; C) Percentage of total sediment carried by transport events of different magnitudes (Section 5.1). Values on the outside of the pie chart specify the actual percentage value.

1061

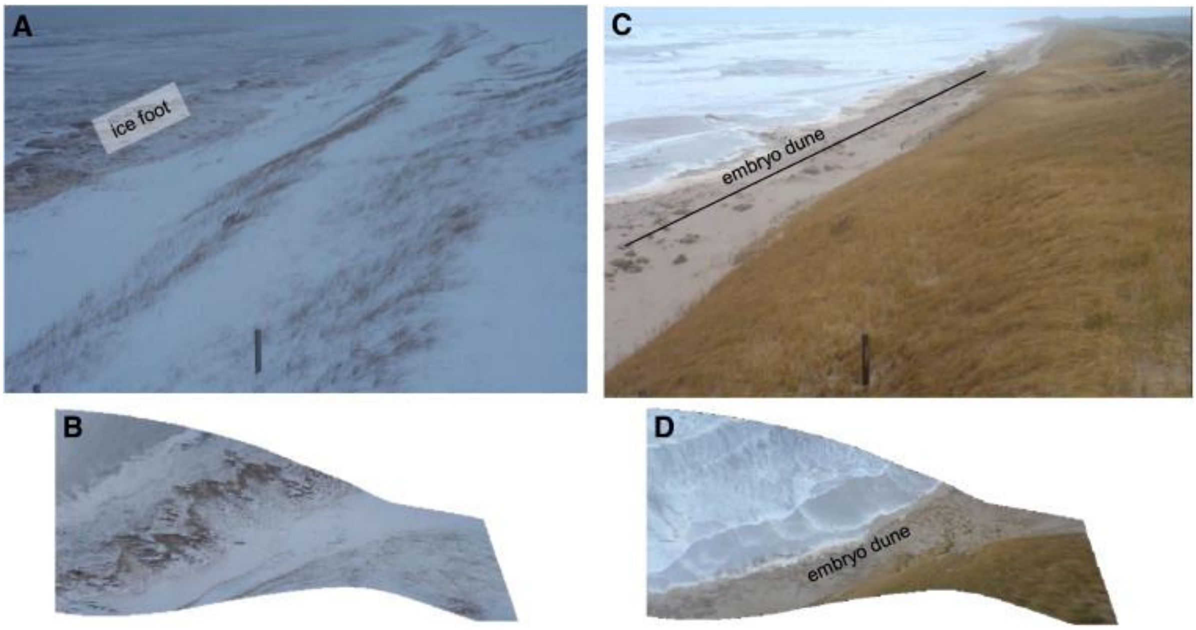

Fig. 9. Example of images taken by the east-facing camera during two large magnitude wind events at Greenwich. A) Gale on December 15, 2007: 30 h of strong winds (mean wind speed = 14.5 m s^{-1}) did not produce any transport because of snow/ice cover; C) Gale on December 1, 2007: strong winds (mean wind speed = 15 m s^{-1}) over 40 h were accompanied by extremely short fetches due to wave run-up. No transport was developed despite an oblique onshore angle of wind approach; B–D) Examples of rectified images from the west-facing camera taken at the same time/date as A and C respectively.

