

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

3

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6

7 **Abstract**

8 Observations of aeolian transport in coastal areas have focused on short-term
9 experiments because of limitations imposed by instrumentation. This paper uses a
10 case study at Greenwich Dunes, Prince Edward Island National Park, Canada, to
11 analyze how sediment transport takes place at the beach over periods of weeks to
12 months. A monitoring station provided hourly time series of vegetation cover,
13 shoreline position, fetch distances, surficial moisture content, presence of ice and
14 snow, wind speed and direction and transport processes over nine months. Analysis
15 shows that high wind speeds may not generate any net transport into the dunes
16 because of the limitations imposed by snow/ice cover, moisture, and short fetch
17 distances. Despite extreme winds during intense storms, such events often lead to
18 wave scarping rather than aeolian sediment input to the foredunes. When sediment
19 was transported on the beach, the magnitude was regulated by a combination of
20 factors including: angle of wind approach, fetch distance, moisture content, and
21 duration of the wind event. In particular, angle of wind approach (and therefore fetch
22 distance) may demote a high magnitude wind event with strong transport potential to
23 one with no transport at all, which poses challenges for predicting the effects of
24 individual storms over the course of several months. A significant proportion of
25 sediment delivery to the foredunes was associated with wind events of low to

26 medium magnitude. It is suggested here that large magnitude wind events have low
27 probabilities of resulting in transport towards the foredune because factors such as
28 wave inundation play an increasing role in preventing sediment movement across
29 the beach. This has implications for modelling and management, and highlights
30 differences between the magnitude and frequency of aeolian transport events in the
31 coastal environment compared to those in deserts and to fluvial sediment transport.

32

33 **Keywords**

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

35

36 **1. Introduction**

37

38 As in many other landscapes, coastal dunes evolve as a consequence of both
39 gradual changes in state variables (e.g., vegetation growth or decay) as well as
40 episodic event-based disturbances (e.g., wave scarping) (Pye, 1983 and Psuty,
41 2005). In particular, sediment input by wind from the beach to the adjacent foredunes
42 is intermittent both at the instantaneous (Stout and Zobeck, 1997) and medium
43 scales (Delgado-Fernandez and Davidson-Arnott, 2009). Knowledge of sand
44 transport by wind is essential for sediment budget calculations because it produces
45 an output of sediment from the beach and constitutes the primary source of sediment
46 supply for building the dune (Svasek and Terwindt, 1974 and Davidson-Arnott et al.,
47 2005). Therefore, understanding the characteristics of aeolian transport events in
48 coastal areas is necessary to predict the evolution of coastal dunes.

49 The role of transport events and their relation to morphological change has been
50 widely recognized in geomorphology (Higgitt and Lee, 2001). In general terms,

51 magnitude and frequency of events are inversely related. Stronger river flows, for
52 example, which have the potential to carry large sediment loads, tend to occur less
53 frequently. Thus, the significance of high magnitude events in terms of the proportion
54 of 'geomorphic work' accomplished may be quite small in comparison to events of
55 intermediate magnitude and frequency that are thought to dominate the fluvial
56 landscape (Wolman and Miller, 1960).

57 Knowledge about the characteristics of aeolian transport events contributing to the
58 long-term evolution of coastal dunes is surprisingly limited. Time series of sediment
59 transport for river flows are available from a variety of monitoring stations world-wide
60 over long periods of time, but there are no equivalent records for aeolian transport in
61 coastal areas. This poses several challenges for coastal aeolian geomorphology.

62 First, the lack of sediment transport time series at the same time resolution and
63 duration as wind records makes it difficult to assess the relative significance of wind
64 events of different magnitude. Prediction of sediment supply to the foredunes is often
65 based on hourly data of wind speed and direction from meteorological stations along
66 the coast that are incorporated into one of many alternative sediment transport
67 models that presume ideal conditions on the beach (e.g., Chapman, 1990 and Miot
68 da Silva and Hesp, 2010). Sediment transport calculations at meso-scales typically
69 assume a correspondence between applied stress (wind speed) and sediment
70 transport rate, and this may be modified by the cosine of the angle of wind approach
71 in order to account for sediment supply to the foredune per unit distance alongshore
72 (Davidson-Arnott and Law, 1996 and Bauer and Davidson-Arnott, 2003). Second,
73 there is a spectrum of problems associated with 'up scaling' results from short-term
74 experiments. The goal of many fieldwork studies is to observe significant events
75 where landform units are modified and forces affecting their evolution can be

76 measured and quantified. But even when a number of geomorphic processes are
77 characterized in detail over the course of a short-term experiment, traditional
78 experimental designs produce knowledge based on 'snapshots', and thus miss the
79 transition from one scale to another (Coulthard, 2009). This lack of a comprehensive
80 view on the dynamics of aeolian sediment transport, beyond the duration of short-
81 term experiments, is a major limitation to providing managers and planners with an
82 appropriate set of tools for decision-making (Sherman, 1995).

83 The recent incorporation of remote sensing techniques to measure aeolian
84 processes at the beach over long periods of time (months to years) has enabled the
85 direct observation of transport rather than relying on inference derived from
86 morphological evidence (e.g., Lynch et al., 2008 and Delgado-Fernandez et al.,
87 2009). The importance of this type of approach is that it allows matching time series
88 of wind speed and direction with observations and measurements of sediment
89 transport on the beach at the same time-scale.

90 The main objective of this paper is to characterize the magnitude and frequency of
91 aeolian transport events on the beach and to assess their role in supplying sediment
92 for foredune building using a data set collected with a remote sensing station at
93 Greenwich Dunes, Prince Edward Island National Park (Canada). The questions
94 addressed here are: 1. how do the frequency and magnitude of transport events
95 compare with the frequency and magnitude of the associated wind events?; and 2.
96 what is the effect of limiting factors such as moisture, fetch, snow and ice, and angle
97 of wind approach? If the presence of other variables weakens the relationship
98 between applied stress (wind) and the rate of sand transport, and if this can be
99 generalized to most beach–dune systems, then the conceptual ideas put forward
100 by Wolman and Miller (1960) may need to be adapted to the particular case of

101 aeolian transport in coastal areas. Information about the characteristics of transport
102 events identified in the time series described here can provide a means of enhancing
103 our ability to model meso-scale sand supply to the foredune.

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

108

109 **2. Regional setting**

110

111 Long-term monitoring of the beach and foredune was carried out at Greenwich
112 Dunes (Fig. 1A), located on the north shore of Prince Edward Island (PEI), Canada.
113 The measurements presented in this paper cover a section of the coast of
114 approximately 1.5 km in length. The foredune ranges in height from 6 to 10 m with a
115 steep stoss slope of 20–25° and the dune crest is aligned roughly east–west. The
116 beach is 30–40 m wide and consists predominantly of quartz sand with a mean grain
117 diameter of 0.26 mm. Marram grass (*Amophila breviligulata*) covers the foredunes
118 and exhibits considerable seasonal patterns of height and density. Summer months
119 are usually characterized by the development of a vegetated embryo dune which is
120 removed or strongly eroded every two or three years during Fall and Winter storms.
121 Monitoring of 9 profiles spaced along the 6 km-long shoreline of Greenwich Dunes
122 from 2002 to 2009 showed an average net deposition of sand in the foredune of
123 approximately 3500 kg m⁻¹ year⁻¹ with most deposition taking place during the Fall
124 and early Winter period and very little deposition occurring during the summer
125 months from June to August. Spatially, net deposition was consistently lowest along

126 the eastern end of the shoreline ($\approx 1250 \text{ kg m}^{-1} \text{ year}^{-1}$) and highest near the centre
127 ($\approx 6700 \text{ kg m}^{-1} \text{ year}^{-1}$). At the study site (white box in Fig. 1B) net deposition rates
128 were close to the average for the whole shoreline. Fig. 1C and D displays net annual
129 changes in deposition measured using a modified bedframe device (Davidson-Arnott
130 and Law, 1990 and Ollerhead et al., 2003) and morphological changes surveyed with
131 DGPS over a profile located within the study site (line W in Fig. 2). During the winters
132 of 2004 and 2008 intense storms resulted in erosion of the embryo dunes and cliffing
133 of the foredune (≈ -800 and $-6150 \text{ kg m}^{-1} \text{ year}^{-1}$ respectively). Annual net
134 deposition during the rest of the years was approximately 5111 kg m^{-1} , with a
135 maximum in 2006 ($\approx 9700 \text{ kg m}^{-1}$) and a minimum in 2003 ($\approx 1280 \text{ kg m}^{-1}$). Net
136 deposition from September 2007 to May 2008 was $\approx 3017 \text{ kg m}^{-1}$. Thus the study
137 site is representative of medium volumetric changes both spatially and temporally
138 and the period of observations presented in this paper is a year of average
139 deposition and storm events.

