Meso-scale modelling of aeolian sediment input to coastal dunes

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Abstract

The collection of a time series coupling hourly wind data (speed and direction) with sand transport over months has provided new insights into the dynamics of transport events that input sediment to the foredune at Greenwich Dunes, Prince Edward Island National Park, Canada. This paper summarises the key aspects of aeolian sediment movement for a period of 9 months and presents a modelling approach for resolving aeolian transport to coastal dunes at the meso-scale. The main hypothesis of the modelling approach is that a small number of key factors control both the occurrence and the magnitude of transport events. Thresholds associated with these factors may be used to filter the time series and isolate potential transport periods over the year. The impacts of nearshore processes are included in the approach as part of the dynamics of coastal dunes, as are supply-limiting factors and trade-offs between fetch distances, angle of wind approach, and beach dimensions. A simple analytical procedure, based on previously published equations, is carried out to assess the general viability of the conceptual approach. Results show that the incorporation of moisture and fetch effects in the calculation of transport for isolated potential transport periods

result in improved predictions of sediment input to the dune. Net changes, measured with three different techniques, suggest that survey data with coarse temporal resolution underestimates the amount of sand input to the dune, because sediment is often removed from the embryo dune and foredune by other processes such as wave scarping. Predictions obtained by the proposed modelling approach are of the same order of magnitude as measured deposition and much less than predicted by models based solely on wind speed and direction. Areas for improvement and alternative modelling approaches, such as probabilistic approaches similar to weather forecasting, are covered in the discussion.

Research Highlights

- Aeolian sediment input to coastal dunes is not only a function of wind speed.
- This work proposes a modelling approach that improves predictions at the meso-scale.
- The incorporation of factors such as fetch and moisture improves calculations.

Keywords

Transport events; Beach–dune interaction; Foredune sediment budget; Foredune evolution

1. Introduction

Coastal dunes occur at the intersection of two geomorphic systems: the aeolian realm which is necessary to create them and the suite of nearshore processes that have a substantial impact on their evolution. A fundamental aspect of beach–dune interaction is the output of sand from the beach by wind processes, which represents the primary sediment input to foredunes and is essential in calculations of coastal dune budgets (Hesp, 1988a, Psuty, 1988a, Psuty, 1988b and Nickling and Davidson-Arnott, 1990). A wind strong enough to transport sediment is a necessary condition for the creation of coastal dunes (Sherman and Hotta, 1990) as is the determination of a surface shear stress threshold value required to set sediment in motion (Coates and Vitek, 1980). Because of the unique location of coastal dunes within a complex suite of aeolian and nearshore processes, Delgado-Fernandez and Davidson-Arnott (2011) suggest that foredune building occurs within a zone whose lower bound is the minimum wind stress necessary for sand transport and whose upper bound marks the transition to foredune scarping by waves.

Sediment input by wind to the adjacent coastal dune system at the meso-scale is usually predicted by incorporating hourly wind speed and direction data measured at standard meteorological stations into sediment transport equations. This procedure often consists of integrating instantaneous transport rate equations (e.g., Bagnold, 1941, Kadib, 1964,Hsu, 1974 and Lettau and Lettau, 1977) in relation to time and wind direction (e.g.,Fryberger and Dean,

1979, Kroon and Hoekstra, 1990, Lynch et al., 2008 and Wahid, 2008). The resulting calculations, however, frequently do not agree with observed values of sand deposition on the dunes (e.g., Hunter et al., 1983, Sarre, 1989, Chapman, 1990 and Davidson-Arnott and Law, 1996). Supply-limiting factors are often cited as being responsible for decreasing potential sediment transport rates and thus confounding predictions of sand input to the foredunes (Nickling and Davidson-Arnott, 1990). Variables such as moisture, presence of snow cover, fetch distances, development of gravel lags, surface crusts, and differences in sediment characteristics may limit sediment supply from the beach surface. All of these factors can vary rapidly both in space and time and are subject to a strong seasonal pattern on mid-latitude beaches as a result of storm action, the growth and decay of vegetation, and temperature fluctuations above and below freezing (e.g., Ruz and Meur-Ferec, 2004).

Research has focused on identifying the effects of each factor individually on instantaneous transport rates, but there is a lack of understanding of their combined effect over weeks or months (Bauer and Sherman, 1999). Not all factors may be of the same relative significance and some may be secondary when modelling at the meso-scale (e.g., the existence of small surface irregularities). Previous studies suggest that sediment input to the dune is primarily controlled by trade-offs between the angle of wind approach, fetch lengths, event duration and surficial moisture content (Bauer and Davidson-Arnott, 2003 and Delgado-Fernandez and Davidson-Arnott, 2011), with these being more or less relevant depending on the type of wind event. Strong

alongshore winds, for example, may generate significant amounts of transport, even with large amounts of superficial moisture content, due to long fetch distances. However, as a strong wind shifts onshore at some angle, the probability of generating sediment movement decreases because the combined effect of surface moisture and short fetch distances can shut down the transport system (Delgado-Fernandez and Davidson-Arnott, 2011). A strong onshore wind may even result in wave scarping of the dune instead of aeolian sediment input from the beach because of storm surge and wave run-up; these, in turn, are dependent on beach width, wind speed and wind direction. Beach width varies with beach slope, tidal range, and wave characteristics, whilst wind direction is of essential importance both in regulating fetch distances and wave run-up (Nordstrom and Jackson, 1993, Christiansen and Davidson-Arnott, 2004, Bauer et al., 2009 and Delgado-Fernandez and Davidson-Arnott, 2011). Nearshore processes and foredune scarping (Psuty, 1988a, Psuty, 1988b, Sherman and Bauer, 1993 and Hesp, 2002) and trade-offs between fetch distances and angle of wind approach (Bauer and Davidson-Arnott, 2003) have been incorporated into conceptual models of beach and dune interaction, but not yet into numerical modelling of aeolian sand transport to coastal dunes (Bauer and Sherman, 1999). There is a need to improve the state of sediment transport predictions at the meso-scale both by exploring new data sets of wind characteristics, supply-limiting factors and fetch distances, and by investigating more comprehensive ways to input data from meteorological stations into available formulae.

This paper makes use of a data base of hourly measurements of winds and sand deposition over months at Greenwich Dunes to develop a modelling approach for resolving aeolian transport to coastal dunes on the meso (time)scale. The first part of the paper introduces the conceptual model (Section 4). This combines information about the nature of aeolian transport events (Delgado-Fernandez and Davidson-Arnott, 2011) and elements of the framework described by Bauer and Davidson-Arnott (2003), which allows parameterization of the fetch and cosine effects. The essential aspect of the modelling approach is that predictions of the rate of aeolian sediment transport, based first on wind speed and direction, can be improved by incorporating relationships between wind, fetch, beach width, and transport-limiting factors such as moisture content and snow cover. The second part of the paper evaluates the viability of the approach using a simple analytical procedure that allows calculation of sand transport from the time series recorded at Greenwich (5 and 6). Results are compared with actual measured net deposition at the foredune over the nine month study period and with predictions based solely on wind speed and direction (Section 7). The discussion (Section 8) focuses on areas of further research, limitations to obtain appropriate observations of sediment deposition that can be compared with meso-scale predictions, and alternative ways (such as probabilistic models) of translating the conceptual ideas presented here into better predictions of sediment input to coastal dunes. The purpose of the modelling approach is similar to that of previous studies such as Fryberger and Dean, 1979 and Davidson-Arnott and Law, 1990, and it is specifically designed to make use of available data from

meteorological stations and/or data that can be measured simply and quickly in the field since this is the only realistic approach (to date) for predicting sediment supply to foredunes on a meso-(time)scale basis. Although the choice of a particular sand transport equation may result in transport rates that differ over an order of magnitude (Sherman et al., 1998) the focus here lies in the way to apply available formulae at the meso scale.

2. Regional setting

This research focused on a 1.5 km-long section of a beach–dune system at Greenwich Dunes, Prince Edward Island (PEI) National Park, Canada (Fig. 1A). The study area is microtidal and has a relatively narrow beach (30–40 m wide) consisting predominantly of quartz sand with a mean diameter of 0.26 mm. The foredune ranges in height from 6 to 10 m and presents a steep stoss slope of 20–25°. The dune crest is aligned from 250 to 270° and the foredune is covered by marram grass (Amophila breviligulata), which exhibits considerable seasonal variations in height and density. Summer months are usually characterised by the development of an embryo dune, which is removed or strongly eroded during winter storms every two or three years.

Annual average precipitation is approximately 1000 mm, with peaks from October to January due to more frequent and intense storms. Snow days (from November to April) account for 30% of days with precipitation. Ice surrounding PEI from January to early April forces a continental climate and strongly affects

temperatures at Greenwich (which may reach − 18 °C). Prevailing winds from the SW and W (offshore) occur predominantly in summer and are largely unable to transport sediment to the foredune despite their higher frequency (Walker et al., 2006). Dominant storm winds from the NE to the NW in the winter can exceed 100 km h^{-1} on occasions. These have a larger potential to deliver sediment to the dune but are often associated with storm surges and heavy rain or snow. Further information of the study site may be found in Walker et al., 2003, Hesp et al., 2005, Davidson-Arnott et al., 2008, Bauer et al., 2009 and Darke et al., 2009.

