Alongshore variation of aeolian sediment transport on a beach, under offshore winds

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Abstract

Understanding the morphodynamics of beach-dune systems requires knowledge of the spatio-temporal variability of the sediment transport system. It is common in aeolian studies to employ a single transect instrument set up, oriented parallel to the wind direction. This experimental design assumes that there is no significant variation in sediment transport lateral to this direction. A limited number of recent studies into this lateral (or spanwise) variability have revealed substantial differences in transport rates over very short spanwise distances (<4 m). Research investigating scales of 10 s of metres is even more limited. This paper examines alongshore variability of aeolian sediment transport at this scale. Data were collected over eight hours during an offshore wind event. Thirteen Jackson traps were deployed, co-located with three-dimensional ultrasonic anemometers (UAs). The instruments were deployed in a grid covering an area of 55 m cross shore and 90 m alongshore. The data were analysed as 5 and 10 min totals, and were mapped for visual assessment of transport patterns. Alongshore variability was quantified using the coefficient of variation (CV). Results confirm identifiable spatio-temporal patterns in sediment transport. The CV results show alongshore variability ranging from 12% to 48%, with the lower beach traps showing much greater spatial variation. These values are comparable to earlier studies. The implications of recent research into secondary airflow patterns over dunes are discussed in light of the results presented.

Highlights

- Addresses gap in field – data on alongshore variation in aeolian sediment transport.
- Data collected under offshore wind, adding to rare studies under these conditions.
- Results clearly identify cross- and alongshore spatio-temporal transport patterns.

Keywords

Aeolian; Beach-dune systems; Sediment transport; Spatio-temporal variation

1. Introduction

In beach-dune systems an understanding of the aeolian sediment transport system is critical to understanding the broader morphodynamic functioning of the system. Numerous factors have been shown to affect rates of sediment transport (Sherman, 1995). These include fluid forcing variables, such as wind speed and direction (Arens, 1996, Jackson and McCloskey, 1997 and Leenders et al., 2005), and factors which control the erodibility of the surface (e.g., moisture content (van Dijk et al., 1996 and Wiggs et al., 2004) or grain characteristics (Arens et al., 2002 and Leys and McTainsh, 1996). Because all of these factors can vary over time and space it is to be expected that the resultant sediment transport will also exhibit spatio-temporal variability. Cross shore variability has been identified by many studies (e.g., Bauer et al., 1990), with zonation of the transport patterns apparent in some cases. Most studies, however, assume lateral variability – perpendicular to the airflow direction – in the fluid forcing (considered the primary controlling factor) is not significant enough to warrant designing experiments to assess this aspect. This has resulted in the use of single transect lines that are aligned parallel to the airflow direction (e.g., Davidson-Arnott et al., 2008, Hesp et al., 2005, Nordstrom et al., 1996 and Walker et al., 2006). This is also the case in many wind tunnel studies, where only one instrument line is common (e.g., Bauer et al., 2004,Butterfield, 1999, Dong et al., 2004 and Rasmussen and Mikkelsen, 1998), in most desert studies (e.g., Baddock et al., 2011, Weaver and Wiggs, 2011 and Wiggs et al., 1996) and in the fluvial literature (Best, 2005). Another likely reason for the use of single transect lines is the common shortage of physical and human resources (Sherman, 1995).

Where lateral variability has been assessed it has been found to fluctuate considerably.Gares et al. (1996) investigated alongshore trends in sediment transport during offshore wind events. Alongshore transport rates were assessed in comparison to spatial variations in a number of variables, including moisture, carbonate content, wind speed and sediment size. Wind gustiness (high variability in speed and direction) and moisture appeared to contribute more to the variable transport rates than any of the other variables. Nordstrom et al., 2007 and Nordstrom et al., 2006 and Jackson et al. (2006)recorded high spatial variability in sediment transport over a 4 m distance for alongshore and offshore winds in a complex human altered beach-dune system. More recently Ellis et al. (2012) have reported substantial lateral variability in sediment transport rates at two separate field sites. Employing similar spatial (<4 m) and temporal (3–20 min) scales they demonstrated that lateral variability in sediment transport rates could lead to up to 100% disparity between predicted and observed transport rates if single point measurements are relied upon.

Recent research on secondary airflow dynamics and the role turbulent structures may play in grain entrainment have highlighted the complex nature of the forcing fluid flow itself. Topographic steering of alongshore winds towards the foredune (Walker et al., 2006), airflow stagnation followed by acceleration up the stoss slope and further steering or flow separation at the crest (Hesp et al., 2005), topographic steering or reversed flow on the lee side of dunes (Lynch et al., 2008, Lynch et al., 2009 and Lynch et al., 2010) have been recorded in coastal dune environments.

