Aeolex II

"Aeolian processes on a natural beach, spatial variability in wind characteristics"

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SUMMARY

In order to further increase the knowledge about the transformation of wind patterns on the supra and intertidal beach during onshore wind events a field experiment was launched during October 2017 on the beach near Egmond aan Zee. Part of this field experiment was measuring wind on different (cross shore) locations on the beach using four mobile sonic anemometers capable of making three dimensional measurements of wind vectors at a rate of 10hz. Based on the data gathered in the field experiment the following research question is answered: **"How do regional wind patterns compare to local wind patterns on the beach during different on-shore wind events?"** Additional knowledge about onshore wind patterns is wanted in order to further improve the predictions of dune development thereby enhancing the water safety of the hinterland. The fieldwork campaign carried out in this research was highly successful due to almost perfect conditions. After the dataset gathered during the experiment was analyzed, it became clear that the wind decreases across the width of the beach during onshore wind events. The amount of decrease is highly dependent on the incident wind direction. Whereas onshore wind events show a potential decrease upwards of 60%, oblique onshore and oblique alongshore show a maximum decrease of 45% and 23% respectively. It has been observed that the turbulent kinetic energy remains constant across the beach. The wind direction changes across the beach and tend to become more dune parallel when the dune foot is approached. Compared to regional wind speed measurements, measurements performed at the back of the beach show a decrease of 48%. Almost half of this decrease however is due to the logarithmic vertical velocity profile of the wind. Furthermore, it has been established that the regional wind direction measurements could closely reassemble local wind directions when a fifth order polynomial formula is applied on the regional measurements. The new insights regarding the decrease in wind speed over distance further complicates the already complex cosine effect. Additional research regarding the interaction of the cosine effect with the new results of this study therefor is recommended.

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1 Introduction

1.1 Introduction

Sandy beaches worldwide are known for their dynamic behaviour. Various marine processes form the intertidal beach whilst Aeolian processes dominate the supratidal beach. The Aeolian processes are important for the growth of the foredune system if present (Hesp, 1984). Predictions made by computer models on Aeolian transport are often wrong compared to occurring grow rates (Keijsers et al., 2016). Many studies focused on supply limiting factors of Aeolian transport events such as fetch distance, grain size sorting and surface moisture (e.g, Bauer and Davidson-Arnott ,2003; Davidson-Arnott 1990; Gares et al.,1996; Jackson and Cooper 1999). Little to none research has been conducted on the evolution of the local wind patterns on the (supratidal) beach under onshore wind events (Delgado-Fernandez, 2010). However, it is observed that wind characteristics such as mean wind speed and direction do change across the width of the beach, yet no attempts have been made to quantify these changes (Bauer et al., 2009; Hesp et al., 2005).

In the current situation Aeolian models over predict the sand deposition when applied to the Dutch coast (Keijsers et al., 2016). Processes considered in current models are amongst other things: grainsize, windspeed, surface moisture and boundary conditions such as beach topography and sediment availability (Hoonhout en de Vries, 2017). A detailed description of processes taken into account is included in the literature review present in this thesis.

This results in inaccuracies in computer models predicting dune development. These inaccuracies are undesirable in the context of the Dutch coastal flood defence. The Dutch Coast is characterized by sandy –wave-dominated beaches with a relatively high foredune system. The beach itself often shows complex morphological patterns which under normal conditions are mainly driven by marine processes on the intertidal beach and Aeolian processes on the supratidal beach. The foredunes provide a natural defence mechanism for the coastline. The presence of the foredune also induces topographical steering near the dune foot, altering the wind patterns on the beach (Walker, 2006). As concluded by Hesp (1984) the natural growth of the foredune is directly influenced by Aeolian transport. In 2015 a field campaign was launched by the Utrecht University in order to investigate the processes of Aeolian transport on a Dutch beach near Egmond aan Zee. Part of this campaign was a preliminary study to cross-shore wind patterns. This resulted in a limited data-set of cross-shore wind profiles measured by sonic anemometers. After studying the measurements it is concluded that (Winter et al., 2015) (see Figure 1.1):

1. The mean wind speed decreases in downwind direction for obliquely onshore winds. Alongshore winds only show a drop in velocity near the dune foot.
2. The direction of local winds changes as the dune foot is approached. The direction tends to become more dune-parallel.
3. It was supposed that the TKE (turbulence kinetic energy) would be related to the mean wind speeds during onshore wind events. Yet the TKE remains constant across the beach whilst the wind speed is dynamic.

Since the conclusions above are drawn on a preliminary study and thus are based on a limited data set, it is important to further substantiate these conclusions and to quantify the observed relations.

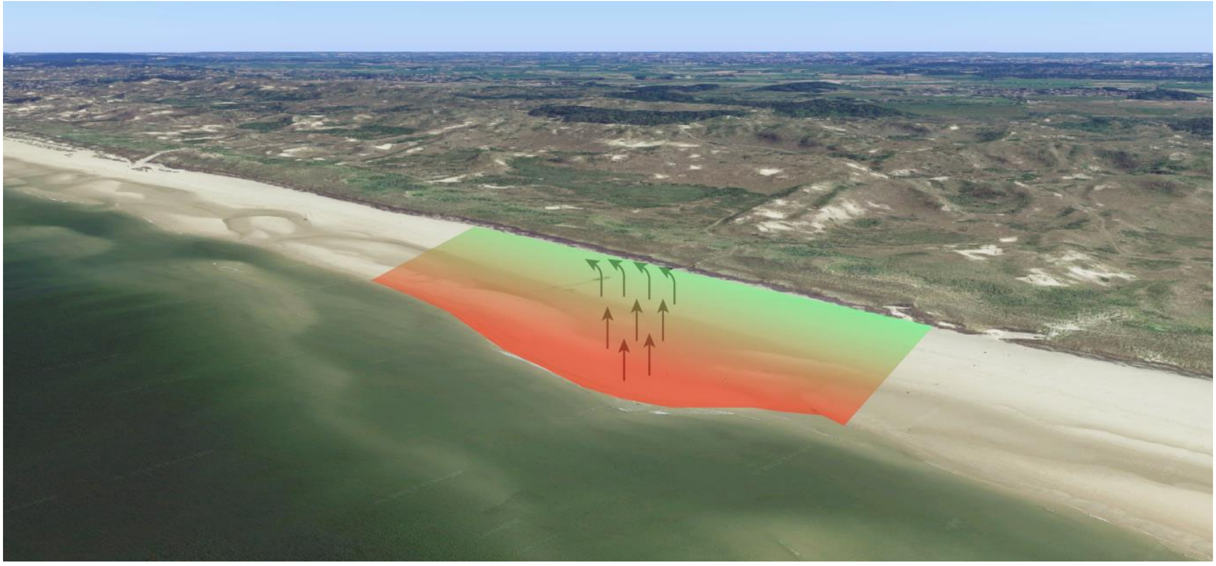

Figure 1.1.: A cross-shore section of the beach near Egmond aan Zee. The colours indicate the maximum wind-speed in which red represent relative high velocities and green relatively low velocities. The arrows indicate the wind direction (Self-made material).

1.2 Scope

This study consists of an in-depth review of coastal wind characterises during onshore wind events on the intertidal and supra tidal beach. A literature review is included in this study reviewing the current state of knowledge regarding wind patterns on the beach. The focus of this study however, is conducting a field experiment gathering (wind) data specifically for conditions typical for the Dutch coast. In the current situation there is not much information available about the behaviour of the wind across the beach itself during onshore winds in areas with high and steep for dunes (I.E. the Dutch coast). Therefore, the main research question this MSc thesis aims to answer is:

“How do regional wind patterns compare to local wind patterns on the beach during different on-shore wind events?”

To answer the main question three sub-questions are defined:

1. In what way does the wind -speed, -direction and -turbulent kinetic energy change from waterline towards the foredune in downwind direction?
2. What is the relative change in wind -speed, -direction and -turbulent kinetic energy under different onshore wind events in relation to the wind characteristics at the most dune ward measurement station?
3. How could regional (offshore) wind velocity measurements at a height of 10 meters above the surface be translated to local wind measurements at a height of 0.9 meters above the beach surface?

A more in-depth motivation of the sub-question and why it is necessary to answer those in relation to previous studies to wind patterns can be found at the end of chapter 2.

The study will include a field experiment to gather data. The true focus of this study is the development of wind patterns during onshore wind events. Potential mechanics occurring during offshore events will not be discussed within this study. Furthermore, during the fieldwork campaign no data will be gathered during offshore wind events.

1.3 Outline

Chapter 2 consists of a literature review in which current knowledge about Aeolian transport mechanisms is reviewed. The 3rd chapter describes the methodology used within this research including a description of the fieldwork experiment. Using the data collected during the fieldwork campaign, chapter 4 provides insight in the change of wind characteristics across the beach whilst chapter 5 provides insight in the comparison between regional and local wind measurements. A discussion about the study is included in chapter 6. Finally, chapter 7 summarizes this study and the main conclusions are stated.

2 Literature review

Coastal wind characteristics in combination with Aeolian sediment transport events have been extensively investigated. However most of the studies conducted focussed on the change in wind characteristics on the foredune itself rather than the wind characteristics on the supra and intertidal beach. Studies in which the supra and intertidal beach are considered, are often studies focussed on Aeolian transport during offshore or dune parallel wind events. (e.g. Mikklesen, 1989; Walker et al., 2006, 2009, 2017; Delgado-Fernandez, 2013; Walker and Shugar, 2013; Hesp et al., 2015). This chapter provides background information to understand the basics of Aeolian sediment transport, and in what way the Aeolian sediment transport can be influenced. First a brief introduction will be given on the basic principles Aeolian transport events and the factors which influence the transport events, afterwards a more in-depth review of the so far observed behaviour of wind will be provided.

2.1 Aeolian transport events

Aeolian transport is the transportation of individual sediment grains from place A to place B. On sandy beaches Aeolian transport is important for the development of the foredune system (Hesp, 1984). Aeolian transport only occurs when the lifting force as a result of shear stress exerted by the wind larger is than the gravitational force. Lifting force is the result of pressure differences on top and at the bottom of sediment grains. The point where the lifting force as result of shear stress exceeds the gravitational force and the sediment grains are lifted vertically in the air is called critical shear stress. (Bagnold 1941, Pye 1983, Sherman & Hotta 1990, Sherman & Bauer 1993). In 1941 Bagnold discovered that this transport almost entirely takes place less than half a metre above the ground surface within nearly 90% in the first three centimetres. On the Dutch coast the most common mechanism of aeolian transport is saltation (Keijsers et al., 2016). Saltation occurs when the sediment grains are suspended for a brief period of time and fall back to the surface in a parabolic trajectory afterwards this process is repeated (Bagnold 1941). The suspension time is mainly determined by grain size, shape and density of the material as well as wind velocity and turbulence.

2.1.1 Supply limiting factors Aeolian transport

One of the first researchers attempting to predict sediment transport was Bagnold who derived the following formula (Bagnold 1941):

Equation 2.1 Potential transport formula as described by (bagnold 1941)

$$q = C\,\frac{\rho}{g}\,\sqrt{\frac{d}{D}}u_*^3$$

This formula determines sediment transport rates q as a function of grain sorting (C), density of air (ρ), the gravitational constant g, the reference grain size (d), a uniform grainsize D and the friction velocity u* which is proportional to the wind velocity and shear stress (Bagnold, 1941). U* can be derived from the (vertical) logarithmic wind profile of. Therefor it is depended on the roughness length of the surface of the sediment and the von Karman constant. The roughness length is the height at which the windspeed theoretically becomes zero whilst the von Karman constant is a dimensionless constant used in the logarithmic law to describe the vertical wind profile. Using a formula U* can be determined as follows: $U *= \frac{k*U(z)}{\log(\frac{Z}{z0})}$.

Wind tunnel experiments proof the correctness of this formula and therefore it is still deemed correct. Although the individual mechanics of Aeolian transport are fairly well understood, in coastal areas measurements of Aeolian transport deviate considerably from the potential rates as predicted by transport equations, the transport equations tend to overpredict sediment fluxes (Arens, 1994; Keijsers et al., 2016). Numerous attempts have been made to address this issue by further researching potential supply limiting factors in sediment transport (e.g, Bauer and Davidson-Arnott, 2003; Davidson-Arnott 1990; Gares et al.,1996; Jackson and Cooper 1999). The main supply limiting factors for Aeolian transport identified so far are surface moisture and wind fetch length. In 2008 Davidson-Arnott, et al. wrote that there are significant differences in transport under different soil moisture contents in relation to changing wind patterns. They concluded that under relative dry conditions there is a rapid response to fluctuations in wind speed whereas for relatively wet conditions this response is far less. They also stated that under wet conditions the mean transport rates are also much less compared to dry conditions i.e. surface moisture can act as a supply limiting factor (Davidson-Arnott et al., 2008). Regarding the fetch effect, a review performed by Delgado-Fernandez (2010) theoretical, wind tunnel and fieldwork experiments where compared. In this review it became clear that there is a significant difference between the critical fetch in controlled environments (i.e. wind tunnel experiments) compared to the critical fetch in natural environments (i.e. field work experiments). Critical fetch is best described as the distance over which saltation needs to build up until it reaches full potential transport as described in equation 2.1 (Bagnold 1941; Keijsers et al, 2014). Experiments in controlled environments tend to show shorter critical fetch distances than experiments in natural environments. (Delgado-Fernandez, 2010). This is partly explained by the supply limiting factors such as soil moisture but on the beach this and the non-uniformity of the bed. The non-uniform geometry of the beach in combination with the forming of a boundary layer downwind reduces the potential sediment transport. (Delgado-Fernandez, 2009). A more in-depth insight in the downwind boundary layer is provided in section 2.2.

In the past a fieldwork experiment has been performed to study the effect of wind direction on Aeolian transport on a narrow sandy beach (Nordstrom & Jackson, 1993). They found that Aeolian transport is greatest when the beach is relatively dry and wide (i.e. during low tide or the transition from low to hightide) This is in conjunction with the later findings of Davidson-Arnot et al. in 2008 and Delgado-Fernandez in 2010.

Another factor limiting the exchange of sediment between the beach and dune system identified so far is the so-called cosine effect. The cosine effect has been researched extensively researched (Davdison-Arnott & Dawson, 2001; Bauer & Davidson-Arnott, 2003). In short, the cosine effect dictates that with an increasing obliquity in wind angle compared to shore normal the shoreward component of the transport vector decreases and thus, the sediment deposition per unit length into the dune system decreases. A schematic overview of this process is included in Figure 2.1.

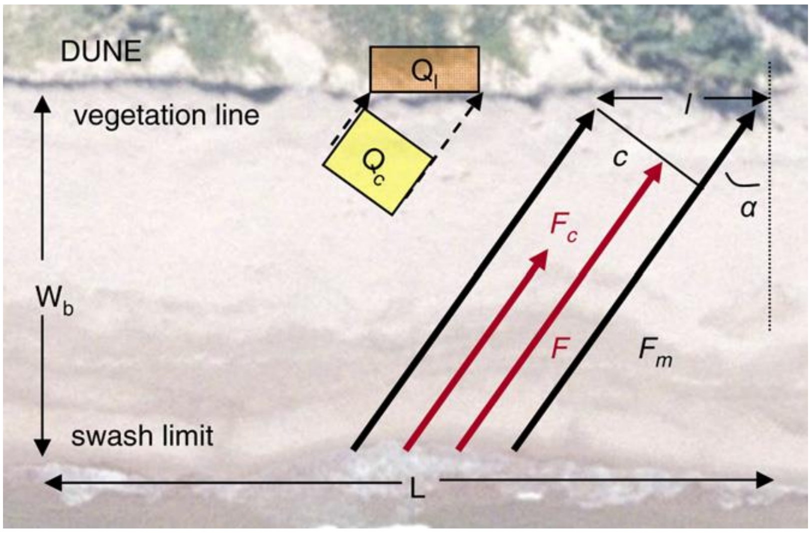

Figure 2.1 Explanation of the cosine effect as explained in Delgado Fernandez 2010 in which Fc stands for critical fetch distance Fm for maximum fetch length and F for occurring fetch length. The angle of wind approach relative to shore normal is expressed as a. l indicates the unit alongshore length at the dune line determined by two parallel streamlines of the wind field. Qc indicates an transport rate at the back of the beach whereas Ql represents the sediment deposition per unit length in the dune. (Delgado Fernandez 2010)

The cosine effect imposes complex problems predicting transport fluxes on narrow beaches, this due to its contradicting behaviour relative to critical fetch length. Alongshore rotation under oblique incoming angles would further increase the complexity of this problem. If the fetch length on a narrow beach increases due to a more oblique wind approach, the net transport should theoretically increase. However due to the Cosine effect the net deposition of sediment in the foredune could also decrease.

2.2 Background on boundary layers

So far this literature review provided insight in the basic principles of Aeolian transport and the current understanding of why actual transport rates deviate from theoretical transport rates. This part of the literature review contains a brief overview of the current understanding of wind patterns on the beach and how the wind interacts with the foredune. But first some basic concepts of fluid dynamics will be introduced.