3. Field measurements and data base development

3.1. Wind characteristics, fetch distances and supply limiting factors

The results presented in this paper cover 9 months of data collection (September 2007–May 2008). The experimental set-up is described in detail in Delgado-Fernandez et al. (2009) and consisted of a camera system coupled with auxiliary instrumentation to measure winds and transport processes (Fig. 1B). The camera system was comprised of three Cannon 8-megapixel digital single lens reflex (SLR) cameras controlled by a Mumford Time Machine ™ programmed to take simultaneous exposures every hour. The cameras were attached to a 6 m-high mast located on top of the 8 m foredune crest. The set-up was completed with a 2-Dimensional Windsonic anemometer on top of the mast at an elevation of 14 m above the beach surface. Wind speed and direction were sampled at a frequency of 1 Hz, with mean values being stored every 2 min on a HOBO Energy Pro data

185 logger. The east-facing camera provided qualitative data on weather and wave
186 conditions over an area of approximately 1.5 km alongshore. The offshore and
187 west-facing cameras covered distances of 40 m and 100 m alongshore,
188 respectively. The images from these two cameras were rectified based on a
189 model developed using 40–50 ground control points (Fig. 2C), and used to
190 generate maps of fetch distances, moisture and supply-limiting factors
191 (Section 3.3).
192
193 3.2. Measurements of sand deposition
194 Measuring aeolian sediment transport over weeks to months is a challenging
195 task. The use of sediment traps at Greenwich was not feasible simply because
196 traps need to be emptied on a regular basis, including trench traps (e.g., Lynch et
197 al., 2008). Traps also present a tendency to clog when the sand is wet and it may
198 be difficult to establish their efficiency (Davidson-Arnott and Law, 1990). Two
199 Safire saltation probes (Baas, 2004) were deployed at the back beach and
200 foredune toe (Fig. 2C–D) within the field of view of the cameras. This allowed
201 assessment of the quality of Safire records by monitoring the height of the
202 piezoelectric sensor with respect to the sand surface. This height was reset to
203 5 cm during site visits of every 2 months but the instruments were sometimes
204 buried or even destroyed and/or removed by nearshore processes (Delgado-
205 Fernandez and Davidson-Arnott, 2011). Although there were transport events
206 over which Safires provided good measurements of saltation intensity (e.g., the

207 storm described inSection 7.3) the time series were not continuous and thus not
208 appropriate for the purpose of long-term analysis.
209 In the absence of other techniques to measure sediment transport rates over
210 weeks directly (to the knowledge of the author), the approach taken at Greenwich
211 consisted on using the volume of sediment deposition on the dune as an indirect
212 measure of sediment transport from the beach. This was based on the work
213 by Davidson-Arnott and Law, 1990 and Davidson-Arnott and Law, 1996 who
214 assumed that, if the vegetation is high and dense, windblown sediment from the
215 beach deposits within a few tens of metres of the vegetation line. Changes in bed
216 elevation were measured using three techniques with different temporal
217 resolutions (Fig. 2C–D), with the objective of obtaining a range of values of
218 measured deposition that, though crude, were adequate to test the validity of the
219 modelling approach. First, two profiles, located on either side of the camera
220 tower and spaced 23 m apart, were surveyed using a Differential Global Position
221 System (DGPS) in May 2007 and June 2008. These provided information on
222 foredune topography before and after the study period. Second, bedframe posts
223 spaced approximately 3 m apart were established along each profile from the
224 embryo dune to the foredune crest, and were surveyed every 2 months. The
225 bedframe enables measurements that do not interfere with the dynamics of
226 vegetation and provides data on surface elevation change at 12 points within a
227 1 m square at each bedframe post (Ollerhead et al., 2003; Fig. 2A). Following the
228 procedure described by Law (1989) a grid was established so a particular
229 bedframe post represented a specific area of the dune with an alongshore

distance of 23 m per 3 m of shore-normal dune profile (Fig. 2D). The bedframe technique was designed such that each bedframe lines would encompass the landward extent of aeolian transport in the vegetated dune (Davidson-Arnott and Law, 1990 and Davidson-Arnott and Law, 1996). Thus, whilst an individual bedframe may show wind erosion, there is no loss to the calculation of net deposition across the profile because deposition is recorded in the landward stations. It was assumed here that offshore aeolian transport from the embryo dune was small and could be neglected. Other sources of sediment loss such as sediment by-passing or wave erosion are discussed in Section 7.3. Finally, a total of 4 Erosion-Deposition (ED) pins were deployed on the embryo dune and back-beach. ED pins are permanent rods marked at regular intervals of 2 cm (Fig. 2B) that are located within the field of view of the cameras. Hourly changes in surface elevation at each ED pin location could be measured with a precision of 1 cm by zooming on the RGB images. This permits a much higher temporal resolution compared to topographic surveys or bedframe measurements.

3.3. Data processing and data base development

Detailed information on data processing and geodatabase development may be found inDelgado-Fernandez and Davidson-Arnott (2011). Measurements of sand deposition and wind speed and direction were processed using standard procedures and available software such as Excel and SigmaPlot. The information from the camera system was processed with ArcGIS 9.2 and PCI Geomatica 9.1, and followed several steps to extract numerical information such as moisture

maps, shoreline position, fetch distances, vegetation density, and ice-snow cover. Moisture maps were created using calibration curves that transform pixel brightness into moisture content at the beach surface (Delgado-Fernandez et al., 2009). The percentage of ice and snow cover was estimated from both the rectified images and the unrectified images of the east camera, and classified into 5 classes with increments of 20% which range from 0–20% of snow cover (first class) to 80–100% of snow cover (last class). Vegetation density raster datasets were extracted using unsupervised classifications with the Image Analysis extension from Leica Systems. The shoreline position was digitised in ArcMap and stored as feature time series, and beach width was obtained from shoreline position and vegetation extent. Fetch distances were calculated from beach width and wind direction.

Because of the need to integrate spatial and time-series data, a geodatabase (PEI GDB) was built with ArcCatalog 9.2 to store the information. The PEI GDB uses four types of time series data: 1) time series tables, which contain time and value attributes for a given type of observation (e.g., hourly percentage of snow and ice); 2) attribute series, which store temporal data for a given type of observation associated with a particular location (e.g., wind speed at 14 m above the beach recorded by the anemometer); 3) feature series, which represent sequences of records in which the feature shape varies over time (e.g.; shoreline position), and; 4) raster series, or time series of raster data in which each raster is a snapshot in time (e.g., moisture maps). The PEI GDB manages relations between different factors, permits multiple querying and allows transition

between the spatial and the temporal domains using temporal geoprocessing techniques.

4. Conceptual model

4.1. Background

A wind event may be simply defined from the point in time when the wind speed exceeds a threshold value for sand movement to the moment when the wind decreases to a value below the threshold. Potential transport for any wind event may be calculated from wind speed and direction using standard equations (e.g., Hsu, 1974 and Fryberger and Dean, 1979). Analysis carried out by Delgado-Fernandez and Davidson-Arnott (2011) using a nine month time series of wind, transport processes and supply-limiting factors at Greenwich suggested three possible scenarios:

1. Wind events may produce no actual transport into the dune for part or all of the duration of the event because the wind angle may be alongshore or offshore, or because entrainment of sand from the surface is inhibited by the presence of snow and ice, short fetch distances, or relatively high surface moisture content.
2. Wind events may produce sand movement to the dunes but the magnitude of transport is much less than the potential transport predicted by equations based on wind speed alone because the rate of sand supply from the surface is reduced as a result of the effects of supply-limiting

factors such as moisture, or because the available fetch (F) is less than the critical fetch (Fc).

3. Transport into the dunes may be of the same order as the potential transport because there are no supply-limiting conditions (e.g., the existence of a wide beach, dry sand and winds with an onshore component).

4.2. Modelling assumptions

The goal of the modelling proposed here is to improve prediction of sediment input to the foredunes at the meso scale (i.e., over a period of months) by recognising the role of a few key factors and their synergistic behaviour within a space that is geometrically constrained. According to Bauer and Sherman (1999), reductionist studies often follow a procedure that consists on an initial simplification of transport as a function of wind. The hope is that subsequent modifications of the equations in order to account for complexities found at a given surface will produce better explanations of the system behaviour. However, even if factors such as moisture (for example) are appropriately introduced in increasingly complex equations, there is no guarantee that these will improve predictions. A wind well above the threshold of moist sand may produce no transport as a result of other key aspects that control sediment movement such as fetch distance or the influence of water levels and wave run-up (e.g., Nordstrom and Jackson, 1993, Jackson and Nordstrom, 1997, Christiansen

and Davidson-Arnott, 2004, Bauer et al., 2009 and Delgado-Fernandez and Davidson-Arnott, 2011).

The main assumption adopted in this study is that sediment transport at the meso scale could be better predicted based on an initial comprehensive combination of key parameters. Simplifications may be introduced in the manner in which this combination is modelled rather than focusing on individual factors. The PEI GDB provides the input data at a level that permits testing of the modelling approach in some detail, and assessment of the relative improvement over calculations of potential transport rates based on wind speed alone.

Foredune morphological evolution has been a subject of conceptual or descriptive studies (Hesp, 1988a, Hesp, 1988b, Psuty, 1988a, Sherman and Bauer, 1993 and Hesp, 2002) but it is difficult to model numerically and is beyond the scope of this study. The focus here lies on the prediction of sediment input to the foredune which, combined with sediment output, will dictate whether the dune will grow or erode (Psuty, 1988b). The area a few metres in front of the foredune is particularly complex in terms of the wind flow and is often characterised by flow steering and stagnation (Hesp et al., 2005 and Walker et al., 2006). When an embryo dune is present in this zone, the embryo dune vegetation retards sediment transport, and there is a complex relationship between the sand accumulated within this vegetation and the sand that is actually transported to and up the dune slope. Much of the sand deposited within the embryo dune may never reach the dune slope because of erosion by waves (e.g., Christiansen and Davidson-Arnott, 2004). The model presented here calculates sediment output

344 from the beach and predicts the mass of sand crossing the “blue line” in Fig. 3A–
345 B. This study does not deal with how sediment is distributed over the dune or
346 with the resulting dune morphologies, which are affected by processes not
347 considered here (e.g., interaction of wind and topography, wave scarping,
348 vegetation patterns). Fig. 3B shows a schematic representation of a beach–dune
349 system, and includes the output area in front of the embryo dune as explained
350 above. According to Bauer and Davidson-Arnott (2003) sediment transport rates
351 may be predicted using Bagnold-type equations when the available fetch (F) is
352 equal to or larger than the critical fetch (Fc) but calculations should account for
353 the reduction in transport due to the fetch effect when F < Fc (see Section 6.2).
354 The red band on the beach surface (Fig. 3B) indicates the distance at which
355 transport is fully developed for a given wind speed (F = Fc) and thus separates
356 the zone where the fetch effect should be considered from that where it does not
357 apply.
358
359 4.3. Modelling approach
360 The modelling approach consists of two steps (Fig. 4): 1) filtering of the time
361 series; and 2) calculation of transport for individual events.
362
363 4.3.1. Filtering
364 Filtering removes periods when transport toward the dune cannot occur because
365 wind speed is below the threshold for dry sand or wind direction is offshore. It
366 also removes those times when the magnitude of supply limiting factors such as

moisture, snow and ice, and fetch length exceed a threshold above which there is no potential for sand entrainment by the wind. In doing so, the filtering isolates potential transport periods (PTPs) and provides information on the frequency and duration of such events.