140 The coast is microtidal with a mixed semidiurnal regime and a maximum range at
141 spring tides of approximately 1 m. Precipitation at PEI is abundant year-round.
142 Annual average totals are approximately 1000 mm, with peaks from October to
143 January due to the more frequent and more intense storm activity. Wet days number
144 130 to 160 a year, with snow days accounting for 30% of them. Ice covers much of
145 the Gulf of Saint Lawrence from January to early April, reducing the marine influence
146 and strongly affecting temperatures in PEI which may fall below $-18 \text{ }^\circ\text{C}$. Drift ice is
147 often found around the Island as late as May and is subject to rapid movement as a
148 result of changing wind conditions (Environment Canada and Atlantic Climate
149 Center). During the 2007–2008 Winter the cameras at Greenwich recorded the
150 dynamics of sea ice, showing several periods of clearing from the nearshore during

151 offshore winds (sometimes in less than 24 h) and corresponding rapid build-up
152 during periods of onshore winds.
153 Prevailing winds from the SW and W occur predominantly in summer. These
154 offshore to alongshore winds are generally not competent to transport sediment to
155 the foredune despite their higher frequency (Walker et al., 2006). Fall and Winter
156 months are characterized by intense mid-latitude storms accompanied by strong
157 winds from the NE to the NW. Powerful North Atlantic storms with winds
158 $> 100 \text{ km h}^{-1}$ have the potential to deliver large volumes of sediment to the dune but
159 they may also be accompanied by heavy rain or snowfall and storm surge. Further
160 information regarding the study site may be found in Walker et al., 2003, Hesp et al.,
161 2005, Davidson-Arnott et al., 2008 and Bauer et al., 2009.

162

163 **3. Material and methods**

164

165 3.1. Instrumentation, data collection and processing

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

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

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

195 Four erosion–deposition (ED) pins were deployed within the field of view of the
196 cameras (Fig. 2B). The ED pins consisted of wooden rods marked at 2 cm intervals
197 driven vertically into the sand surface. Changes in the level of the sand against the
198 rod could be measured with an accuracy of 1 cm on the hourly photographs to give a
199 profile of net change in the sand surface elevation. The volume of sediment
200 deposition along two survey lines across the stoss slope and toe of the foredune was

201 measured every two to three months using a bedframe (Davidson-Arnott and Law,
202 1990 and Ollerhead et al., 2003). A series of wooden posts were augered into the
203 sand along the profile and levelled forming permanent stations spaced 3–5 m apart.
204 Measurements of the distance to the bed at 12 points within a 1 m × 1 m square
205 were made using a portable bedframe device consisting of an aluminum frame with
206 tabs to locate the measurement points. The bedframe has a square sleeve which
207 allows it to be slotted exactly over the 0.1 m × 0.1 m top of the post and thus permits
208 repeated measurements at each station with a high degree of accuracy. The
209 bedframe is moved from station to station and stored away from the line. Net erosion
210 or deposition at a particular station is determined by averaging the measurements
211 made at the 12 points within the frame.

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

224 Vegetation was extracted from each image using an Unsupervised Classification
225 available as part of the Analysis extension from Leica Systems, which isolated pixels

226 where vegetation was present. The 3D Analyst Tools was used to reclassify the
227 output into NoData values for all classes except the ones containing vegetation. The
228 shoreline was digitized manually for each photograph. Beach width was obtained
229 hourly from the position of the shoreline and the vegetation line. Storm surge, high
230 water levels, or spring tides (often in combination) strongly reduced beach width,
231 which also varied due to seasonal changes in the extent of embryo dune vegetation.
232 Beach width and mean angle of wind approach for a given hour were used to
233 calculate maximum fetch distances (Bauer and Davidson-Arnott, 2003).

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

251

252 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 measurements
	Transport intensity(qualitative)	2 h	Tabular data	
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 direction	2 min	Tabular data	

253

254 3.2. Analysis of wind and transport events

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

261

262 3.2.1. Wind events

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

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

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

278

279 Table 2. Wind classification used to group events based on the mean wind speed.
 280 Note that the Beaufort scale goes up to 12 (hurricanes have wind speeds
 281 $> 33 \text{ m s}^{-1}$).

282

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

283

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

291

$$292 \quad q = 1.16 \times 10^{-5} \cdot U^3 \quad \text{equation (1)}$$

293

294 where U is the mean wind speed in m s^{-1} and q is the instantaneous transport rate
295 in $\text{kg m}^{-1} \text{s}^{-1}$. The value of q represents the potential of wind to transport sediment
296 in the direction of the wind vector. In order to obtain a magnitude based on the
297 potential of wind to deliver sediment towards the foredune, q was modified by the
298 angle of wind approach (α) relative to shore normal (Davidson-Arnott and Law,
299 1996 and Bauer and Davidson-Arnott, 2003):

300

$$301 \quad q_n = q \cdot \cos \alpha \quad \text{equation (2)}$$

302

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

306

$$307 \quad Q = \sum_{i=1}^N q_i \cdot 3600 \quad \text{equation (3)}$$

308

309

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

313

314 $Q = \sum_{i=1}^N q_i \cdot \cos \alpha \cdot 3600$ equation (4)

315

316 Wind events were grouped into five classes ranging from very small to very large
317 potential transport based on the criteria outlined in Table 3 for both Q and Q_n . It is
318 worth noting that the absolute value for sediment transport predicted by
319 Eq. (1) depends in part on the constant which Hsu developed for the beaches he
320 worked on. According to Sherman et al. (1998), Hsu's equation calculates transport
321 rates close to those predicted by Bagnold's (1941) equation which are in the middle
322 range respect to other equations commonly used in aeolian geomorphology.

323 Furthermore, the focus of this study was on the relative magnitude of predicted
324 transport which is controlled primarily by U^3 and the duration of the event. Most
325 models use a cubic relationship between sediment transport rate and wind speed or
326 shear velocity, and in this regard, the approach was consistent with normal practice.

327

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

Q or Q_n (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

331

332 3.2.2. Transport events

333 Measuring sediment transport rates is a challenging task at the meso-scale.

334 Instrumentation needs to be deployed at the beach and left unattended over long
335 periods of time. There are a number of shortcomings associated with different types
336 of deployment, such as instrument failure or periods of low quality data (e.g., ED pins
337 may be removed by waves or Safires buried by sediment accumulation). However,
338 until alternative ways of measuring actual transport rates at the beach over the time
339 frame of months are developed, available instrumentation designed for short-term
340 experiments needed to be adapted. The approach at Greenwich to overcome these
341 adversities consisted of combining the techniques described in Section 3.1 (Table 1):
342 (1) Direct measurement of saltation intensity using Safires permanently deployed at
343 the back beach and embryo dune; (2) Indirect measurement of saltation intensity
344 using RGB image interpretation. Two consecutive snapshots were necessary to
345 observe sediment movement at the beach, shown by the migration of bedforms or
346 dry sand patches. For each event, information was extracted from the offshore-,
347 west-, and east-facing cameras, and compared amongst each other; (3)
348 measurement of erosion or deposition at a point on an hourly basis using the ED
349 pins; and (4) measurement of deposition in the embryo dune/foredune every
350 2 months along two survey lines using the bedframe technique.

351 In order to integrate this diverse information a qualitative scale was developed,
352 based primarily on the hourly photographic record, describing the intensity of
353 transport at the beach (Table 4). This classified transport into 6 codes ranging from 0

354 for no transport observed or measured, to 5 with large quantities of sand being
 355 transported across the entire beach. Events were associated with a transport code
 356 that reflected the peak of transport intensity (in any direction) observed during the
 357 event, together with the number of hours when transport was observed. In order to
 358 obtain a qualitative approximation of how much sand was moved towards the
 359 foredune, the transport code identified in Table 3 was modified by $\cos \alpha$ to produce
 360 a code which is equivalent to q_n predicted by Eq. (2). Thus for example, a code 4
 361 condition with strong transport on the beach could be reduced to a code 1 for highly
 362 oblique winds.

363

364 Table 4. Criteria used to classify transport events into different classes of transport
 365 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.

366

367 3.3. Supply-limiting conditions and fetch distances

368 Moisture maps were stored with a 0.05 m spatial resolution. Moisture content
369 exhibited very complicated patterns and its relation to sediment transport and wind is
370 worthy of detailed investigation beyond the scope of this paper. For the purpose of
371 the analysis reported here the spatial distribution of moisture values was simplified
372 into three broad categories: 1) 'dry', with at least 90% of beach surface containing
373 $\leq 2\%$ of moisture; 2) 'threshold-changing', with moisture of 2–10% covering the
374 beach surface; and 3) 'wet', when transport was completely shut down because of
375 rainfall or melting of snow/ice (moisture $> 10\%$ over the entire beach). The goal was
376 to differentiate clearly between moments when large values for moisture content
377 ('wet') yielded no transport (Davidson-Arnott et al., 2008) while acknowledging that
378 with smaller values of surface moisture ('threshold-changing') wind gusts and drying
379 may create a diversity of transport situations (Wiggs et al., 2004 and Davidson-Arnott
380 and Bauer, 2009).