2.2.1 Boundary layer

As mentioned under the supply limiting factors, Aeolian transport rates in natural environments differentiate considerably from transport rates in controlled environments. Especially on beaches this difference could partly be explained due to the presence of a downwind atmospheric boundary layer. A boundary layer forms when a fluid (in this case air) flows over a flat surface (in this case the beach), the air directly in contact with the beach doesn't move relative to the beach (see Figure 2.2). At distance Y away from the beach the air is moving at the same speed as the remainder of the airflow. Between distance Y and the beach is a velocity gradient in which the speed increases with distance Y. The total distance of Y increases with distance X. Meaning that further downwind, the boundary layer becomes larger (see F)

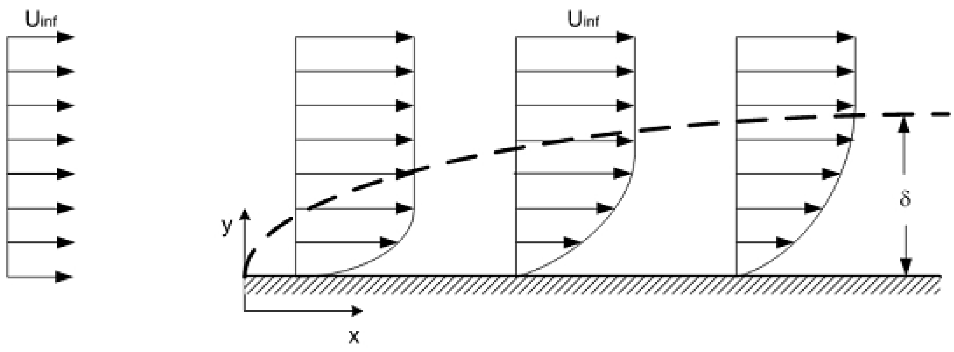

Figure 2.1 Schematic rendering of the forming of a boundary layer

Keeping in mind the dependency of Y based on X and the measurements of the wind, this results in an inherent decrease in wind speed in downwind direction when all measurements take place at set height above the surface. The magnitude of decrease in wind in vertical direction(Y) is coherent with the Reynolds number. The Reynolds number is a dimensionless number which is used in fluid dynamics to describe if a flow is laminar or turbulent. In the fluid dynamic field, a Reynolds number <2000 is considered as laminar flow whilst a number >4000 is considered turbulent (Mott 2011). Any number between those two is qualified a Laminar-turbulent transition flow. The Reynolds number could be calculated using the following equation:

Equation 2.2 Reynolds equation:

$$Re = \frac{V\ L}{\nu}$$

In which:

$$\nu = \frac{\mu}{\rho}$$

- V=velocity in m/s
- L=Length in m (Y) in Figure 2.2
- ν= Kinematic viscosity
- ρ=Density of the fluid (1,293kg/m³)

In equation 2.2 it becomes clear that the Reynolds number Re is dependent on the velocity. This results in it being more likely for fluids to become turbulent when the velocity increases assuming the other parameters remain unchanged. Opposing to laminar flow, a turbulent flow motion introduces additional drag, therefore further decreasing the downwind wind speed.

2.2.2 *Separation flow*

Boundary layer separation flow occurs when there is a sufficient adverse pressure gradient. An adverse pressure gradient occurs typically when air flows around an object or round surface (See Figure 2.3. An adverse present gradient means that the air is flowing from a low-pressure point (on top of the geometry) to a high-pressure point at the lower part of the geometry. Because the air pressure is lower near the top of the object the air flowing towards the high-pressure zone at the back of the object is sucked back into the low-pressure area imitating a reversal flow.

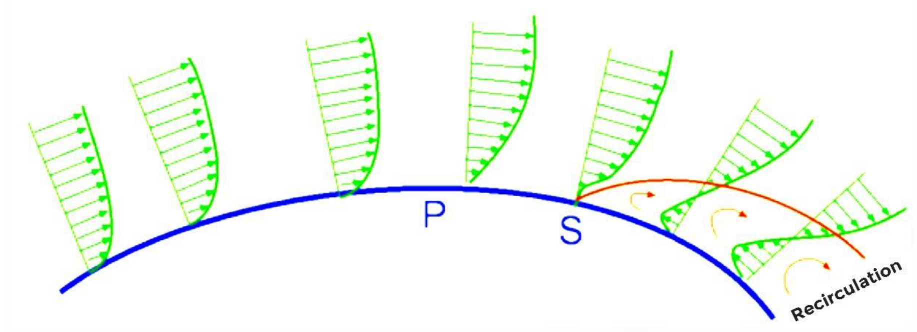

Figure 2.3 Indication of flow reversal and how it happens

The point where the reversing flow meets the flow flowing forwards a stagnation point is created at which the flow is directed upwards. This point is also referred to as separation point since the fluid hitting this point is directed upwards separating from the boundary layer. However, flow reversal is not likely to occur on the beach itself during onshore wind events. It might occur on small scale if wind flows across embryo dunes.

2.3 Studied wind patterns on the beach and dunes

As mentioned in the introduction of this chapter studies to the interaction between wind patterns and dunes have been investigated before. With the elementary basics explained in section 2.2, an in-depth look of the findings of these studies is provided in this section.

2.3.1 The influence of the beach on the surface boundary layer

The field experiment conducted by Bauer et al. in 2009 to further map the supply limiting factors of sediment transport on the beach included an array of anemometers located between the foreshore and upper beach. The paper included detailed measurements of this array for October 11^{th} 2004, a day with highly variable meteorological conditions (see Figure 2.4 The wind speeds measured that day ranged from 4 m/s to over 12 m/s, with a direction varying between 60° and 85° relative to shore normal.

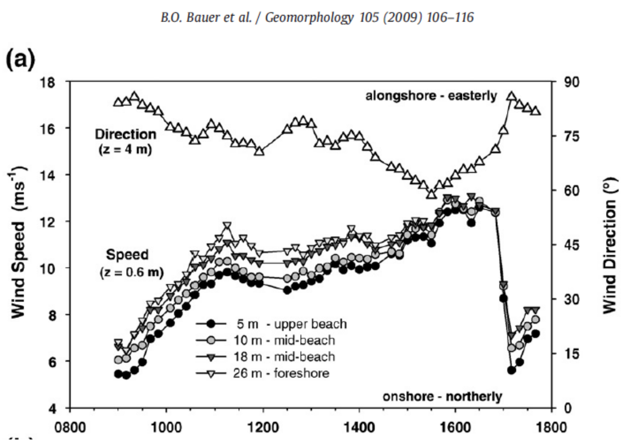

Figure 2.4 detailed view of the wind measurements on October 11^{th} 2004, at Greenwich dunes Prince Edward Island National Park.

Looking at Figure 2.4,**Fout! Verwijzingsbron niet gevonden.** a consistent decrease in wind speed in landward direction can be discovered. All wind speeds are measured at 0.6 m above the surface. The decrease in wind speed is consistent with the effects of the beach induced internal boundary layer. Especially since the wind direction is highly oblique, it is not likely this decrease is the effect of a dune-imposed stagnation zone. The stagnation zone would be much closer in this case (Bauer et al.,2009). However, to further substantiate this conclusion vertical measurements of the wind profile are necessary.

2.3.2 Potential shelter effect due to the presence of the foredune

Another study performed in the Greenwich Dunes at Prince Edward Island in Canada as part of a larger research to the sedimentary dynamics of the beach dune complex focused on flow dynamics over a foredune. The field experiment corresponding with this study was carried out in May 2002 (Hesp, 2005). Within this field experiment, several anemometers (cup and sonic anemometers) were deployed. The deployment took place on the upper beach and the stoss side of a for Dutch standards relatively low foredune, topping of around 8 meters above sea level. An overview of the deployment is included in Figure 2.5.

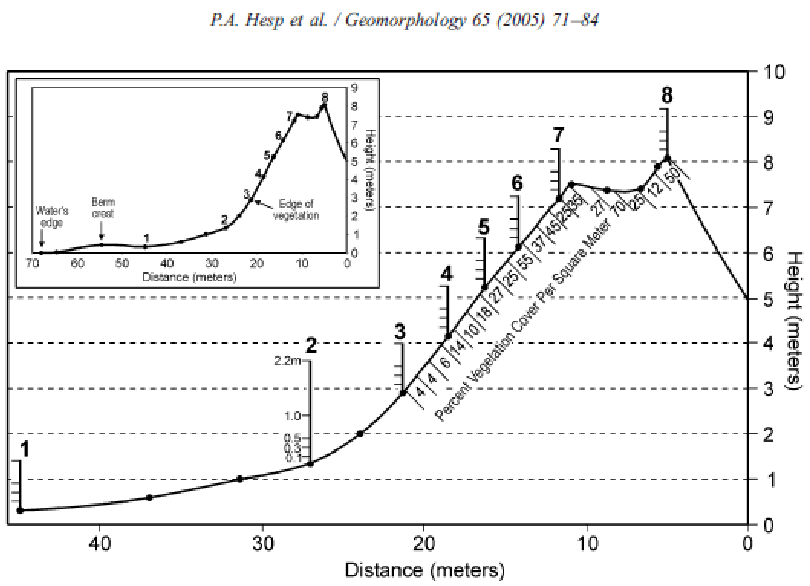

Figure 2.5 detailed view of the deployment of anemometers in the study performed by Hesp et al, 2005.

The anemometer located on the top of mast 2 is used to normalize the measurements of the other stations. Wind speeds were collected across seven different 10-minute windows to produce time averaged wind speed measurements. Measurements were only collected with an incident wind angle (measured at mast 2) ranging from 0-4° relative to shore normal to include only normal onshore winds. The incident wind speed ranged from 4 meters per second to 8 meters a second. The results of these measurements are displayed in Figure 2.6

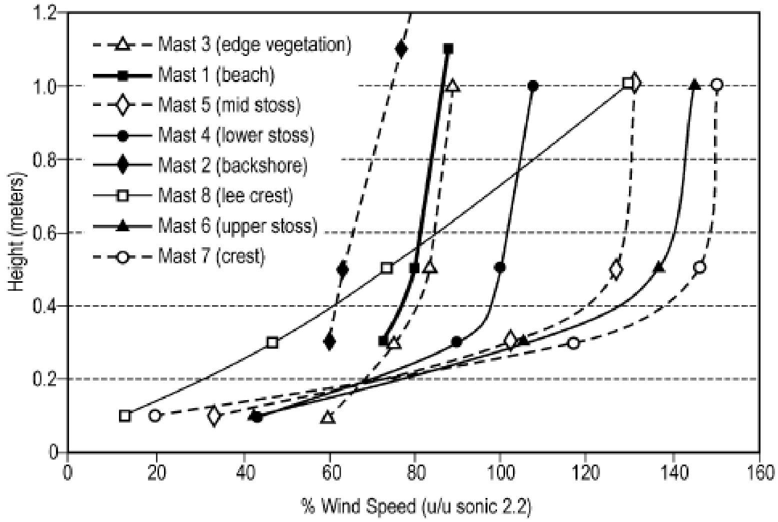

Figure 2. 6 measurements taken by Hesp et al in 2002.

In Figure 2.6 it becomes clear that the wind speed measured at mast 2 (the backshore) is consistently higher compared to flow at the beach (mast 1) (Hesp et al., 2005). This flow reduction at the toe of the dune has been observed at some desert dunes, but at the time the paper corresponding to the research was published, this had not been discovered in coastal areas. This decrease in wind speed is explained by a pressure rise in the airflow due to the approach of a relatively steep (25°) incline at the toe of the dune (Hesp et al., 2005). This effect has been successfully recreated in a controlled environment using a wind tunnel by Bowen and Lindley in 1977. Their experiments demonstrated that reduction of flow could potentially occur near the base of a slope with starting with a gradient of 25% (Bowen and Lindley, 1997). The other masts show flow acceleration at the stoss side of the dune. The flow acceleration is courtesy of the induced favourable pressure gradient towards the dune top. The low-pressure area on top of the dune sucks the airflow across the toe side of the dune. Speedup on the stoss side of the dune is also observed by Arens, 1997. It is important to note that the conclusion above and especially the results shown in Figure 2.6 are based exclusively on onshore wind events.

The experiment was repeated with more oblique oriented wind events (13° NNE compared to 4° NNE), and comparable incident wind speeds of 5,4 m/s and 5,96m/s respectively, the measured speeds at the different masts and heights varied from each other as can be seen in Figure 2.7

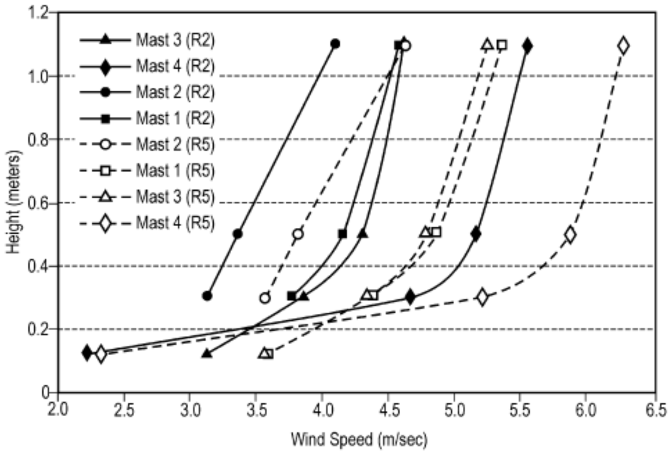

Figure 2.7 comparison between two similar experiments with different incident wind directions. R2 indicates measurements taken at an incident wind speed of 5,4 m/s and an direction of 4° (onshore) whereas R5 indicates measurements taken at an incident wind speed of 5,96m/s and an oblique direction of 13°. All values are based on a 10 minute average. (Hesp et al., 2005) The masts

By comparing the measurements of the different conditions with each other, a general trend becomes visible. All measurements taken during the oblique wind event, show higher wind speed compared to the onshore wind events. Especially the measurements of Mast 2 (located at the backshore) show a relatively large decrease across all heights, whilst the mean wind speed is only a fraction higher than at the onshore wind event (Hesp et al., 2005). These findings support the findings form (Arens et al., 1995) who discovered that flow deceleration at the dune toe was greatest with onshore oriented winds whilst the flow deceleration decreased with increasing obliquity.

2.3.3 Wind deflection

During field experiments aiming to get a better understanding to the speed wise behaviour of airflow across beach dune systems, a dune parallel deflection in wind direction towards the dune crest was noticed (Arens, 1995; Hesp et al., 2005). However, data gathered during such field campaigns was not sufficient to gather meaningful insight in this deflection process (ARENS, 1995; Hesp et al., 2005). Measurements on wind direction usually serve limited purposes such as showing that a wind field was directionally uniform or not (Bauer et al., 2012). Another purpose wind measurement are generally used for, is to improve the understanding of how local wind patterns might deviate from regional wind patterns due to topographical steering mechanisms. However, it is important to note that traditionally these steering mechanisms have been classified as secondary airflow effects (Walker 1999, Walker & Nickling, 2002; Walker et al., 2008; Bauer et al.,2012). More recent studies however show that there is an increase in evidence that this secondary airflow effect might be of critical importance to maintaining dune forms and providing pathways for sediment transport. (Walker et al., 2006, 2009; Jackson et al., 2011; Chapman et al., 2012; Bauer et al.,2012). Not many field experiments had the equipment available to measure the spatial distribution of wind patterns as well as gathering detailed information about sediment transport fluxes.

In May 2002 a field campaign was launched in in the beach-dune complex in the Greenwich Dunes located in Canada (Walker 2006). Part of this field campaign was taking high frequency measurements of airflow from during an oblique alongshore sediment transport event. The main reason these measurements were taken was to study the interactions between beach-dune topography and near surface airflow. This study indicated that local wind patterns deviated significantly from the regional wind patterns due to topographic steering and forcing effects. The main area of focus within this study however was on the dunes and beyond, not necessarily the beach.

A more sophisticated field experiment in an attempt to map the wind deflection due to the presence of a foredune was performed by Bauer et al. in 2010. In this experiment they took detailed measurements of wind vectors across a beach dune system located within the Greenwich beach dune complex in Canada. The measurements taken are part of a long term field experiment within this region. Figure 2.8 includes an overview of the placement of the measurement equipment in relation to the beach dune profile.

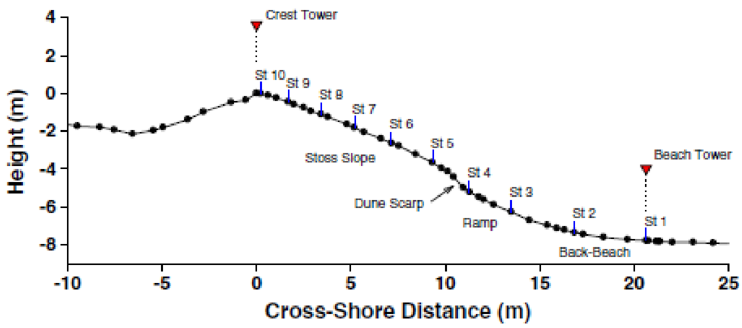

Figure 2.8 overview of the measurement stations as used by Bauer et al., 2010 in their field experiments

On April 30th 2010, an onshore wind was recorded containing wind speeds of 4.7 – 5.3 m/s with an angle between 160-190° relative to magnetic North. Within this day was a 41 minute event occurred in which the wind was directly onshore as measured by the mast at the dune crest as well as on the dune foot. Detailed measurements of this period are included in table 1. The records shown in table 1 indicate that although the wind was directly onshore some minor topographic steering effects occurred at the stations located on the stoss side of the dune. The maximum deviation in wind direction however is less than 10°.

