



Aeolian activity in foredune notches: Evidence from multiannual wind observations

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Abstract Coastal dunes are increasingly threatened by human activities and climate change, often with adverse effects on biodiversity. Excavating gaps, or notches, through densely vegetated foredunes is an increasingly adopted dynamic management measure aimed at enhancing aeolian sand transport from the beach to beyond the foredune, supporting both ecological diversity and coastal resilience. However, observational evidence of the wind conditions that support notch activity and of the influence of notch geometry on long-term sand transport remains limited. Using near-bed wind data collected from 2016 to 2023 in three geometrically distinct notches at Bloemendaal, the Netherlands, we found that these notches were active across a wide range of incident wind directions (130–150°; centred on the notch axis), with higher incident wind speeds required (up to 15 m/s at 10 m height) as winds became more oblique to the notch axis. Although notch geometry did not systematically affect how often notches were active over time, the results indicate that steeper deflation basin slopes increase annual sand transport through stronger slope-induced airflow acceleration. Together with previous studies, these findings suggest that notches with moderate deflation basin slopes (3–10°) and large widths (≥ 50 m) are most effective in promoting landward aeolian sand transport through the foredune.

Non-technical summary Coastal dunes play a vital role in protecting shorelines and supporting biodiversity, but they are increasingly threatened by human activity and climate change. A new management approach involves cutting ‘notches’, or gaps, into the most seaward dune. These notches create pathways for wind to carry sand from the beach further inland, helping to build more resilient dunes while also supporting a wider variety of habitats. We studied three different notches at Bloemendaal, the Netherlands, using seven years of wind measurements. The notches were predicted to be active under a broad range of wind directions, though stronger winds were needed when the wind did not blow directly into the gap. The general shape of a notch did not influence how often it was active, but steeper slopes inside the notch increased sand movement because they accelerated the wind. Taken together with earlier studies, our results suggest that notches with moderate slopes and wide openings are especially effective in moving sand inland.

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1 Introduction

Coastal dunes are biodiversity hotspots, protect low-lying coastal areas from marine flooding during storms, and attract tourists (Everard et al., 2010; Barbier et al., 2011). Despite these and other benefits to humanity, urbanisation and other human activities increasingly interfere with natural dune dynamics (Gao et al., 2020; Nordstrom and Jackson, 2021), damaging, degrading, or even destroying dune ecosystems around the world. Ongoing climate change further adds to these human-induced pressures on dunes (e.g., Jackson et al., 2019; Petrova et al., 2023). Rising mean sea levels and more extreme water levels during storms increase both the risk and magnitude of dune erosion (e.g., De Winter and Ruessink, 2017; Masselink et al., 2022) and can additionally reduce the ability of a dune to recover fully before the next erosion event because of the long (typically

years) time scales involved (Houser et al., 2015; Castelle et al., 2017). In addition, changes in wind climate, temperature, precipitation and groundwater regime in the dunes can alter conditions for plant life, potentially disrupting the feedbacks between vegetation and abiotic factors that govern dune formation and development (Bakker et al., 2016; Raman et al., 2025).

Interventions to restore coastal dune ecosystems are highly diverse (Nordstrom and Jackson, 2021; Farrell et al., 2024) and tailored to specific issues. They include the removal of invasive species (Pickart et al., 2002; Konlechner et al., 2015), supply of sediment to support natural dune-building processes (Nolet et al., 2018), construction of new dunes (Kroon et al., 2022; Matzke and Leege, 2025), planting of dunes to stabilise bare sand patches (Rozé and Lemauiel, 2004) or, conversely, removal of vegetation to increase geomorphological dynamics and eventually floral diversity (Ruessink et al., 2018; Laporte-Fauret et al., 2021). Especially in the Netherlands and the United Kingdom, the

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removal of vegetation and the subsequent excavation of gaps within or through the foredune have become a commonly adopted dynamic intervention (Pagon et al., 2025) aimed at expanding areas of bare sand and early-successional habitats. In the Netherlands, for example, more than 60 such gaps, commonly referred to as notches, have been excavated since 2010. These notches are designed to act as corridors for wind-blown beach sand to be transported landward of the foredune, where it accumulates on inland migrating lobes (Ruessink et al., 2018). These lobes bury late-successional species, thereby locally resetting ecological succession. In addition, inland transport of fine calcareous material, sometimes up to hundreds of metres beyond the foredune (Van Hateren et al., 2020), is expected to benefit plant species landward of the lobes by counteracting soil acidification (Kooijman, 2004). Although many notching interventions were initially implemented with biodiversity goals in mind, it was soon recognised that landward sediment transport also contributes to dune growth, potentially aiding coastal adaptation to sea level rise. For example, Ruessink et al. (2024) estimated that the positive sand budget landward of five foredune notches within a 1 km stretch of coast near Bloemendaal, the Netherlands, was equivalent to a 5.5 km² region accreting at the same rate as the current increase in sea level along the Dutch coast.

Notches are often regarded as functional analogues of natural gaps in the foredune, known as trough blowouts. According to the evolutionary model proposed by Schwarz et al. (2019), trough blowouts typically progress through three sequential stages: geomorphological, bio-geomorphological, and ecological. These stages reflect shifting interactions between physical (e.g., wind speed, sand transport) and biological processes. The full progression through the three stages can span several decades (Van Kuik et al., 2022; Talavera et al., 2024). From a dune restoration perspective, the first two stages are of particular interest. The geomorphological stage is characterised by active landward sand transport and an expansion of bare sand areas, while the bio-geomorphological stage involves the colonisation of these areas by early-successional plant species. In the final ecological stage, biotic processes begin to dominate, resulting in a marked reduction in the transport of sand and the eventual closure of the blowout or notch.