4.3.2. Calculation of transport for individual PTPs

The filtering simplifies the time series and reduces the volume of information to analyse. This allows concentrating on the details of particular PTPs, such as the spatial pattern of factors at an hourly scale (e.g., maps of moisture content). PTPs may be characterised by different levels of complexity depending on the dynamics of a few key controlling variables, namely wind speed and direction, fetch distance (and thus beach width), and superficial moisture content. This paper proposes the following classification of PTPs:

Type A: dry conditions—no restriction

PTPs may occur during onshore or oblique winds blowing over a relatively wide beach with a dry surface (Fig. 5A). The saltation system is allowed to develop fully for the incoming wind speed (fetch is not important) and thus transport may be calculated at the output area using Bagnold-type equations and modified by the cosine of wind angle following the procedure suggested by Bauer and Davidson-Arnott (2003). On narrow beaches this type of event will only occur under low wind speeds (short critical fetches). For wide beaches the range of wind speeds involved in Type A transport will likely increase.

Type B: dry conditions — restricted

PTPs may consist of medium complexity transport periods resulting from changes in the position of the area where F = Fc due to varying wind speeds and/or direction. Bagnold-type equations may be applied at an hourly basis when F ≥ Fc, whilst transport is reduced due to the fetch effect when F < Fc (i.e., when the red band is landward of the output area in Fig. 5B). This type of PTP may follow two general patterns:

B1 - Time-varying wind speed restrictions; wind direction (and thus fetch length, F) may be relatively steady, but wind speed fluctuates so that there are periods of time where F < Fc (t_2).

B2 - Time-varying, wind direction restrictions; changes in wind direction over strong wind events may introduce complexities associated with available fetch distances. On a narrow beach a strong wind may only fully develop saltation with highly oblique wind angles (t_1–t_3) with transport being limited when the wind direction is close to shore perpendicular because F < Fc (t_2).

Type C: moist conditions

Transport often develops under very complex conditions with changes in wind speed, direction, fetch lengths and moisture. The saltating system during Type C PTPs is rarely fully developed because moisture limits entrainment and interacts with the fetch effect in ways that are still not fully understood (Delgado-Fernandez, 2010). Davidson-Arnott et al. (2008) suggest that the curve relating

413 transport rate with fetch distance over a moist surface may be similar to that over
414 a dry surface, only with a longer critical fetch “adjusted” to wet conditions. In
415 other words, it is likely that the proportion of time during which the red band
416 in Fig. 5C is landward from the output area will increase, thus reducing transport
417 rates at the top of the beach. PTPs Type C may be divided into two general
418 categories:
419 C1 - Uniform moisture restrictions: moisture content is included via an increase of
420 the calculated Fc for an incident wind speed (Section 6.2). Moisture interacts in
421 complex ways both with the sediment transport threshold and the mass flux on
422 beach surfaces. The maximum sediment flux for dry sand as predicted by
423 transport equations (e.g., Bagnold, 1941 and Hsu, 1974) may be lower than that
424 for moist sand, similar or even higher if sediment moves across a moist, harder
425 surface (McKenna Neuman and Maljaars Scott, 1998 and Davidson-Arnott et al.,
426 2008). However, there seems to be enough evidence suggesting that the critical
427 fetch increases with increasing beach surface moisture (Delgado-Fernandez,
428 2010).
429 C2 - Spatially complex moisture restrictions (“patch”): areas with large amounts
430 of moisture content may be considered sinks rather than source zones. The fetch
431 length can be thus measured as the distance between moisture patches and the
432 output area, that is, moisture zones reduce the actual space for transport to
433 develop. The data set obtained at Greenwich contains several onshore transport
434 periods where the foreshore area became progressively wetter as a thin layer of
435 sediment was removed by wind gusts whilst the back-beach became

436 progressively drier because of accumulation of dry sand. This resulted in a
437 decrease of the fetch distance over time. The approach taken here oversimplifies
438 the dynamics of events of type C2 but incorporates hourly variations of fetch
439 distances.
440
441 **5. Description of the data set**
442
443 The input data for the model consisted of hourly values of wind speed and
444 direction (obtained from 2 min records from the Windsonic on top of the
445 mast; Section 3.1), beach width, snow and ice cover, fetch distances and
446 moisture content. The PEI GDB contains detailed information on the spatial
447 distribution of some of these factors for every given image (e.g., shoreline
448 position) (Section 3.1) but for the purpose of this paper only hourly averages
449 were considered.
450 Moisture maps were stored at a 0.05 m grid resolution within the PEI GDB. The
451 mean hourly value was obtained by considering an area of 10 m in front of the
452 embryo dune. This area was usually out of the tidal influence and wide enough to
453 obtain representative mean values of moisture content due to rain fall, snow melt,
454 or large wave swash. The mean value for moisture (μ) was then classified into
455 three categories: 1) “dry”: $\mu \leq 2\%$; 2) “medium”: $2\% < \mu < 10\%$; and; 3) “wet”:
456 $\mu \geq 10\%$. The objective of this classification was to broadly differentiate periods of
457 time when moisture is not likely to play a major role (“dry”) from moments when
458 moisture completely prevents transport (“wet”) (Davidson-Arnott et al., 2008).

459 The “medium” class comprises all cases (the majority) when complex interactions
460 between wind thresholds and rapid drying of superficial sediments are expected
461 (Wiggs et al., 2004 and Davidson-Arnott and Bauer, 2009).
462 Snow-ice cover was averaged from measurements obtained from three
463 simultaneous images taken from the cameras. Delgado-Fernandez and
464 Davidson-Arnott (2011)observed that transport was completely shut down at
465 Greenwich when half or more of the beach was covered by ice-snow.
466 Complications associated with modelling aeolian sand transport in the presence
467 of snow are beyond the scope of this paper and thus only the threshold
468 associated with ice-snow presence is used here in the filtering stage
469 (Section 6.1). Beach width was obtained from mean values of shoreline position
470 and vegetation extent for the offshore and west-facing cameras. The available
471 fetch distance (F) was then calculated considering the relation between beach
472 width (W) and the angle of wind approach from shore perpendicular (α) using the
473 following expression:
474

$$F = {}^{W}/_{\cos\alpha} \qquad \text{Equation(1)}$$

475
476 Finally, the majority of night exposures were enhanced as described by Delgado-
477 Fernandez et al. (2009) which allowed extraction of the variables mentioned
478 above. There were only a few very dark night shots when measurements were
479 not possible and thus mean values were interpolated based on conditions during
480 the last exposure in the evening and the first exposure the following morning and

on predicted tidal elevation. This introduced a small level of uncertainty but resulted in a data set of synchronised mean hourly values of wind speed and direction, snow-ice cover, beach width, fetch distances, and moisture content that could be used for modelling purposes.

6. Analytical procedure

Section 8 discusses possible alternatives to develop numerical models based on the approach described in Section 4. Only a simple analytical procedure was conducted here to test whether calculations of sediment input to coastal dunes based on deterministic formulae (e.g., Hsu, 1974, Fryberger and Dean, 1979 and Davidson-Arnott and Law, 1996) may be improved using the modelling approach.

6.1. Filtering the time series

The numerical values for the thresholds used for isolating PTPs were based on the work of Delgado-Fernandez and Davidson-Arnott (2011). These authors observed that no significant sediment input to the dunes occurred at Greenwich under any of the following conditions: wind speed (U) < 6 m s^{-1}; offshore wind direction; “wet” surfaces (μ ≥ 10%); snow and ice cover > 50%; and beach inundation by nearshore processes. This is the combination of all thresholds is a necessary condition for the potential existence of transport:

$$if \rightarrow \begin{matrix} U > 6\,\mathrm{m\,s^{-1}} \\ onshore\ component \\ \mu < 10\% \\ W > 0\mathrm{m} \\ snow\ and\ ice < 50\% \end{matrix} \rightarrow PTP$$

Whilst any one of these thresholds will inhibit transport, the PTPs isolated by this procedure may not all include periods of actual transport (Section 8). The filtering technique, however, narrows down potential transport events whilst preventing the loss of data. Importantly, and because of the inclusion of beach width (and therefore fetch distance) as a necessary condition for transport to develop, the filtering eliminates from the time series those periods where storms with strong onshore winds produce storm surge and wave run up that inundates the beach.

6.2. Calculating transport for individual PTPs

A key aspect of the conceptual model is the importance of considering other factors in addition to wind speed and direction. The choice of a particular formula for predicting sediment transport is important for calculating absolute values of sediment output from the beach, but establishing the suitability of a particular equation over another is beyond the scope of this paper. For detailed reviews about instantaneous transport equations see Horikawa et al., 1986, Nickling, 1994 and Sherman et al., 1998. The focus here was to assess the performance of the two modelling steps and for this purpose any relatively simple expression relating wind speed and sediment transport rate was sufficient. The empirical equation proposed by Hsu (1974) was selected here simply because it relates

transport directly with wind velocity rather than with shear velocity. Estimations of shear velocity require measurements of velocity profiles or detailed knowledge of the roughness length (z_0) and internal boundary layer development, which changes considerably spatially and temporally (Davidson-Arnott and Law, 1996). Whilst it would have been possible to estimate shear stress from assumptions of surface roughness this was likely to be a constant in this study and therefore would have had no impact to improve the modelling. Hsu's formula introduces a degree of uncertainty because Hsu adjusted the constant to the particular beaches he worked on. However, it is based on a previous version using shear velocity (Hsu, 1973) which predicts sediment transport rates close to those calculated by Bagnold's (1941) model and that are in the middle range compared to a number of models tested by Sherman et al. (1998). Hsu's equation was also adopted in a similar type of study by Davidson-Arnott and Law (1996), who included the cosine effect for its use when wind speed and direction are the only data available. According to these authors, the potential transport rate into the dunes per unit alongshore distance (qn, kg m^{-1} s^{-1}) may be expressed as:

$$q_n = 1.16 \times 10^{-5} \times U^3 \cos\alpha \qquad \text{equation (2)}$$

where U is hourly wind speed in m s^{-1}. Thus qn is the predicted rate of sediment movement at the output area (Fig. 5A) based on wind speed and direction alone, and hence only applicable in type A PTPs (no restrictions), or during t1 and t3 in type B PTPs.