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

389

390 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%

391

392 **4. Magnitude and frequency of wind events**

393

394 4.1. Wind events and potential transport in all directions

395 A total of 184 wind events were detected from September 1, 2007 to May 31, 2008
396 (Fig. 3). These encompass all the potential sediment transport events and thus the
397 starting point for prediction of sediment transport to the foredune. As expected
398 (e.g. Mathew, 2006) the frequency of events decreased with increasing values of the
399 mean wind speed class (Fig. 3A). Approximately half of wind events were ‘moderate
400 breezes’ with mean wind speeds of 6–8 m s⁻¹, 30% were ‘fresh breezes’ and 13.5%
401 were ‘strong breezes’. The remaining 10 events ranged from ‘very strong breezes’ (6
402 events) to a single ‘fresh gale’ with a mean wind speed exceeding 16 m s⁻¹. In
403 general event duration was greater with increasing mean wind speed (Fig. 3A, bar
404 graph) with most of the highest mean wind speed events lasting more than 24 h.
405 Because of the direct relationship between event duration and mean wind speed,
406 and the fact that aeolian sand transport scales with U³ rather than U, the mean wind
407 speed did not provide a good measure of the magnitude of the event. The potential
408 transport associated with each wind event was calculated using Eqs. (3) and (4) and
409 this value was used as a measure of the magnitude of the event for total transport
410 and for the proportion directed towards the foredune respectively (Section 3). Fig. 3B
411 shows the frequency of wind events by magnitude class as defined
412 in Table 3. Table 6 contains the relation between events magnitudes and mean wind

413 speeds. Approximately 60% (109 events) of all wind events fell into the very small
 414 magnitude class ($Q < 3 \times 10^2 \text{ kg m}^{-1}$) as a result of short durations and/or very low
 415 wind speeds (83% of events of very small magnitude were moderate breezes).
 416 There were 11 large magnitude wind events ($27 \leq Q < 81 \times 10^2 \text{ kg m}^{-1}$) and 4 very
 417 large magnitude wind events with the potential to transport more than
 418 $8.1 \times 10^3 \text{ kg m}^{-1}$.

419

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

Mean wind speed (m s ⁻¹)	Event magnitude (Q)				
	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

422

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

430

431
$$Q_{m\%} = \frac{(Q_i \times F)}{Q_{tot}} \cdot 100$$
 equation (5)

432

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

446

447 4.2. Wind events and potential transport toward the foredune

448 The formation of coastal dunes requires onshore winds capable of moving sediment
449 landward (Pye, 1983 and Davidson-Arnott and Law, 1990). Offshore events
450 accounted for almost half of the total events recorded at Greenwich (90 out of 184).
451 If offshore wind events are eliminated the total predicted transport decreases to 71%
452 of the original amount. As winds with an onshore component approach the beach at
453 an increasingly oblique angle, the cosine effect drastically reduces the amount of
454 sand delivered to the foredunes per unit distance alongshore (Bauer and Davidson-
455 Arnott, 2003). The reduction in potential transport due to the cosine effect decreased
456 the predicted amount delivered to the foredune to approximately 41% of the total

457 potential transport. Fig. 4B displays alongshore to onshore wind events which
458 magnitude was reduced according to how much the wind direction departed from
459 onshore perpendicular (Q_n). Despite an overall decrease in the number and
460 magnitude of events, the percent of sediment potentially carried by onshore wind
461 events remained essentially the same as that for all wind events (compare pie
462 graphs in Fig. 4A and B).

463

464 **5. Magnitude and frequency of transport events**

465

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

476

477 5.1. Transport in all directions

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

482 There was only one very strong transport event resulting from a very large
483 magnitude wind event (mean speed of 12–14 m s⁻¹, duration 90 h) starting on
484 November 9 (discussed in detail in Section 6.2). There were 6 strong and 18 medium
485 transport events, which were primarily associated with medium and large magnitude
486 wind events (mean wind speeds between 8 and 12 m s⁻¹; Table 6). Only 2 out of 18
487 medium transport events resulted from wind events with mean speeds < 8 m s⁻¹.
488 The first occurred on March 26, 2008 with constant alongshore winds of
489 7.25 m s⁻¹ blowing over 24 h; the second developed on April 30, with offshore winds
490 of 7.8 m s⁻¹ blowing dry sand from the dune and blowouts to the beach.
491 The number of hours over which transport was observed increased with the transport
492 code. Fig. 5B shows that transport events with lower codes (trace and low transport)
493 tended to last 5 h or less, while the mean duration of strong and very strong
494 transport events was over 25 h (note that there was only 1 very strong transport
495 event). The Fall was the most active season for aeolian sediment transport (Fig. 5C).
496 November contained the only event coded as 5 (very strong transport) and the
497 majority of code 4 (strong transport) events. Very few transport events were
498 recorded in the winter months of December, January and February, but transport
499 events became more frequent early in the spring and continued through
500 May. Section 6 compares transport events in Fig. 5C with wind events in Fig. 4A and
501 examines the effects of supply-limiting factors.
502 In order to obtain an approximation of the relative proportion of sand moved by
503 transport events of different magnitude, a simple calculation multiplying the transport
504 intensity code by the duration of transport event was computed (Fig. 5D) and the
505 procedure described in Section 4.1 was applied. It is assumed here that the transport
506 classes are exponential rather than linear to account for the relationship with U³. In

507 other words, the increase in transport is larger when going from medium to strong
508 than from trace to low. Almost 40% of the total sediment was carried during medium
509 transport events (of medium frequency and duration according to Fig. 5A and B).
510 Approximately 33% of the sediment was moved during strong transport events of low
511 frequency, followed in percentage by low intensity but frequent events (17%) and a
512 single very strong transport event (8%). Very small (trace) transport events were
513 insignificant in terms of the amount of sediment they carried (2.5%). Thus, medium
514 and strong transport events were most important from the perspective of aeolian
515 sediment movement at Greenwich but how much of this sediment played a role in
516 building the foredune? What controls beach and dune sediment exchange and sand
517 input to the foredune?

518

519 5.2. Transport toward the foredune

520 Fig. 6 shows the transport events according to the predominant wind direction during
521 the event. Note that there was almost no transport associated with wind directions
522 alongshore from the east, and that the majority of transport was developed during
523 westerly winds. Most transport periods coded as 4 (strong) were associated with
524 alongshore and offshore wind angles. Alongshore winds blowing over long fetch
525 distances along the beach were able to accumulate and build-up dry sand patches
526 quickly even in the presence of high surficial moisture content. These sand bedforms
527 progressively migrated over the moist surface, 'sliding' over the beach. Fig. 7 shows
528 two examples of typical alongshore wind events with strong transport and sediment
529 moving over a moist or a frozen surface. Topographic steering might result in some
530 sediment going into the foredune with alongshore or even offshore winds (Lynch et
531 al., 2008). However, the existence and strength of recirculating eddies producing

532 onshore transport during offshore winds still needs to be explored and is likely
533 related to factors such as dune height, wind direction, and wind speed. In agreement
534 with previous observations at Greenwich (Walker et al., 2006) the net quantity
535 delivered to the dune during offshore flows was found to be insignificant compared to
536 the total transport during the event.

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

557

558 **6. The role of limiting factors**

559

560 The comparison between applied stress (wind events) and transport processes
561 observed at Greenwich leads to several questions. The first question is why so many
562 of the observed wind events did not result in any transport, despite having the
563 potential to do so based on theoretical considerations. In particular, there is a need
564 to assess the conditions regulating the strongest wind events at the beach because
565 of their extraordinary potential to move large amounts of sediment
566 ($> 27 \times 10^2 \text{ kg m}^{-1}$ per event). The windiest season (Winter) is the least effective
567 season for transport (compare Fig. 4A and B with Fig. 5 and Fig. 8, respectively).
568 While extensive snow/ice cover was responsible for preventing many transport
569 events during the winter, the comparison between Fig. 4 and Fig. 8 suggests that
570 there were other factors limiting the development of transport over the entire study
571 period. There is a need to clearly identify the role of fetch distances and moisture
572 content, and in what type of situations they play a significant role in shutting down
573 sediment transport.

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

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

585

586 6.1. Inhibition of sediment transport during wind events

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

604

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

Date	U	U _{max}	WD	α	Q	Q _n	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 Q _n in 9 months					37%	45%		

608
 609 The most important limiting factor was the presence of snow and ice over the beach
 610 surface during the winter months. This factor shut down sediment transport during 6

611 of the 10 events listed in Table 8. Included in this group is the fresh gale on
612 December 3, 2007, with the highest potential sand transport of the study period. In
613 this instance transport would also have been shut down for a large portion of the
614 event by storm surge and wave run-up, as wave action resulted in significant erosion
615 of the embryo dune. The gales on December 12 and 15 presented similar conditions,
616 with 80–90% of the surface covered by snow/ice (Fig. 9A and B). Storm surge and
617 wave run-up were the key factor preventing sediment transport during the third gale
618 on December 1 as well as wind events on October 29, 2007 and January 14, 2008.
619 The gale lasted 46 h but no sediment movement was recorded despite an oblique
620 onshore wind direction from the west, because of beach inundation due to wave run-
621 up (Fig. 9C and D). Rain was a primary factor preventing sediment transport alone
622 (event on October 4, 2007) or in combination with other factors (event on September
623 23, 2007) (Table 8).