In theory, the spatio-temporal variations evident in airflow should be reflected in the sediment transport patterns. It is on this premise that Baas and Sherman (2006)investigated the lateral variability of sediment transport using statistical characterization analyses. Their field study found that variability increases with spatial scale, with impact sensors 4 m apart recording up to 266% differences in transport rates. These differences occurred under fairly constant wind conditions (within 15° of array normal).

While Baas and Sherman (2006) targeted an environment where a uniform boundary layer was expected, to date, no studies have been undertaken to incorporate recent advances in our understanding of secondary airflows in controlling lateral variability in sediment transport patterns.

The research reported here was designed to investigate if lee side secondary airflow structures that may occur during offshore winds result in alongshore variations in sediment transport on the beach. Delgado-Fernandez et al. (2011) quantified near surface airflow patterns under offshore conditions at the Magilligan Strand, Northern Ireland, using quadrant analysis to propose a quantitative model describing airflow reversal, transition and its re-attachment in the lee of a coastal dune. Findings from Delgado-Fernandez et al. (2011) were later used as a basis for Computational Fluid Dynamics (CFD) simulations, with results suggesting the nature of the airflow response in the lee of the dunes was not uniform alongshore (Jackson et al., 2011). In simulations, using a detailed digital elevation model of the site incorporating dune crest irregularities and dune lee side complex topography, heterogeneity within the secondary airflow patterns was evident. Zones of enhanced transport potential (i.e., higher wind speeds close to the surface) were seen to alternate with zones of reduced potential, with spacing in the order of 10–50 m. While Jackson et al. (2011) presented wind simulations in three-dimensions their field airflow data was recorded along a single cross shore transect, making it insufficient for the purpose of investigating alongshore wind patterns in the field.

A field experiment was designed to assess spatio-temporal patterns of sediment transport and secondary airflow, under offshore winds. This paper reports on the variability of sediment transport on the beach [a companion paper reports the finding regarding the airflow dynamics, with another companion paper reporting on the role turbulent airflow structures play in the initiation of sediment transport.

2. Study site

Magilligan Strand, Northern Ireland was used as a study site (Fig. 1). The beach is oriented along a north west – south east axis and is dominated by prevailing south westerly offshore winds. The foredunes are up to 12 m in height at the site and are backed by dune ridges of similar height. All ridges are densely vegetated by *Ammophila arenaria.* The slope of the foredune facing the beach (the lee side under off shore airflow) is abrupt and is thought to enhance airflow separation under certain conditions (Beyers et al., 2010). The foredune toe section at the site had been accreting for a number of years at the time of the study, with embryo dunes up to 1 m height in place. The beach is generally planar, and up to ~100 m wide during spring low tides. Sediments consist predominantly of very well sorted, fine-grained quartz sand, with a mean grain size of 0.17 mm. The beach was relatively free of drift material and vegetation at the time of the experiment. The site was chosen based on previous observations of airflow separation and reversal during offshore winds. Recent research by Lynch et al. (2010) observed that different dune morphologies along Magilligan Strand interacted differently with the flow. Sharp-crested, high dune sections such as the one of the study site resulted in flow separation and reversal while more rounded, shorter dunes along the NW end of the spit resulted in deflection of attached airflows. Numerical simulations using CFD tools by Beyers et al. (2010) and Jackson et al. (2011), and field data presented by Delgado-Fernandez et al. (2011) confirmed the existence of clear patterns of airflow separation and reversal at this particular site.

3. Methods

3.1. Field measurements

Data were collected over eight hours during an offshore wind event on 26 April 2010. The surface was dry and relatively free of shell lag deposits, algae, and other debris strongly affecting general transport dynamics. Micro topographical features such as ripples developed before and during the experiment (Fig. 2). Thirteen continuously weighing horizontal sediment traps were deployed. The traps are a modified form of the Jackson trap (Jackson, 1996) where the tipping bucket mechanism was removed and the load cell upgraded to hold approximately 3.5 kg of sand before it required emptying. This greatly reduced data post processing time. The traps were co-located with three-dimensional ultrasonic anemometers (UAs), each placed at a height of 0.5 m. (Fig. 2). The instruments were deployed in a grid covering an area of 55 m cross shore and 90 m alongshore. Cross shore spacing between each pair of instruments was 10 m. Additional traps were deployed along Transect B to give a 5 m spacing for this line of instruments. Alongshore spacing of the transects was 30 m, intended to sample zones of enhanced and reduced potential transport suggested by Jackson et al. (2011). An anemometer (Gill HS-50 model) was also positioned at the foredune crest at a height of 6 m (18 m above the beach surface). All instruments were connected to an on-site personal computer and logged simultaneously at 25 Hz. A total of 14 traps were deployed during this run, however, instruments located in position D1 did not perform correctly and hence have been excluded from the analysis. Instrument positions and survey data were gathered with a Trimble 4800 Differential Global Positioning System (DGPS). Topographic information of the beach surface as used to create a detailed digital elevation model of the study site (Fig. 3).