The severity of aeolian activity, including the magnitude of erosion and deposition within the notch, relative to plant tolerance (e.g., Maun, 1998) largely determines whether plant re-establishment is entirely prevented or merely restricted to a limited number of early-successional species; in other words, it governs whether the notch remains in its geomorphological or bio-geomorphological stage. Based on wind observations in a 20–30 m wide trough blowout at Fiona Beach, Australia, Hesp and Hyde (1996) suggested that especially winds aligned approximately parallel to the blowout's long axis can drive substantial aeolian activity and sand transport across the deflation basin onto the depositional lobe, facilitated by accelerating jet flow. When winds approached the axis more obliquely, the

jet flow transitioned into helicoidal vortices due to flow separation from the upwind lateral wall (see also Pease and Gares, 2013). This more turbulent flow type, with (time-averaged) wind speeds reducing landward, may result in lower sand throughput and bed-level dynamics. Later work, in which airflow, sand transport, and erosion–deposition patterns were measured simultaneously, confirmed that accelerating jet flow enables a blowout to act as a conduit for sand to reach beyond the foredune (e.g., Hesp et al., 2017; Rene et al., 2025). However, under highly oblique wind conditions, part of the sand entering the blowout was deposited within the blowout itself (Nguyen et al., 2022). Therefore, these observations corroborate the suggestions of Hesp and Hyde (1996).

Drawing on these two types of airflow and additional wind measurements during a 2-day period in a 6.5 m wide notch at St Kilda Beach, New Zealand, Nguyen et al. (2021) proposed a conceptual notch-activation model that links incident (offshore) wind speed and direction to the expected geomorphological dynamics of the notch (Fig. 1). In this model, an ‘active notch’ is defined as one in which the wind speeds across the deflation basin are consistently high enough to transport sand through the notch. The light orange area in Fig. 1, parts I and II above the dashed line, represents conditions under which wind is sufficiently strong throughout the notch to sustain aeolian sand transport. In contrast, below the dashed line (Part III), wind speeds fall below the transport threshold, and the notch is considered inactive. The incident wind speed required for notch-activation increases with greater wind obliquity relative to the notch's long axis, due to a corresponding decrease in the ratio of the wind speed in the notch to the offshore wind speed. Parts I and II in Fig. 1 represent subsets of the active regime, corresponding to wind acceleration (jet flow) and deceleration (helicoidal flow) on the deflation basin, respectively. The vertical dashed line marks a critical wind angle beyond which the flow decelerates (Part II). In Nguyen et al. (2021)'s measurements, this critical angle was approximately 30°, although it is probably site-specific. Pease and Gares (2013), for example, reported a critical angle of approximately 50°, and observations in Hesp and Pringle (2001) likewise suggest a larger critical angle. It is possible that the width-depth ratio of the notch influences the magnitude of the threshold angle, with a higher ratio leading to a higher threshold angle (Smyth et al., 2020). If active conditions predominantly fall within Part I, the notch may widen and deepen. Conversely, if conditions in Part II dominate, sand will accumulate and the notch may close. Although the conceptual notch-activation model provides an appealing framework for linking incident wind conditions to notch-activation, it remains unvalidated against long-term (years) wind records. Such records are required to capture virtually all possible wind conditions throughout the lifespan of foredune notches in their (bio-)geomorphological stage, which has been observed to range from several years to several decades (Van Kuik et al., 2022). Moreover, the extent to which the shape of the activation model depends on notch geometry (Fig. 1) is still unknown. This lack of empirical

validation limits its applicability to real-world dynamic dune management.

This paper aims to test and quantify the empirical notch-activation model using long-term time series of near-bed wind data from three foredune notches at Bloemendaal, the Netherlands. The notches differ in orientation, width, and deflation-basin slope, allowing us to assess how these geometric factors influence the activation model. By coupling the measured near-bed wind flow with an aeolian sand transport equation, we also examine whether differences among the notches, such as the fraction of time each notch is estimated to be active, translate into different annual sand-throughput levels. This approach provides insight into which geometric features most strongly control long-term inland sand transport, with potential implications for the design of future notches in dune management. The structure of the paper is as follows. Section 2 introduces the field site and wind data and describes the methodology used to construct the notch-activation models. Section 3 presents the main findings, which are discussed in Section 4. The paper concludes with a summary of the key insights.

2 Study area and methodology

2.1 Regional setting

The study area is located in the Zuid-Kennemerland National Park between the towns of Bloemendaal aan Zee and IJmuiden, along the west coast of the Netherlands (52°25.5'N, 4°33.5'E; Fig. 2a). Due to more than a century of intense dune management (predominantly planting of European marram grass), the foredune has become approximately 20–25 m high, 100–150 m wide, and alongshore uniform. Before notch excavation, approximately 27 m³ of wind-blown beach sand was deposited annually on the seaward side of the foredune per m along the shore, with the deposition volume increasing in the northern direction (Ruessink et al., 2018). The deposition landward of the foredune crest was minimal, illustrating the strong limiting effect of dense marram grass on aeolian transport beyond the foredune. On the seaward side, the foredune in the study area borders a wide (≥ 100 m), low-sloping beach, often with one or two intertidal sandbars (Fig. 2b). The upper beach may encompass embryo dunes (incipient foredunes) exceeding 2 m in height. The backdune topography is characterised by vegetated parabolic dunes that increase in size in the landward (northeast) direction. These parabolic dunes formed during three phases of large aeolian activity in the past millennium. The most recently formed parabolic dunes, situated next to the foredune, originated several hundreds of years ago (after 1600 CE) (Jelgersma et al., 1970; De Jong, 2005).