547 Despite advances in the modelling of the fetch effect in agricultural areas
548 (e.g., Stout, 1990, Gillette et al., 1996 and Fryrear et al., 2000) there is no
549 accepted equation describing the increase of sediment transport rate with fetch
550 distance on beaches (Delgado-Fernandez, 2010). This poses major difficulties
551 when trying to incorporate the fetch effect into the modelling of aeolian sediment
552 input to the foredunes, especially with strong winds associated with long critical
553 fetch distances (Davidson-Arnott and Law, 1990, Spies and McEwan,
554 2000 and Dong et al., 2004) (during t2 in PTPs type B). Bauer and Davidson-
555 Arnott (2003) proposed four harmonic functions to describe the increase of
556 sediment transport with distance. According to Delgado-Fernandez (2010), their
557 Equation 2a is consistent with other empirical equations in agricultural areas and
558 thus it is used in here:
559

$$q_n(F) = q_n \sin\left(\frac{\pi}{2}\frac{F}{F_c}\right) \qquad \text{Equation (3)}$$

560
561 Eq. (3) needs numerical values for Fc but there are no current methods to
562 calculate this (Delgado-Fernandez, 2010). There is, however, some supporting
563 evidence suggesting that it is reasonable to estimate Fc given a particular wind
564 speed blowing over a dry surface. Fig. 6 shows a high correlation between wind
565 speed and the distance where transport attains a maximum as reported in the
566 numerical simulations by Spies and McEwan (2000) (curve A) and field results
567 by Davidson-Arnott and Law (1990) (curve B). Curve B has a steeper slope in

agreement with other studies in natural areas showing critical fetch distances that are longer than those found by numerical simulations or laboratory analysis (e.g., Gillette et al., 1996, Fryrear et al., 2000 and Davidson-Arnott et al., 2008). The expression associated with curve B is used here:

$$F_c = 4.38 \times U - 8.23 \qquad \text{Equation (4)}$$

This permits the generation of a set of Fc for a relevant range of wind speeds (U) and testing of the modelling approach. No claim is made here regarding the general applicability of Eq. (4) beyond this analytical procedure.

Whilst the filtering deals with “wet” periods and Eqs. (2) and (3) are used for “dry” PTPs type A and B (respectively) there is a need to include “medium” (2% > μ > 10%) moisture content values characteristic of PTPs type C. There are several equations relating the threshold of sand movement with moisture content (e.g., Belly, 1964, Logie, 1982 and McKenna Neuman and Nickling, 1989) or with sediment transport rates (e.g.,Hotta et al., 1984 and Sarre, 1987) but none on the relation between moisture and critical fetch distances (Delgado-Fernandez, 2010). Ideally this research would benefit from studies targeting aeolian sediment transport during PTPs Type C, the most common situation at the meso scale (Delgado-Fernandez and Davidson-Arnott, 2011). In the absence of tools to model the complex interactions between moisture, fetch, and wind characteristics, the following procedure was adopted. 1) Based on observations byDavidson-Arnott et al. (2008) it was assumed that homogenous moisture

591 content (PTPs Type C1) increased the critical fetch calculated for dry sand (Fc)
592 to a new larger value (Fcμ) for a given wind speed with the increase being
593 proportional to the value for moisture content. On this basis, a simple arbitrary
594 scheme was utilised, with Fcμ resulting from an increase of Fc by 50% when
595 4% ≤ μ < 6%, and by 75% when 6% ≤ μ < 10%. For 2% ≤ μ < 4% it was assumed
596 that the surface was likely subject to rapid drying and stripping of sand grains by
597 wind gusts (Wiggs et al., 2004) and Fc was not modified. 2) When clear
598 "patches" of moisture vs. dry zones were present at the beach surface, Fcwas
599 calculated for dry sand but the available fetch (F) was measured from the
600 landward limit of damp areas. Again, it is acknowledged here that this is an over-
601 simplified procedure adopted to permit operationalization of the model in the
602 absence of an adequate technique based on field and/or laboratory data.
603 Fig. 7 shows a diagram of the analytical procedure. The steps may be
604 programmed with any scripting language such as Python or even conducted with
605 Excel. For a given hour in a selected PTP the model calculates Fc based on wind
606 speed using Eq. (4), checks the mean moisture content, and obtains (if
607 applicable) Fcμ. If Fc (or Fcμ) ≤ F (red band in Fig. 5is seaward from the output
608 area) then the model applies Eq. (2). If F_c (or Fcμ) > F the model applies Eq. (3).
609 Finally, the procedure calculates the total amount of transport for a particular
610 PTP (QPTP) by adding hourly values of sand transport rates:
611

$$Q_{PTP} = \sum_{q=1}^{q=n} q_n \qquad \text{Equation (5)}$$

612

613 **7. Modelling approach results and testing**

614

615 The modelling approach predicts a total amount of sand crossing the output area
616 over any period of time longer than 1 h. To compare this amount with actual
617 deposition at the dune the assumption is that the embryo dune and foredune trap
618 everything that is delivered to them over the time period considered. There are
619 several uncertainties associated with this. First, survey methods or bedframe
620 posts record net deposition, and thus do not reflect potential periods of erosion.
621 Second, sediment by-passing and being transported over the dune crest and
622 beyond is not measured by the techniques used in this study. These limitations
623 are discussed in the following sections.

624

625 7.1. Measured deposition over 9 months

626 Fig. 8 shows the results of both topographic profiles (A) and bedframe
627 measurements (B). Net changes from May 2007 to June 2008 were minimal and
628 concentrated at the lower sections of the foredune (lower slope and dune toe)
629 and embryo dune. Bedframe posts landward of the foredune crest (1–3 W)
630 showed no substantial changes over the study period. The largest net deposition
631 occurred from October to December 2007, which was probably related to a single
632 very strong transport event on November 9–13 (Section 7.3). Table 1 shows
633 values of erosion and deposition recorded by each of the bedframe posts (BP).
634 The mean net change over the dune stoss slope (bedframe posts seaward from

635 the crest, cross-shore distance = 18 m) was 9.2 cm on Line E and 6.9 cm on line
636 W, which give an average accretion of 8.05 cm over 9 months.
637
638 Table 1. Results for bedframe posts (BP) over 9 months of data collection. Note
639 that BP1-3 in line W was not included in the calculations. Changes are expressed
640 in cm. Fig. 2 and Fig. 8 show the location of the bedframe posts.

Line E	Deposition	Erosion	Net change	Location	Net change	Erosion	Deposition	Line W
–				Dune trough	− 1.94	− 2.41	0.47	BP1
–				Dune trough	1.79	− 0.33	2.12	BP2
–				Dune trough	0.43	− 1.45	1.88	BP3
BP1	1.48	− 0.47	1.01	Dune crest	− 0.94	− 1	0.06	BP4
BP2	3.9	− 2.64	1.26	Upper slope	1.81	− 0.28	2.09	BP5
BP3	6.5	− 0.47	6.03	Upper slope				–
BP4	20.47	− 2.83	17.64	Low stoss slope				–
BP5	20.52	− 0.28	20.24	Dune toe	13	− 4	17	BP6
–				Embryo dune	13.95	− 0.36	14.31	BP7
	10.6	− 1.3	9.2	Mean	6.9	− 1.4	8.4	

641
642 Davidson-Arnott and Law (1996) used the following relationship to convert values
643 of volume of sediment deposition (or erosion) to a total sediment transport (q):
644

$$dq/dx = \left(dh/dt\right)\gamma \qquad \text{Equation (6)}$$

where dh/dt is the change in elevation over a particular time period and x = distance along profile. A mean value for bulk density (γ) of 2082 kg m^{-3} was obtained from sand samples at the laboratory and corresponded to that estimated assuming a sediment density of 2650 kg m^{-3} (Bagnold, 1941) and a porosity of 0.23 (Fetter, 1994). Note that for the reason noted above, the bedframes landward of the dune crest (1–3 W) were not considered in the calculations. The net average change over 9 months recorded by the bedframes was $Q_{BF\text{-}net}$ = 3017 kg m^{-1} (1.45 m^3 m^{-1}), based on a net average accretion of 8.05 cm along the profile.

The values in Table 1 reflect net quantities, and thus may be missing important information about sediment deposition or erosion between surveys. In fact the bedframe posts recorded a few periods of erosion (or possible compaction), which introduces the question of whether net changes over months underestimate sand delivered by wind over shorter periods of time. If only deposition is considered (average = 9.5 cm) the gross amount of sand deposited over the dune is increased to $Q_{BF\text{-}only\_dep}$ = 3560 kg m^{-1}(1.71 m^3 m^{-1}).

Fig. 9 displays the ED pins hourly records during the 9 months of study period. Elevation changes were quite dynamic at the back beach and embryo dune, with many small erosion and deposition periods of less than ± 5 cm, and several of more than ± 10 cm.Table 2 shows the result of summing periods of erosion and

deposition, and the net changes recorded at the end of the study period by the ED pins. The average net deposition at the embryo dune was 26.5 cm. This results in $Q_{ED\text{-}net}$ = 4966 kg m^{-1}(2.38 m^3 m^{-1}) according to Eq. (6). The average gross deposition (erosion not considered) at the embryo dune was approximately 83 cm, which equates to $Q_{ED\text{-}only\_dep}$ = 15552.5 kg m^{-1} (7.47 m^3 m^{-1}). A discussion about the significance of these differences is presented in Section 8.

Table 2. Results for ED pins over 9 months of data collection. Changes are expressed in cm. Fig. 2 shows the location of ED pins.

ED pin	Deposition	Erosion	Net change	Location
1	94	− 67	27	Embryo dune
2	72	− 46	26	Embryo dune
3	51	− 60	− 9	Back beach
4	71	− 67	4	Back beach
Mean ED1-2	83	− 56.5	26.5	Embryo dune
Mean ED3-4	61	− 63.5	− 5	Back beach

7.2. Sediment input predicted over 9 months

The analytical procedure was run using data for a nine month period (6576 h). Table 3summarises the output of both the filtering ($Q_{filtering}$) and calculation of transport over isolated PTPs (Q_{PTP}). Qn is the total amount of sediment transport predicted using Eq. (2), which represents the quantity that would be calculated using a traditional approach based solely on wind speed and direction (e.g., Fryberger and Dean, 1979 and Wahid, 2008). Q_{PTP} represents the actual output of the analytical procedure, or transport calculated for all PTPs considering supply-limiting conditions and different types of events. Results are

685 expressed in kg m^{-1} (Q_i), the number of hours of predicted transport and the
686 percent of time they represent over 9 months, and, most importantly, the relation
687 with measured values (Q_i respect $Q_{BF\text{-}net}$). For consistency with previous studies
688 (e.g., Davidson-Arnott and Law, 1996) the modelling output was compared
689 against the average net change recorded by the bedframes over the entire
690 foredune (BP 1–3 W excluded). The rest of observed changes have been
691 included in Table 3 for discussion purposes (Section 8).
692
693 Table 3. Output of the modelling procedure and comparison of predicted
694 quantities with observed net deposition at the embryo dune and foredune. Q_n:
695 total amount of sediment transport predicted using Eq. (2); $Q_{filtering}$: output of the
696 filtering step; Q_{PTP}: output of the calculation of transport over isolated PTPs; $Q_{ED\text{-}only\_dep}$
697 : average gross deposition (erosion not considered) measured by ED pins
698 at the embryo dune; $Q_{ED\text{-}net}$: average net change measured by ED pins at the
699 embryo dune; $Q_{BF\text{-}only\_dep}$: average gross deposition (erosion not considered)
700 measured by bedframes over the foredune; $Q_{BF\text{-}net}$: net average change
701 measured by bedframes over the foredune. Note that in the particular case of this
702 time series the majority of events resulting in wave run-up or storm surge (beach
703 width > 0 m) were already filtered by the effects of high amounts of moisture
704 content or snow-ice cover (thus the low values associated to a few remaining
705 periods of time).