3.2. Analysis methods

The trap data were analysed as 5 and 10 min totals, and were mapped for visual assessment of transport patterns. The co-located anemometer data were used to infer transport direction. Anemometers were oriented in the field in similar directions with respect to North and levelled with respect to the horizontal gravity plane. Each anemometer was sampled at 25 Hz and provided time series of three components of the wind vector, *u* (streamwise), *v* (spanwise), and *w* (vertical). These were first averaged into 5 and 10 min periods and subsequently used to calculate wind direction (*α*) and wind speed (*S*) as:

$$\alpha = 180 - atan2(u, v) \qquad \text{equation (1)}$$

$$S = (u^2 + v^2 + w^2)^{0.5} \qquad \text{equation (2)}$$

The sediment transport data were converted to total accumulation in g m^{-2} for 10 and 5 min periods.

In order to compare the results here directly with those of Gares et al. (1996) alongshore variability was quantified for each cross shore beach zone. The range of variation coefficient (RVC) and the coefficient of variation (CV) were calculated for the lower, mid and upper beach. The RVC is obtained by dividing the average value for a set of traps by the minimum and maximum values for that set. The CV is obtained by dividing the standard deviation for a set of traps by the average value for that set.

4. Results and discussion

Spatio-temporal patterns are evident from a time series plot for the eight-hour period. A distinct clustering of sediment transport is evident in the data over the duration of the event (Fig. 4). System organisation develops quite quickly after the beginning of the transport event and persists, with some variation, until the end of the event. Shore parallel zonation is evident for the upper and mid beach, with the lowest sediment flux on the upper beach (yellow) and the high flux values for the mid beach (pink). The lower beach position, however, ranges from the highest transport rates to the lowest over the course of the event (blue). The spread of the data lines on the plot gives a direct indication of the alongshore variation of transport. Tight clustering on the upper beach (yellow lines) indicates little alongshore variability in the total sediment trapped within this zone; less clustering is apparent on the mid beach (pink lines); while a high degree of variability in sediment transport is evident on the lower beach (blue lines).

A quantification of the alongshore variability for the upper, mid and lower beach sets of traps is shown in Fig. 5. Although the sediment transport rate on the mid beach (2.51 kg m^{-1} hr^{-1}) was twice that of the upper beach (1.23 kg m^{-1} hr^{-1}) the range of variability is quite similar (RVC, respectively of 92–114% and 84–112%). The lower beach on the other hand has a much greater range of variability (52–165%), while sediment transport rates are within the range of the other zones (1.74 kg m^{-1} hr^{-1}). The CV results show the contrasting variability more clearly, with upper (12%) and mid beach (14%) traps exhibiting similar values and the lower beach traps showing much greater spatial variation (48%).

4.1. Cross shore patterns

The patterns described above are further elucidated by mapping the transport quantities and adding a direction component. A 1 h subset of data were used from a period when airflow was directly offshore at the crest and of a sufficient speed to enable sediment transport on the beach surface. Transect B was used for this analysis as it had the most instrumentation, thereby giving the most detailed picture of the cross shore sediment transport patterns, and allowing a much clearer differentiation between zones. There are clearly identifiable trends in both magnitude of transport and the direction of movement (Fig. 6). Transport on the lower beach does not exceed 373 g m^{-2} for any 10-min period and consistently blows offshore (Zone I). The next two traps up the beach collected considerably more sediment ranging from 403 to 997 g m^{-2}, with movement fluctuating between obliquely offshore to directly offshore (Zone II). Landward of this a zone of shore parallel sediment transport is evident, with maximum transport of 845 g m^{-2} (Zone III). Transport at the dune toe diminished to range between 113 and 667 g m^{-2}, with movement consistently directed onshore (Zone IV). The sediment transport zonation across the beach remains consistent over the one hour period.