Table I. Summary statistics from 41-minute anemometer time series (15:53.58 to 16:35.00) on April 30, 2010 during onshore (northerly) flow

Location	Height (cm)	Mean speed (SD) (m s^{-1})	Mean direction (SD) (deg)	Deviation from Crest Tower
Crest Tower	364	10·0 (0·99)	181 (5·9)	—
St 10	20	6·9 (0·93)	182 (6·4)	+1
St 9	20	5·2 (0·88)	181 (7·2)	0
St 8	20	5·4 (0·97)	172 (7·2)	−8
St 7	20	6·3 (0·94)	181 (7·5)	0
St 6	20	5·6 (1·04)	187 (9·0)	+6
St 5	20	5·8 (0·92)	188 (12·3)	+7
St 4	20	3·7 (0·67)	190 (20·5)	+9
St 3	20	3·8 (0·70)	186 (17·8)	+5
St 2	20	2·7 (0·70)	190 (19·9)	+9
St 1	20	3·7 (0·77)	184 (12·5)	+3
Beach Tower	381·5	6·4 (0·92)	180 (8·5)	−1

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Table 2.1 Source: Bauer et al 2012

On May 2nd wind speeds of 4.4-5.8 meters a second were recorded with a range starting around 10° relative to magnetic word (offshore) veering towards 50° oblique in the afternoon. During this day effects of topographic steering toward more dune parallel angles were reported.

In the night from May 3rd to May 4th 2010, a severe storm approached the Greenwich dune complex. During this event wind speeds exceeded 15 meters a second. Wind direction was aligned alongshore at 95-120°. A comparison was made between wind directions measured at the mast located on the dune foot as well as on top of the dune. The results of these measurements are included in Figure 2.9. The top two graphs show the measurements taken at the top of mast at beach (3.8 m) on the left and top of the mast at the dune crest on the right (3.64 m) respectively. The bottom two graphs contain measurements on same location but at a height of only 20cm.

From Figure 2.9 several differences become apparent within the measurements. The mast at the dune crest seems to measure higher oblique wind angles compared to the mast located at the beach. Furthermore, there is a difference in direction visible on different heights. The measurements taken at a height of 0.2 m also tend to show a more oblique wind direction, indicating effects of topographical steering is present (Bauer et al. 2012). Bauer et al. also state that both measurement deviate from regionalised wind measurements.

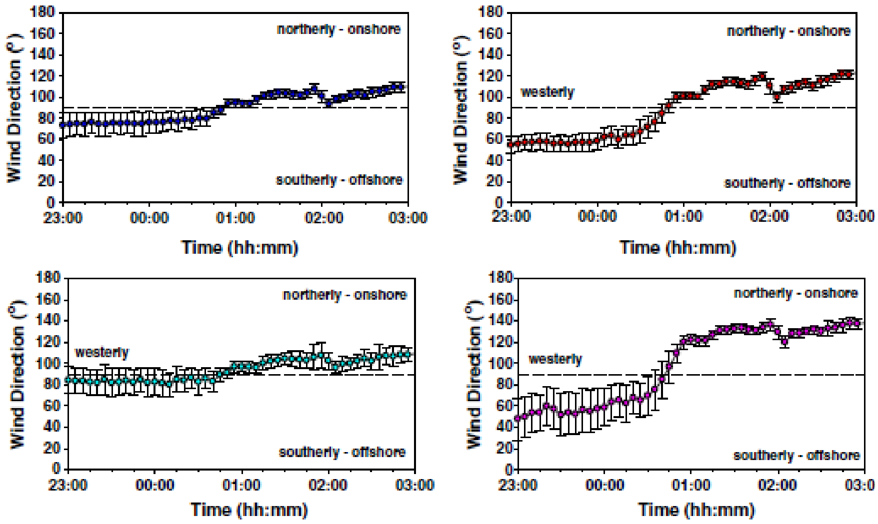


Figure 2.9 Measurement taken during a storm on May 3rd and 4th within the Greenwich dune complex Canada (Bauer et al. 2012)

Based on the data gathered during their campaign Bauer et al. proposed a conceptual model from which the onshore directions are included in Figure 2.10. Within their model they state that onshore winds do not necessarily change in direction, whilst oblique onshore winds deflect crest parallel. Furthermore, it is proposed that vertexes occur on the stoss side of the dune during onshore winds. The conceptual model is valid for foredunes around 8 meters in height.

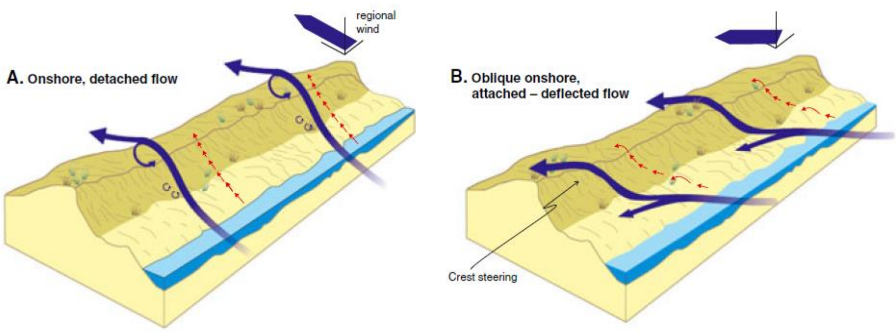


Figure 2.10 Conceptual model proposed by Bauer et al. (2012). The model has been proposed on the data acquired during their campaign at Prince Edward Island in 2010. This figure includes only the onshore directions

2.3.4 *Turbulent Kinetic Energy*

Turbulent Kinetic Energy, called TKE is a term used in fluid dynamics to describe the kinetic energy per unit mass associated with eddies in turbulent flow (Wyngaard & Coté, 1979). In other words, this means it is a measure of how turbulent the flow of (in this case) air is. TKE is derived from all three wind vectors. Although the transformation of TKE has not been studied specifically for the behaviour on the beach, limited studies have been carried out to the behaviour on the foredune (e.g. Chapman et al., 2012, 2013 & Smyth et al., 2014). These studies showed an increase in TKE across the stoss-side of the foredune. In 2013 measurements were made at the (back of the) beach. This measurement indicated that during onshore winds there was not necessarily an increase in TKE whilst this was the case for alongshore oriented winds. Other derived parameters like Reynolds stress showed similar results although the relative difference within this parameter between the different stations was less. I.E. the Reynolds stress was more constant on this spatial scale. ((Chapman et al., 2012, 2013).

2.3.5 *Computer models to predict airflow*

In the past many studies have been conducted to airflow patterns across the beach and dunes using CFD simulations. CFD stands for computational fluid dynamics. Most of these studies however focused on the dynamics on the foredune itself rather than the effects the foredune might have on the beach. Still information of these studies can be used to predict what might happen on the beach. Especially information about what happens at the toe of the dune is relevant too for this study. A study conducted by Parsons et al. published in 2004, consisted of a CFD experiment using a by then commercially available CFD program. The model used within this study was validated based on earlier study of Parsons et al (2002) in which they successfully recreated the results of a wind tunnel experiments performed by (Walker & Nickling, 2002). The result of the validation of the model in comparison with the wind tunnel experiment is included in Figure 2.12 (next page). The model consists of different grid cell for which mass fluxes were specified in the upstream inflow. This is done to provide a velocity profile necessary to simulate the upwind effects of the dune like flow deceleration and flow stagnation. The simulated velocity profile is included in Figure 2.12. The results of different simulations performed within the study are included in Figure 2.11 (next page). Again, the focus point of this study was what happened on the stoss side and behind the dune rather than wind patterns developing on the beach. Yet the results still contain information about flow patterns before the dune which makes it relevant for this study. Although the dunes modelled in this study are very small compared to the Dutch foredunes of around 25m in height, it is interesting to see that different sizes of dunes interact differently with the airflow (i.e. size does matter). Data shows that flow field dynamics over transverse dunes are especially sensitive to a change in overall dune height. Not only the flow at the stoss side of the dune and beyond are affected by dune height, the flow velocity at the dune toe is affected as well. This study shows that by an increase in dune height there is also a more significant deceleration at the dune toe. In Figure 2.13 (next page) a simulation of TKE near a small dune is included. This figure clearly shows an increase in TKE at the Lee side of the dune as well as a small increase at the dune toe at the Stoss side.

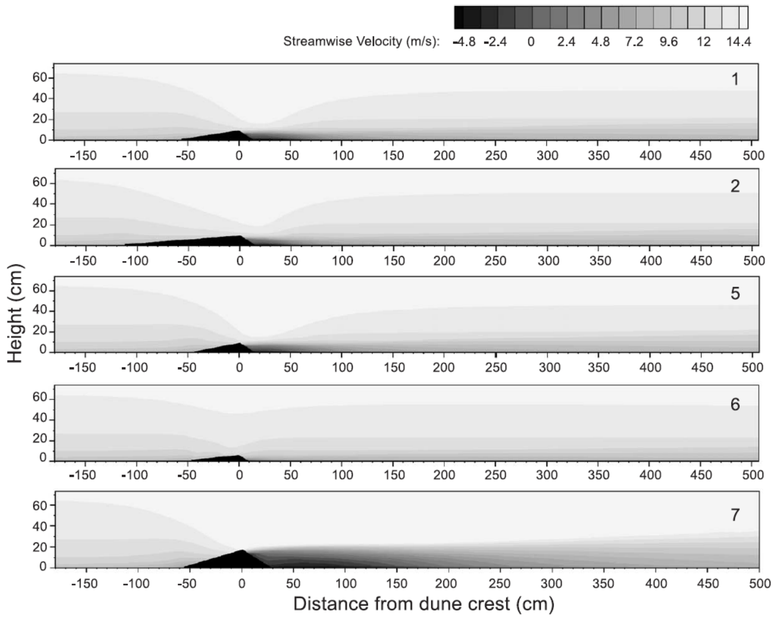
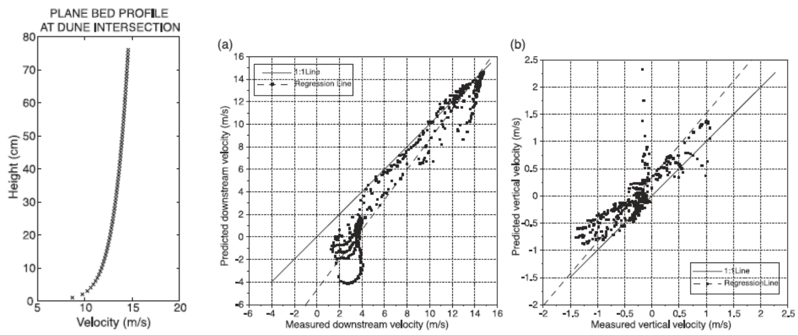


Figure 2.10 comparison of flow changes imposed by different sizes and shapes of dunes (Parsons et al., 2014)



z

Figure 2.11 incoming velocity profile used in the study conducted by Parsons et al., 2004 (left) and validation of the model used (right)

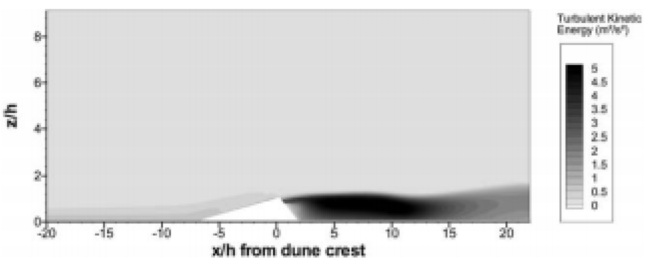


Figure 2.13 Simulated TKE near a small dune by Parsons et al. 2004

2.4 Current state of Aeolian prediction models

Throughout this thesis it has been mentioned that computer models tend to overpredict sediment fluxes, yet no description has been given about the processes considered in such models. To describe the processes included in such models, the 'Aeolis' model created by Hoonhout is taken as example. This model is chosen because it is recently developed and therefor best representing the current state of prediction models.

2.4.1 Aeolis model

In studies conducted trying to explain the difference between predictions and measurements it is often emphasized that bed surface properties could play a significant role. Sediment supply, and transport limiting factors related to the bed surface properties researched are: salt crusts (e.g. Nickling & Ecclestone 1981), vegetation (e.g. Arens 1996; Li et al., 2013), bed slopes (e.g. Iversen and Rasmussen, 2006), moisture content (e.g. Bauer et al 2009), sorted and armoured beach surfaces (e.g. Cheng et al., 2015) and shell pavements (e.g. McKenna Neuman et al., 2012). Attempts made to translate effects of these bed surface properties on aeolian transport predictions often resulted in a modification of the velocity threshold (e.g. Nickling & Ecclestone 1981; Arens, 1996; King et al., 2005;) Relaying on only the threshold velocity to cope with the influence of bed surface properties introduces a severe limitation in the ability to predict aeolian transport rates in natural conditions. Using the threshold velocity alone to incorporate the effects of bed surface properties is that it changes inherently in time and space (Stout, 2004). While in controlled environments (i.e. Wind tunnel experiments) the effects introduced by this limitation are negligible, in real-world field conditions it is not (Hoonhout, 2016). Especially in areas where the spatial variability in bed surface properties is high (e.g. intertidal beach and supratidal beach).

Within the Aeolis model sediment availability is determined using the approach proposed by De Vries et al. (2014). It introduces multi-fraction aeolian sediment transport to simulate both limiting and enhancement factors regarding sediment availability. Utilizing this approach, it becomes possible to include an arbitrary spatiotemporal configuration of bed surface properties (Hoonhout, 2016). Key bed surface properties included in the Aeolis model are: Hydraulic Mixing infiltration and evaporation, Non erodible roughness elements, sediment sorting and beach armouring. Compared to conventional models, the results of the Aeolis model look promising, especially for the hindcast of the development of the Sand Motor. However, validation of the results is still ongoing (hoonhout, 2016).

Within the current Aeolis model spatial variations in wind characteristics are not simulated. Due to this, the model is not suitable to simulate dune formation and growth. (Hoonhout, 2016)

2.5 Current knowledge gap

This literature review combined with the introduction of this thesis, provides insight in the current understanding of Aeolian sediment transport. It also becomes clear that multiple studies (e.g. Hesp, 2005; Bowen and Lindley, 1977; Arens, 1997; (Winter, Ruessink, & Donker, 2017)) indicate that the wind speed decreases as the wind approaches the dune foot. Other studies (e.g. Arens, 1995; Walker 1999, Walker & Nickling, 2002; Walker et al., 2008; Bauer et al.,2012) state that during oblique wind events, the angle of approach tend to become more dune parallel as the wind approaches the foredune. In the current situation it is not possible to predict these described behaviours (flow deceleration and wind deflection) based on regionalised wind predictions.

The literature study also provides the theoretical background on site specific factors which might influence the transport rates and recommendations on future field experiments to develop even more insight in the physical processes regarding Aeolian transport events. It also establishes why it is important to further develop the knowledge of such transport events (especially for the Dutch coast). In short, a better understanding of these Aeolian transport events contributes to an enchanted safety of the Dutch hinterland.

2.5.1 Aim of this research

The objective of this MSc thesis is to translate regional wind patterns to local wind patterns on the beach. In order to achieve this, the spatial variability in wind speed, direction and turbulence characteristics on the beach under different onshore wind events have to be determined. This determination will be done based on fieldwork campaign held during October 2017 on the beach near Egmond aan Zee.

The questions this research aims to answer, are already defined within the introduction. Based on the literature review however more context could be provided why it is necessary to answer these questions

The first question originated from the results of the preliminary study conducted by de Winter et.al. (2015) and is mainly in place to further substantiate their findings by testing their results on a larger dataset and check whether the topography of the beach itself plays a significant role.

The second question is important to answer in order to make this research of added value compared to previous field experiments. Within the literature review it becomes clear that changes in wind speed and direction are observed before, yet meaningful and quantitative relationships are not derived based on these observations. An example from this is the study of Bauer et al. published in 2009 (see Figure 2.4). They clearly show that wind speed decreases across the beach but not tried to derive a meaningful quantitative relationship from the dataset. Moreover, it is important to note that most studies referred to in the literature review were based on fieldwork campaigns held in the Greenwich dune Complex Canada, where compared to Dutch standards the foredune is relatively low (8m at Greenwich). It has been established that the size of the dune has significant influence on wind patterns both up and downstream the dune (Parson et al., 2004).

The Third question can be explained in the same manner as the second question. Deflection in wind direction is noticed during previous fieldwork campaigns, yet they were deemed mostly as secondary effect (Bauer et al., 2012). Although Bauer et al., provided an excellent framework describing the general effect topographic steering has on local wind patterns, they did not map the wind patterns across the whole beach. Additionally, no attempts have been made yet to translate regional wind measurements to local wind characteristics specifically for the Dutch coast.