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

629 The exclusion of offshore wind events decreased the amount of total predicted
630 sediment transport (Q) to 71% of its original amount. The reduction in potential
631 transport due to the cosine effect for those winds with an onshore component was of
632 41% respect to the transport predicted in all directions (Q_n respect Q). Limiting
633 factors preventing sediment entrainment during entire onshore wind events further
634 decreased the potential input to the foredune to 16% of the original amount.
635 Furthermore, when transport was observed, limiting factors often reduced its

636 magnitude due to complex relationships between wind speed, event duration, angle
637 of wind approach and fetch distance. This will be discussed in the next section.

638

639 6.2. 'Time limited' and 'magnitude limited' events

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

651 In order to show some these interactions it is instructive to focus on the detailed time
652 series recorded during the only very strong transport event on November 9–13, 2007
653 (Fig. 10). This event led to burial of vegetation of the embryo dune due to deposition
654 of approximately 25 cm of sand. Despite of strong winds exceeding the threshold for
655 sand movement for 90 h, transport was only recorded by the Safires on the upper
656 beach for approximately 28 h. High surface moisture content due to rainfall
657 prevented transport during the first 20 h of the storm. An increase of wind speed on
658 the morning of November 10 (blowing obliquely from the NE and therefore yielding a
659 relatively long fetch distance) favoured sediment movement during the second
660 portion of the storm, though the magnitude of transport was limited due to

661 intermittent rain. A subsequent increase of wind speed coinciding with low tide (and
662 therefore a wide beach and long fetch distance) generated intense instantaneous
663 transport on the back beach. The wind direction changed from oblique to nearly
664 shore perpendicular on the morning of November 11, producing a storm surge
665 which, coupled with a rising tide, led to inundation of the beach during the final
666 portion of the storm. This resulted in a complete shut down of the aeolian transport
667 system and partial erosion of the embryo dunes.

668 In summary, transport was only detected during 28 h (time limited) and its intensity
669 was reduced at least over 15 h (magnitude limited). Furthermore, the peak in wind
670 speed did not coincide with the peak in aeolian transport, but rather with sediment
671 output from the dune because of wave scarping. This suggests that in this system
672 the strongest stresses may not yield the greatest amount of geomorphic work. These
673 results are in-line with observations on the importance of oblique angles of wind
674 approach (long fetch distances) and their relation with increases in sediment
675 transport rates on narrow beaches (Nordstrom and Jackson, 1993 and Bauer et al.,
676 2009).

677

678 **7. Discussion**

679

680 7.1. Characteristics of wind events delivering sediment to the foredunes

681 Three events at Greenwich accounted for approximately 75% of the total transport
682 delivered to the foredune over the 9 month study period and the remainder was
683 accounted for by a small number of events of lesser magnitude
684 (Section 5.2). Fig. 11 displays transport events toward the foredune (coden) with
685 respect to wind event magnitude. For the purpose of generalizing the discussion to

686 other locations, wind events blowing over a surface significantly covered by snow/ice
687 are not included (total of 48). Observed transport (continuous line) was calculated by
688 adding the total transport for all events within each of the graph bars. The total
689 transport for each event is a relative value based on the intensity transport code
690 (coden) and duration of transport event (Section 5.1). This allows for an estimation of
691 the type of wind events that were responsible for sediment input to Greenwich dunes
692 over the period.

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

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

715

716 7.2. Conceptual model for aeolian sediment input to foredunes

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

736 actual “work” performed by most of these large magnitude wind events was
737 insignificant and this was the primary source of over-prediction of sediment input to
738 the foredune at the site.

739 Fig. 12C compares predicted and observed transport at Greenwich based on the
740 results of this study. Curve d is repeated from Fig. 12B and represents the predicted
741 sediment transport in any direction, and curve e represents the predicted sediment
742 transport toward the foredunes (these are equivalent to Q and Q_n in the pie graphs
743 of Fig. 4A and B, respectively). As discussed in Section 4.2, the predicted sediment
744 transport towards the foredune was approximately 41% of the total potential
745 transport but the percent of sediment potentially carried by different magnitude wind
746 events remained essentially the same despite introducing the cosine effect.

747 Curve f is repeated from Fig. 11 and represents observed transport at Greenwich.
748 This curve summarizes, conceptually, results discussed in Section 6: sediment input
749 to Greenwich dunes was both time and magnitude limited and decreased with
750 increasing wind magnitude because of the role imposed by limiting factors such as
751 moisture or fetch distances. Gales and very strong breezes blowing over snow-free
752 surfaces resulted in storm surge and even wave scarping (Section 6.1), and thus
753 were associated with sediment removal from the foredune rather than sediment input
754 through aeolian processes. Thus, the probability of large magnitude wind events
755 producing correspondingly large magnitude transport events decreases as the mean
756 wind speed of the event increases. While the high wind speeds associated with low
757 frequency, high magnitude events are important in calculating sediment erosion and
758 transport in desert environments and agricultural fields, these may be completely
759 counterbalanced in coastal areas by processes related to nearshore dynamics and
760 beach–dune interaction (Psuty, 1988 and Sherman and Bauer, 1993).

761

762 7.3. Implications for numerical modelling

763 Meso-scale modelling approaches based on hourly measurements of wind speed
764 and direction (e.g. Fryberger and Dean, 1979) calculate sediment transport based
765 on U^3 and thus magnify the potential of strong (and long) wind events that, in the
766 coastal zone, have a very low probability of resulting in any significant sand
767 movement. Over-prediction of sediment input to the foredune on a time-scale of a
768 year is thus likely due primarily to the inclusion of large magnitude wind events
769 during which transport either does not occur or is significantly reduced, rather than to
770 uncertainty associated with estimates of the threshold value for sand movement or
771 simplifications of sediment characteristics at the beach surface (e.g., grain size).

772 There are two primary problems in attempting prediction of sediment inputs to
773 coastal dunes over periods of weeks to years: 1) determining an appropriate set of
774 equations that incorporate complexities such as surface moisture content, beach
775 width and fetch distances; and 2) securing quantitative data on these variables for
776 input into a model at time scales of weeks to months. Although an exact prediction of
777 dune development over years may not be possible using deterministic equations,
778 such simulations could aid in our understanding of the most likely scenarios
779 (Sherman, 1995). Probabilistic approaches such as those commonly used in
780 meteorological modelling may improve meso-scale sediment transport predictions in
781 coastal areas, and measuring their quality may be more critical than measuring their
782 absolute accuracy (Sutherland et al., 2004).

783 Finally, predictions of sediment supply to the foredune at the meso-scale should be
784 based on factors that can be measured or estimated rapidly and at minimal expense
785 (Davidson-Arnott and Law, 1990). Most meteorological stations along the coast

786 contain hourly data sets of wind speed and direction, precipitation (both snow and
787 rain), water levels, temperature and other variables. Additionally, beach width can be
788 predicted by combining tide data and storm surge predictions based on standard
789 meteorological data. The time series at Greenwich are currently being used to
790 determine how factors such as surficial moisture content and fetch distances may be
791 estimated in this way and to assess the reliability of such predictions.

792

793 **8. Conclusions**

794

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

810 snow/ice cover on this beach. At least 60% of the largest magnitude wind events
811 encountered a surface protected by a frozen beach.

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

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

832 Although key factors controlling sediment dynamics will likely vary depending on the
833 geographical location and beach dimensions, the contribution of this paper was to
834 demonstrate that the largest transport rates do not necessarily occur during periods

835 when wind speeds are at their greatest. This is linked to the essential characteristics
836 of aeolian transport on coastal areas, which yield tradeoffs between beach geometry,
837 angle of wind approach and fetch distance. These critical interrelationships reinforce
838 the uniqueness of coastal dunes.

839

840 **Acknowledgments**

841

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859 anonymous reviewers.

860

861 **Appendix**

862

863 This research makes use of hourly wind speed recorded at 14 m height over the
864 beach surface. Thus, there is a need to justify the use of both the wind velocity and
865 the minimum velocity to keep sand in saltation at 14 m as a surrogate for drag
866 velocity and threshold shear velocity. According to Fryberger and Dean (1979, p.
867 146) one may use hourly wind speed data at 10 m height over the beach surface to
868 predict transport by making several simplifying assumptions. If shear velocity is
869 proportional to the wind velocity at any given height then the Lettau and Lettau
870 (1977) equation may be modified as follows:

871

872 $q \propto U^{*2}(U^* - U_t^*)$ equation (6)

873

874 into:

875

876 $q \propto U^2(U - U_t) \cdot t$ equation (7)

877

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

885

886 $U_{t(z)} = 5.75U_t^* \log(z/z') + U_t'$ equation (8)