4.2. Alongshore patterns

Alongshore patterns are assessed using the cross shore trends described in the previous section, rather than on a trap by trap basis. As the traps on Transects A, C and D had a 10 m spacing only the equivalent traps on Transect B are used for this analysis. The sediment transport on Transect A seems to follow the magnitude and direction patterns of Transect B, with the only deviation being onshore directed transport during the second 10 min period for the mid beach position (Fig. 7). The transport magnitudes of Transect C are less than that of all other lines. The transport direction on the lower beach is orientated more consistently directly offshore, with the mid beach transport direction orientated alongshore to onshore in comparison to alongshore to offshore for the other mid beach traps. Line D shows the highest transport rates with consistent oblique offshore transport. Considering these data, therefore, it may be said that the cross shore zones – identified in Fig. 6 – are replicated at each position along the beach and do so consistently for the period of the transport event. Where slight alongshore deviations exist they do so in a consistent manner, suggesting there may be a fairly fixed alongshore controlling factor at play. The variability of transport direction alongshore is largest within the mid beach zone, with Transects A and C showing a majority of onshore directed transport and Transects B and D showing offshore directed transport. This also suggests the existence of preferential zones for onshore directed transport that are fairly permanent through time.

To assess cross and alongshore patterns further the data from 08:10 to 08:40 were binned at 5 min intervals (Fig. 8). At this time scale the the cross shore zonation for lines B and D again match those at the longer time scale, with the lower and upper beach transport patterns of lines A and C also following the trend. The mid beach traps for lines A and C exhibit highly variable transport from one period to the next. The beach sediment transport zonation at this time scale may then be described as: Zone I – lower beach, offshore directed transport of a magnitude less than the mid-beach and greater than the upper beach; Zone II – mid beach, high directional variability and highest transport rates; Zone III – upper beach, onshore directed sediment transport of realtively low magnitude. Alongshore patterns also remain fairly consistent at this time scale. However, as the time scale decreased directional variability at many of the traps locations increased, especially those within the mid beach zone.

5. Results and discussion

5.1. Alongshore sediment transport complexity

The results presented here show alongshore heterogeneity in sediment transport occurs under offshore winds at this site. The pattern of variation in transport along transects spaced 30 m apart correspond, at least qualitatively, with the CFD simulation results ofJackson et al. (2011). That is, areas of higher transport (Transects A and C) interspersed alongshore with areas of lower transport (Transects B and D). Interestingly the alongshore zones persisted over the one hour period presented here – this may suggest that there is a controlling factor at play that is orientated along a cross shore plane, or that fixes the forcing airflow in that plane. So, while spatial complexity is evident in the sediment transport data, it is not chaotic and may be described as organised – possibly driven by coherent lee side airflow structures such as roller and helical vortices described by Walker and Nickling (2002). The fact that there is an oblique facet to the transport direction would be better explained if a helical vortex was present. It may be noted, however, that the alongshore component was a small fraction of the sediment being moved on the beach. If there was a more significant amount of sediment moving parallel to the dunes the alongshore variation in transport rates may not have occurred. For example, with significant shore parallel movement Transect C would be fed by Transect B and might have expected to display similar transport rates, rather than the low relative rates it actually recorded. Similarly there was a large degree of directional variability alongshore suggesting that transport was at some points directed even in opposite directions within the same zone. For example, the period of time from 8:30 to 8:35 in Fig. 8 shows transport to the west in the upper beach trap (onshore) and the mid beach trap (offshore) along Transect A. Transport is aligned almost cross shore along Transect B, and it changes to the east in Transect C and D. That is to say, sediment transport was not consistently steered in one direction which suggests that there might be differentiated areas of complex airflow reversal and helical vortices deflected in different directions during perpendicular offshore winds. Although a counter point here is that sand transport may have been quite localised; relatively high mid-to-lower beach rates were not observed feeding the lower beach traps just 5 m away where the transport rate was on average 36% of the mid-to-lower beach traps on Transect B (Fig. 6). The interpretations suggested here are based on the assumption that other factors that can have a strong influence on spatio-temporal variations in sediment transport were not significant here. The shoreline during the period of time covered in Fig. 6, Fig. 7 and Fig. 8 was at least 30 m apart from the last trap (low tide) and the beach surface was dry and free of debris.