Factor		No. of hours	% time	Q_i (kg m^{-1})	Q_i respect $Q_{BF\text{-}net}$
Predicted Q					
Q_n	Wind	2018	31	86 458	28.7 $Q_{BF\text{-}}$

	Factor	No. of hours	% time	Q_i (kg m^{-1})	Q_i respect $Q_{BF\text{-}net}$
	speed > 6 m s^{-1} onshore direction				net
$Q_{filtering}$	Snow < 50% cover	1442	22	55 073	18.2 $Q_{BF\text{-}net}$
	Moisture < 10%	1119	17	35 921	11.9 $Q_{BF\text{-}net}$
	Beach width[1] > 0 m	1110	16.9	35 632	11.8 $Q_{BF\text{-}net}$
Q_{PTP}	Fetch effect	1110	16.9	24 877	8.2 $Q_{BF\text{-}net}$
	Moisture	1110	16.9	18 663	6.2 $Q_{BF\text{-}net}$
Observed Q					
$Q_{ED\text{–}only\_dep}$	–	–	–	15 552	5.1 $Q_{BF\text{-}net}$
$Q_{ED\text{–}net}$	–	–	–	4966	1.6 $Q_{BF\text{-}net}$
$Q_{BF\text{-}only\_dep}$	–	–	–	3560	1.2 $Q_{BF\text{-}net}$
$Q_{BF\text{-}net}$	–	–	–	3017	1

Predicted sediment output from the beach based only on wind speed and direction (Q_n) was almost 29 times larger than observed net deposition at the foredune measured by the bedframes ($Q_{BF\text{-}net}$). The filtering improved the accuracy of transport predictions by decreasing the calculated value to a quantity 11.8 times larger than the observed net deposition. Finally, the effects of moisture and the fetch effect introduced to calculate transport for each PTP resulted in predicted quantities that were 6.2 times larger than the observed deposition.

716 7.3. Measured deposition over a storm event

717 A storm that began on November 9, 2007, was selected as an example of the
718 performance of the modelling approach over a particular wind event because of
719 several tradeoffs between key factors, such as the cosine and the fetch effect, or
720 the influence of moisture content. This event is described in detail by Delgado-
721 Fernandez and Davidson-Arnott (2011), and is a typical example of transport
722 occurring under Type C conditions (Section 4.3.2).

723 Fig. 10 displays the time series of wind speed and direction (A), tidal elevation
724 and saltation intensity recorded by a Safire located at the back-beach (B), beach
725 width (C), and fetch distances and classified moisture content (D) (Section 5).
726 The wind started blowing over the threshold for dry sand movement at 10 am on
727 November 9 and died out at 3 am on November 13, resulting in a wind event
728 duration of 90 h. Strong transport was observed under specific conditions on
729 November 11. Relatively low wind speeds combined with moisture content from 2
730 to 4% precluded grain entrainment on November 9. An increase in wind speed
731 on the morning of November 10 generated limited sand transport, which fully
732 developed during the day due to a further increase in wind speed coinciding with
733 low tide and oblique angle of wind approach. A gradual change in wind direction
734 to onshore-perpendicular decreased the available fetch distance and produced
735 wave up-rush eventually resulting in the beach inundation. The peak wind
736 speeds coincided with onshore winds thus precluding sediment movement during
737 the rest of the event because of storm surge and wave run-up.

738 The complexity of the ED pin records at the end of the storm illustrates some of
739 the points raised in the discussion (Section 8). ED pins 1 and 2 recorded net
740 deposition of 4 and 25 cm respectively at the embryo dune (see Fig. 2 for
741 location). ED 4 recorded 10 cm of net deposition at the back beach but ED 3
742 recorded 15 cm of erosion at the back beach. If an average deposition of 14.5 cm
743 at the embryo dune is assumed, the total amount of sediment deposited during
744 this particular event was of 905.7 kg m^{-1} length of shoreline (0.43 m^3 m^{-1}). Note
745 that this does not consider sediment deposited at the dune toe and beyond
746 because of the absence of instrumentation.
747
748 7.4. Sediment input predicted over a storm event
749 Fig. 10E–G displays the analytical procedure output at an hourly scale.
750 Prediction of sediment output from the beach based on wind speed and direction
751 only resulted in a peak of transport rates coinciding with the peak of strong
752 onshore winds (Fig. 10E), over-predicting the amount delivered to the dune
753 (Q_n for this event = 9470 kg m^{-1}). The introduction of thresholds for moisture
754 content ($\mu < 10\%$) and beach width ($W > 0$ m) as necessary conditions for
755 transport removed the majority of strong onshore winds (Fig. 10F), resulting in
756 improved predictions ($Q_{filtering}$ = 3720 kg m^{-1}). Predicted transport was
757 Q_{PTP} = 1698 kg m^{-1} (0.65 m^3 m^{-1}) after considering Fc or Fcμ (Fig. 10G), which
758 was slightly higher but on the same order of magnitude as the observed
759 deposition over the storm, thus confirming the viability of the modelling approach.
760

8. Discussion

The filtering improved calculations of sediment input to the foredunes by eliminating periods of time where transport was predicted based solely on wind speed and direction, but where no transport occurred because of the effect of one or more limiting factors. The improvement made by incorporating both the fetch effect and moisture was significant and suggests that further advances in modelling instantaneous relations between wind speed, fetch distances, moisture content and transport over a variety of situations will aid in refining predictions. The results of the analytical procedure suggest, however, several areas where the two modelling steps can be further refined. The thresholds used in the filtering step for this particular study were quite conservative with the result that the number of PTPs identified is much greater than the 27 transport events actually observed over the same time period by Delgado-Fernandez and Davidson-Arnott (2011). As shown in Fig. 11, all observed transport events were included within the set of predicted PTPs; i.e., no actual transport events were missed. However, there were a number of predicted PTPs where no transport was observed. In the majority of cases this occurred where winds were slightly above the threshold for dry sand but transport did not occur because of moderate levels of moisture on the beach. Transport would have occurred with either stronger winds or drier sediments. In some cases transport may have been inhibited by factors which could not be measured by the remote station at Greenwich (e.g. topographic changes). In any case the filtering did not eliminate

observed transport events from the calculations suggesting appropriate threshold values at this site (i.e., no loss of data). Transport within a number of PTPs was also over-predicted. In many cases this was the result of the inadequacies of the modelling of transport rates associated with moderate wind speeds and moderate levels of surface moisture content and/or spatially complex patterns of moisture content. For example, during the first quarter of the storm described in Fig. 10, low wind speeds of ≈ 10 m s^{-1} yielded a short Fc of ≈ 15–20 m. Moisture ranged from 2 to 4% due to intermittent rain and thus Fcμ = Fc. F oscillated from 30 to 50 m due to a relatively wide beach and oblique angle of wind approach. BecauseFc < F transport was predicted with the same magnitude as the rate solely based on wind speed and direction (compare E and F in Fig. 10). The effect of both moisture and fetch was more visible during the second quarter of the storm, when strong wind speeds and larger moisture contents resulted in Fcμ > F. This research will thus benefit from detailed studies on the combined effect of fetch distances and moisture content at the beach, because they play an important role in modifying the magnitude of calculated transport for individual PTPs.

The substantial differences in observed deposition with different techniques introduce uncertainty with respect to the appropriate (‘true’) value used in the comparison with predicted quantities. In part this reflects inadequacies in the number and placement of both bedframe stations and ED pins, and in particular a failure to recognise the ease with which a large number of ED pins could have been deployed. The simplicity and higher temporal resolution provided by placing

807 the ED pins in the field of view of the cameras greatly enhances the potential of
808 the camera monitoring system for future studies of beach/dune interaction and
809 changing dune morphology. The hourly time series of the ED pins permitted
810 much better assessment of periods of erosion as well as accretion and indicated
811 that net changes measured by sampling at relatively long time intervals (e.g., bi-
812 monthly bedframe measurements) underestimate the gross amount of sand
813 delivered to the dune. All ED pins recorded several periods of sand removal due
814 both to wave and wind erosion (as observed from the cameras). This suggests
815 that some of the sediment delivered from the beach to the embryo dune was
816 never actually recorded by low temporal resolution techniques, because these
817 integrated erosion and sand removal within net deposition observations.
818 Nevertheless, they also serve to highlight the difficulty of distinguishing wave
819 erosion and deposition from wind erosion and deposition in the area of
820 overlapping influence, and the limitations associated with a few point
821 measurements within this zone.
822 Efforts to fully explore the capabilities of the time series stored in the PEI GDB
823 are currently being developed. The PEI GDB contains raster datasets and
824 feature series with information about shoreline configuration, vegetation patterns,
825 or spatial changes on moisture every hour. In particular, it is at the PTP level that
826 the complexities associated with these factors may improve the model
827 performance, especially during scenarios such as PTPs type C. However, in the
828 broader context of sand transport prediction at the meso scale, two important
829 aspects are worthy of consideration: 1) the potential benefits of adopting

probabilistic approaches versus a deterministic procedure; and 2) the potential for extracting estimates of key controlling variables, such as surface moisture content and beach width, from data measured at standard meteorological stations for the majority of situations where there is no direct monitoring of the beach and dune system. Probabilistic approaches are common in weather forecasting and estimate the probability of an event occurrence/magnitude based on past (historical) data whilst including information on the uncertainty of the prediction. However, they need historical records of several environmental factors and there is a lack of long-term datasets on sediment transport processes at the beach. The monitoring station at Greenwich has being collecting data for over a period of 2 years so further analysis of wind, supply limiting factors, and transport processes may provide a good basis for a probabilistic model.