The most common and strongest winds are south to west (Fig. 2a), with the direction mode at 225°N (south-west), and thus approach the study area alongshore to shore normal, but mostly obliquely onshore. East winds are also common (Fig. 2a), but the second direction mode near 90°N is presumably a local topographical disturbance due to the presence of the east-

west-orientated North Sea Canal (entrance to Amsterdam harbour) east of the wind station (Fig. 2a). Wind recordings further at sea do not show this mode (Barth, 2008). The annual average 10-minute wind speed is about 7.3 m/s (at 10 m height). The 90% and 99% percentiles of 10-minute wind speed between 2008 and 2023, the period on which the wind rose in Fig. 2a was based, were 12.6 and 17.8 m/s; the maximum 10-minute wind speed in this time interval was 31.4 m/s. During rare but severe storms from the northwest, the water level in front of the coast can increase by up to 2 m above the tidal level. However, erosion of the foredune in the study area is rare due to the wide beach and the wave-sheltering effect of the IJmuiden harbour moles during these storm conditions.

2.2 Foredune notches

In winter 2012–13, five notches were excavated in an approximately 850 m long stretch of the foredune in the study area (Fig. 2b), as part of the Noordwest Natuurkern project (Kuipers, 2014). By increasing aeolian sand dynamics and geomorphological diversity, the project aimed to expand the Natura 2000 habitat 'white-dunes' and to restore the further landward located 'grey-dunes'. Sand deposits migrating landward from the notches were expected to bury existing climax vegetation, creating new opportunities for white-dune pioneer species, and the deposition of fine calcareous material far inland was expected to counteract soil acidification in the grey-dunes. The Noordwest-Natuurkern project also involved the removal of vegetation and soil from parts of several parabolic dunes landward of the foredune (Figs 2a and b; Kuipers (2014)).

About 170,000 m³ of sand was removed from the foredune with heavy machinery to construct the five notches (Ruessink et al., 2018). Because the Noordwest Natuurkern project was designed as learning by doing, the five notches were implemented with different characteristics. The three southern notches, labelled N1 to N3 in Fig. 2b, were excavated to have their long axis approximately parallel to the shore-normal direction, while the long axes of the two northern notches (N4 and N5 in Fig. 2b) were more aligned with the prevailing southwest winds. The notches also differed in their cross-shore length (≈ 100 m at N1–N3 to 200 m at N5), alongshore width (≈ 50 m at the top of N2 to 100 m at N1), maximum excavation depth (≈ 9 m in N3 to 12.5 m in N5) and outline (roughly rectangular at N2 and N5 and trapezoidal, narrowing landward, at the other three notches). Fig. 2c provides a visual impression of N4 in September 2017. Repeat topographic surveys available since the excavation of the notches (Ruessink et al., 2018, 2024) have demonstrated that the lateral walls steepened and slightly retreated, causing the notches to widen, and that depositional lobes developed landward of the notches. The lobes, visible as the bare sand areas landward of the notch contours in Fig. 2b, grew landward up to 30–50 m/yr. The deflation basins remained largely unchanged, except in N2, where the basin floor eroded substantially. The surveys further illustrated that the volume of sand landward of the foredune in-

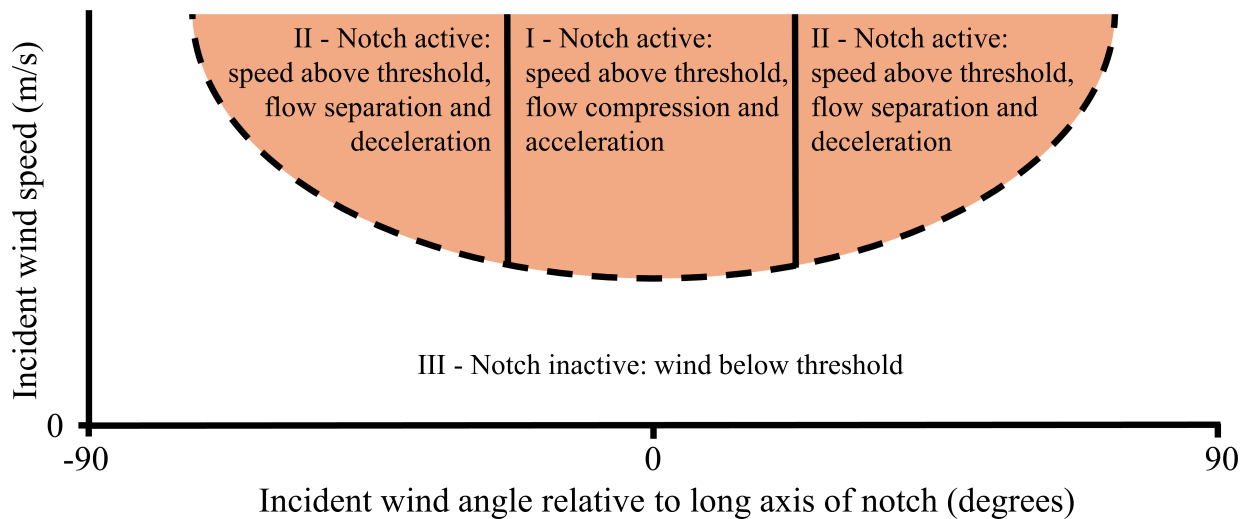


Figure 1 Schematic model of notch-activation as a function of incident wind angle (relative to the notch's long axis) and wind speed, based on [Nguyen et al. \(2021\)](#). See text for further explanation. This figure presents a generalisation of the original model, which was developed for a specific site where the notch geometry and local wind climate restricted the analysis to positive angles. Here, we have drawn the model symmetrically for illustrative purposes; however, the model is unlikely to be symmetric in real-world conditions e.g., due to differences in the steepness of the notch's lateral walls.

creased by nearly 33.000 m³ per year, of which about 16.500 m³/yr is estimated to originate from the beach. The observed geomorphological dynamics implies that all five notches have been in the geomorphological stage since excavation and have acted as effective conduits that channel windblown beach sand beyond the fore-dune.