887

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

891

$$z' = 3.05 \times 10^{-3} \text{ m}$$

$$U_t' = 2.74 \text{ m s}^{-1}$$

892 $U_t^* = 0.16 \text{ m s}^{-1}$

893

894 The resulting wind impact threshold wind velocity at Greenwich following Fryberger
895 and Dean's approach is $U_{t(14 \text{ m})} = 6.11 \text{ m s}^{-1}$, which is similar to the one used in this
896 study based on calculations by Delgado-Fernandez and Davidson-Arnott (2009) after
897 a short-term experiment at Greenwich beach. These authors compared mean values
898 of wind speed at 0.25 m and 14 m height over the beach surface extracted from 20
899 10-minute runs (Fig. 13) and suggested an approximate correlation factor of 0.66.
900 Previous research by Davidson-Arnott et al. (2008) involving the use of cup
901 anemometers and saltation probes at the same study site suggested a minimum
902 wind speed of 4.2 m s^{-1} at 0.3 m high for measuring transport (average value for cup
903 anemometer at the foreshore). Delgado-Fernandez and Davidson-Arnott
904 (2009) decreased this threshold to 4 m s^{-1} to ensure that no transport periods were
905 lost during a filtering procedure. Thus, a wind of 4 m s^{-1} at 0.25 m high corresponds
906 to 6.1 m s^{-1} at 14 m.
907 Finally, Bagnold (1941, p. 101) suggests that the threshold velocity at any
908 height z may be calculated as follows:

909

910
$$U_{t(z)} = 5.75A \sqrt{\frac{\sigma - \rho}{\rho} g d \cdot \log(z/k)}$$
 equation (9)

911

912 where $A = 0.1$, σ is the density of grain material (2650 kg m^{-3}), ρ is the density of air
913 (1.22 kg m^{-3}), d is the grain diameter (0.26 mm at Greenwich beach), k is the
914 roughness factor ($z' = 3.05 \times 10^{-3} \text{ m}$), and $z = 14 \text{ m}$. Under these
915 conditions, $U_{t(14 \text{ m})} = 4.99 \text{ m s}^{-1}$, which is significantly lower than the values predicted
916 previously.

917 The use of one threshold value for wind speed over months contradicts many
918 findings about the high variability of thresholds for sand movement at the
919 instantaneous scale (e.g., Wiggs et al., 2004 and Davidson-Arnott and Bauer, 2009).
920 Furthermore, any of the methods above require several assumptions regarding
921 sediment and flow characteristics, which introduce uncertainties in calculations (e.g.,
922 an increment of z' from 0.0018 to 0.01 decreases $U_{t(14 \text{ m})}$ from 6.55 to 5.63 m s^{-1} in
923 Eq. (8)). Variations in sediment size and sorting, packing and surface characteristics
924 will introduce large variations in the critical shear stress and hence will have
925 significant effects on transport. However, one may assume a low enough wind
926 threshold for dry sand under which transport is not likely to occur. Sediment transport
927 rates around this threshold are also likely to be small, so the effect should be
928 insignificant in predicting total sediment transport over a period of months. Analysis
929 in this study suggest that the refinement of the wind threshold for dry sand may not
930 be a first order priority if this is used to isolate moments where transport has the
931 potential to occur (wind events). There was only one transport event of less than
932 6 m s^{-1} over nine months at Greenwich (mean wind speed = 5.1 m s^{-1} , duration of
933 wind event = 10 h ; transport code = 1-traces; duration of transport = 2 h). Events with

934 wind speeds from 6 to 8 m s⁻¹ were responsible of only 2.5% of the total transport in
935 all directions. Wind events driving the majority of sediment to the foredunes
936 presented higher wind speeds.

937 Two images were necessary to observe evidences of sediment movement from
938 bedform migration or ED pins records and thus this dictated the minimum duration of
939 an event. Isolated hourly records of wind speeds over 6 m s⁻¹ did take place in the
940 time series but were ignored in the analysis, which was also supported by the lack of
941 transport evidences from the Safires records during those particular short time
942 periods. Even if transport may have occurred this was negligible over the long-term
943 because isolated records of wind speed tended to be of very low magnitude. There
944 were 83 isolated hourly values of wind speeds > 6 m s⁻¹ and 78 (94%) of them were
945 < 8 m s⁻¹.

946

947 **References**

948

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

951 Baas, A.C.W., 2007. Complex systems in aeolian geomorphology. In: Murray, A.B.
952 and Fonstand, M.A. (Eds.), Proceedings of the 38th Binghamton
953 Geomorphology Symposium, Duke University, October 5-7. Geomorphology
954 91 SI, 311-331.

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

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

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

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

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

969 Darke, I., Davidson-Arnott, R.G.D. and Ollerhead, J., 2009. Measurement of beach
970 surface moisture using surface brightness. *Journal of Coastal Research* 25,
971 248-256.

972 Davidson-Arnott, R. G. D. and Law, M. N., 1990. Seasonal patterns and controls on
973 sediment supply to coastal foredunes, Long Point, Lake Erie. In: Nordstrom,
974 K. F., Psuty, N. P. and Carter, R. W. G., (Eds.), *Coastal Dunes: Form and*
975 *Processes*, John Wiley & Sons Ltd., 177-20.

976 Davidson-Arnott, R. G. D. and Law, M. N. 1996. Measurement and prediction of
977 long-term sediment supply to coastal foredunes. *Journal of Coastal Research*
978 12, 654-663.

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

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

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

988 Delgado-Fernandez, I. and Davidson-Arnott, R.G.D., 2009. Sediment input to
989 foredunes: description and frequency of transport events at Greenwich
990 Dunes, Prince Edward Island, Canada. *Journal of Coastal Research*, SI 56,
991 Proceedings of the 10th International Coastal Symposium, Lisbon, Portugal,
992 302-306, v1.

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

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

999 Hesp, P.A., Davidson-Arnott, R.G.D., Walker, I.J. and Ollerhead, J., 2005. Flow
1000 dynamics over a foredune at Prince Edward Island, Canada. *Geomorphology*
1001 65, 71-84.

1002 Higgitt, D.L., and Lee, M.E., 2001. *Geomorphological processes and landscape*
1003 *change: Britain in the last 1000 years*, Wiley-Blackwell, 320 pp.

1004 Hsu, 1974. Computing eolian sand transport from routine weather data. Proceedings
1005 of the 14th Conference on Coastal Engineering, ASCE, New York, 1619-1626.

1006 Lynch, K., Jackson, D.W.T. and Cooper, A.G., 2008. Aeolian fetch distance and
1007 secondary airflow effects: the influence of micro-scale variables on meso-
1008 scale foredune development. *Earth Surface Processes and Landforms* 33,
1009 991-1005.

1010 Mathew, S., 2006. *Wind Energy. Fundamentals, Resource Analysis and Economics*,
1011 Springer, xii+246 pp.

1012 Miot da Silva, G., Hesp, P.A., and Dillenburg, S.R. (in press). Coastline orientation,
1013 aeolian sediment transport and foredune and dunefield dynamics of
1014 Moçambique Beach, southern Brazil. *Earth Surface Processes and*
1015 *Landforms*.

1016 Nordstrom, K.F., Jackson, N.L., Bruno, M.S. and de Butts, H.A., 2002. Municipal
1017 initiatives for managing dunes in coastal residential areas: a case study of
1018 Avalon, New Jersey, USA. *Geomorphology* 47, 137-152.

1019 Ollerhead, J., Johnson, P., Davidson-Arnott, R.G.D., Walker, I. and Hesp, P.A.,
1020 2003. Sediment supply to coastal foredunes, Greenwich Dunes, *Proceedings*
1021 *of the Canadian Coastal Conference*. CCSEA, Kingston, Ontario, pp. 12.

1022 Psuty, N.P., 2005. The Evolving Paradigm of Coastal Geomorphology Inquiry. In:
1023 Sanjaume, E. and Mateu., J. (Eds.), *Geomorfologia Litoral i Quaternari*,
1024 *Homenatge al professor V.M. Rossello i Verger*. Universitat de Valencia,
1025 Spain, 373-382.

1026 Pye, K., 1983. Coastal Dunes. *Progress in Physical Geography* 7, 531-597.

1027 Sherman, D.J., 1995. Problems of scale in the modeling and interpretation of coastal
1028 dunes. *Marine Geology* 124(1-4): 339-349.

1029 Stout, J.E. and Zobeck, T.M., 1997. Intermittent saltation, *Sedimentology* 44, 959-
1030 970.

- 1031 Sutherland, J., Peet, A. H. , and Soulsby, R.L., 2004. Evaluating the performance of
1032 morphological models. *Coastal Engineering* 51, 917-939.
- 1033 Svasek, J. N. and Terwindt, J. H. J., 1974. Measurement of sand transport by wind
1034 on a natural beach, *Sedimentology* 21, 311-322.
- 1035 Walker, I.J., Hesp, P.A., Davidson-Arnott, R.G.D. and Ollerhead, J., 2003.
1036 Topographic effects on airflow over a vegetated foredune: Greenwich Dunes,
1037 Prince Edward Island, Canada. *Proceedings Coastal Sediments '03*. ASCE,
1038 New York, pp. 15.
- 1039 Walker, I. J., Hesp, P.A., Davidson-Arnott, R.G.D., and Ollerhead, J., 2006.
1040 Topographic Steering of Alongshore Airflow over a Vegetated Foredune:
1041 Greenwich Dunes, Prince Edward Island, Canada. *Journal of Coastal*
1042 *Research* 22, 1278-1291.
- 1043 Wiggs, G.F.S., Atherton, R.J. and Baird, A.J., 2004. Thresholds of aeolian sand
1044 transport: establishing suitable values. *Sedimentology* 51, 95-108.
- 1045 Wolman, M.G. & W.P Miller. 1960. Magnitude and frequency of forces in geomorphic
1046 processes. *Journal of Geology* 68, 54-74.