3 Method

This chapter describes the methodology used to carry out the research related to the MSc thesis. Based on the literature review included in chapter 2 from this thesis a knowledge gap has been defined, which is also included in chapter 2. To answer the research questions raised in relation to this knowledge gap, data was needed. To gather this data a field campaign was launched which is elaborated on more in section 3.1. The gathered data was processed and ordered after the fieldwork campaign and a quick scan was carried out to verify the hypothesis afterwards a more in-depth analysis has been carried out consisting partly of a quantification. The described verification of the hypothesis and the in-depth quantification of the results has been carried out for the analysis of the spatial transformation of wind patterns across the beach and the comparison between regional and local wind patterns separately. Techniques used to accomplish this are described in section 3.2 and 3.3

3.1 Fieldwork

The fieldwork campaign has been conducted from 02-10-2017 till 03-11-2017 and is called Aeolex II. The overall goal of the Aeolex II fieldwork campaign is to gain insight in beach dune dynamics surrounding aeolian transport specifically for the Dutch coast. In the past (during the Aeolex I experiment back in 2015), it has been noticed that the relatively high foredune (up to 25 meter) has a significant impact on aeolian transport dynamics on the beach. Therefore, the focus of Aeolex-II will be on this effect (Reussink 2017).

3.1.1 Study site and conditions during fieldwork campaign.

The study site is located South of 'Egmond aan Zee' at beach pole 42500 to be specific (see Figure 3.1b). The study site is characterized as a wave-dominated coast. The beach slope is approximately 1:30 (flat) and the foredunes are roughly 25 m high. The exact beach slope throughout the campaign is illustrated on the bottom of figure 3.1b, each line indicates the beach surface at a given date. Overall the beach is very dynamic because of the pronounced marine activity (de winter et al., 2015). Figure 3.1a includes an overview of the study site taken from approximately halfway up the foredune. Within appendix II more impressions of the study site are included.

Figure 3.1a Overview of study site near Egmond aan Zee. Impression from hallway up the +- 25 high foredune.

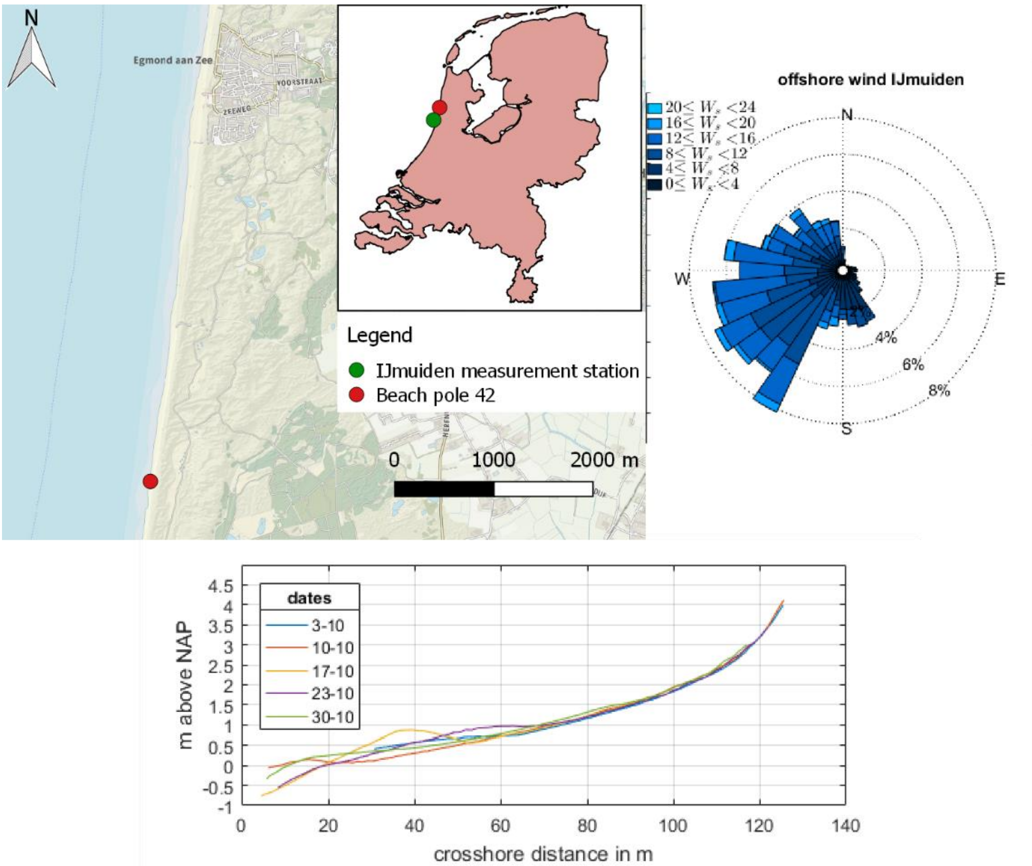


Figure 3.1b Overview of study site near Egmond aan Zee. The colours within the Wind Rose diagram indicate the windspeed in m/s.

As can be seen in Figure 3.1b even in the timespan of our field work campaign the intertidal part of the beach changed quite a lot. Halfway throughout the campaign a berm formed which during the rest of the campaign got redistributed along the entire beach.

The predominant wind direction is South-West and the beach is relatively narrow with a width of around 100 meters during spring low-tide (Smit et al., 2017). The regional (offshore) wind conditions during the fieldwork campaign are also included in Figure 3.1b. These conditions were measured approximately 10 km away from the study site (see green dot).

3.1.2 Data collection

During the Aeolex II campaign an extensive data set was collected. An overview of the instruments used to gather data required to answer the research questions specific for this thesis can be found in table 3.1

table 3.1 Overview of instruments deployed

instrument	abbreviation	Deployment	note
Sonic anemometer 02	**SA02**	Temporary [15x]	location varied
Sonic anemometer 03	**SA03**	Temporary [23x]	location varied
Sonic anemometer 04	**SA04**	Temporary [24x]	location varied
Sonic anemometer 05	**SA05**	Permanent	Base station
Saltation dectection device 02	**Saldec02**	Temporary	When used SA placement dependent on saldec location
Saltation dectection device 03	**Saldec03**	Temporary	
Saltation dectection device 04	**Saldec04**	Temporary	
Offshore RWS station IJmuiden	**-**	Permanent	Permanent device maintained by the Dutch government
Realtime kinematics GPS	**RTK-GPS**	Manual	Handheld device

3.1.3 Sonic anemometers.

A sonic anemometer (see Figure 3.2) is a device capable of performing solid state wind measurements in three dimensions (U,W,V) at a high frequency. It accomplishes this by measuring time of flight of ultrasonic pulses between a pair of transducers. For the sake of this thesis four YOUNG 81000RE Sonic Anemometers were used operating at a frequency of 10hz. Data generated by the Sonic Anemometers was logged in a logging device which recorded timestamp, windspeed in m/s for all three vectors (U,W,V), temperature and potential error code. As from now references to Sonic Anemometers will be made by stating SA followed by the station number (e.g. Sonic anemometer 02 will be referred to as SA02). Every time a SA was deployed, the exact location was measured using an RTK-GPS, this way the exact position of the deployment is known with an accuracy of 0.02m. The height of the measurement volume was set at 0.9 m above the bed, however as there are small scale topographic differences the accuracy of setting this height is low (<0.05 m). Apart from measuring the precise location it is also important to align/aim the SAs in order to transform the data in N-S, E-W and vertical directions. The alignment was performed on a solid recognizable object. In this case beach pole 40000.

Figure 3.2 example of anemometer used during the fieldwork

Four SAs were used to collect data for his thesis, only one SA had a fixed location (SA05). SA02, SA03 and SA04 were so called ‘mobile SA’. This means they were not bound to a permanent location but were moved throughout the campaign. The main reason for this is that these devices were allocated to measure wind vectors across the (intertidal) beach. Since the SAs are not (salt) waterproof they must be moved every high tide. There is also a lot of activity on the Dutch (intertidal) beach so it was not considered safe to leave these instruments unsupervised on the beach. Additionally, the mobile SAs had to be placed outside the measuring array on a few occasions either to support the Saldec measurements or to be placed exactly downwind of SA05. An overview of every deployment relative to SA05 is included in Figure 3.3.

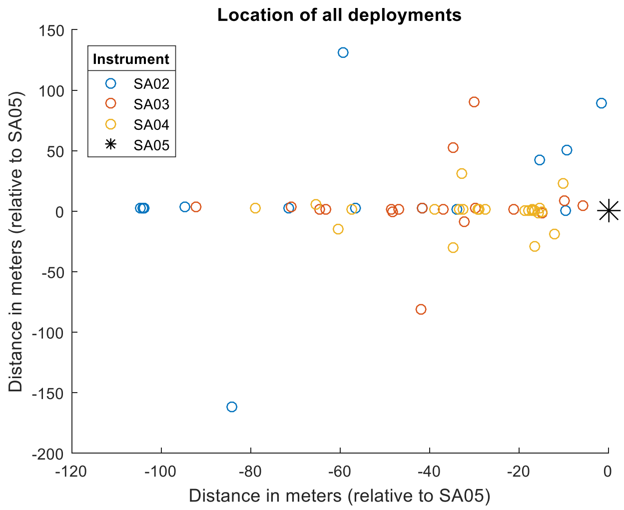


Figure 3.3 Overview of the location of every deployment of the mobile sonic anemometers used in this study.

The overview was created by normalizing the GPS-coordinates measured during the campaign based on the coordinates of SA05. The coordinates were then rotated so they are oriented shore-normal. The total degree of rotation needed was 7,2°. Negative numbers indicate that the deployment of a mobile SA was located seaward relative to SA05.

3.1.4 Base station SA05

SA05 is designated to be the reference station for the data collected by the mobile SAs. SA05 was placed near the dune foot just outside of the intertidal beach (see Figure 3.4) This way this station was able to take permanent measurements during the campaign. Although it was intended to measure permanent this station was dismantled during the first Spring-tide of the campaign in combination with a significant North-Western wind. This period ranged from 04-10-2017 ~16:00 till 06-10-2017 ~11:00. In which during daytime SA03 was placed at the location of SA05 to gather the data. Some technical issues later on during the campaign also resulted in a small loss of data for SA05. From now on the SA05 will also be referred to as base station. As Figure 3.4 shows, south of SA05 some embryo dunes are presents which are very likely to disturb the measurements taken during South alongshore wind events. Yet the location at the transition point between foredune and beach area suits the research question well.

Figure 3.5 DEM surrounding SA05 and picture taken in the field on the left

3.1.5 Ijmuiden measurement station

The automated weather station, located near IJmuiden 10 kilometers south of the study site (see green dot in Figure 3.1), collects data 24/7 and its data is often used in computer models to predict dune development. Therefore, it is useful to see to what extend the data gathered by this weather station correlates to the data gathered on the beach near Egmond aan Zee. The regionalised wind measurements take place at an offshore station measuring wind speed and direction as well as nautical parameters like significant wave height and wave direction

3.2 Data analysis

This subsection describes the methods used to analyse and store the gathered data. As well as a description of the general approach in which globally the steps taken to answer the research question are briefly explained.

3.2.1 Database AeolexII

After the fieldwork campaign a significant amount of data was gathered. To analyse the data Matlab was used to create a centralized database in order to be able to systematically store the data and access it later on. Another benefit of using a database is that it increases the repeatability of this research based on the same dataset. The database is called “Aeolex II”. A key feature of the database is the distinction between raw data and processed data. The techniques used to process the data are described in subsection ‘3.2.2 Data processing’. The scripts used to prepare the data are also made in the database.

3.2.2 Data processing mobile SAs

To process the data gathered by the mobile SAs (three-dimensional wind vectors, temperature and error codes) the various deployments had to be ordered in such a way it is clear at what time and location a mobile SA was deployed (see Figure 3.3) The location of the deployments were determined by normalizing the GPS-coordinates measured during the campaign based on the coordinates of SA05. The coordinates were then rotated so they are oriented shore-normal. The total degree of rotation needed was 7,2°. Negative numbers indicate that the deployment of a mobile SA was located seaward relative to SA05.

After the deployments were systematically ordered the data was filtered. The filtering of the data has been done mostly automatic and partly manual. The automatic filters applied are:

› Filter based on error code, every datastring with an error code other than ‘0’ is considered corrupted and therefor translated into NaN values;

› Filter based on temperature change within 5 seconds. If the temperature changes with more than two degrees relative to the median temperature in this timeframe, the data is considered as corrupted and therefor translated into NaN values;

After the automatic filtering, the dataset is filtered manually for each deployment individually. This is done based on the normalized vectors containing the three dimensions of the measured winds. Any sudden, unnatural looking changes are filtered out. For example a sudden spike in the w vector without a noticeable change in the u and v vectors.

3.2.3 Parameters based on the three-dimensional wind data

The mobile SAs measure the wind vectors in three dimensions. Apart from the wind vectors itself other statistical could be determined based on this data. Parameters determined in this study are: mean windspeeds per vector. wind direction, the turbulent kinetic energy(TKE), wind-gusts and wind-lulls.

The first step in the data processing is to smooth the 10hz data into time series consistent of three second running averages per vector (U,V and W). This is done utilizing the following formula (see equation 3.1).

Equation 3.1: Equation used to smooth the raw data

$$ys(i) = 12N + 1(y(i + N) + y(i + N - 1) + \ldots + y(i - N))$$

In which ys(i) equals the smoothed value for the 'i'th data point and *N* is the number of neighbouring data points on either side of $y_s(i)$ while 2*N*+1 represents the span of the data. Smoothing makes the data consistent with the data processing of the KNMI wind-velocity measurements. After the data is smoothed to three second time series mean values were determined per vector (see equation 3.2):

Equation 3.2: obtaining mean of time series

$$\overline{X} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Since 10Hz data is converted in to 10-minute averages n equals 6000.

In order to quantify the wind direction in degrees ranging from 0-360 in which 0 is absolute north, the four quadrant inverse tangent of the (smoothed) U vector and V vector is multiplied by 180/ π and 360° is added if the direction is negative. See equation 3.3:

Equation 3.3: Equation used to obtain wind direction

$$Direction(°) = atan2(\overline{u},\overline{v})/(180 * \pi)$$

The TKE is determined by calculating the mean wind speed for every vector (u,v and w) after which the residuals are determined by subtracting the mean from every observation. By adding the sum of squares of the residuals from U,V and W direction and multiply it by 0,5. See equation 3.4:

Equation 3.4: Equation used to obtain TKE

$$TKE = 0.5 * ((u - \bar{u})^2 + (v - \bar{v})^2 + (w - \bar{w})^2)$$

In which

$\bar{u}: mean\ value\ of\ the\ time\ serie\ (u)$

Other parameters like wind gusts and lulls (high and low windspeeds) are obtained from the combined total windspeed calculated using equation 3.5:

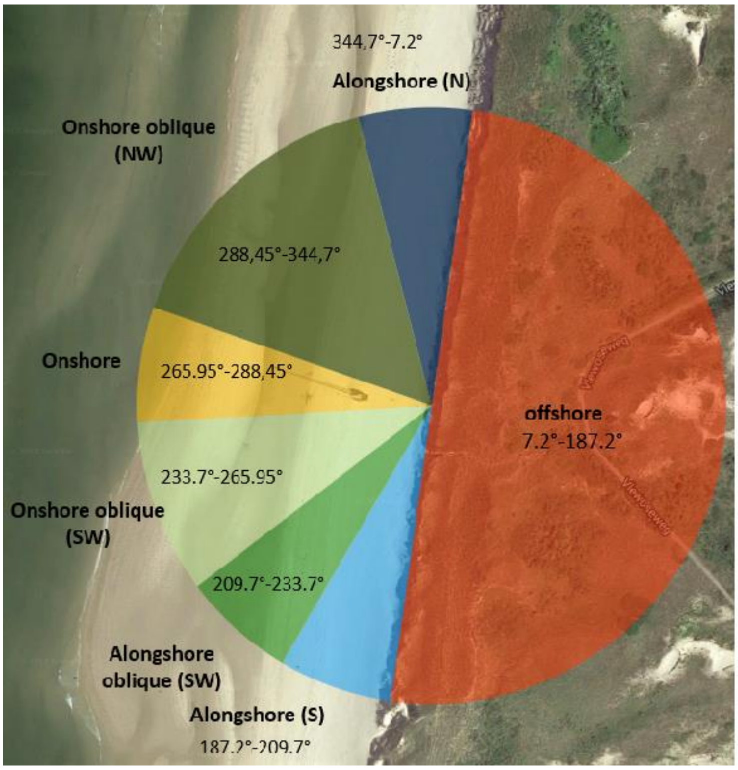
Equation 3.5: calculating resulting windspeed

$$resulting\ windspeed\ (\frac{m}{s}) = \sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2}$$

3.2.4 Data ordering

Using the overview provided in Figure 3.3, different 'distance' classes were created to further analyse the dataset. The distance from each deployment relative to SA05 is determined using the GPS-data collected. Only the distance in cross shore direction is considered since this equals the distance away from the foredune. Using this distance, the deployments were grouped into classes spanning 10 meters. Besides classifying data based on cross-shore distance from the base station, the available data has also been classified based on wind direction (measured at station 5). Originally 12 distance classes were present. However not enough data points were available to draw meaningful conclusions for every incident wind direction. Therefore, it has been decided to merge all the distance classes greater 50 meters away from the dune foot into one. This is done because during the research it was discovered no significant changes in wind patterns occurred in this higher distance classes.