5.2. Comparison with other studies

Gares et al. (1996) is the only study that had similar conditions to this one: offshore winds, a 12 m foredune and a relatively clean, flat beach surface. The positioning of their 30 m trap line is approximatley comparable to the lower beach traps used in this study, while their 55 m trap line would be seaward of this position. The alongshore variability at the 30 m line (Run 10) had a range of variation from 39% to 175% (RVC; or CV 43%, calculated from values in Gares Fig. 8) compared to 52% to 165% (CV 48%) for this study. Seaward of this position the range of variation reduced considerability to 78% to 119% (RVC; CV 17%), which would be expected as the topogaphical influence of the foredune recedes and a new internal boundary layer becomes established. In contrast, the results of this paper may be considered unexpected. The quantitative description of the airflow patterns (Delgado-Fernandez et al. companion paper) locates the mid and upper beach traps in highly turbulent areas (reversal; transition; re-attachment zones) where higher relative variations in wind speed and direction were recorded in comparison to the lower beach trap position, where a new inner boundary layer had begun to form. The alongshore variations in sediment transport do not match this pattern. The alongshore variation between traps located in the relatively more turbulent areas show low CV values of 12% for the upper beach and 14% for the mid beach (and as stated above 48% for the lower beach). A possible explanation for this unexpected finding is that alongshore each set of traps – with little variability – is in the same cross shore zone, while the set of traps with high variability are in fact in different cross shore zones. In other words, all the upper beach traps are in the reversal cell, all the mid beach traps are in the transition/re-attachment zone, while for the lower beach traps some may still be in the transition/re-attachment zone, with others in the newly forming inner boundary layer. This assumes that there is a characteristic magnitude-distribution sediment transport signal for each cross shore zone.

Alongshore variation values reported here are comparable to other studies that have investigated variations in transport perpendicular to the airflow direction. Nordstrom et al. (2006) recorded a value of 12% variability (CV) for 3 traps on the foreshore over a distance 20 m alongshore, under offshore winds for a 2 h period (The CV value is calculated from Table 2). Over shorter scales Baas and Sherman (2006), using 35 safires over 4 m for 2 min, found CV 48% in alongshore (spanwise) variation. Also over 4 mJackson et al. (2006) utilised five traps over a periods from

25 min to 1 h and recorded spatial variation perpendicular to the airflow of between 33% and 91%.

It is significant that the results presented here show patterns evident in the sediment transport system persist over time for a relatively long record (8 h) with relatively long (10 min) averaging intervals (Fig. 4, Fig. 6, Fig. 7 and Fig. 8). Most studies on variability in sediment transport investigate the (apparent) randomness of the system, with fluctuations in the transport expected to diminish as longer averaging intervals are used. This is not the case in the results presented here, suggesting that the secondary airflow patterns (thought to be controlled by topographic variations at the fordune crest) impart a structure on the sediment transport patterns; reflected in alongshore and cross shore variability.

5.3. Aeolian sediment transport and beach-dune dynamics

Despite the alongshore variability in sediment transport patterns it is worth noting that the average rate of transport on the upper beach was 1.23 kg m^{-1} hr^{-1} and was directed onshore, aiding in dune maintanance during offshore airflow. This finding, in addition to the alongshore variability in transport shown here, has significant implications for the modelling of beach-dune morphodynamics. In aeolian dune settings secondary airflow patterns are an inherent component. These airflows have been shown here and elsewhere to influence the sediment transport system, therefore models based on primary (regional) data alone will be fundamentally flawed. When investigating offshore airflows the use of a single cross shore transect may misrepresent the overall sediment transport budget depending on placement, even at an averaging time scale in the order of 10 min.

6. Conclusions

An understanding of secondary airflow patterns and the three dimensional nature of sediment transport is critical to understanding the morphodynamics of beach-dune systems. This study has documented various aspects of the sediment transport system on a sandy beach under offshore winds.

Quantifiable spatio-temporal variability in aeolian sediment transport is evident during offshore wind events. In a cross shore direction, zonation may be identified from transport magnitude and direction characteristics. These zones of sediment transport may persist over time. The cross shore trends, although consistent over time, have been shown here to vary according to their alongshore position. These results highlight the important three-dimensional nature of aeolian sediment transport in complex beach-dune systems and the need to incorporate an alongshore (or lateral) dimension in any attempts to model this environment.

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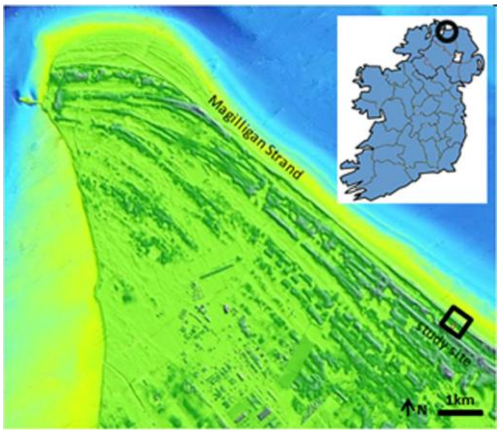

Fig. 1. Location of study site at Magilligan Strand, in Northern Ireland. The area of interest (square) covered a section of approximately 100 m alongshore.