1047

1048 References Online:

10491. Environment Canada, Atlantic Climate Center

1050 <http://atlantic-web1.ns.ec.gc.ca/climatecentre/default.asp?lang=En&n=CACEE433-1>

1051 [Consult : July 30, 2009]

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1053 **List of Figures**

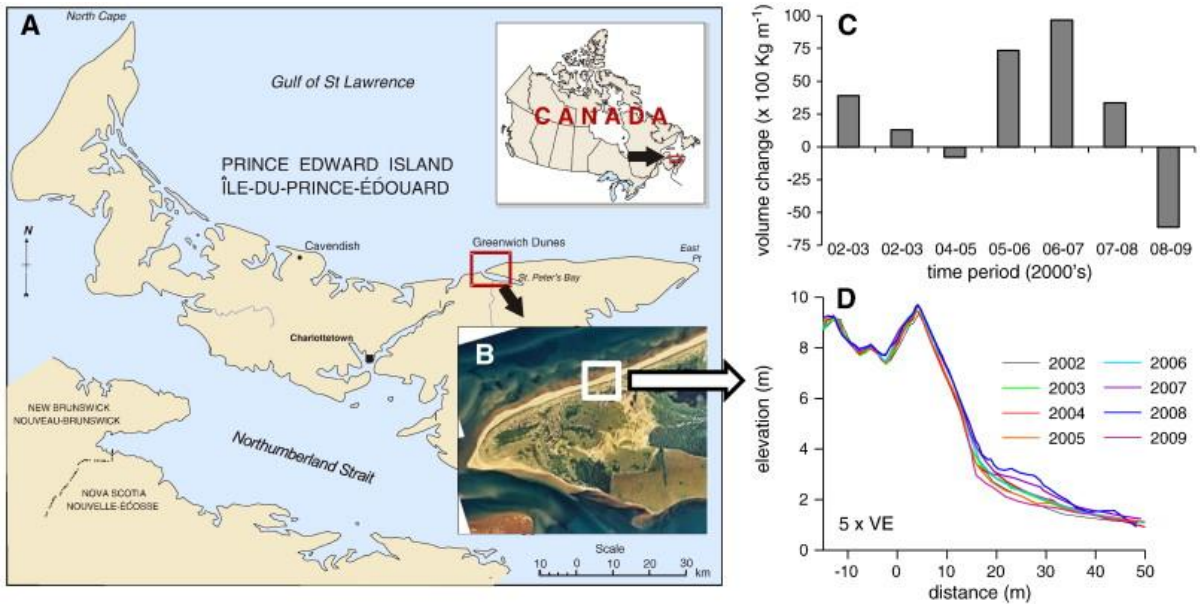


Fig. 1. A) Location of study area; B) Close up on Greenwich Dunes and location of the study site (white box); C) Net volume changes measured by the bedframe technique at line W located within the study site during the decade of the 2000s (see relative location in Fig. 2); D) DGPS surveys of line W reflecting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

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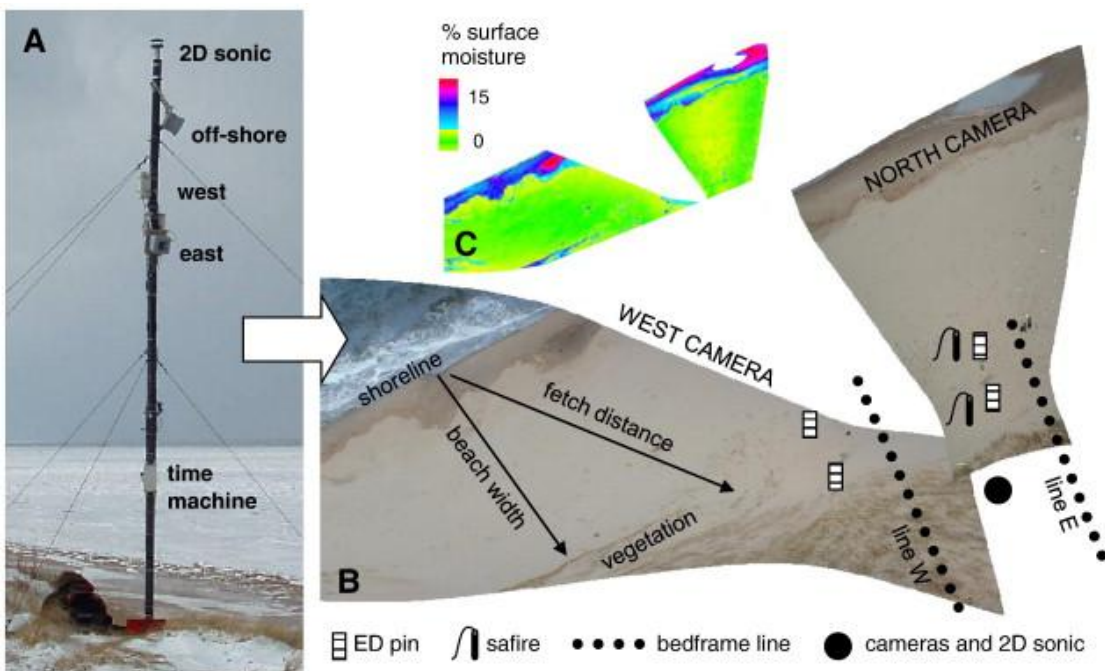


Fig. 2. A) Principal components of the long-term monitoring station. A 2-D sonic anemometer was located at the top of the mast, with three digital cameras below it; B) Example of rectified images for the offshore (north facing) and west-facing cameras and instruments deployment; C) example of moisture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

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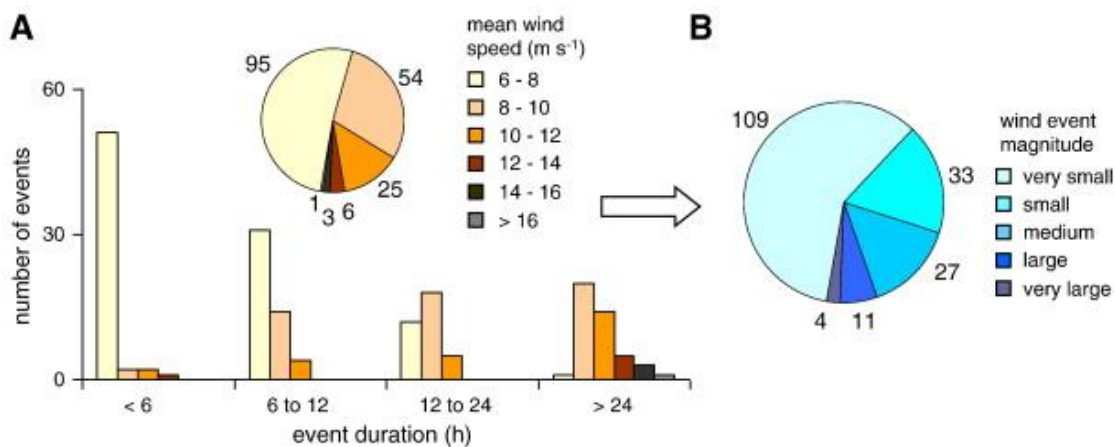


Fig. 3. A) Percentage and duration of wind events with different mean wind speeds. In general, the number of events decreased and the event duration increased with increasing mean wind speed; B) Magnitude of wind events based on potential sediment transport Q (kg m^{-1}) calculated using hourly wind 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.

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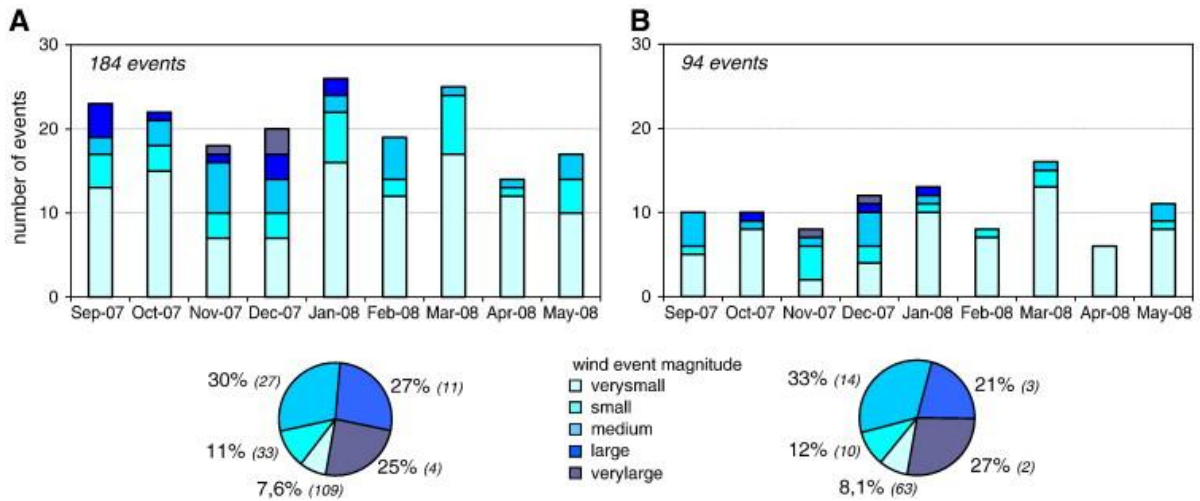


Fig. 4. A) Monthly distribution of all wind events (all directions), with magnitudes based on Q (kg m^{-1}); B) Monthly distribution of wind events potentially delivering sediment to the dune (onshore to alongshore), with magnitudes based on Q_n (kg m^{-1}). Offshore events make up approximately half 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.