Secondly, it would be worth exploring ways in which limiting factors such as beach surface moisture, snow and ice and beach width could be estimated from, e.g., hourly values for rainfall or snowfall, temperature, tidal range, average beach width and some simple storm surge and run-up model.

Finally, it is worth stressing that the purpose of this work was not to provide an absolute accurate prediction of sediment input to Greenwich Dunes over 9 months (if this is possible at all) but to test the effectiveness of a modelling approach that explicitly acknowledges the key role played by supply-limiting factors such as moisture, fetch and vegetation in determining the actual sediment supply from the beach to coastal foredunes over periods of months and years. The results demonstrate that an approach based on transport-limited models is

inadequate at this temporal scale and that improved accuracy in prediction will come not from small refinements to traditional transport-limited models, but rather from the incorporation of the supply-limiting complexities. Whilst some of the variables identified at Greenwich may be irrelevant at other sites (e.g., snow-ice cover), the thresholds associated with beach inundation or moisture content are probably more universal and others, such as pebble lag development and flotsam, may also be relevant. New time series based on the type of monitoring system deployed here are, thus, desirable as they will aid in identifying particular key factors regulating the frequency and magnitude of aeolian transport events at other beach–dune systems and provide a rich data base which can be used to generate an improved supply-limited approach to meso-scale modelling of sediment supply from the beach.

9. Conclusions

The analyses presented in this paper show the potential for improved predictions of sediment input to coastal dunes using a simple modelling approach incorporating two steps. The first step reduces prediction of sediment supply to the foredune by removing wind events that do not result in transport because of a high threshold for sediment movement due to the magnitude of one or more supply-limiting variables, and thus isolates periods of time (PTPs) where predictive efforts should focus. The second step introduces the effect of fetch distances and limiting factors such as surface moisture content, which regulate

876 the supply of sediment from the surface and thus reduce the magnitude of
877 transport compared to that predicted by transport-limited models. The use of the
878 modelling approach greatly improves calculations of sediment supply toward the
879 dune area, and suggests that further improvements can be made through the use
880 of similar monitoring systems in other coastal dune environments. Finally the
881 results of this study show that further improvements in our ability to predict
882 sediment supply to coastal foredunes will require improvements in our ability to
883 measure sand transport from the beach and deposition in the foredune at the
884 same temporal scale.
885
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887
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903
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List of Figures

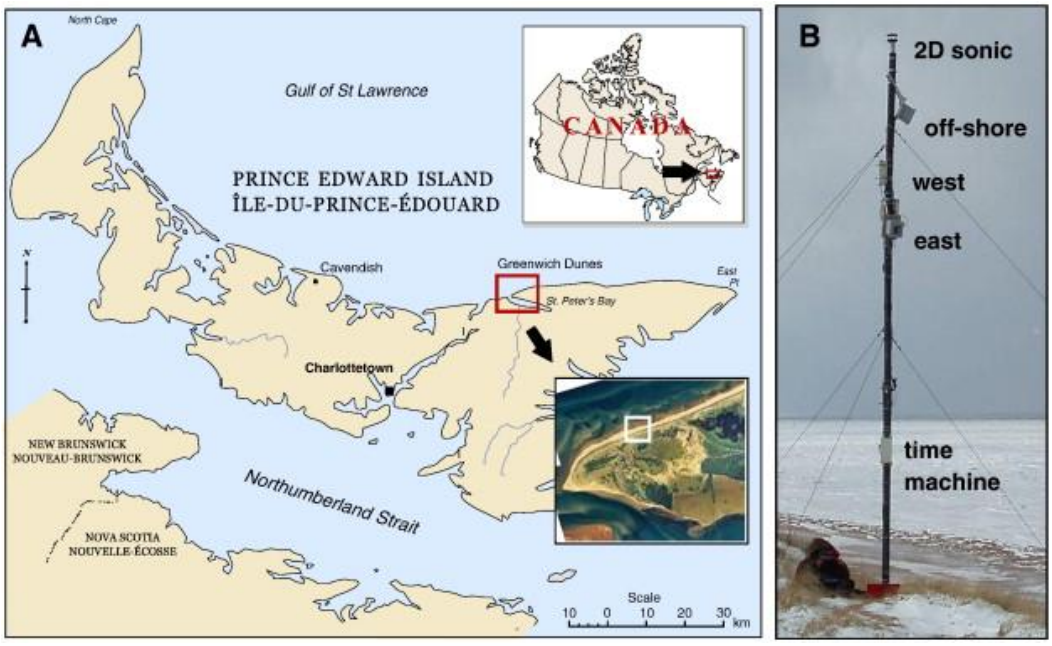

Fig. 1. A) Location of study area; B) Principal components of the camera system and 2-Dimensional Windsonic anemometer located on top of the 6 m mast (elevation over the beach surface of approximately 14 m).

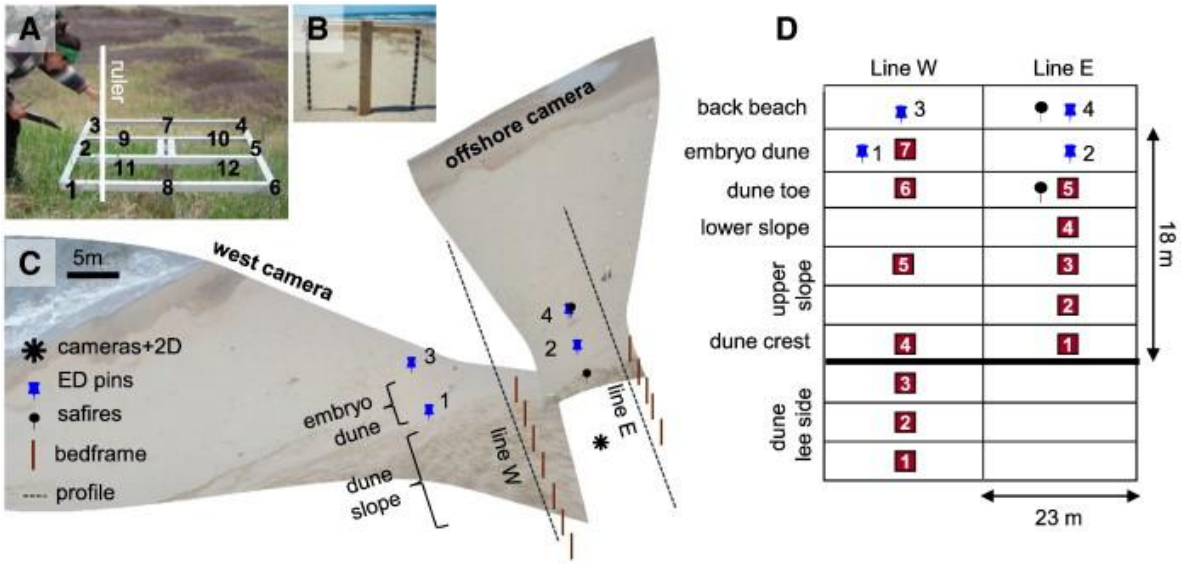

Fig. 2. A) Bedframe device deployed at a bedframe post at the dune. The average of the distance from the ground to the 12 points marked in the image provides data on surface elevation change at that location (Ollerhead et al., 2003). B) Erosion-deposition (ED) pin; C) Location of transport measurement points and survey profiles with respect to the camera system; D) Distribution of bedframe posts along line E and W, covering a total area of 46 m alongshore x 18 m across the dune. Each bedframe post represented an area of 23 m alongshore × 3 m cross-shore. No bedframe posts were located on line E beyond the dune crest. Bedframe posts 1–3 in line W were used for monitoring but not in actual calculations (Section 7.1). Safires and ED pins are included in the closest grid cell. Topographic details of lines E and W are included inFig. 8.

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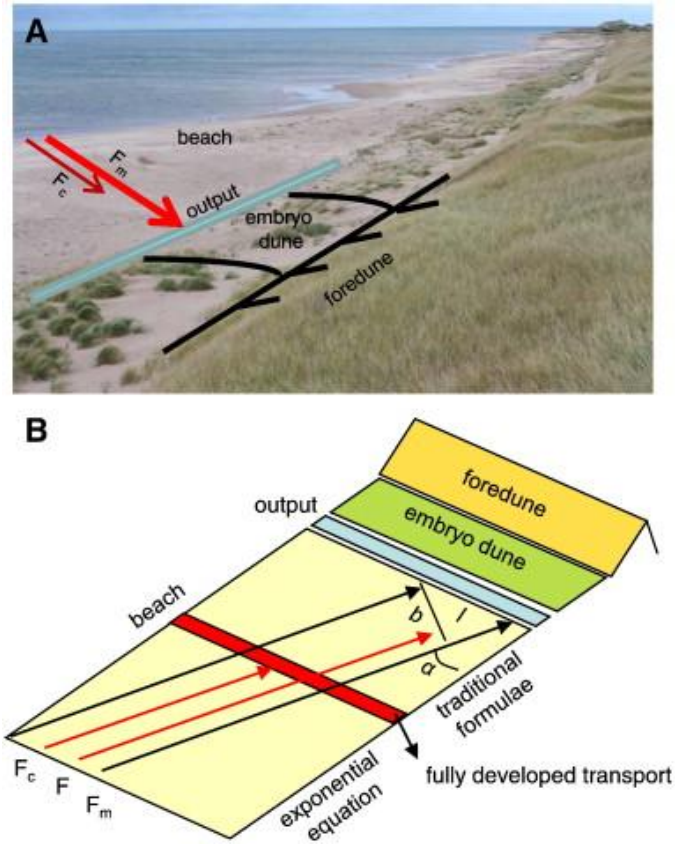

Fig. 3. Framework for modelling aeolian sediment output from the beach to the dune based on the study by Bauer and Davidson-Arnott (2003). A) Image taken by the east-facing camera at Greenwich, showing the location of the output area; B) Scheme for modelling. The red line on the beach surface indicates the area where transport is fully developed for an incoming wind speed. *Fm* is the maximum available fetch, *Fc* is the critical fetch and *α* is the angle of wind approach. Traditional formulae to predict sediment transport rates may be applied where $F > Fc$, whilst transport follows an exponential relation with distance where $F < Fc$.