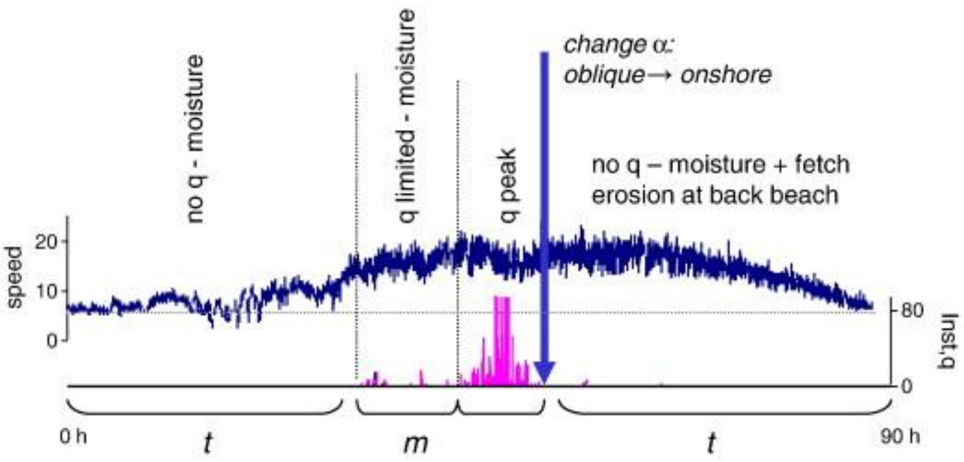

Fig. 10. Time (t) and magnitude (m) limited event. Wind speed (upper line, scale on the left) is expressed in m s^{-1}; saltation intensity (scale on the right) refers to the number of grains per second counted by a Safire averaged over 2 min. The x axis represents the time from 0 (beginning of wind event) to 90 h (end of wind event).

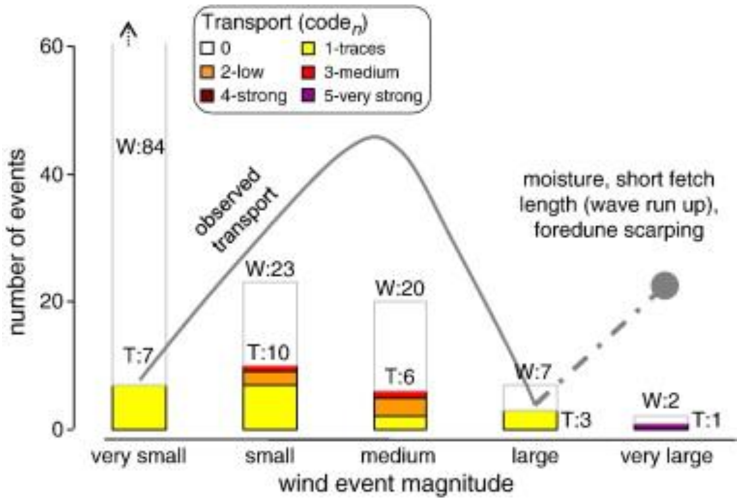

Fig. 11. Transport events (bar graph) and aeolian transport (line graph — Section 5.1) associated with different wind event magnitudes at Greenwich. The line graph is the result of adding the calculated transport of all events within the same bar in the graph. Wind events blowing over a snowed/iced surface have been excluded. W: number of wind events; T: number of transport events. As the magnitude of wind event first increased the proportion of wind events resulting in transport (T/W) increased. The peak of aeolian transport was associated with small to medium magnitude wind events. A further increase of the magnitude of wind event did not result in an increase of transport because the presence of factors such as moisture and short fetch distances. Only 1 out of 9 large and very large wind events produced strong transport, though sediment movement during this event was both time and magnitude limited (Section 6.2) and thus lower than the theoretical maximum.