The sheer size of the dataset made it possible to use 10 minute average values which greatly improved the precision of the relative relationships between two stations as well as made it possible to compare it with regionalised 10 minute averaged by default dataset. The accuracy of the relative relationships improves with an increasing averaging time because the unsteadiness within the wind. For example, station A is located 100 meters downwind of station B, and the goal is to compare mean wind speeds between those two stations. By doing this on 10 second basis the measurements are extremely vulnerable for wind gusts, since these gusts have to travel from station A to station B it is possible that the final gusts in the first average only was measured at station A and before station B measured it, it is already counting towards the second average. The likelihood of this happening is highly dependent on incident wind speed and relative distance between the stations. However the effect such measurements have on the total average is dependent on the number of samples taken during the averaging time. If for example data is recorded at 1hz and an averaging time of 10 seconds is used even one 'faulty' measurement has an relative big (10%) influence on the total average whilst by the same recording rate an averaging time of 10 minutes is used one faulty measurement is only accountable for (0.16%) deviation of the total average.



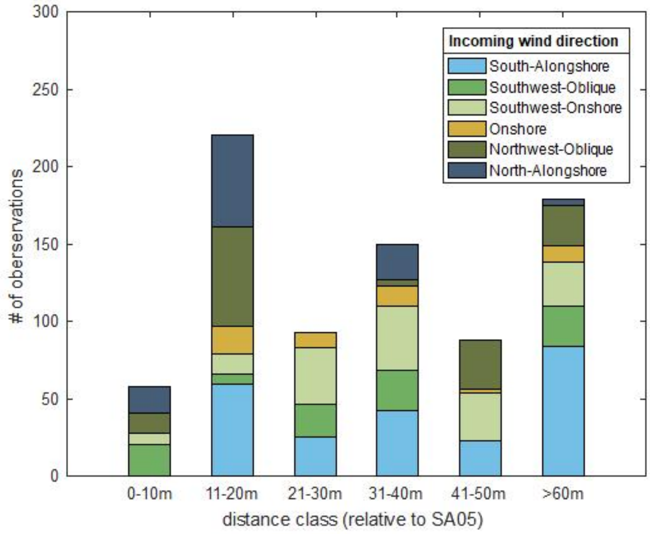


Figure 3.6 Overview of classification based on wind direction and distribution of available datapoints per wind direction as functions of the cross-shore distance relative to SA05.

The number of observations shown in Figure 3.6 are converted to 10-minute averages because it makes more sense to compare averages instead of instantaneous windspeeds. By comparing averages timing differences are minimized and measurements across different stations correlated to each other. Additionally, measurements taken while SA05 was malfunctioning are also excluded. Using this distribution together with the previously calculated parameters as described in section 3.2.3, the spatial variability in wind patterns could be analysed.

A classification based on incident wind directions was made because literature indicated the foredune poses a different effect on wind patterns based on incoming direction. Yet no study made a clear analysis per incoming wind direction due to a lack of data.

3.2.5 Validating the hypothesis

After the gathered data was processed daily comparisons were made of individual deployments on daily basis. Within this comparison the following parameters were included: resulting mean windspeed, Direction, TKE, placement, lulls and gusts. Furthermore, an assessment is made to windspeed across the beach to gain insight over the overall decrease in windspeed.

3.2.6 Quantification of relative speed change

To determine the relative speed change based on distance, the wind speed data must first be normalized. This is done based on the wind speed measured at SA05. Observations made at the same moment on a different station are transformed into a value which represents the percentage of wind relative to station 5. This is done by first calculating the absolute difference between a measurement station and the base station after which this difference is divided by the measured wind speed at station 5. This way initial windspeed should not influence the results. This was done using equation 3.6)

Equation 3.6: Normalisation of windspeed

$$Speedchange\ [\%] = \frac{windspeed\ distance\ class\ x}{windspeed\ SA05} * 100$$

It was decided to standardize the measurement based on a ratio between incident wind speed and resulting wind speed measured at the base station. This was done because the literature study (Hesp et al. 2002; Bauer et al., 2009) indicated that the decrease in wind speed is partly dependent on incident wind speed. This seems logical in the context of the beach induced boundary layer. By standardizing the measurements this effect it became possible to derive a general trend in change in wind speeds across the beach.

3.2.7 *Regional wind measurements*

Part of the research question is how the local wind patterns on the beach near Egmond aan Zee compare to regional wind measurements performed by Rijkswaterstaat (RWS). Chapter 5 consists of an in-depth comparison between the measurements taken at the dune foot of the study using SA05 and regionalized measurements taken by an automated weather station located offshore of Ijmuiden. It is expected the wind direction will be less dune parallel in comparison with station SA05 and the wind speeds will always most likely be higher. Moreover it is important to note that the wind speed measurements on this station are taking place ten meters above the surface instead of 0.9m.

The goal of the comparison between regionalised wind measurements and local wind measurements is to check whether or not it is possible to predict local wind patterns based on regional wind measurements. In order to accomplish this goal, a prediction model has to be created based on the dataset gathered. This prediction model will be derived using statistics as described in section 3.5.

It has been explicitly decided to perform the comparison between local and regional wind measurements using data from SA05 for local winds. This is done because this was the only permanent station available. A permanent placement is beneficial for the available data points and different placements do not have to be considered. A side effect of picking SA05 as data source for local wind is that this station is might be influenced by the presence of the foredune.

3.3 Statistics used

During this thesis, statistical analyses are applied. This is done in order to derive relative relationships within the dataset gathered during the fieldwork campaign. This subsection provides background information about the statistics used.

3.3.1 *Data comparison*

To compare measurements for a possible relationship between the data points (observations), a logical starting point is to calculate the correlation coefficient 'r', r is a dimensionless estimate of the degree of interrelation between two variables. To calculate the correlation coefficient, the covariance between the two measurements has to be determined, this a measure of how much two variables are related. The covariance is calculated using the following formulae:

$$\mathrm{cov}(x_1, x_2) = \frac{\sum_{i=1}^{n}(x_{i,1} - \overline{X}_1)(x_{i,2} - \overline{X}_2)}{n-1}$$

After calculating the covariance the correlation coefficient can be calculated using the following equation:

$$r = \frac{\mathrm{cov}(x_1, x_2)}{s_1 \cdot s_2}$$

Since the correlation looks linear it is decided to derive a linear prediction model from the dataset using the regression equation as shown below:

$$\hat{y}_i = b_0 + b_1 x_i$$

ŷi is the estimated value of the y axis (local wind speed) at the specific value of the x axis in this case the regional wind speed. b0 marks the intercept value with the y-axis and b1 represents the slope of the line. B0 and B1 will be estimated using the least squares method. This method determines the b0 and b1 in such a way the sum of squares of the deviations between the predicted value ŷi and observed values yi are minimized.

Before assuming this is true the model is tested for the goodness of fit, expressed as R^2. This variable is calculated based on the total variance in the Y value (in this case the local wind speeds) and the sum of squares due to regression. In other words, how much does the estimated values of ŷi deviate from the mean of y. However, to be sure, the regression model should be tested for significance. The model is considered statistically significant when the variance of the population error is equal to the variance around the regression.

4 Spatial wind changes

This chapter describes the way wind characteristics change across the beach under different onshore wind conditions. Therefore, this chapter provides the context necessary to answer questions "In what way does the wind -speed, -direction and -turbulent kinetic energy change from waterline towards the foredune in downwind direction?" and "What is the relative change in wind –speed, -direction and –turbulent kinetic energy under different onshore wind events in relation to the most dune ward measurement station." Prior to the fieldwork campaign the hypothesis was that mean wind speed decreases in downwind direction for obliquely onshore oriented winds. Alongshore winds only show a drop in velocity near the dune foot. The direction of local winds changes as the dune foot is approached. The direction tends to become more dune-parallel. And finally it is found that TKE (turbulence kinetic energy) is related to the mean wind speeds during onshore wind events. Although the mean wind speed is dynamic over the beach the TKE remains constant across the beach. (Winter, Ruessink, & Donker, 2017):. Using the more extensive dataset created in this campaign this hypothesis is validated for correctness after which an attempt is made to quantify the relative spatial relationship.

4.1 Validating the hypothesis

In order to validate the hypothesis, the statements made by Winter, Ruessink, & Donker, 2017) tested based on the dataset gathered for this study following the method as described in section 3.2.6.

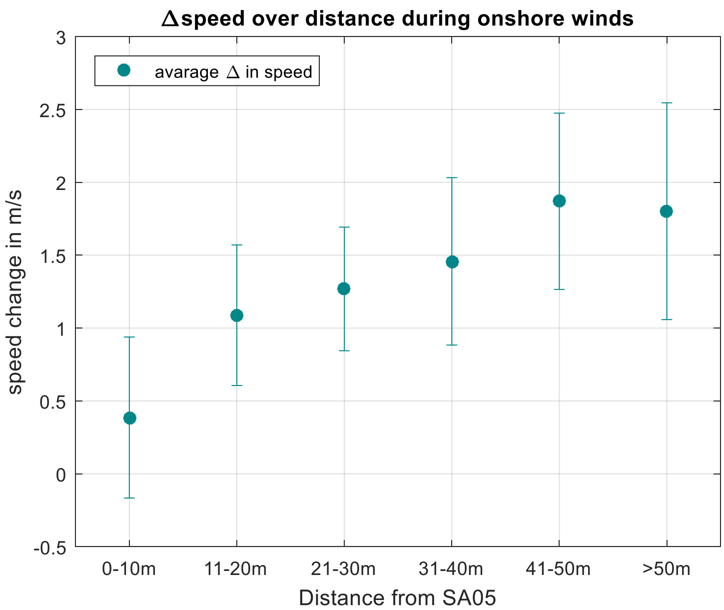


Figure 4.1 Overall change in windspeed (absolute) during onshore wind events (187,7°-7.7° relative to true north)

Looking at Figure 4.1 a general trend could be discovered. A decrease in wind speed in downwind direction is present. As can be seen in Figure 4.1, there is a positive speed change mean wind speed per distance class in m/s relative to the base station. This means that at that particular distance class the wind speed measured at that moment in time was larger than at the base station.

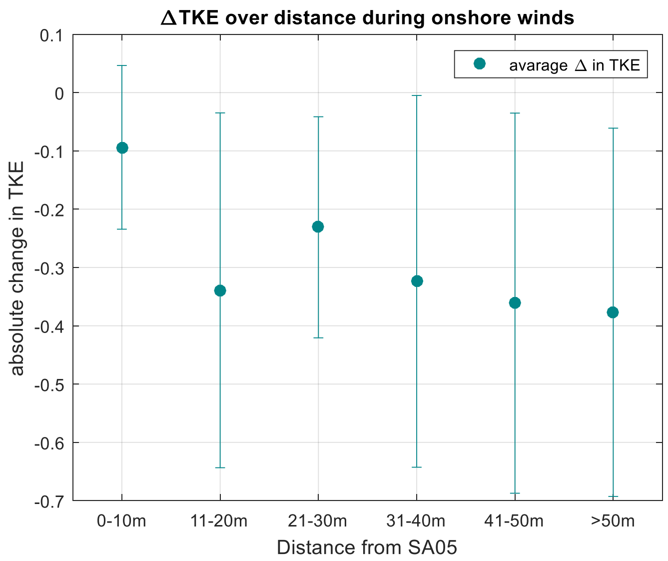


Figure 4.2 Overview of the difference in mean wind speed over across the beach under NW and SW oblique onshore wind conditions including error bars.

Figure 4.2 shows that the absolute change in TKE is relatively stable over the beach, yet it is consistently lower then at the reference station. Furthermore the error bars are show the standard error is relatively high. Before the hypothesis is validated this has to be analysed more. An in-depth analysis is conducted in section 4.2.

To enhance the readability of this thesis and not include to many figures, it is decided not to visually show the behaviour of wind direction in this part of the thesis since it is not feasible to look at the change in direction for the whole onshore spectrum without making a distinction between northern and southern oriented wind events. This is because the wind is expected to become more dune parallel meaning southern wind events will decrease in absolute value whilst northern oriented will increase in absolute value. When added together, the effect would be cancelled out. Still looking at the daily deployments during the quick scan the turning of the wind became visible.

4.1.1 Results of quick scan

Within Appendix I an impression of the quickscan, which is carried out to verify the hypothesis is included. Although in the appendix just an impression is included, the raw data is made available within the Aeolex-II database. The general conclusion based on the quickscan was that there was that the hypothesis could be verified for the most part. The findings regarding the TKE however deviated from the hypothesis, but this will be addressed in subsection 4.2.

4.2 Quantifying relative changes in spatial wind patterns

In subsection 4.1 it becomes clear changes in wind characteristics on a spatial scale are present. Some basic observations are provided to validate the hypothesis. In this subsection an attempt is made to quantify the relative relationships in wind characteristics based on the spatial scale and a further distinction based on incoming wind angle. Again, this is done by using SA05 as a base station.

4.2.1 Relative speed change on a spatial scale

From Figure 4.3 and 4.4 a spatial trend can be discovered in wind speed. The wind speed decreases as it approaches the dune foot or as presented in Figure 4.3 and 4.4 increases as the distance away from the dune foot increases. Unfortunately, the dataset is not comprehensive enough to give meaningful insight in distances greater than 50 meters away from the dune station. It also becomes clear that there are spatial differences in speed reduction per wind direction. Overall wind speed could reduce up to 55% as it approaches the dune foot. Distances greater than 50 meters away from the foredune do not seem affected, however there are not enough data points available to prove this statement.

To further specify the change in mean wind speed every on-shore wind event is analysed on its own.

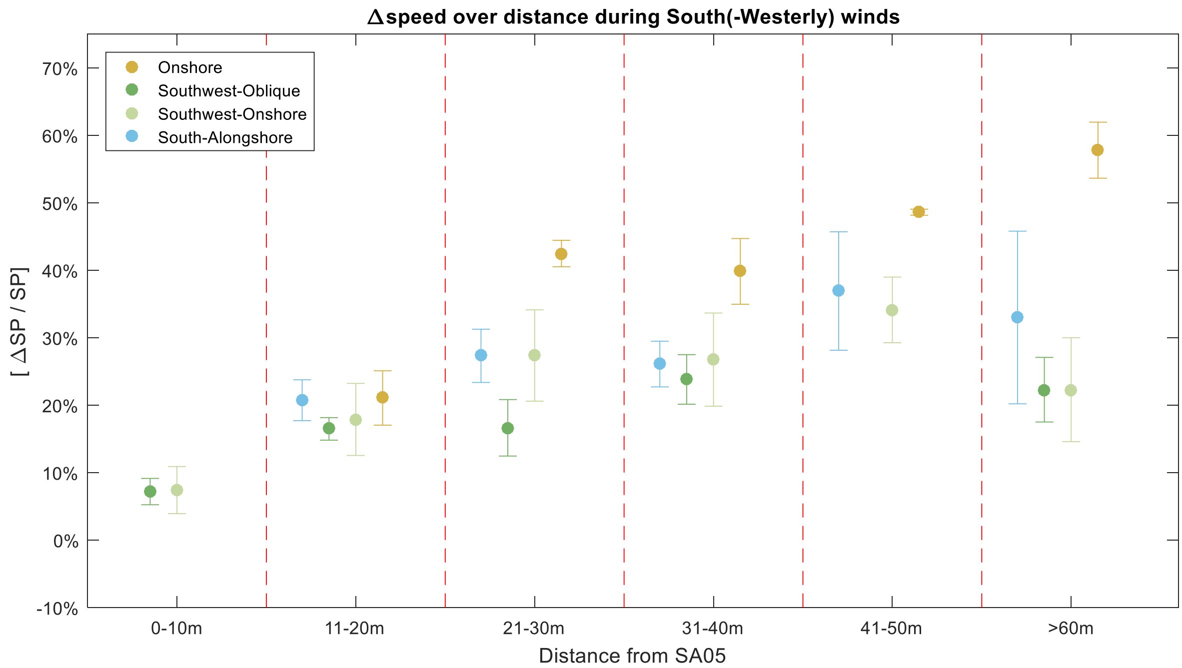


Figure 4.3 Spatial change in windspeed relative to the base station SA05. South-(westerly oriented wind events)

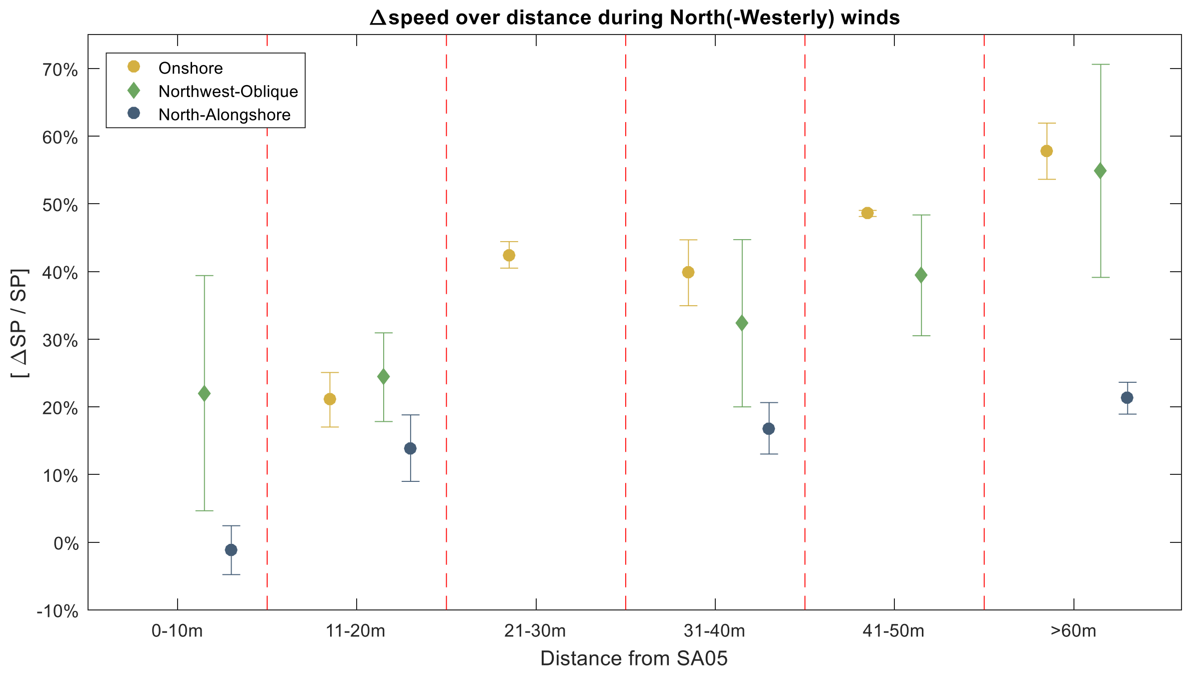


Figure 4.4 Spatial change in windspeed relative to the base station SA05.North-(westerly) oriented wind events

Southern oriented wind events

In the case of Southern oriented wind, the wind flows across the embryo dune mentioned in subsection 3.1.4. before it approaches the base station.