2.3 Wind data collection and processing

Wind measurements were performed almost continuously between November 2016 and October 2018 in N4, between October 2018 and November 2020 in N3, and between September 2020 and December 2023 in N2 (Table S1). During each deployment, four 3D ultrasonic anemometers (Young Model 81000RE) were placed at the mouth of the blowout (sensor 01 in Fig. 2b), half way on the deflation basin (sensor 02), at the landward end of the notch (or, in other words, at the transition from the notch to the depositional lobe; sensor 03) and on the lobe (sensor 04). Sensors 01 to 03 were placed parallel to the long axis of the notch (255°N in N4, see Fig. 2c, and 276°N in N3 and N2). Incident winds, which serve as offshore reference, were measured by the IJmuiden Weather Station (WMO 06225), operated by the Royal Netherlands Meteorological Institute (KNMI) at the landward end of the southern IJmuiden harbour mole, about 4 km to the north of the study area (Fig. 2a). The four ultrasonic anemometers in the study area collected *uvw* wind data at 10 Hz, with the two horizontal velocities *u* and *v* orientated east-west and north-south, respectively, and the vertical velocity *w* positive in the upward direction. All data were temporarily stored on a Campbell CR1000 data logger, from which they were transferred to an SD card on an hourly basis. Each anemometer was powered by two 12V batteries, which were stored in a waterproof box buried beneath the surface of the sand. The batteries were charged by a solar panel. A barbed-wire fence was placed around each instrument configuration (see Fig. 2c) to avoid damage by large animals (deer, horses, cows) that walk freely in the

area. Once every two to four months, the SD cards were replaced, the instrument heights were measured, and each instrument configuration was serviced. The nominal measurement height was 0.9 m, but because of erosion and sedimentation in the notch, the measurement height varied by several decimetres during deployment. If logistically possible, the anemometers were adjusted to their intended height of 0.9 m during a service. Comparable measurement heights were used in previous coastal-dune field campaigns (e.g., [Pease and Gares, 2013](#); [Smyth et al., 2013](#); [Schwarz et al., 2021](#)). The measurement height at the IJmuiden station was 10 m. Since moving the instrument configurations from one notch to the other took several weeks, there is some overlap between the consecutive deployments (Table S1).

Each time series *uvw* was checked using 10-Hz data quality parameters provided by the anemometers, and all erroneous data were set to NaN (Not a Number). The series were then processed into 10-minute average (1) wind speed *U* as $U = \sqrt{\bar{u}_i^2 + \bar{v}_i^2 + \bar{w}_i^2}$, in which the overbar represents the average over time and the subscript *i* indicates the instantaneous nature of the variable; (2) wind direction relative to North θ_N based on $\bar{u}_i$ and $\bar{v}_i$; and (3) turbulent kinetic energy *tke* as $tke = 0.5 (\bar{\tilde{u}_i^2} + \bar{\tilde{v}_i^2} + \bar{\tilde{w}_i^2})$, in which the tilde indicates a de-meaned variable (that is, $\tilde{u}_i = u_i - \bar{u}_i$; etc.). The direction of the wind was also calculated relative to the long axis of the notch, θ_A , with $\theta_A = 0^\circ$ for onshore winds that blow parallel to the notch axis; negative and positive θ_A are from the southern and northern directions relative to the notch axis, respectively. The values of *U*, θ_N , θ_A and *tke* were not retained if more than 15% of the *uvw* series was labelled NaN. This could happen during heavy rain, intense sand saltation, below-freezing temperatures, and moments when the power supply is insufficient. The 10-minute block size was chosen for compatibility with the IJmuiden data. Also, for compatibility, all wind statistics for time step *t* were based on instantaneous data in the previous 10 minutes. Values of *tke* are unavailable from the IJmuiden station. In