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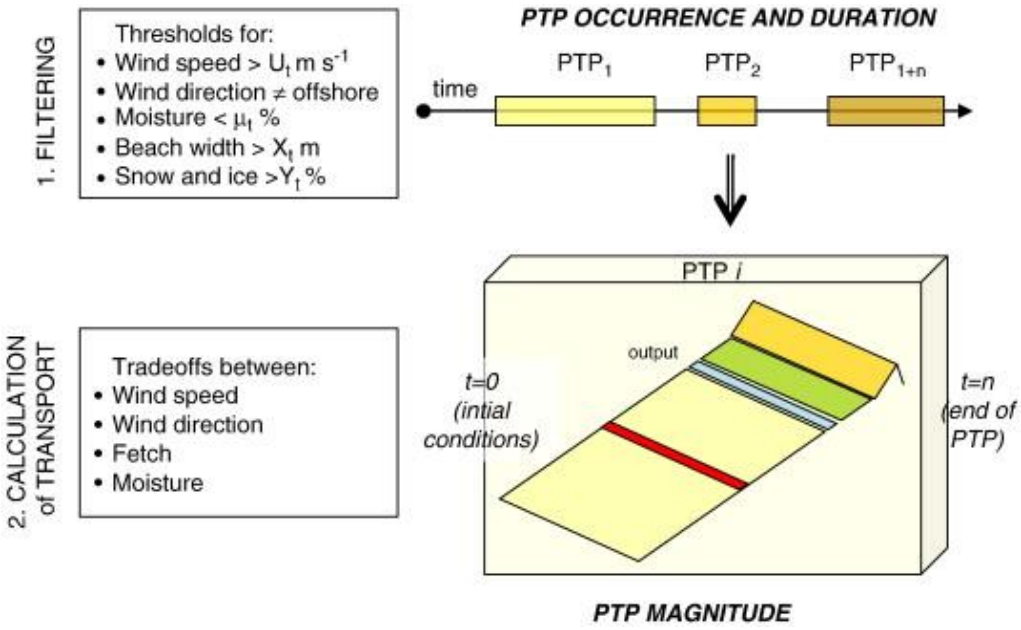

Fig. 4. Modelling approach following two steps: 1) the filtering reduces the time series and isolates potential transport periods (PTPs) providing valuable information about potential occurrence and duration of transport events and 2) calculation of transport focuses on particular PTPs, where the magnitude of sediment input to the foredunes is computed considering the fetch and the cosine effects and moisture content. This step may allow incorporation of the spatial variability of key factors, such as variations of beach width and moisture content over a particular event.

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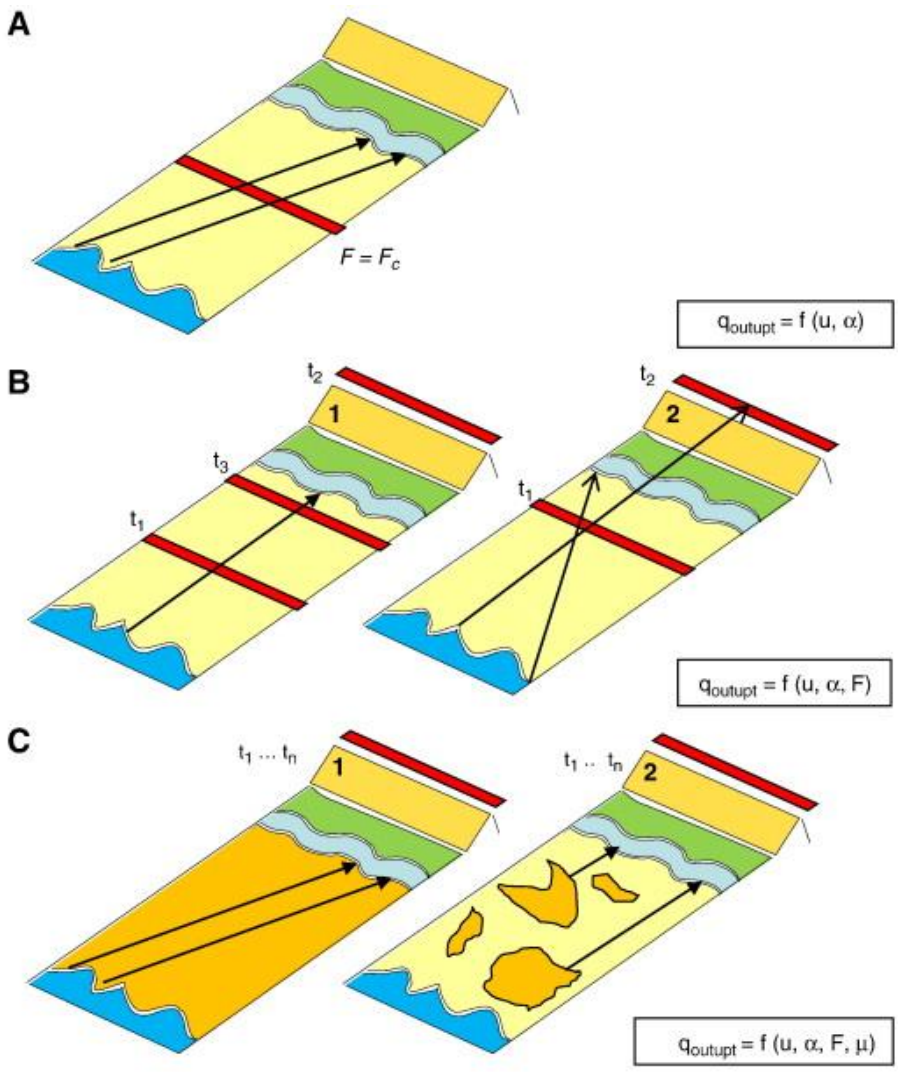

Fig. 5. Modelling scenarios for calculating sediment output from the beach (*qoutput*) and hypothetical examples of potential transport periods (PTPs). Note that a red band beyond the foredune crest indicates that the fetch distance is shorter than the critical fetch (*F* < *Fc*) at the output area and thus the fetch effect needs to be considered. A) Type A PTP: transport at the output area is solely based on wind speed and direction and may be predicted using Bagnold-type equations (e.g., oblique-onshore winds over a dry surface); B) Type B PTPs: the fetch effect needs to be considered during $t_2$periods. The beach surface is dry

but the area (red line) where *F* = *Fc* changes spatially because of increases on wind speed (B1) or changes in the angle of wind approach (B2). B1 shows an example of a situation with a low wind speed (t_1) becoming increasingly strong (t_2 — longer *Fc*), followed by a final period of low wind speed (t_3). B2 shows an example of a strong oblique wind (t_1) shifting to directly onshore (t_2 — *Fc* remains constant but *F* decreases during onshore winds). C) Type C PTPs: both the fetch effect and moisture (in orange) need to be considered. Uniform moisture (C1) increases the *Fc* and thus transport may never fully develop at the beach. Moisture patches (C2) reduce the available *F* between the onset of transport and the output area.

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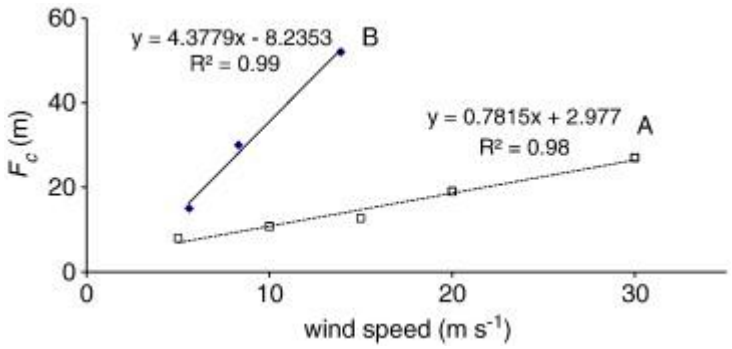

Fig. 6. Correlation between wind speed and critical fetch (*Fc*) for the data presented by A) Spies and McEwan (2000) and B) Davidson-Arnott and Law (1996). Note that wind speed (U) for curve A has been calculated from friction velocities (u*) reported by Spies and McEwan using the Law of the Wall ($U = \ln(z/z_0)\, u^*/k$) and assuming a grain size of 0.25 mm.

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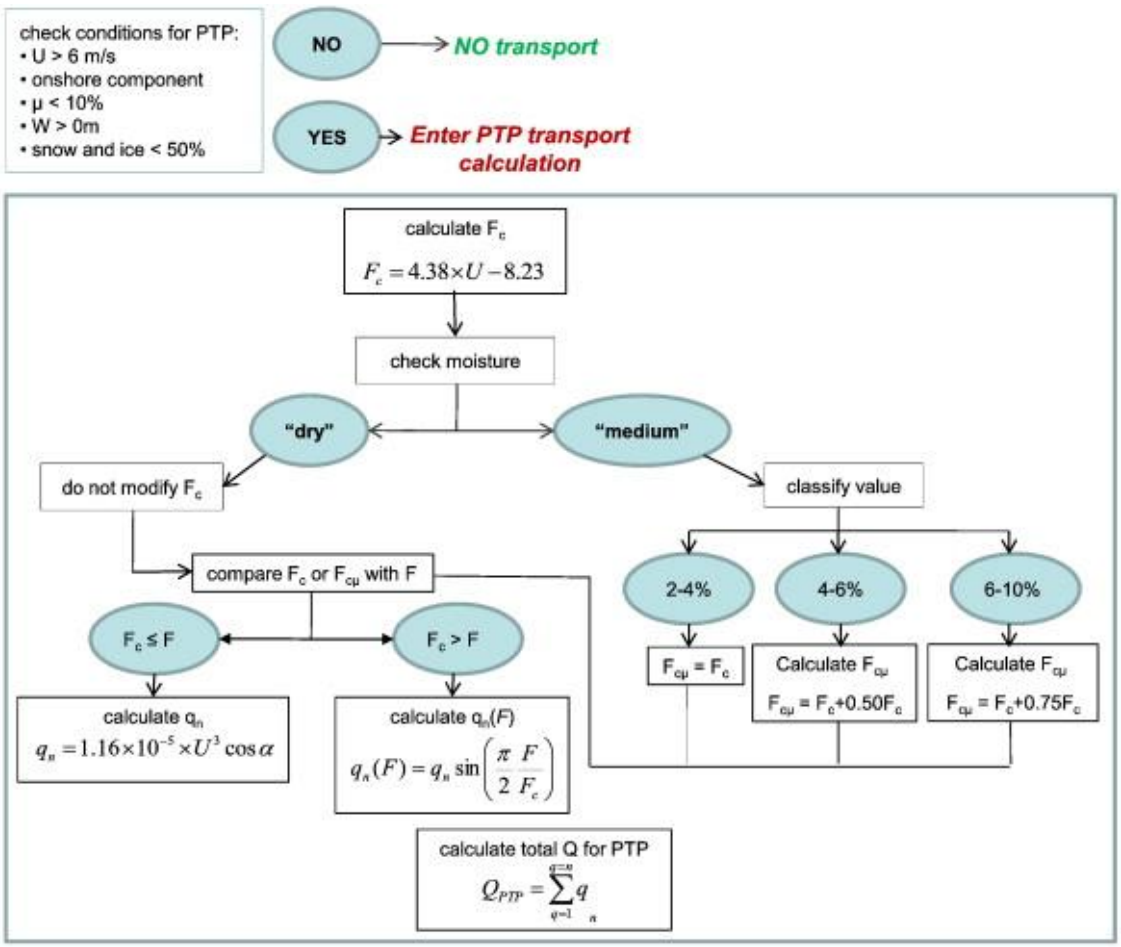

Fig. 7. Modelling steps and analytical procedure applied to hourly records of wind speed (U) and direction (α), fetch distance (*F)*, critical fetch distance (*Fc*) and moisture (μ) for potential transport periods (PTPs) isolated by the filtering.