In Figure 4.3 SW oblique wind events are illustrated using different tones of green. It becomes clear that there is a slight difference between the two directions. The decrease in wind speed towards the dune is relatively higher during onshore SW-oblique wind events compared to alongshore SW-oblique events. The maximum decrease in wind speed during onshore SW-oblique events is roughly 35%, whilst for the same distance class during alongshore SW-oblique events is only 25%. Although it has to be mentioned that this comparison is not within the same distance class yet the error bars of the Oblique-onshore wind direction class indicate a higher decrease throughout all distance classes. The dissimilarity between the two SW oblique events is most likely caused by the angle the wind approaches the dune foot. The steeper the angle, the more effect the presence of the dune has on the local wind patterns in terms of velocity drop off.

Unfortunately there is no data gathered for southern alongshore wind events between 0 and 10 meters away from the dune foot. The hypothesis stated that there would be a significant velocity drop off near the dune foot based on this dataset however this cannot be verified for southern alongshore winds.

Northern oriented wind

Northern oriented Oblique wind events show similarities with Southern Oblique wind events. Especially the SW-Oblique onshore oriented wind events. Furthermore it becomes clear that the decrease in windspeed as the wind approaches the dune foot is less than during onshore oriented wind events. The maximum decrease within the valid distance classes is relatively comparable (around 35%) to SW oblique wind events.

Regarding the Northern alongshore oriented wind events the in the hypothesis described velocity drop off near the dune foot is clearly visible. Furthermore the spatial decrease in windspeed stays relatively low and stable as expected.

Onshore

Compared to both Oblique onshore conditions there is a steep incline in relative speed change between 21-30 meters away from the base station. Whereas the relative speed change 11-20 meters away from the base station is roughly the same for all wind events, at a distance of 30 meters away from the base station the differences become more apparent.

Deriving formula's based on observations

To further quantify the change in wind speed, an attempt is made to derive formulas per direction class. The formulas are derived based on the method described in subsection 3.3.1. This yielded the results shown in table 4.1. The variable 'Dist' refers to the actual distance from the dune foot.

table 4.1 Derived formula per wind condition with corresponding R^2 values

Wind condition	Derived formula	R^2
SW Obllique-Onshore	$windspeed\ increase(\hat{y})[\%] = -1.164e^{-04} \times Dist^2 + 0.01205 \times Dist + 0.0217$	0.9564
SW Oblique	$windspeed\ increase(\hat{y})[\%] = -9.694e^{-05} \times Dist^2 + 0.0087 \times Dist + 0.03526$	0.9064
Onshore	$windspeed\ increase(\hat{y})[\%] = -3.161e^{-03} \times Dist^2 + 0.012 \times Dist - 0.1051$	0.8511
North-West Oblique	$windspeed\ increase(\hat{y})[\%] = 7.8656e^{-05} \times Dist^2 + 0.0003471 \times Dist + 0.218$	0.9966

The derived formulas provide an estimate about the increase in wind speed percentage wise relative to the wind speed measured at the base station at the distance desired. However as the R^2 value indicates not all estimates are correct. Especially during onshore wind events the estimates have quite a high error. The formulas are all based(except for North-West Oblique predictions) on a negative second order polynomial. Inherent to a negative second order polynomials formula is a decrease in Y at larger values of X. In this case this results in a clouded view of the reality. To be specific, according to the derived formulas the wind speed will first increase and at a certain distance decrease again while in reality the wind speed seems to stabilise at a certain distance away from the dune foot. Therefor this formulas are not suitable for an extrapolation of windspeed increase more than 50 meters away from the base station. This is also true for the formula used for the North-West Oblique directions since in theory this formula will increase the windspeed up to infinity at greater distances.

Figure 4.5 includes the plotted prediction lines compared to the actual datapoints the prediction is derived from. The formulas are derived from all available datapoints per direction class up to a distance of 50 meters away from the dune foot, since at greater distances not enough data points were available. The error bars are left out of this plot to improve the readability of this plot.

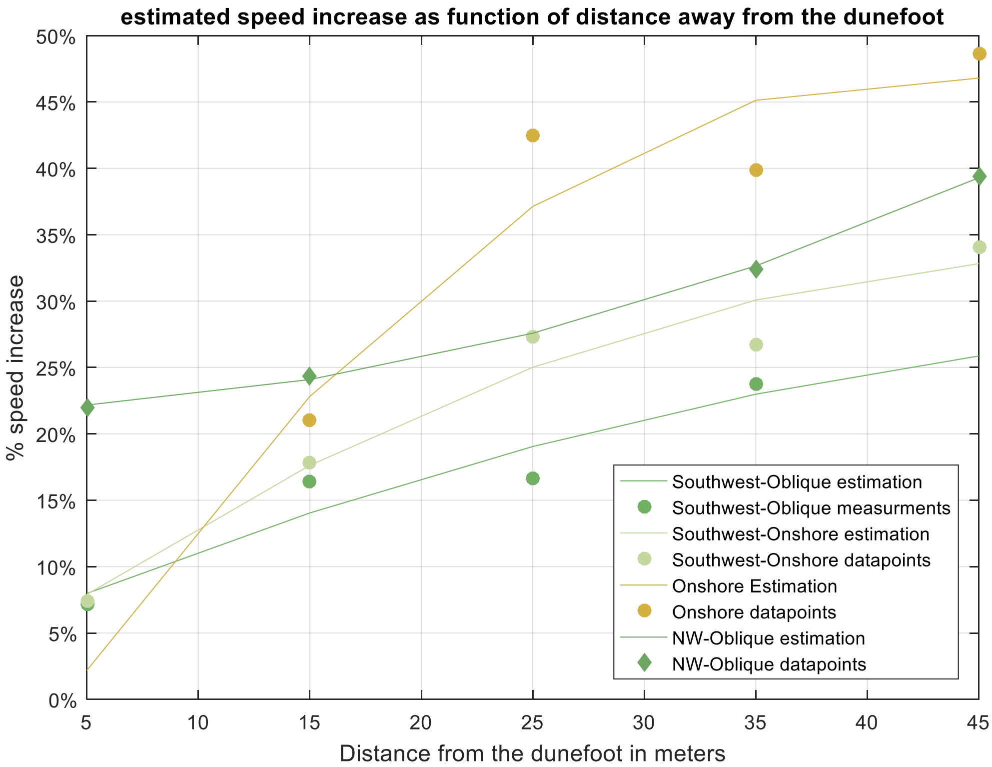


Figure 4.5 Derived formulas for different windspeed in relation to the established average observations.

4.2.2 Change in local wind direction on spatial scale

Although it has already been established that the wind direction tends to become more dune parallel depending on the obliquity of the incoming wind direction. No additional study has been carried out towards the differences per incident wind direction. Figure 4.6 includes a quantified study towards the change in wind direction per incident wind direction.

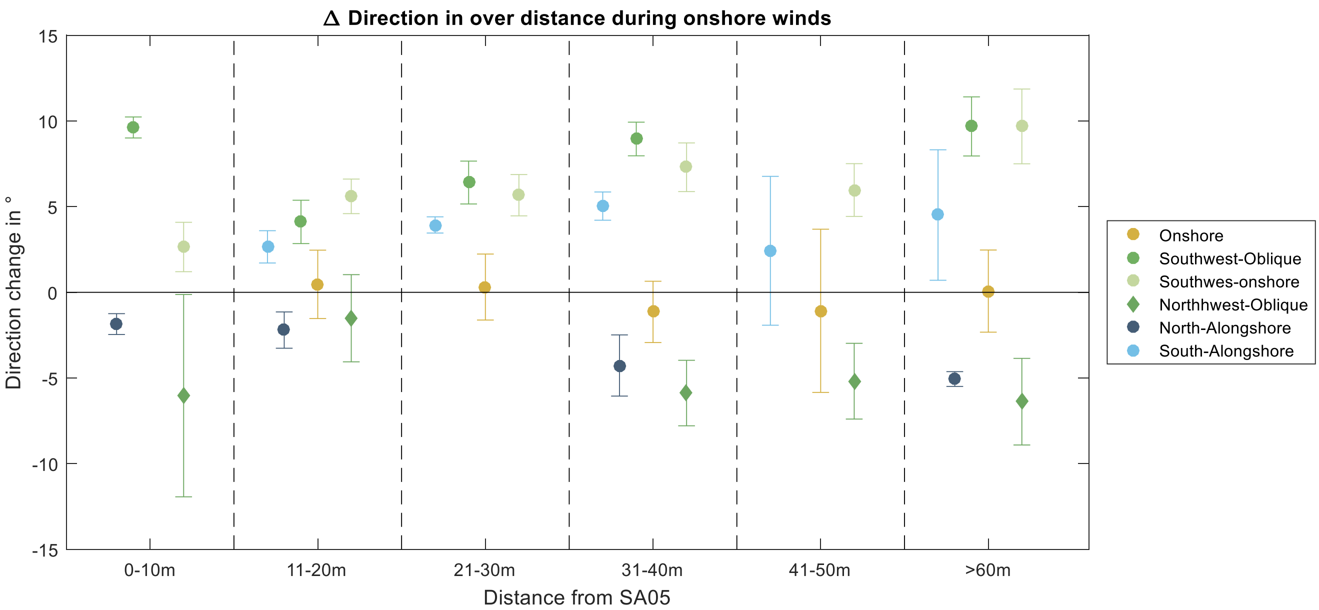


Figure 4.6 Absolute change in wind direction per incident direction

Within Figure 4.6 change in wind direction is indicated in degrees. For southern oriented winds the wind would be dune parallel when the direction is 187°. For Northern winds this is the case by a wind direction of 7°. By subtracting the values measured by the base station (SA05) from the values measured by the station on the beach an absolute change in wind direction is obtained. For Southernly onshore winds higher numbers regarding wind direction on the beach then at the base station means that the wind direction tend to become more dune parallel at the dune foot. This is because the window used to define Southernly onshore conditions consists of directions larger than 187°, therefore lower numbers represent a more dune parallel wind direction. For NW oblique wind events this is the other way around. From Figure 4.6 it becomes clear that Oblique-Winds deviate most from their original direction. Whilst onshore winds do not show any significant deviation.

4.2.3 TKE

The spatial distribution of the relative change Turbulent kinetic energy (TKE) is included in Figure 4.7 for southern oriented wind events and Figure 4.8 for northern oriented wind events.

Southern oriented wind events

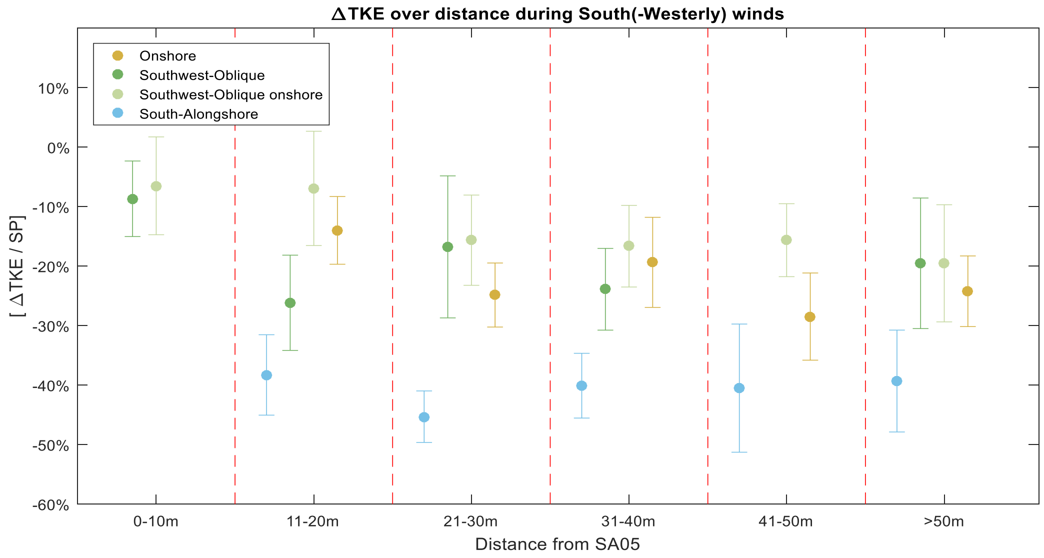


Figure 4.7 Relative TKE change over distance for Southern oriented winds

It is striking that the TKE remains relatively constant across the beach, yet the TKE is consistently lower at the beach compared to the dune foot. Generally speaking, there is not much difference between onshore and oblique measurements. Southern Alongshore wind events however stand out compared to the rest of the graph averaging around 40% lower at the beach compared to the dune foot.

Northern wind events

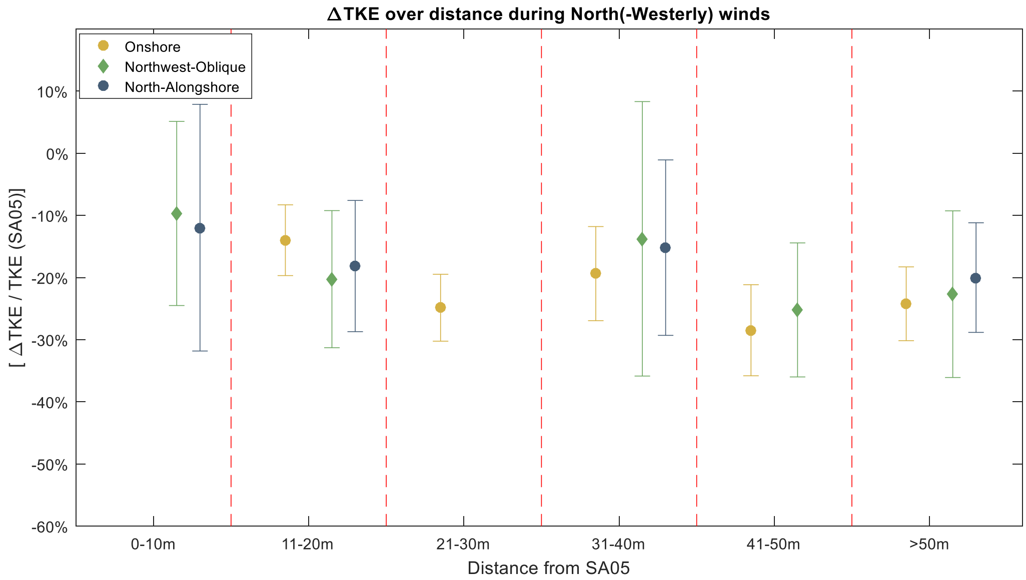


Figure 4.8 Relative TKE change over distance for Northern oriented winds

Again, the average TKE values of Northern oriented wind events are relatively lower at the beach compared to the dune foot. However, the standard deviation values of measurements at the beach sometimes exceed the avarage TKE value measured at the dune foot. Yet this only occurs in distance classes with limited observations. For Northern oriented wind events the difference between Alongshore, Oblique and onshore wind directions is not comparable to the difference southern oriented wind directions.

5 Comparison regional wind measurements

This chapter provides the context necessary to answer the question: “How do the measurements of most dune ward measurement station compare to regional wind measurements? “

5.1 Statistical comparison datasets

The dataset of both the regional and local wind were trimmed to include only onshore wind directions as defined in chapter 3. After performing a preliminary statistical analysis as described in subsection 3.3.1 on the trimmed dataset, a correlation coefficient of r=0.88 for the wind speed measurements, whilst for the direction measurements r=0.97 is obtained. Both coefficients indicating a relatively strong correlation for both the speed measurements and the direction measurements while looking at the whole onshore spectrum. Yet this numbers do not necessarily indicate a linear relationship.