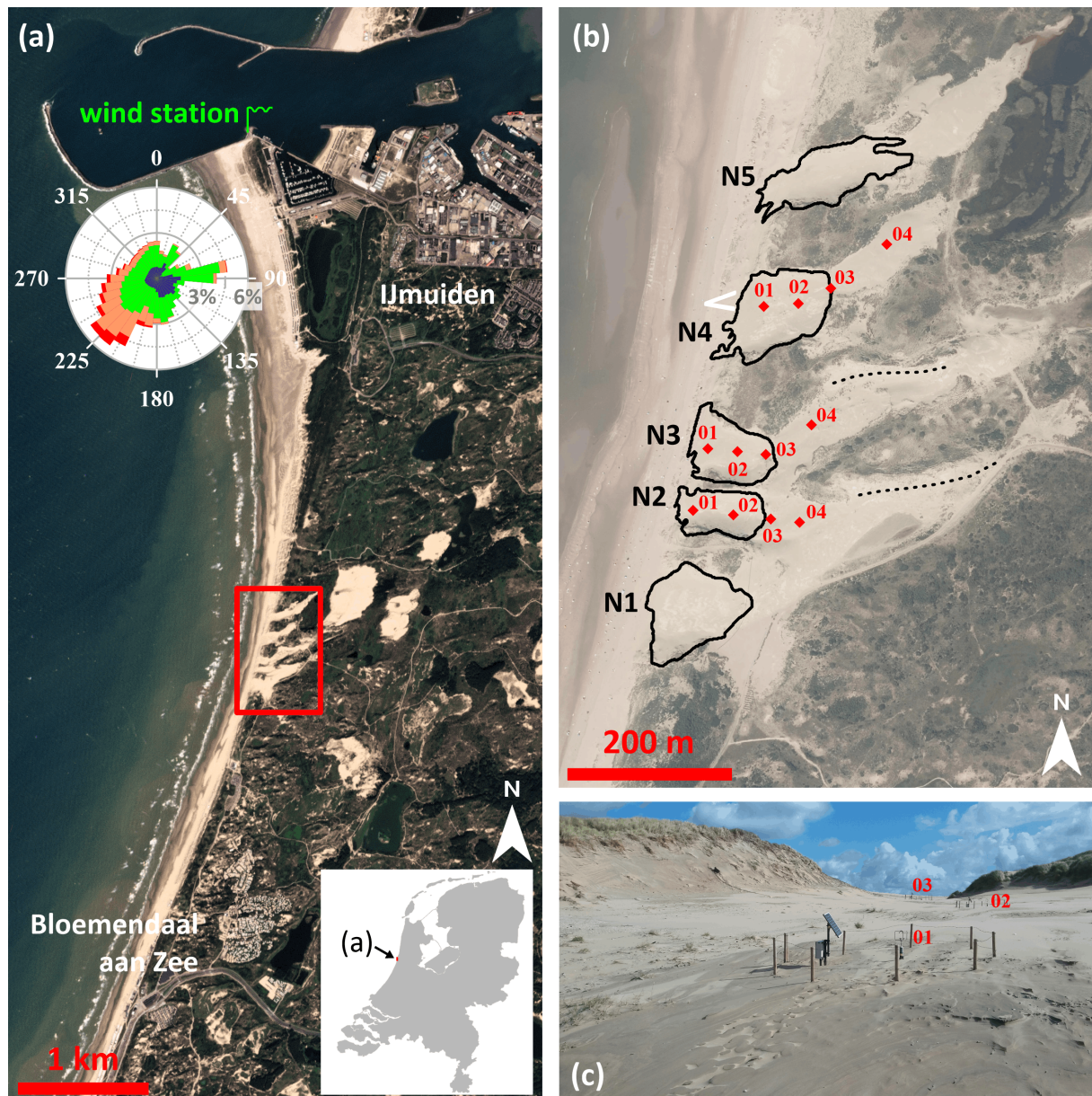


Figure 2 (a) Location of the study area along the west coast of the Netherlands. The red rectangle is the region with the five foredune notches, and is shown in more detail in (b). The five notches are labelled N1 to N5 from south to north. The black lines in (b) are the notch contours immediately after construction. The two dashed lines indicate reactivated parabolic dunes. The three bare-sand regions to the east-north-east of the notched foredune in (a) are also reactivated parabolic dunes. The red symbols in (b) are the locations of the ultrasonic anemometers, labeled 01 to 04 in the landward direction. (c) shows the anemometers 01 to 03 in N4. The white triangle in (b) indicates the approximate view angle of the photo in (c). The wind rose in (a) contains four wind speed classes: dark blue, ≤ 5 m/s; green, $> 5 - 10$ m/s; orange, $> 10 - 15$ m/s; red, > 15 m/s, and is based on 10+ years of recordings at 10 m height at the wind station located on the landward end of the southern IJmuiden harbour mole. Panels (a) and (b) contain the 3 m RGB PlanetScope satellite image of 21 August 2020, and the PDOK 0.25 m RGB aerial photo of summer 2020, respectively. The photo in (c) was taken on 12 September 2017.

the following, the subscript SA denotes measurements in a notch, and the sensor number specifies the location. For instance, U_{SA01} represents the 10-minute average wind speed at sensor 01. The subscript ref indicates IJmuiden values.

Because the present work focuses on the activation of the notches, data from all sensors 04 (on the lobes) will not be used in the remainder of this paper. Table S1 shows that there are about 56 000 10-minute blocks from the deployments in N4 and N3 for which there are simultaneously wind speed and direction values at the IJmuiden weather station and at sensors 01, 02 and 03. The number of blocks with simultaneous wind speed and direction values for the N2 deployment is somewhat lower (approximately 47 000) despite the longer

duration of the deployment (Table S1). This is due to more common technical problems with one or more of the anemometers and, as illustrated in Section 2.6, substantial deposition of sand at sensor 01, causing it to be buried for several months.

2.4 Notch activation model

Calculating the empirical notch-activation model from the present data requires the calculation of a threshold velocity value U_t , above which the sand begins to move on the surface. Sand sampling campaigns in N2 (October 2022) and in N4 and N5 (December 2016) showed that the median grain size D_{50} of the top sediment layer in the deflation basins varies between about 220 and

300 μm , with a spatially averaged value of 260 μm . Using this average value and the threshold formulation of Shao and Lu (2000), results in a threshold friction velocity u_{*t} of 0.278 m/s. Under the assumption of a logarithmic velocity profile with the commonly applied roughness length of 0.001 m (e.g., Van der Wal, 1998; Keijsers et al., 2014; De Winter et al., 2020), the threshold velocity U_t is estimated at 4.62 m/s at 0.9 m above the bed, which was the intended measurement height. Unpublished data on the intensity of aeolian saltation in the mouth of N2, collected as part of the Aeolex III field campaign in October 2022 (Schuring, 2023), showed that sand transport began when U at 0.9 m above the bed exceeded 4 to 5 m/s, confirming the appropriateness of the U_t estimate. Clearly, the use of a different U_t will affect the results presented below, for example, the fraction of time that a notch is considered to be active. However, varying U_t within a reasonable range given the observed median grain sizes and the uncertainties in the measurement height of the anemometers showed that the main results of this paper are robust. In the remainder of this paper we therefore consider a notch to be active when the measured U at sensors 01, 02 and 03 were all ≥ 4.62 m/s.

To actually construct the empirical activation model as in Fig. 1, the $\theta_{A,\text{ref}}$ and U_{ref} were grouped into 10° and 1 m/s wide bins with bin midpoints of $-90, -80, \dots, 80, 90^\circ$ and $0.5, 1.5, \dots, 30.5, 31.5$ m/s, respectively. For each $(U, \theta_A)_{\text{ref}}$ bin, the percentage of observations in which the notch was active was determined. The total number of observations used in the binning is provided in the last column of Table S1. Clearly, these numbers are lower than the total number of observations, because data with $|\theta_{A,\text{ref}}| \geq 95^\circ$ are not considered in the binning. The line that separates the non-active part from the active part in $(\theta_A, U)_{\text{ref}}$ space was then taken as the 50% contour. The active part is thus made up of $(\theta_A, U)_{\text{ref}}$ bins in which more than 50% of the observations in the notch were labelled as active. The 10% and 90% contours were also calculated to see whether the division between the nonactive and active parts was gradual or sharp. The percentage in a bin was not determined when fewer than 5 observations were in the notch.