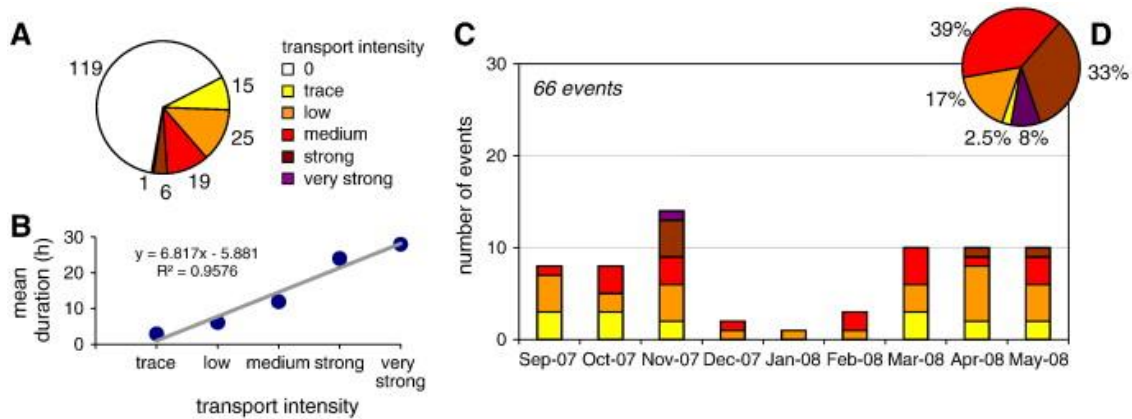


Fig. 5. Observed transport from all directions, based on the qualitative transport code assigned to each event (Table 4). A) Frequency of transport events. Values on the outside of the pie chart indicate the number of events with different transport intensities. The total number of transport events was 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.

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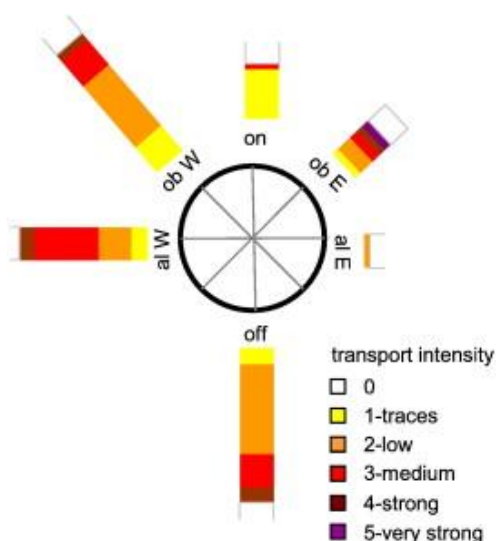


Fig. 6. Grouping of transport events at Greenwich Dunes based on the predominant wind direction for each event; “on” = onshore; “ob” = oblique; “off” = offshore. Note that a large percentage of the observed transport was associated with either offshore or alongshore wind directions which are assumed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

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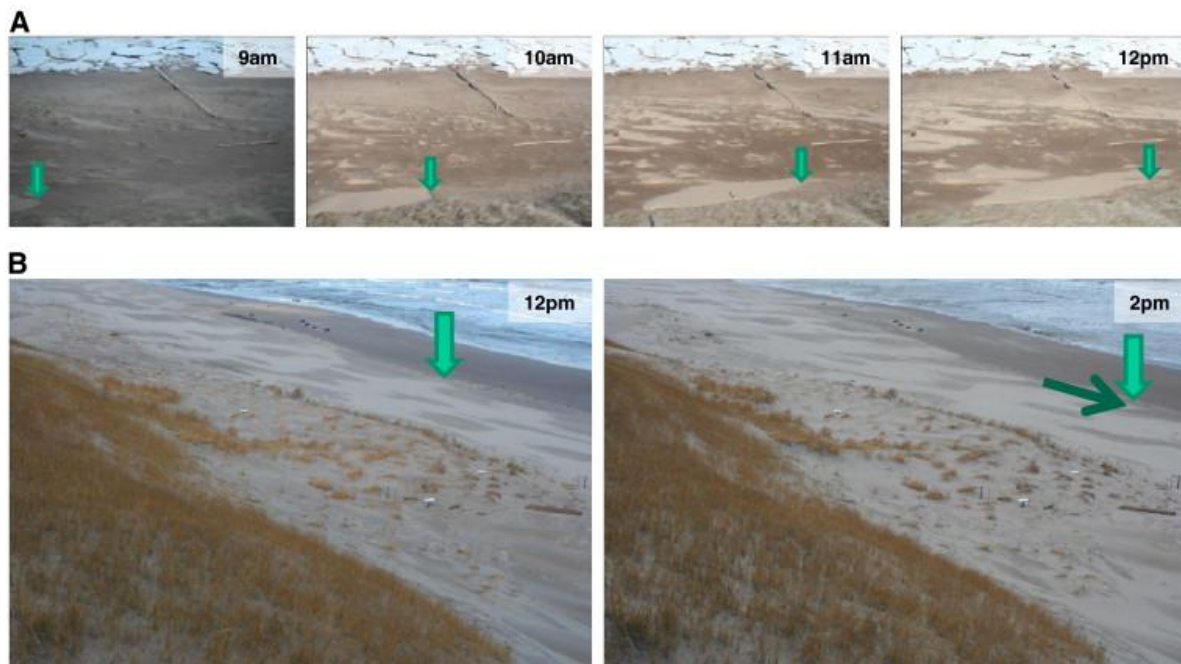


Fig. 7. A) Time series of images taken by the onshore camera during an alongshore transport event on April 3, 2008. Note that the shoreline is frozen and that dry sand transported by the wind seems to “slide” over the beach surface. The arrow points to the beginning of the sand patch as it enters into 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.

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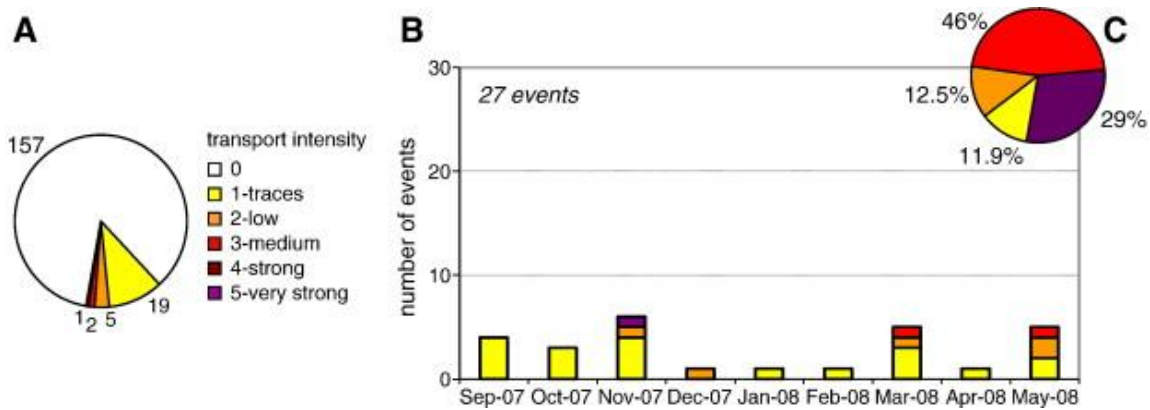


Fig. 8. Observed total transport modified by the angle of wind approach (coden — Section 5.2). A) Frequency of transport events delivering sediment to the foredune. Values on the outside of the pie chart specify the absolute number of events with different transport intensities. The total number of events 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.