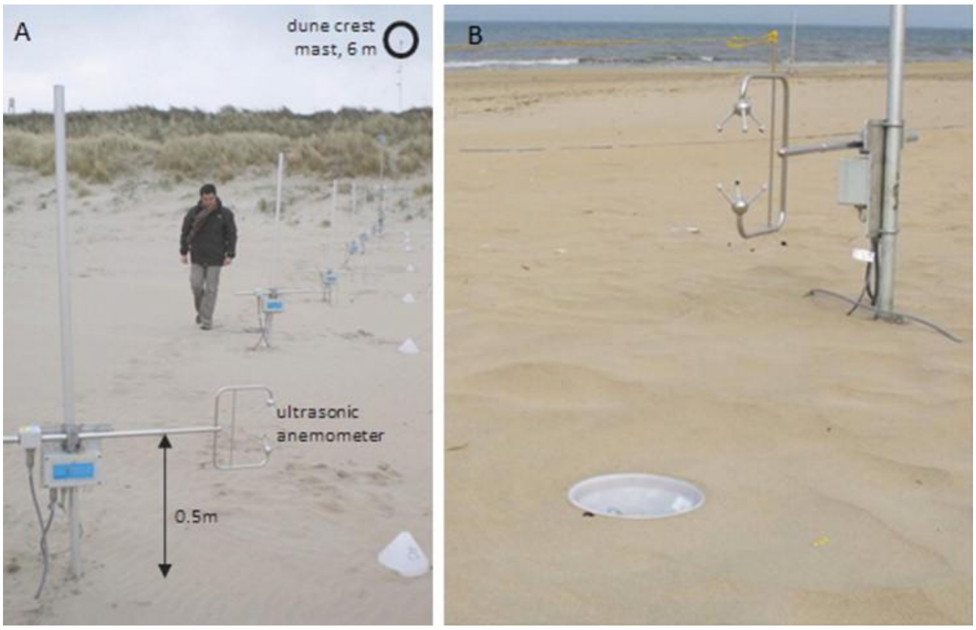

Fig. 2. (A) Close up on station in position B7. Ultrasonic anemometers (UAs) were deployed at 0.5 m elevation over the beach surface and co-located with a sand trap; (B) Close up on sand trap and UA at position D3 and surface conditions during the run presented here, showing a dry, free of debris beach surface with small aeolian ripples.

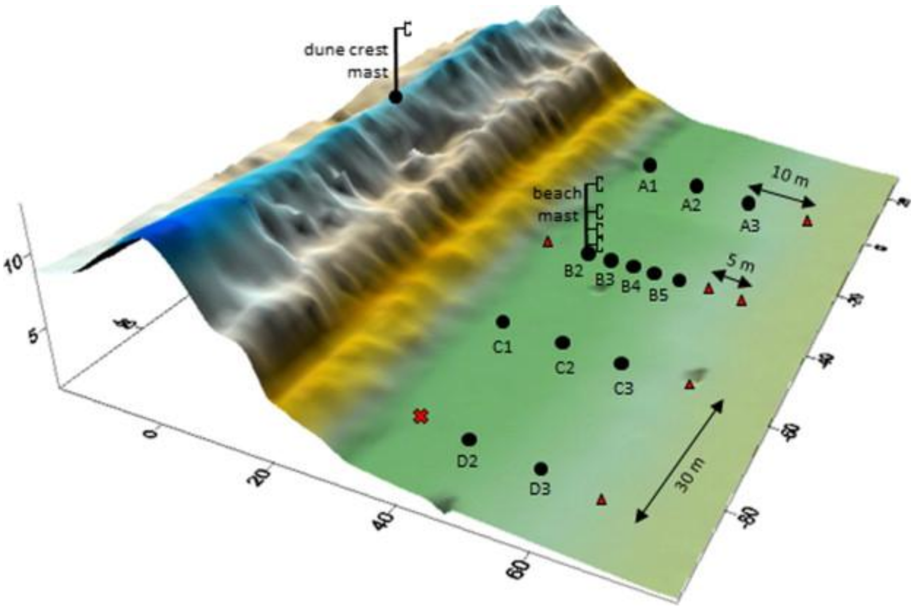

Fig. 3. Topographic surface of the study site and experimental setup. Black dots

indicate groups of UAs, traps, and safires; triangles indicate only UAs. Instruments located at position D1 (cross) did not function properly during the period of time considered in this paper and hence have been excluded from the analysis. The beach mast contained four UAs at elevations of 0.5, 1, 2, and 4 m over the beach surface (Fig. 4B) and was located at position B2. The dune crest mast contained one UA mounted on a 6 m high mast on top of the dune crest. The horizontal distance from the dune crest mast to station B1 was approximately 30 m. The vertical axis is exaggerated.