5.2 Translation windspeed at 0.9m to windspeed at 10m

It has been established there is a difference in windspeed between 10 meters above the surface and at heights closer to the surface due shear stress and the forming of boundary layers. To analyse this decrease in wind speed the local wind speeds will be recalculated to height of 10 meters. This is accomplished using a logarithmic function. The vertical distribution of wind velocities follows a logarithmic profile which is influenced by shear velocity the wind experiences at the surface (Oke, T. 1987). The shear velocity is mainly influenced by the roughness height and von Karman constant. The von Karman constant is set to 0.41, which is good representative for the conditions on the Dutch coast. The roughness length (z_0) parameter is determined using data from a seawards deployment of SA02. On October 25th, station SA02 was deployed at the shoreline 105 meters away from the dune foot (in cross shore direction). The wind direction measured at SA02 on October 25th varied between 280°-300°. Based on the findings in Chapter 4 this deployment should not be affected by the presence of the foredune. Therefore it is suitable to estimate the roughnesslength(Z0) at the beach of Egmond aan Zee. To estimate the z0 parameter, a comparison is made between the regional wind speeds at 10 meters above the surface and the recalculated values of the measurements at SA02 for a height of 10 meters based on an empirical value of z0. After several iterations a value for z0 of 0.001 meter yielded the best results. This specific roughness length is often used for sandy beaches. (Gillette, D. A. et al., 1998). With the empirically determined value for z0, the wind speed measurements of SA05 are recalculated to a theoretical wind speed 10 meters above the surface and compared to the regional wind speed measurements. Based on the local theoretical windspeeds at 10 meters a formula (equation 5.1) is derived. This yielded the following graph (see Figure 5.1 next page)

Equation 5.1: Formula used to estimate local windspeed at 10m

$$Estimated\ localwindspeed\ at\ 10m\ (\hat{y}) = Regional\ windspeed * 0{,}758$$

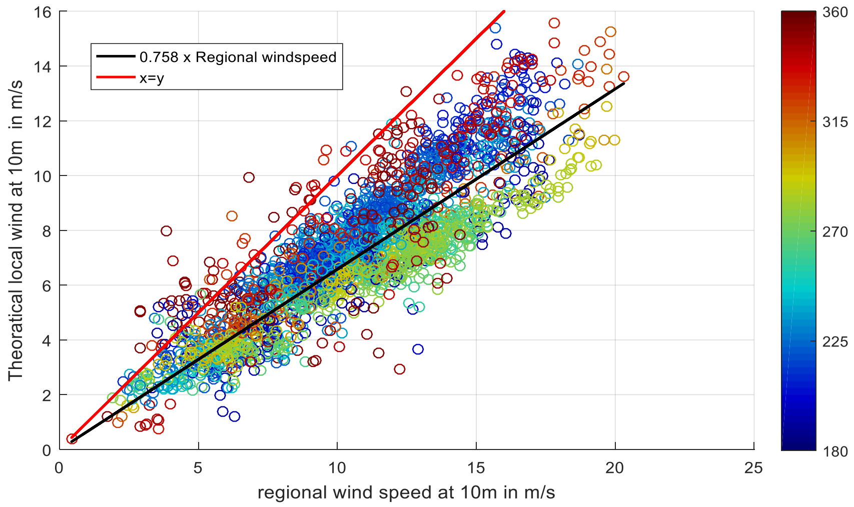


Figure 5.1 regional wind direction vs. local wind direction and fitted formula to predict the local wind speed based on regional windspeed including 95% confidence intervals. On the righthand side correspondent with the direction of the local windspeed measured at the dune foot

The derived formula indicates that on average during onshore oriented winds there is a decrease of roughly 25% in windspeed between the local (recalculated) windspeeds measured near the dune foot and the regional measured windspeeds offshore which is coherent with the findings in section 4.2.

The different colours within Figure 5.1 indicate different wind directions as shown in the colormap on the right-hand of the graph. The colours correspondent with the local wind direction measured near the dune foot. Based on Figure 5.1 a primarily discrimination could be made showing the influence wind direction has on the relation between regional and local windspeeds. It becomes clear that during onshore winds (tinted yellow and green) the local windspeeds are relatively lower compared to more alongshore oriented winds (tinted red and blue). This observation further substantiates the findings in Figure 4.5 which indicates that there the decrease in windspeed across the beach is the strongest during onshore wind. I.e. the local windspeed should be relatively low compared to regional windspeeds.

Furthermore, a x=y line is added within Figure 5.1 (see red line). This way it becomes visible when local windspeed exceed regional windspeeds. Relatively speaking observations like this are made mainly during (northern) alongshore wind directions. Judging on Figure 5.1 this is more common during low wind speeds.

5.3 Correlation in wind direction

In Figure 5.2 (next page) the relation between both the regional and local wind directions is graphically shown. Looking at this graph, it becomes clear the strong correlation discovered earlier is not linear. The dataset (y) is best expressed by a high order(3^{rd}-5^{th}) polynomial fit dependent on (x). This is coherent with the findings in chapter 4, in which was explained that during oblique wind directions, the wind to become more dune parallel as it approaches the dune foot. Since the regional measurements take place at a more seaward location relative to the base station SA05, this means that for southern oriented winds, the regionalised wind directions will be higher in terms of degrees compared to the local wind directions whereas for the Northern oriented wind directions the opposite is true. In other words, X>Y for Southern oriented wind events while X<Y for northern oriented wind events.

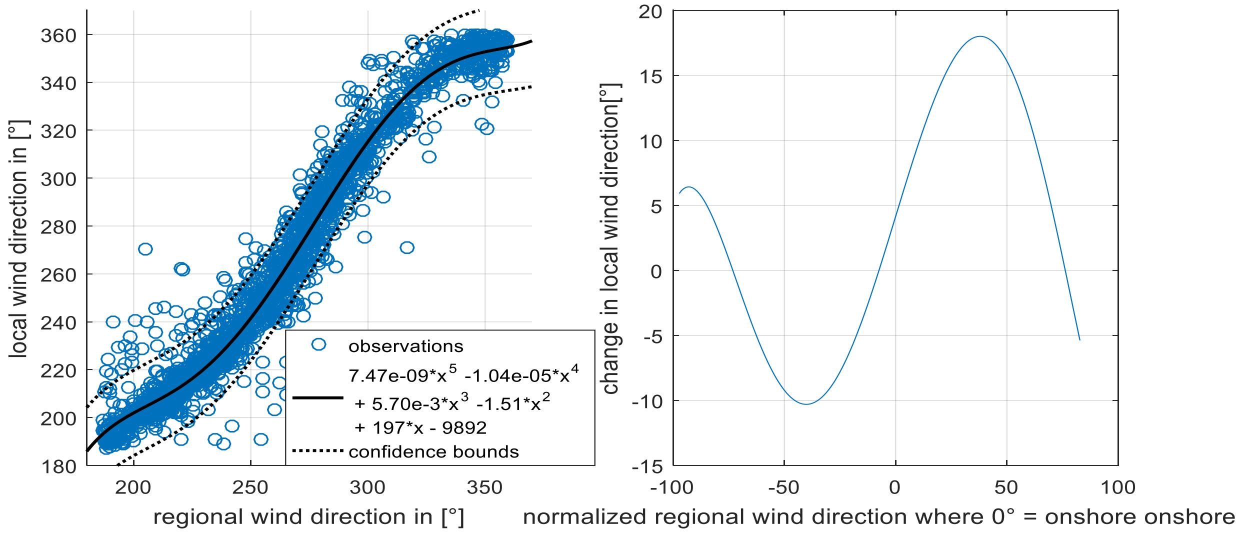


Figure 5.2 regional wind direction vs. local wind direction and fitted formula to predict the local wind speed based on regional windspeed including 95% confidence intervals on the left. And 5.1 degrees of change in local wind direction compared to the regional wind direction normalised on a on/offshore scale. The change in local wind direction is a consequence from the presence of the foredune on the right

After the statististical tests as described in subsection 3.3 it is decided to derive a polynomial formula consisting of five orders to predict the local wind speeds (y) based on the regional windspeeds (x). The formula derived is shown in Equation 5.2 (in which x represents the regional wind direction.):

Equation 5.2: Formula used to estimate local windspeed at 10m

$$Estimated\ localwindspeed\ at\ 10m\ (\hat{y}) = 7.47e-09*x^5 - 1.04e-05*x^4 + 5.70e-3*x^3 - 1.51*x^2 + 197*x - 9892$$

The other results of the statistical test are presented in table 5.1. A graphic representation of the fitted formula relative to the dataset is already included in Figure 5.2. The scatter present around the wind directions of 187-210° has most likely to do with the presence of the embryo dune southwards of the base station which will be further discussed within the discussion.

table 5.1 Statistical comparison different prediction models in which s stands for standard deviation

Statistical comparison different prediction models				
Model type	SSE	dfe	s	R^2
linear	3,49*10^5	2699	11,37	0,95
quadratic	3,46*10^5	2698	11,33	0,951
cubic	2,39*10^5	2697	9,29	0,952
4th order polynomial	2,34*10^5	2696	9,24	0,963
5th order polynomial	2,25*10^5	2695	9,14	0,967

Although statistically speaking the different types of prediction models do not vary much, there is a difference in the 'behaviour' of the models in terms of representing the actual truth compared to the statistical truth. This is especially noticeable in the linear and quadratic types of prediction models. In these models there is no simulated effect of the wind becoming more dune parallel when the local wind patterns approach the dune foot. Keeping in mind the scope of the thesis this model is only suitable for predicting onshore wind events. Although no fit is perfect, the 5^{th} order polynomial fit is the closest reassembly of the relation between regionalised wind directions and local wind directions.

It is possible to quantify the change in wind direction on the regional to local scale. Using the derived formula based on the left-hand side of Figure 5.2, the graph on the right-hand side is created. The graph clearly shows the wind turning dune parallel relative to the regional wind direction. Moreover, the differences in magnitude of change becomes visible. The sharpest changes occur near the most oblique wind direction.

6 Discussion

This chapter is dedicated to discuss the results from this MSc thesis. Nuances about the results will also be present in this chapter if deemed necessary. Apart from a critical examination of the results, this chapter contains also contains a comparison with the earlier conducted literature review. Ideas for further research will also be proposed within this chapter

6.1 Fieldwork

A labour-intensive fieldwork campaign inherently increases the chance of human error resulting in measurement inaccuracies. It is plausible measurements made to check the height of the sonic anemometer above the surface are off by a centimetre or two. This has effect on the measured speed at the specific anemometer. Lower heights above the surface will result in lower speed measurement whilst higher heights will result in higher windspeed. This is due to the logarithmic nature of the vertical distribution of windspeed which is influenced by the shear stress as explained in chapter 5. Yet the relatively small deviation in height should not have caused significant

Hindsight the locations of the deployments of the mobile sonic anemometers could have been structurally better. During the experiment they were mainly placed to form an even grid across the beach however it was not measured on site what the exact distance in meters away from the base station was. Eventually this resulted in a nonuniform distribution of measurements per distance class as shown in the results. Perhaps this could have been avoided by structurally placing the mobile anemometers on a predefined spatial grid. It is also important to note that the exact method of data analysis was not specified before the experiment. This is because the method used is highly dependent on the data (and amount of data) gathered during the campaign. This is further described under conditions.

Conditions provided during the Aeolex II campaign were above expectations. However as shown in chapter 3, North-Western oblique conditions were limited, therefor it is difficult to draw conclusions for this wind direction.

6.2 Results

The amount of data also dictated the methodology used to answer the research questions.

6.2.1 Results

Within this study it has been established that during onshore wind directions windspeed decreases over the width of the beach. Although no studies had been conducted on this scale specifically for mapping wind patterns across the (intertidal)beach, observations showing a decrease in windspeed across the (back) beach have been made before. E.g. (Arens 1995; Hesp et al., 2005; Bauer et al., 2009; Winter et al., 2017). Compared to previous studies, this study showed a greater decrease in windspeed at the beach. It is believed this is a consequence of the differences in morphological setting. Many studies investigating wind patterns have been carried out at the Greenwich Beach dune complex (Hesp et al., 2005; Bauer et al., 2009, 2012; Walker et al., 2006, 2009, 2017). Compared to the study site of Aeolex II the Greenwhich beach dune complex is relatively flat and low (see Figure 6.1)

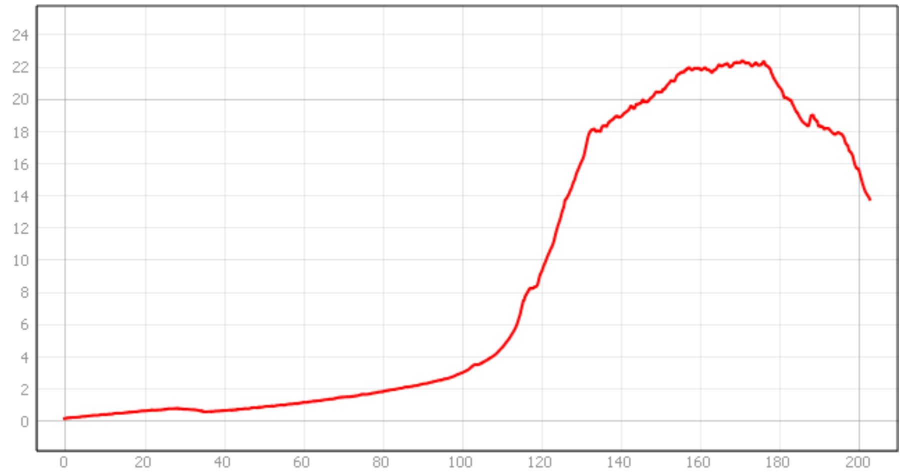


Figure 6.1 The beach profile of the study site near the end of september 2017 in more detail compared to the profiles included in chapter 3. The x axis represents the distance relative to the (average) shoreline whilst the Y axis represents the height of the beach surface in M relative to N.A.P.

Hesp and Arens also discovered that the amount of decrease is dependent on incoming wind direction. Findings further substantiated within this research. This study showed that during onshore wind events the overall decrease in windspeed is greatest, whilst this decrease is less for alongshore oriented wind events. An explanation for this phenomenon could be the forming of some sort of flow stagnation layer introduced by the presence of the dune in which the wind speeds drastically decreases. This effect becomes even more noticeable by onshore winds, since the wind has to go across the dune instead of going dune parallel. Leading to an increase in shear stress while reducing the velocity. This is better described by looking at the wind vectors for oblique alongshore, oblique-onshore, and onshore winds as shown in Figure 6.2. In this case the U vector represents the dune parallel direction and the V vector the crossdune direction. The U vector is less affected by the presence of the dune speed wise relative to the V vector. Oblique alongshore wind directions consist mainly of the U vector and just partly of the V vector. Hence the red arrow, which represents the actual direction, is less affected, since in this case it is mainly based on the U vector. The opposite is true for the Oblique Onshore winds in which the actual direction is mainly based on the V vector, which is relatively more affected by the presence of the dune speed wise. Finally, the Onshore direction is even more affected since this direction is fully dependent on the V vector.

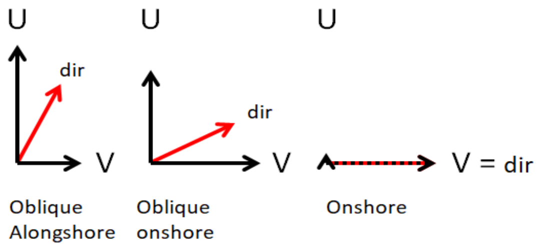


Figure 6.2 simplified breakdown of a two dimensional wind vectors lacking the vertical component (W).

During this study it became clear observations made during northern and southern wind events differed considerably indicating the findings are not symmetric. The root cause of this non-symmetry could be derived back to the morphological setting of SA05. As elaborated on in chapter 3, SA05 was located North(east) of a small (vegetated) embryo dune. According to literature data collected at this location during southwestern oriented winds is disturbed due to the presence of the foredune (Pearson et al., 2004; Walker & Nickling 2002). Pearson et al.

(2004) used a CFD program to simulate airflow across idealised transverse dunes of different dimensions. Based on his research Results of this study were already included in chapter 2. His research showed that at the lee side of the dune airflow velocities are significantly less whilst TKE increases. Walker and Nickling reviewed literature about near surface airflow patterns across dunes. This review showed that the wake of the wake of the embryo dune could extend up to 10 times the height of the crest. Within the wake eddy vortices are present indicating an increased measure of turbulence.

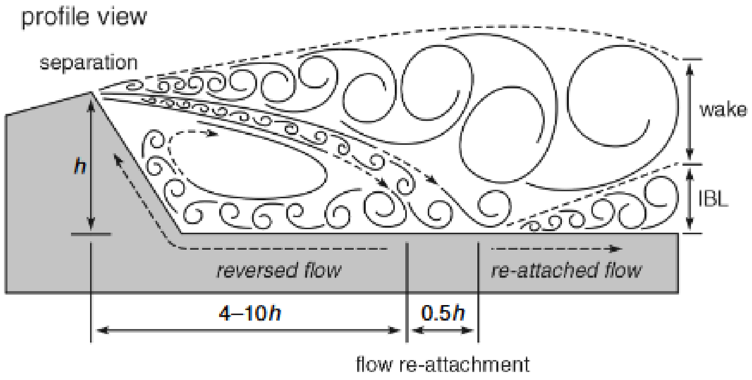


Figure 6.3 theoretical background on wind patterns at the lee side of a small dune.