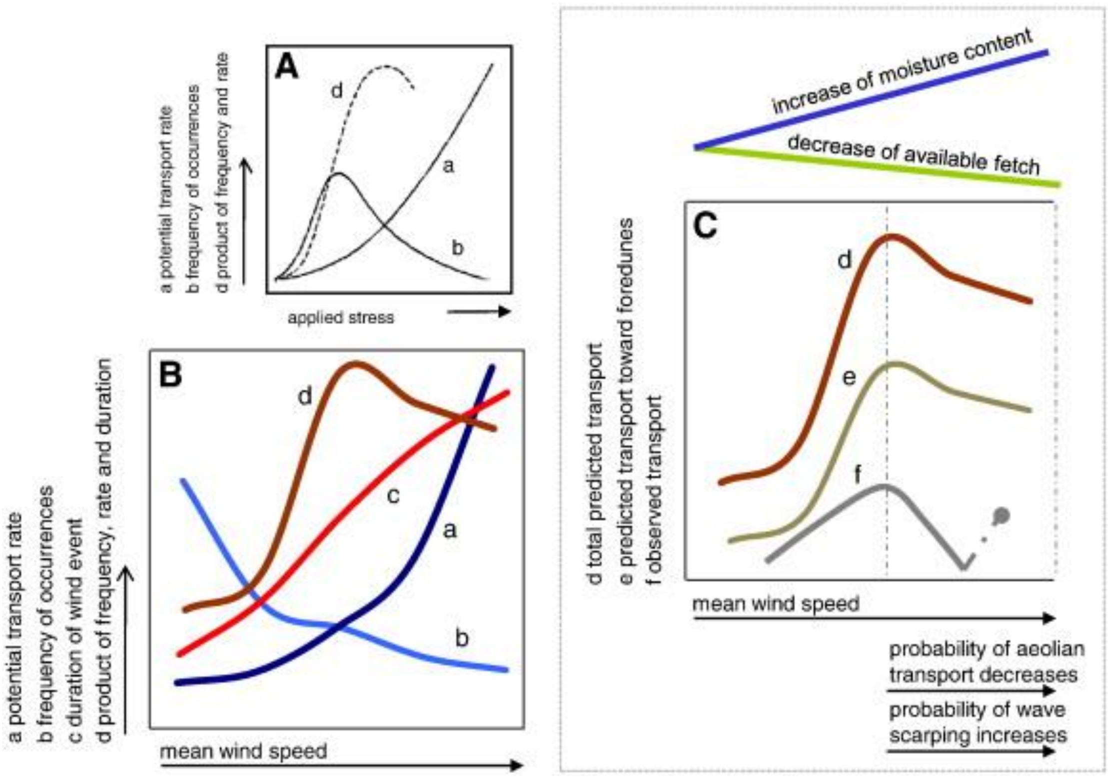

Fig. 12. A) Original model proposed by Wolman and Miller (1960) relating the frequency and magnitude of events in geomorphology; B) Modified model for wind events at Greenwich, showing the relation between wind event mean velocity and mean potential transport rate (a), frequency of wind event (b), duration of wind event (c), and product of event frequency, duration and potential sediment transport rate (d, equivalent to predicted Q). Note that winds below the threshold of 6 m s^{-1} are not included; C) Relation between Q, Qn, and observed transport toward the foredune at Greenwich. As the wind event magnitude increased the probability of transport approaching the theoretical value decreased and the probability of wave scarping increased.

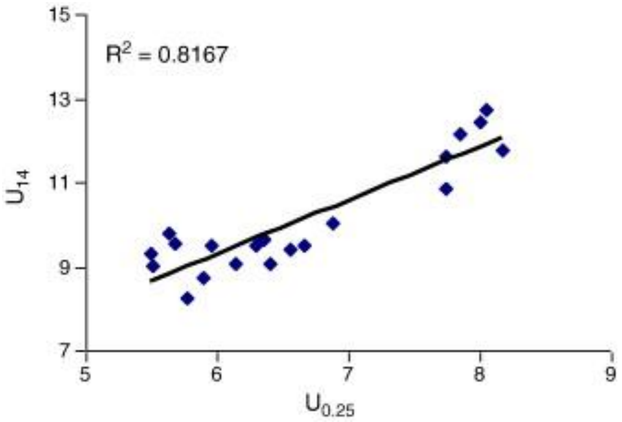

Fig. 13. Linear regression between wind speeds measured at 0.25 m over the beach surface with a cup anemometer ($U_{0.25}$) and at 14 m over the beach surface with the 2D sonic anemometer on top of the mast (U_{14}). Mean values (in m s^{-1}) are calculated for 10 min runs of data collected during a short-term experiment in October 2007.