2.5 Sand transport computations

Although the notch-activation model provides insight into how often and in what part of $(U, \theta_A)_{\text{ref}}$ space a notch is active, it does not provide information on the amount of sand transported from the notch to the depositional lobe. A higher frequency of activity does not necessarily equate to a higher sediment throughput when the notch is primarily active under $(U, \theta_A)_{\text{ref}}$ conditions when transport is low. As a first attempt to include transport magnitudes into the activation model, we calculated the aeolian sand transport past each sensor 03 (that is, from the deflation basin to the lobe) using the transport rate equation proposed in Kok et al. (2012),

$$q = C_{\text{DK}} \frac{\rho_a}{g} u_{*t} (u_*^2 - u_{*t}^2). \quad (1)$$

Here, q is the aeolian sand transport rate [kg/m/s], the

constant $C_{\text{DK}} = 5$, ρ_a is the density of air [kg/m³] (for air with a temperature of 10°C , $\rho_a = 1.25$ kg/m³) and u_* [m/s] is the shear velocity, calculated from the measured U_{SA03} with a logarithmic velocity profile and a roughness length of 0.001 m. Each q was subsequently multiplied by $\Delta t = 600$ s, to obtain the total sand transport Q [kg/m] beyond sensor 03 in the measurement time frame of 10 minutes. Clearly, Q is not the total sand transport on to the lobe, as this would require estimates of Q along the entire width of the notch (not just at sensor 03) and subsequent spatial integration. However, this is beyond the scope of this paper. To be able to compare the calculated Q of the three deployments, each Q was finally divided by the duration of the deployment in years, resulting in the annual transport Q_{annual} in kg/m/year.

2.6 Deployment conditions

Fig. 3 shows the time series of the wind speed in IJmuiden (U_{ref}) during the measurement period between November 2016 and December 2023. The 15 storms during this period are also indicated, with a storm defined as an event in which U_{ref} exceeded 20.7 m/s for at least six consecutive observations (that is, one hour). The maximum U_{ref} (31.4 m/s) was measured on 5 July 2023 during a storm named Poly, one of the most severe summer storms in the last 50 years in the Netherlands. Most of the other storms occurred in autumn and winter (November–February). The 90-day moving average wind speed was typically 6–7 m/s in summer (June–September) and 8–9 m/s in winter. Consistent with longer-term wind observations in IJmuiden (Fig. 2a), the winds during the measurement period were predominantly from the southwest (Figs 3b–d). In more detail, there were slight differences in the wind conditions during the three deployments. The modal wind direction was 220° for the deployments in N3 and N2 ($\theta_A \approx -55^\circ$), and approximately 230° for that in N4 ($\theta_A \approx -25^\circ$). During this latter deployment, the strongest winds (> 15 m/s) were more or less uniformly spread between 205 and 285° , while those during the N3 and N2 deployments were more concentrated at the modal wind direction (Figs 3b–d). We return to these differences in wind conditions and their impact on the results in Section 4.

Figs 4a–c and 5 illustrate the topography of the three notches at the start of each deployment. In addition to the differences and similarities in cross-shore length, alongshore width, depth, outline, and orientation described in Sections 2.2 and 2.3, both figures show that the notches differed in the cross-dune profile of the deflation floor and the steepness of the lateral walls. The basin floor sloped more or less linearly upward in N4 ($\approx 1 : 30$ from sensor 01 to 03) and N3 ($\approx 1 : 20$), while that of N2 had an increase in the mouth (near sensor 01) and a decrease halfway through (near sensor 02). The northern wall (south-facing) in N3 and N4 was somewhat steeper than the southern wall (north-facing), while this was opposite in N2, although the differences here were only small. During each deployment, the lateral walls eroded (Figs 4d–f and Figs 5d–