Increase in turbulence is also noticed within this study. When looking at the TKE during south Alongshore wind directions there is a lot more turbulence measured at the base station compared to the measurements on the beach. This correlates to the findings of (Walker & Nickling 2002). However it does not fully explain why the TKE constantly higher at the dune foot compared to the beach for the other wind directions. An explanation for this can be found in (Pearson et al., 2004). Simulations they performed, showed an increase in TKE at the stoss side of the dune foot increases(see Figure 2.13 within the literature review). Chapman et al. (2012) indicates that near the dune foot flow destabilisation occurs, hinting on an increase in TKE. It is also possible that horizontal vertices occur just in front of the dune due to the wind deflection during onshore wind. Horizontal vertices increase the TKE.

Another cause of deviation between Northern and Southern wind events concerning North-west and South-west Oblique wind events in particular, is the relative wide angle of approach used to classify North-west oblique wind events. In this research is has been established that decrease in windspeed is highly depended on angle of approach. Since the angle of approach for the NW-Oblique class is rather large and NW conditions limited, it is possible that between distance classes only consist of a single wind event. Single wind events relative to each other can differ from direction quite significant. This could explain why the derived formula in chapter 4 is a positive second order polynomial for the NW-Oblique direction class whilst the other directions all show a negative trend. The downwind distance the wind has to travel before it approaches the dune foot, is in contrast to absolute distance from the dune foot depended on angle of approach.

The conceptual model proposed by Bauer et al. (2012) (shown in Figure 2.10 within the literature review) could be verified based on the results of this study. Like Bauer et al. 2012, this study also concludes that oblique wind deflects dune parallel as is approaches the dune foot and a little to no deflection during onshore winds. Furthermore, it indicates an increase in TKE at the dune foot during onshore winds.

Transforming wind speed from a speed measured at 0.9m above the surface to theoretical values at a height of 10m by validating the z0 on only two points as done in during this study has consequences for the absolute accuracy of the theoretical values. However, the effect of this inaccuracy in relative perspective could be neglected since the translation works out to be a constant.

6.3 Impact

The overall goal of this study was to gain insight in wind deformation across the beach during onshore winds specifically for the Dutch coast. Detailed information about the spatial deformation of wind patterns across the width of the beach has been obtained. Especially the decrease in wind speed has been investigated deeply. During this research it became clear that the decrease in wind speed is dependent on the incident wind direction. The wind speed behaves differently under different wind directions. This is something observed by Hesp in 2002 before. Hesp (2002) concluded that during directly onshore wind the wind speeds decreased more at the back of the beach compared to incident wind speed then during oblique onshore wind events (see Figure 2.7). Within this study the same effect is observed although the magnitude of this effect is different, most likely due to lower and less steep foredunes. The data gathered clearly shows that during onshore wind the relative decrease in wind speed is substantially higher than during alongshore and oblique onshore wind events. Not only does this study observe this effect, even a quantification is made in the dependence of incident wind angle and decrease in wind speed specific for the Dutch Coast. It is specific for the Dutch coast due to the unique topography of the foredune. Dutch foredunes are considered relatively high in comparison with the rest of the world. Parsons et al discovered in 2002 that based on their CFD simulations, the size of the dune has a significant influence on the effect the dune has on upstream wind patterns.

Like Bauer et al. (2009) (see Figure 2.4), this study also showed a decrease in wind speed across the beach. They stated that the decrease in windspeed was most likely the result of the beach induced boundary layer since the wind direction was highly oblique. However, based on the results of the Aeolex II campaign question marks should be raised about this statement. Based on the Aeolex II campaign it has been observed that the TKE remains constant across the beach (by multiple wind directions) and only increases near the dune foot. This suggests that there is no increase in friction and therefor no altering of the boundary layer. Aditionally a study performed by Jin Wu (1980) showed that the roughness height of z0 across the ocean during natural conditions is varying between 0,05 and 0,5 cm which is within the same range as the roughness height which is often used at sandy beaches. Therefor it is unlikely a so-called beach induced boundary layer is causing a decrease in windspeed across the beach.

Overall this study provides a comprehensive review of wind patterns specific for the Dutch coast. The vast amount of data gathered during the fieldwork campaign enabled us to derive quantitative relations to estimate wind decrease across the beach during different onshore wind directions. It was also possible to relate the measurements performed on the beach to regionalised measurements which are often used in model predictions. These new insights are useful to more precisely predict aeolian transport and thus dune growth.

6.3.1 Future posibilites

The results of this study further complicate the already very complex theory of the cosine effect as described by Hesp, (2002) and Delgado Fernandez (2010). An increase in obliquity results in an increase in available fetch length, however it also imposes potential decrease in wind speed. This might be related to the development of the boundary layer, but this could also be related to the shelter effect imposed by the foredune. The latter is highly dependent on the level of obliquity. When predicting dune growth, it is important to incorporate this effect within the model. To test the significance of this effect an additional study is recommended.

Futhermore, existing prediction models for aeolian transport (like the Aeolis model from Hoonhoudt and de Vries (2017)) should be adjusted to at least contain a wind prediction module. Within this prediction module effects described in this thesis should be included. This way a spatial accurate wind model could be created resulting in better spatial transport predictions.

The exact wind patterns occurring at the shoreline, the transition from ocean to land to be specific hasn’t been investigated within the Aeolex II campaign. Perhaps this is something which could be done during a next study. This way the suggestions made in this study that the effect of the beach induced boundary layer are neglectable in relation to wind speed decrease could be verified. However a floating gyro stabilised platform suitable for mounting a sonic anemometer should be developed first in order to perform measurements 24/7 at an fixed height relative to the sea surface.

7 Conclusion

The main question answered in this thesis is:

“How do regional wind patterns compare to local wind patterns on the beach during different on-shore wind events?”

Currently computer models used to predict the development of the foredune overestimate the dune growth. Numerous studies have been conducted in a bid to explain the deviations between predictions and observations. However, previous studies did not manage to gather enough data to map the onshore wind patterns in detail.

A fieldwork campaign to map onshore wind patterns using four sonic anemometers was held during October 2017 near Egmond aan Zee.

The data gathered during the fieldwork campaign confirm that a coastal foredune system substantially influences local wind patterns in a beach dune system. Analysis shows that wind speed decreases over the width of the beach, but this decrease in wind speed is dependent on wind direction. During full on onshore wind directions, wind speed could decrease more than 60%. Oblique onshore directions showed a potential decrease upwards of 40%. The decrease in wind speed for oblique along shore directions is generally around 20% was noticeable. It was also observed that the TKE remained constant across the width of the beach.

A correlation between regional wind speed and local wind speed was found. The regional wind speed measured was during the whole campaign 76% higher than the local wind speed measured at the back of the beach.

It has been observed that wind directions tend to divert dune parallel as it approaches the stoss side of the foredune. Furthermore, a relationship has been quantified between quantified between regional wind direction and wind direction measured at the back of the beach. It turns out this relationship is best described using a 5^{th} order polynomial formula. Again this formula indicates that the degrees of change in local wind speed is highly dependent on the measured wind direction at the regional measurement station.

It is highly recommended to translate the findings of this research into (existing) aeolian prediction models to further increase the accuracy of such models.

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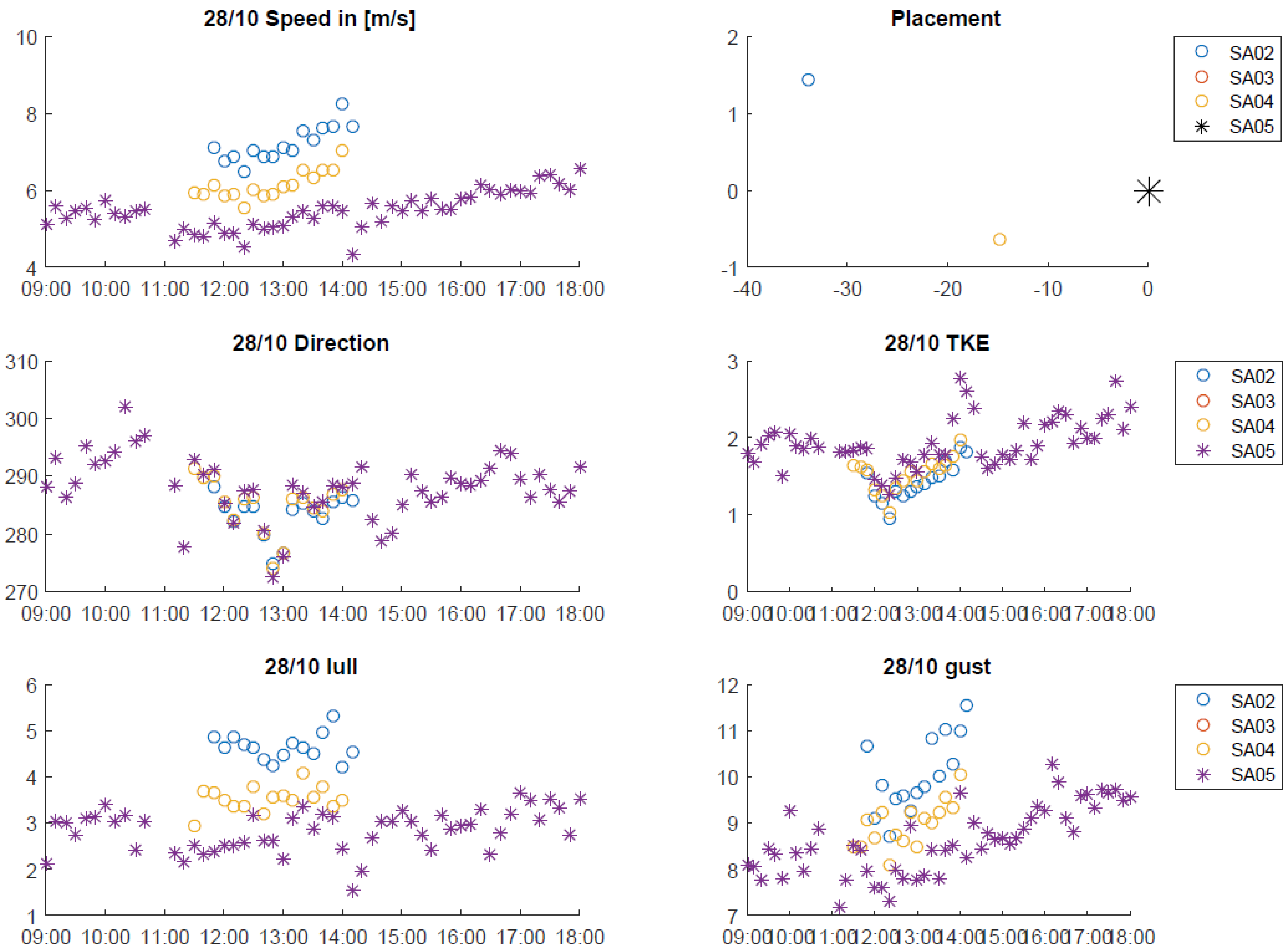
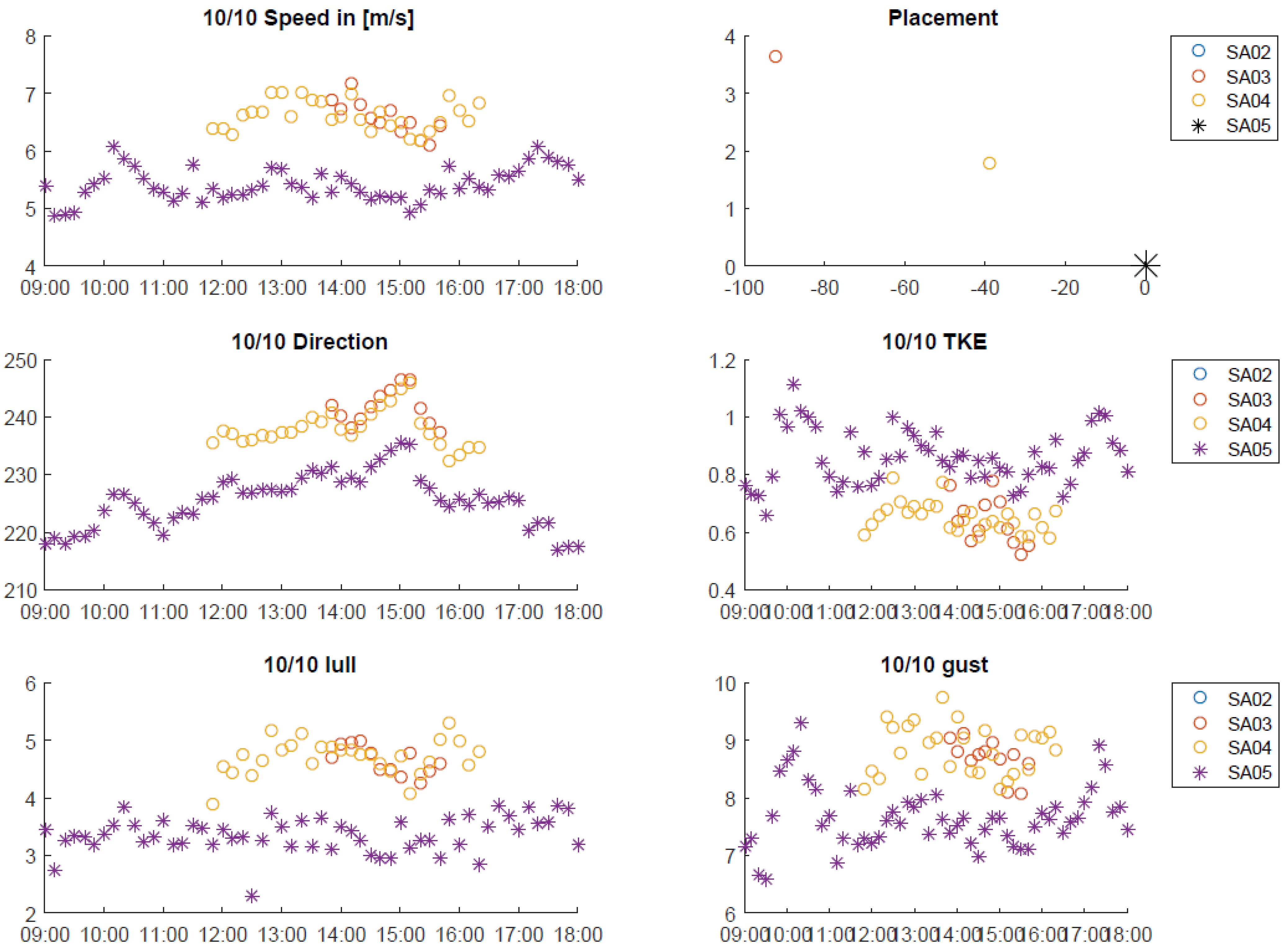
I. Appendix I example of Quickscan

Within the Quickscan a quick overview is plotted consting of the Windspeed, Placement of the SAs, Direction, TKE, Lulls and gusts. Two examples are provided and explained within this appendix. The other days of the campaign are available as pdf format in the database. As well as the matlab script used to generate this overviews.



The 28th of October was a day with a NW-onshore wind. This day SA02 and SA04 were deployed in addition to the ever present basestation SA05. Looking at the placements they were more or less deployed in a straight line relative to SA05 +- 1,5m deviation between them. Immediately it indicates that there is a difference in speed measured at SA02, SA04 and the base station. The wind decreases across the width of the beach. The direction does not vary much between the deployments, this is due to the relatively onshore wind. The TKE is consistently higher near the dun efoot, while the absolute lulls and gusts are showing similar behaviour as the windspeed. The differences between lulls and gusts however, are relatively higher at the dunefoot



October the 10th was a day with Southwest Oblique onshore winds. This day SA03 and SA04 were deployed in addition to the ever present basestation SA05. Looking at the placements they were more or less deployed in a straight line relative to SA05 +- 4m deviation between them. It indicates that there is a difference in speed measured at SA03, SA04 and the base station. However the biggest drop off in velocity occurs between SA04 and the base station, which was to be expected looking at the hypothesis and the incoming wind direction. The direction does vary between the deployments and varies a lot relative to the basestation. Also it is consequently more onshore at the location of SA03 and SA04 relative to the basesation. Indicating that the wind is indeed deflecting dune parallel. The TKE is consistently higher near the dunefoot, while the absolute lulls and gusts are showing similar behaviour as the windspeed. The differences between lulls and gusts however, are relatively higher at the dunefoot.

II. Apendix II – Impression of fieldwork (pictures)

Figure 8.1 Impression study site with saldec and Sonic anemometer on the foreground. Other equiment in the background

Figure 8.2. Setting up of equipment, adjusting g height of Sonic Anemometer before setting it level

Figure 8.3. Data logger

Figure 8.4. Our Daily transportation an

Figure 8.5. Impression of an sonic anemometer on top of the foredune +- 25 high in conditions of high winds. .