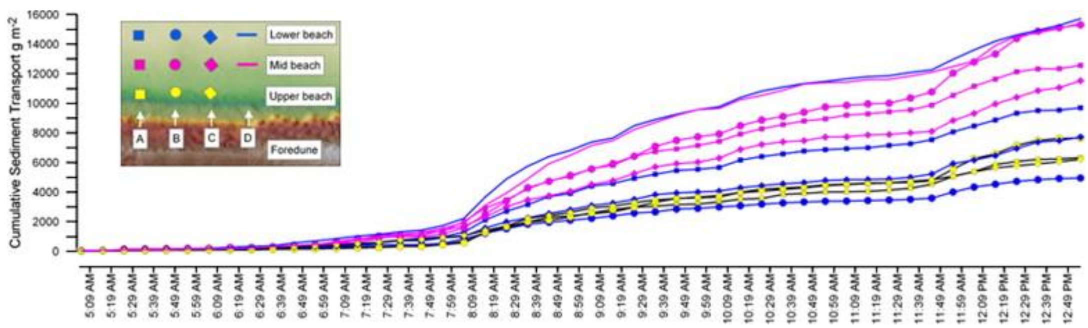

Fig. 4. Sediment accumulation across the beach (10 min accumulations). Trap lines are indicated by symbol shape. Cross-shore position on the beach is indicated by color. It is evident over the course of the event that sediment transport is not uniform across the entire beach. Spatial patterns emerge soon after the beginning of the event. For example, all three upper beach traps (yellow lines) are tightly clustered throughout the time series. Another pattern is that, generally, the mid beach positions (pink line) record the highest transport rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

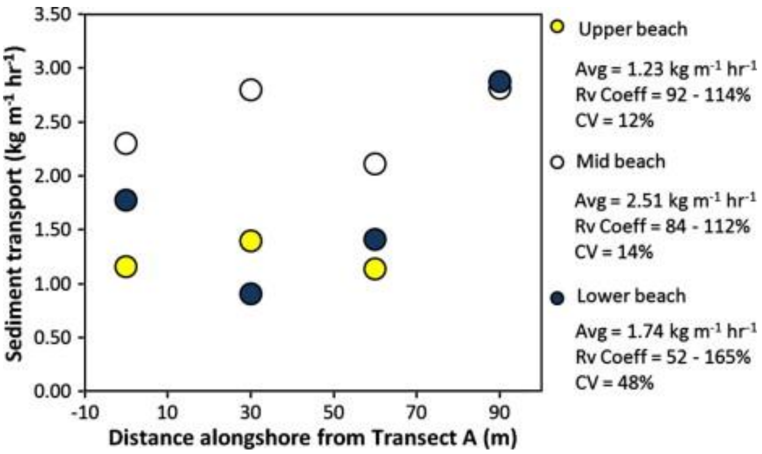

Fig. 5. Quantification of alongshore variability in sediment transport rates. Average (Avg) sediment transport rates on the mid beach were twice that of the upper beach. The range of variability (Rv Coeff) and coefficient of variation (CV) were similar and lower at the upper and mid beach but larger at the lower beach, indicating a much greater alongshore variation within this zone.

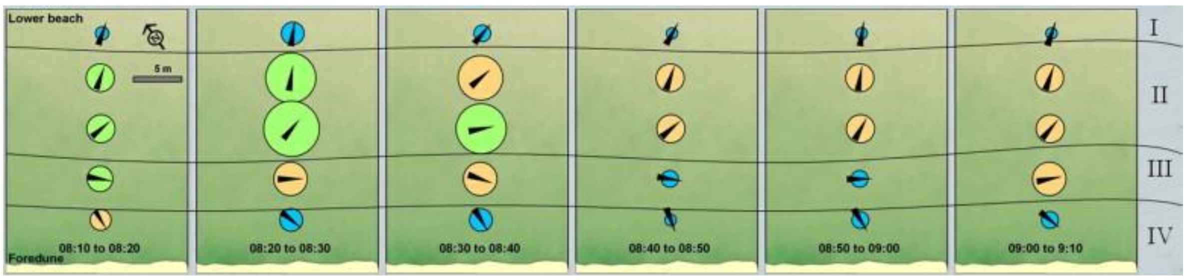

Fig. 6. Cross-shore zonation of sediment transport. Transport data corresponds to 10-min averages over a subset of 1 h during the transport event. Areas of the beach with consistent sediment transport rates and direction are evident in the data. Zone I – offshore movement of low magnitude. Zone II – highest transport rates on the beach with movement directly or obliquely offshore. Zone III – shore parallel transport of intermediate magnitude. Zone IV – low rates of obliquely onshore sediment transport.