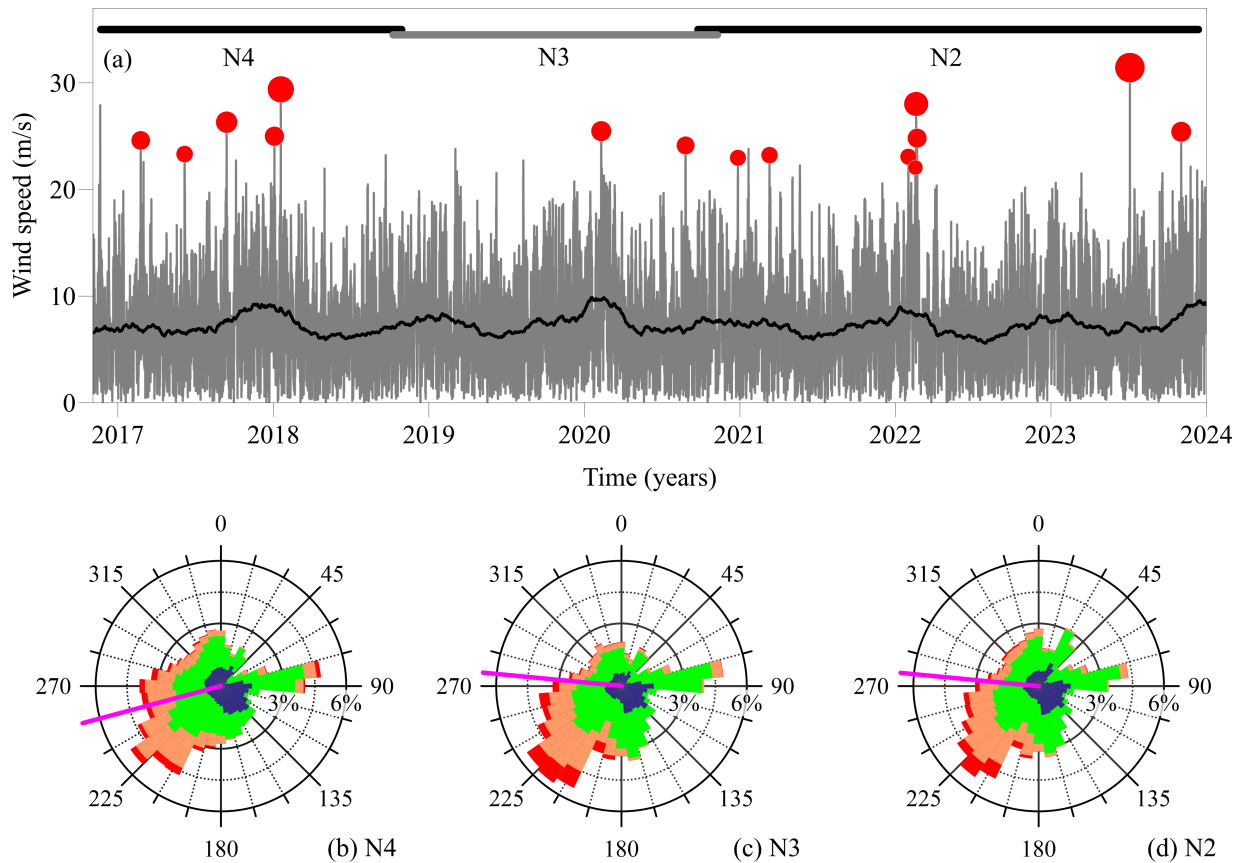


Figure 3 (a) Time series of 10-minute (gray line) and 90-day moving average (black line) wind speed at 10 m height at the IJmuiden wind station (for location, see Fig. 2a), U_{ref} . The red dots are storms, defined as wind events when U_{ref} exceeded 20.7 m/s for at least six consecutive 10-minute measurements. The size of the dots is scaled by the maximum wind speed during the storm. The three horizontal lines illustrate the measurement periods in the three notches (see also Table S1). The ticks on the horizontal time axis are at the start of the year. Panels (b), (c) and (d) are reference wind roses for the deployments in N4, N3 and N2, respectively. The directions are with respect to North. The four wind classes are ≤ 5 m/s (dark blue); $> 5 - 10$ m/s (green); $> 10 - 15$ m/s (orange); > 15 m/s (red). The magenta line is the long axis of the notch and shows when $\theta_A = 0^\circ$.

f) and the lobes landward of sensors 03 increased in height and grew landward (Figs 4a–c and Figs 5a–c). Together with the absence of vegetation and embryonic dunes on the deflation basins (Figs 2b–c), these observations confirm that all three notches were in the geomorphological stage of Schwarz et al. (2019)’s evolutionary model during instrument deployment. The erosion of the basin floor was generally small (Fig. 5d–f); instead, sand was deposited in the mouth of N3 and especially N2 (Figs 4b–c), where the maximum deposition in the slightly longer than 3-year deployment period was close to 2.5 m. This caused the bed elevation in the mouth to exceed that further landward near sensor 02 by almost 4 m (Fig. 5c) at the end of the deployment period.

3 Results

3.1 Notch activation

Of the 36,116 observations in N4 used to determine the activation model ($|\theta_A| < 95^\circ$), 39.7% (= 14 348 observations) were classified as active (Table 1, column ‘Observations’). In N3 and N2, these numbers were 34.2% (11 809 observations) and 29.9% (7 778 observations), respectively (Table 1). Figs 6a–c show the activation models for the three notches. In general terms, the three models resemble the conceptual model inferred from Nguyen et al. (2021) (Fig. 1). Winds blowing along the

main axis of the notches ($\theta_A = 0^\circ$) required the lowest offshore wind speed U_{ref} to produce active conditions. Here, this U_{ref} was 7.25 m/s (mid of the 7.0–7.5 m/s bin; see also Fig. 6d). As $|\theta_A|$ increases to approximately 30° , the required U_{ref} increased weakly to 8–9 m/s. For larger $|\theta_A|$, the increase in the U_{ref} required for aeolian activity was more marked, especially for $|\theta_A| > 50^\circ$, to values above 15 m/s for $\theta_A < -60^\circ$ (Fig. 6d). Although the largest θ_A still resulting in active conditions differed slightly between notches (e.g., $\approx -60^\circ$ and $\approx -80^\circ$ in N4 and N3, respectively; Fig. 6d), it is obvious from Fig. 6a–c that aeolian activity in all three notches was possible for a wide range of incident wind directions ($\approx 130 - 150^\circ$), provided that U_{ref} was sufficiently high.

Given the dependence of the 50% contour on θ_A , it is not surprising that the probability that a wind blowing directly into the notch induces aeolian activity was greater compared to more oblique winds (Fig. 6e). Approximately 50 to 70% of the winds in the θ_A bins around 0° were labelled as active compared to less than 40% for bins with $|\theta_A| > 60^\circ$. This does not imply that the $\theta_A \approx 0^\circ$ winds were also the most common winds with aeolian activity during a deployment. Rather, aeolian activity was most commonly induced by winds that aligned with the modal θ_A (Fig. 6f; near -25° at N4, and -55° at N3 and N2). This is also obvious in Figs 6a–c, as there are more individual observations (dots) above the 50% activity contour for θ_A near the modal θ_A than for $\theta_A = 0^\circ$.