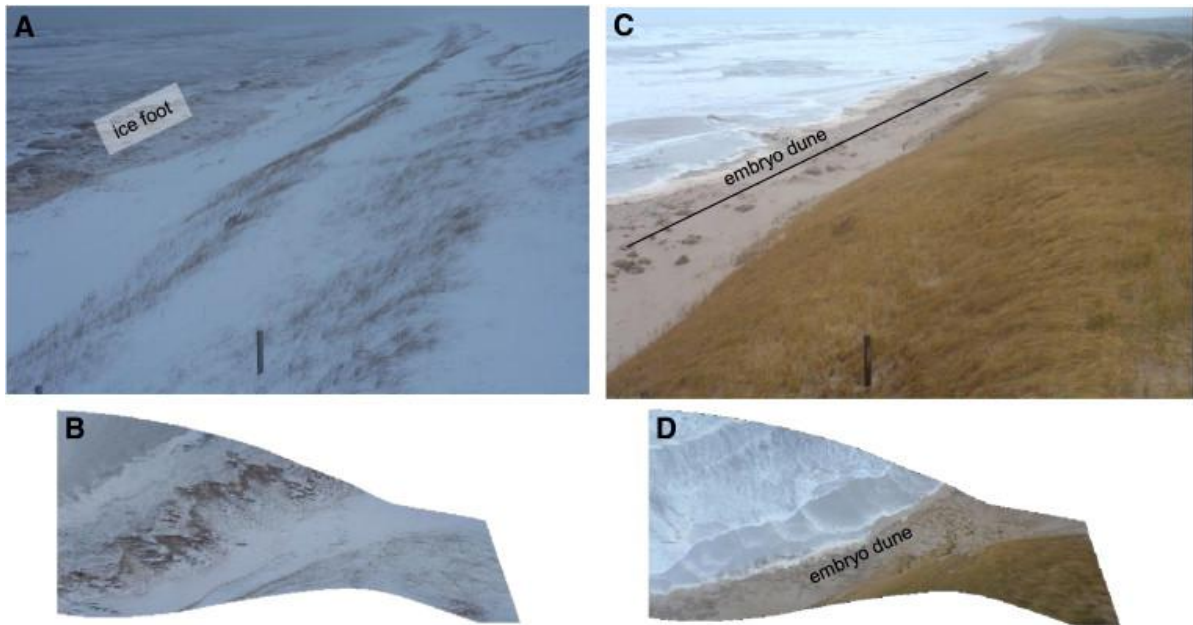


Fig. 9. Example of images taken by the east-facing camera during two large magnitude wind events at Greenwich. A) Gale on December 15, 2007: 30 h of strong winds (mean wind speed = 14.5 m s^{-1}) did not produce any transport because of snow/ice cover; C) Gale on December 1, 2007: strong winds (mean 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.

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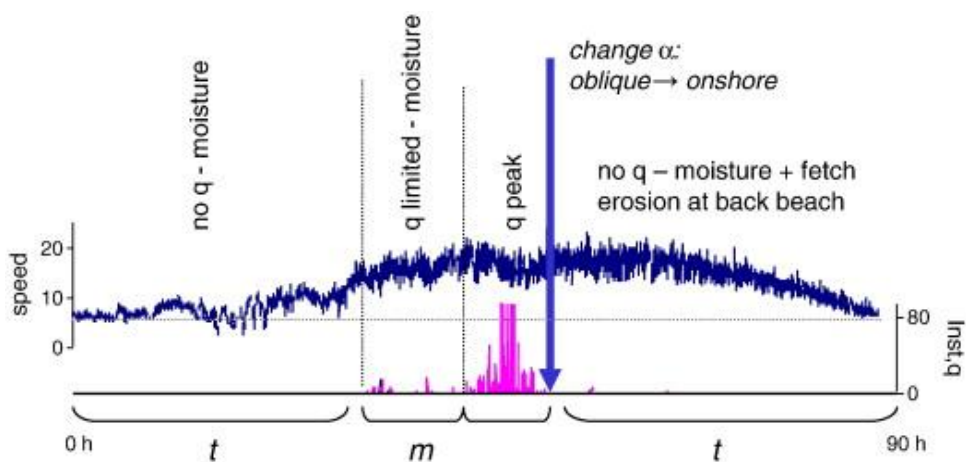


Fig. 10. Time (t) and magnitude (m) limited event. Wind speed (upper line, scale on the left) is expressed in m s^{-1} ; saltation intensity (scale on the right) refers to the number of grains per second counted by a Safire averaged over 2 min. The x axis represents the time from 0 (beginning of wind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

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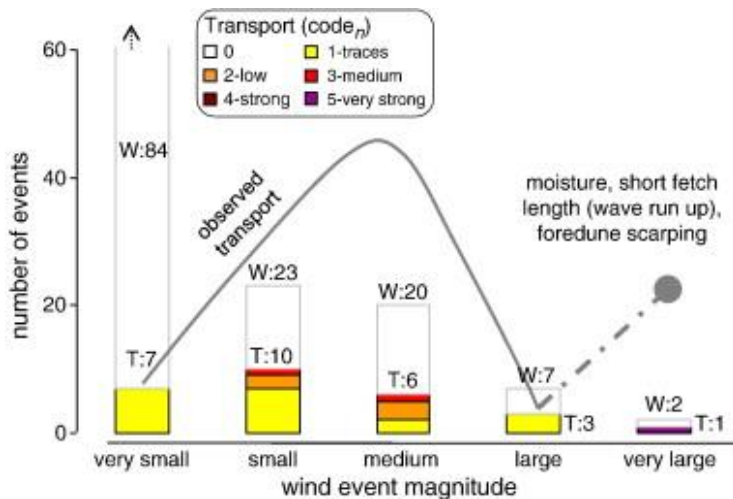


Fig. 11. Transport events (bar graph) and aeolian transport (line graph — Section 5.1) associated with different wind event magnitudes at Greenwich. The line graph is the result of adding the calculated transport of all events within the same bar in the graph. Wind events blowing over a snowed/iced surface 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.

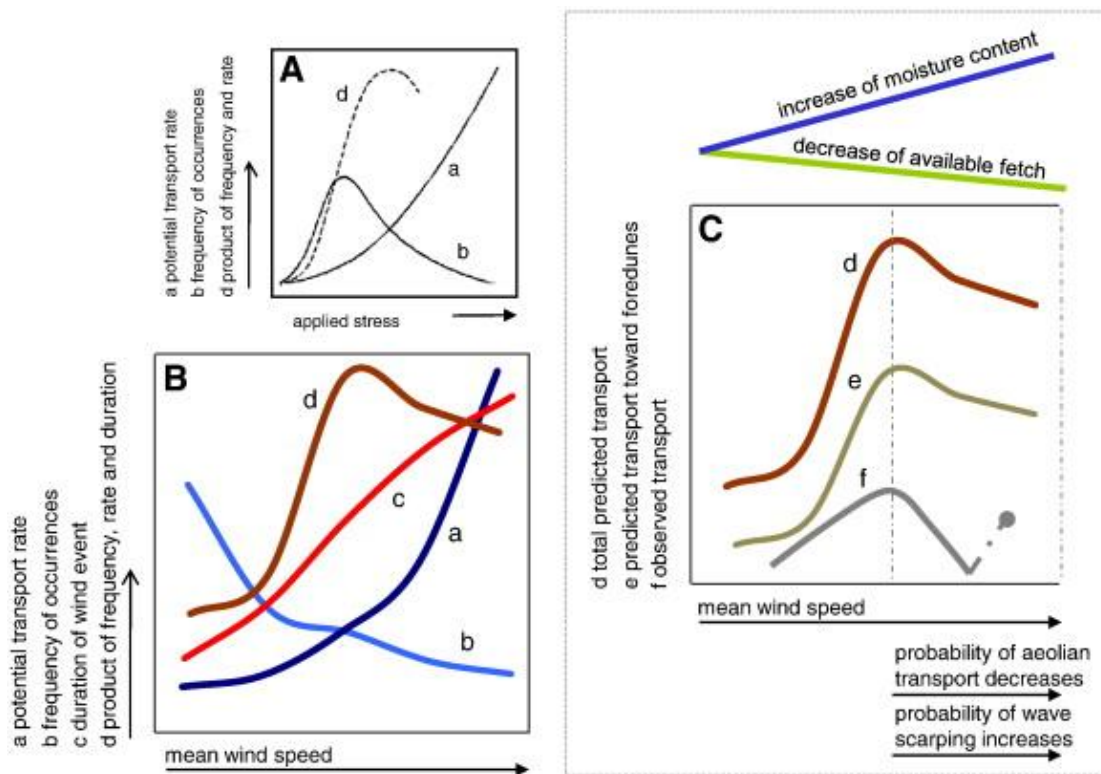


Fig. 12. A) Original model proposed by Wolman and Miller (1960) relating the frequency and magnitude of events in geomorphology; B) Modified model for wind events at Greenwich, showing the relation between wind event mean velocity and mean potential transport rate (a), frequency of wind event (b), duration 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 , Q_n , 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.

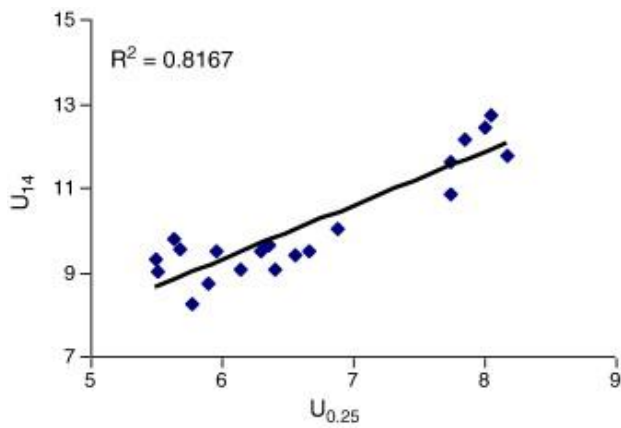


Fig. 13. Linear regression between wind speeds measured at 0.25 m over the beach surface with a cup anemometer ($U_{0.25}$) and at 14 m over the beach surface with the 2D sonic anemometer on top of the mast (U_{14}). Mean values (in m s^{-1}) are calculated for 10 min runs of data collected during a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