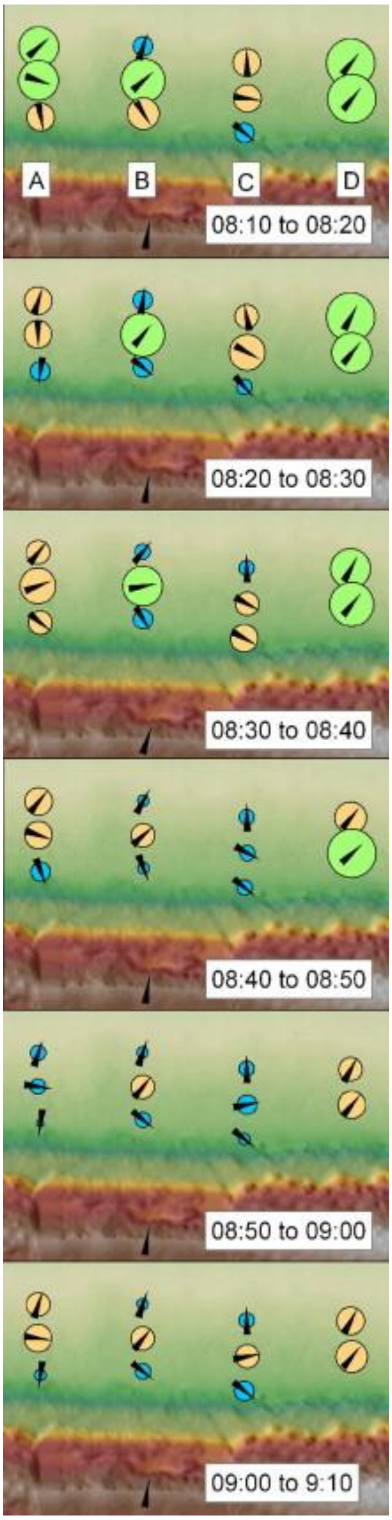

Fig. 7. Alongshore variations in cross-shore zonation of sediment transport.

Deviation in the cross-shore trends identified for line B are evident alongshore, this may be expected – the striking aspect is the cross-shore trends for each line show a considerable degree of consistency (in transport direction and relative magnitude) for the hour of data presented here.

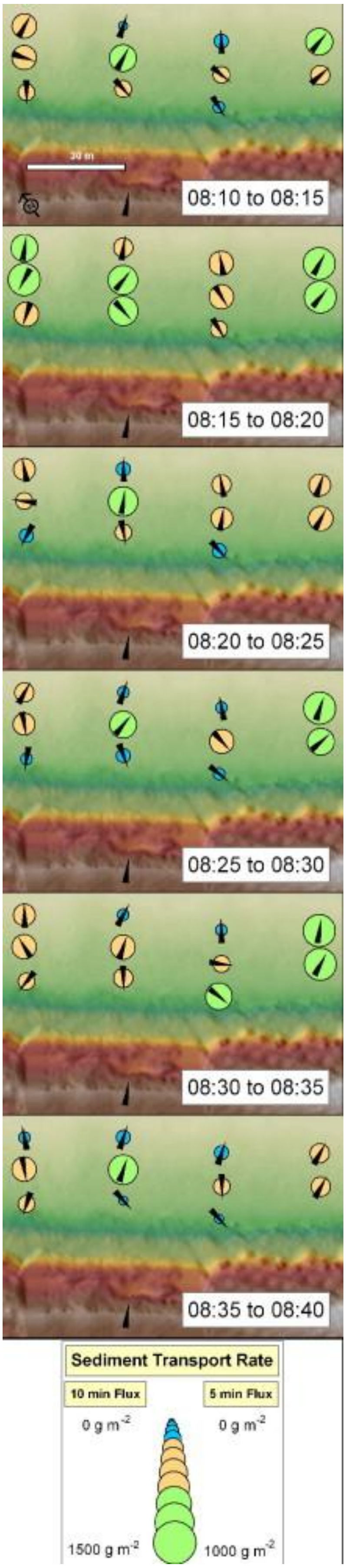
30 m
08:10 to 08:15
08:15 to 08:20
08:20 to 08:25
08:25 to 08:30
08:30 to 08:35
08:35 to 08:40
Sediment Transport Rate
10 min Flux
5 min Flux
0 g m-2
0 g m-2
1500 g m-2
1000 g m-2

Fig. 8. Five-min intervals of sediment transport. Cross-and alongshore patterns identified at the longer timescale remain identifiable at this scale, suggesting complex yet semi-fixed controlling factors are present. The decrease in time scale increased the complexity of transport patters, suggesting that the wind was steered in opposite directions alongshore within the same zone during certain time intervals (e.g., at the upper beach from 8:35 to 8:40).