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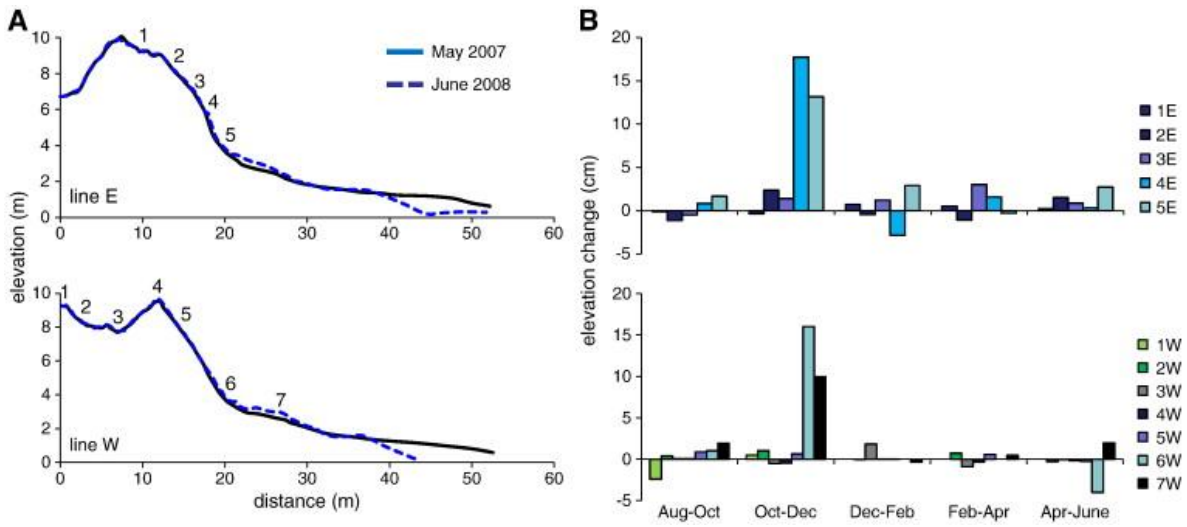

Fig. 8. A) Topographic profiles on May 2007 and June 2008. The numbers over the profiles show the location of bedframe posts; B) Bi-monthly net changes from August 2007 to June 2008 detected with the bedframe technique. Note that the largest change on the foredune stoss slope is of + 3 cm in post 3E. Most significant changes occurred from October to December 2007 at the lower sections of the dune (posts 4–5E and 6–7 W).

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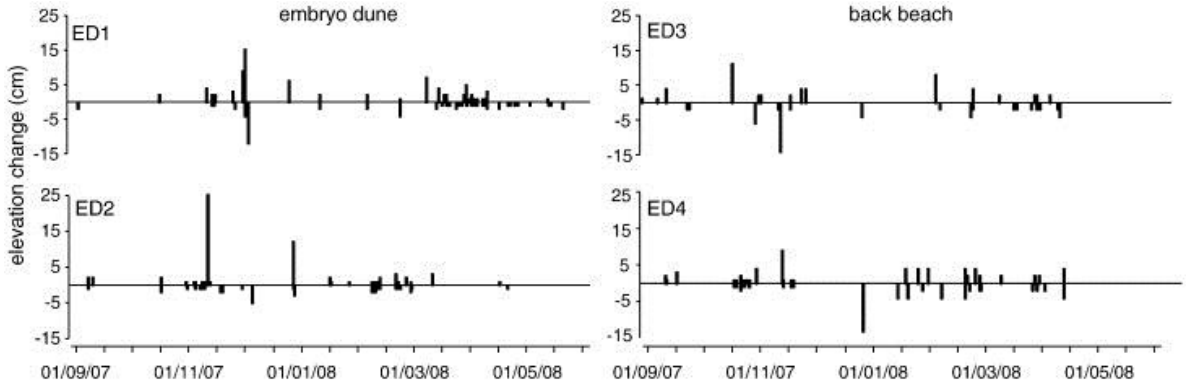

Fig. 9. Erosion-deposition (ED) pin records show several periods of accumulation and erosion. The majority of changes are of less than ± 5 cm, but there are several hourly changes of ± 15 cm and a single record of + 25 cm associated with the in

November 9, 2007 (Section 7.3).

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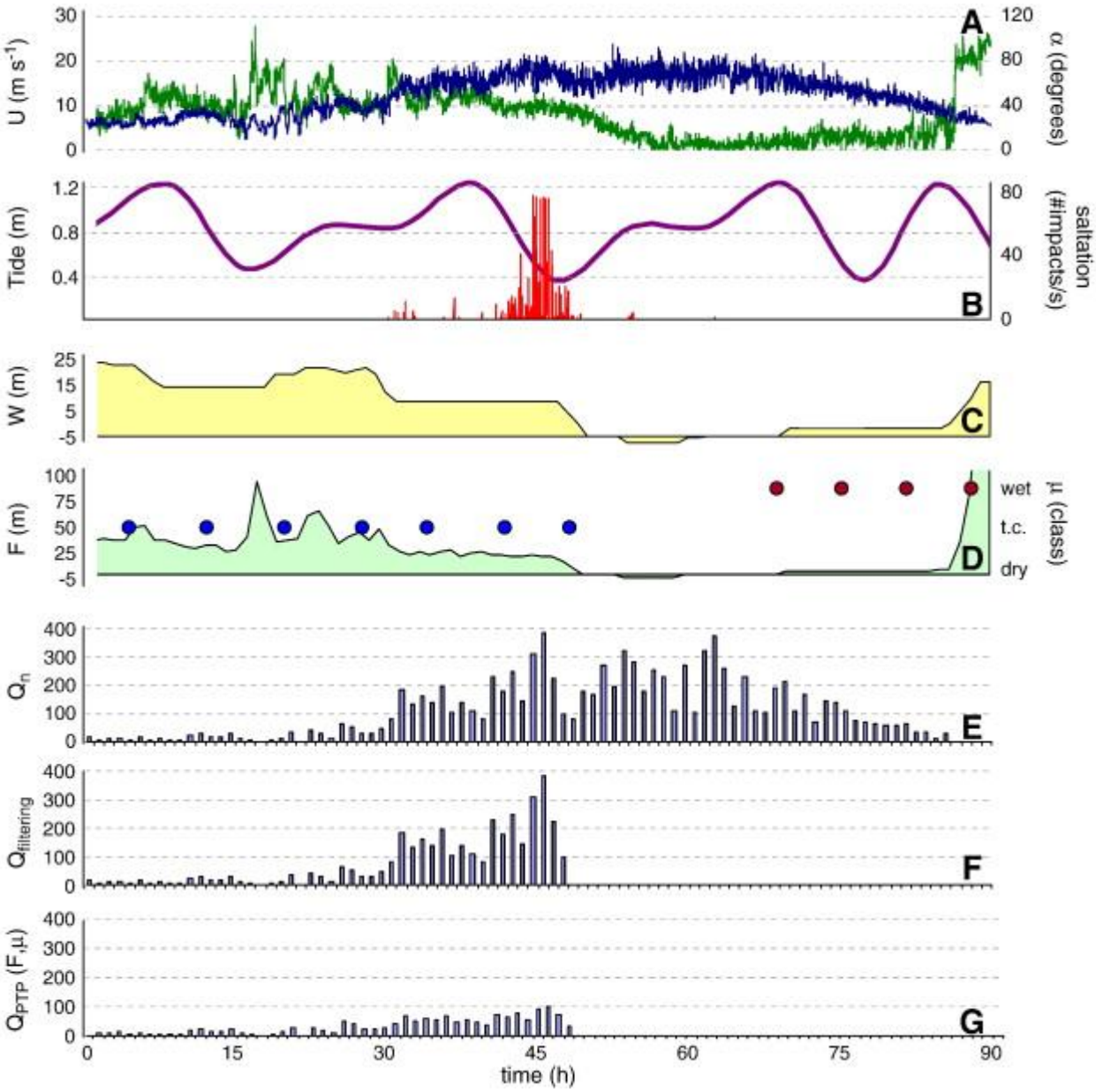

Fig. 10. Modelling output for a 90-hours storm approaching Greenwich from the North on November 9, 2007. A) 2-min records of wind speed (U) and direction (α); B) saltation intensity and tide elevation; C) beach width (W); D) fetch distance (F) determined by beach width and wind direction, and classified moisture values (μ); E) hourly transport

based on wind speed and direction (Q_n); F) output of the filtering step ($Q_{filtering}$); G) output of the calculation of transport over the isolated potential transport periods (Q_{PTP}) including fetch distance and moisture. Transport in E–F is expressed in kg m^{-1}.

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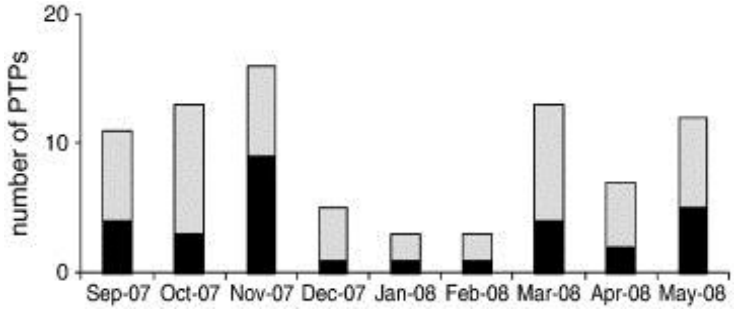

Fig. 11. Isolated potential transport periods (PTPs) where transport was observed (black) and where transport was not developed (grey).

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