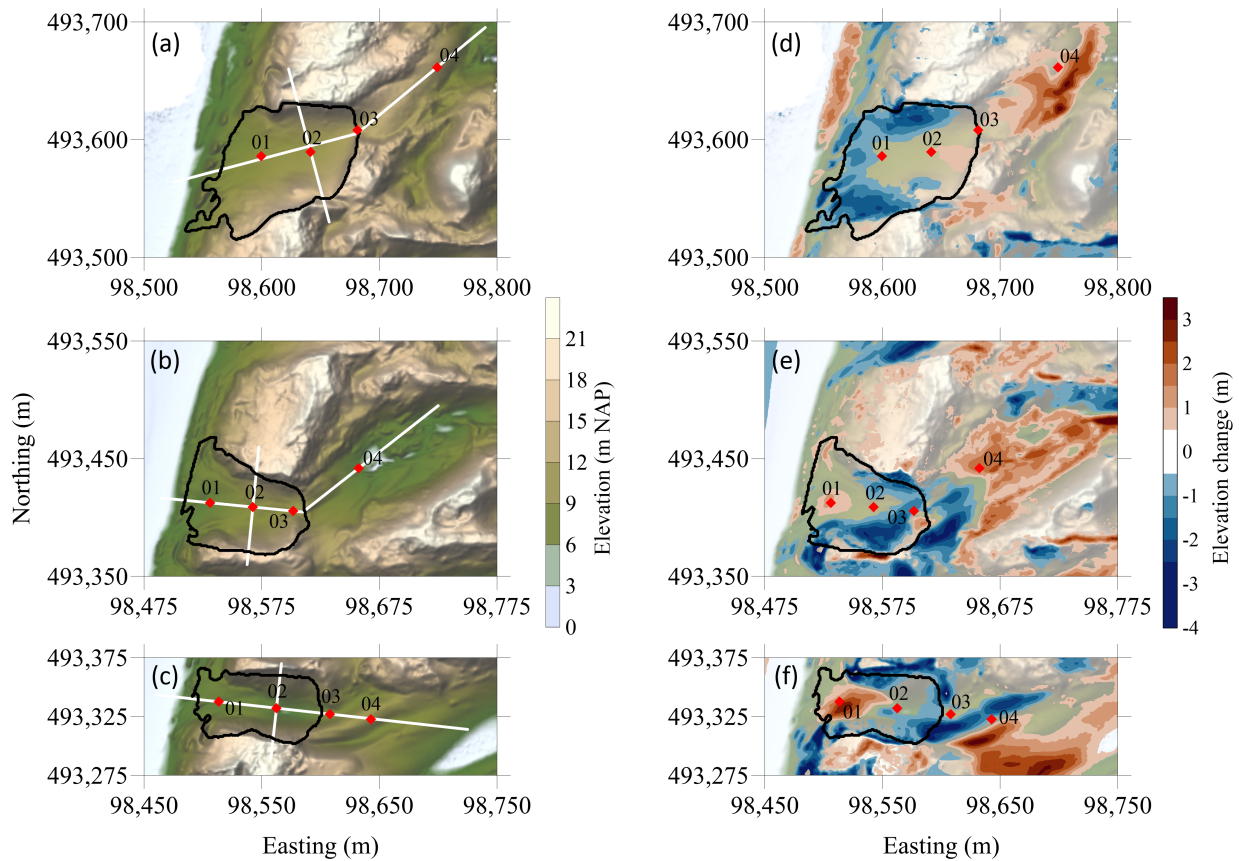


Figure 4 Digital elevation models (DEMs) at the start of the deployment in (a) N4, (b) N3, and (c) N2, and the DEMs of Difference over the deployment period in (d) N4, (e) N3 and (f) N2. In all panels, the four ultrasonic anemometers (01 to 04) are shown with the red symbols, and the notch contours with the black lines. The white lines in (a)–(c) are cross-dune and along-dune transects to illustrate two-dimensional variations in topography (see Fig. 5). Topographic data shown in (a)–(c), and used to calculate (d)–(f) are from Ruessink et al. (2024).

Table 1 Percentages of active conditions of all winds with $|\theta_A| < 95^\circ$

Notch	Observations	Gap filled	Predicted with forcing from		
			N4	N3	N2
N4	39.7	38.8		37.7	40.1
N3	34.2	38.9	39.2		39.3
N2	29.9	34.1	37.4	47.6	

3.2 Wind patterns

Figs 7, 8 and 9 display the relationship between the wind conditions in each notch and the reference direction $\theta_{A,ref}$, where the values of U_{SA} are normalized by U_{ref} and those of the square-root of tk_{eSA} by U_{SA} . For all $\theta_{A,ref}$ with active conditions, the values of U_{SA}/U_{ref} , $\theta_{A,SA}$ and $\sqrt{tk_{eSA}}/U_{SA}$ were closely related to $\theta_{A,ref}$ (Figs 7, 8 and 9). Only for the most oblique angles, when the notch was inactive (Figs 6a–c), the scatter in $\theta_{A,SA}$ and $\sqrt{tk_{eSA}}/U_{SA}$ increased at all sensors. In N4 and N3, the wind increasingly aligned with the blowout axis across the basin floor (Fig. 8). At both sensors 01, the local wind direction was approximately equal to $\theta_{A,ref}$, while at both sensors 03, the local direction differed less than 20° from the blowout axis for all $\theta_{A,ref}$ with active conditions. In the narrower N2, the wind pattern appeared more complicated. In its mouth, the wind was already aligned more with the blowout axis, whereas further in N2, $\theta_{A,SA}$ fluctuated around 0° . For $\theta_{A,ref}$ up to 40° , the local and reference directions had the same sign, while for larger $\theta_{A,ref}$, the sign changed. This indicates that under such oblique conditions, the wind de-

flected off the steep side wall and left the notch in the opposite direction, creating a C-shaped flow.

At all sensors 01 the U_{SA}/U_{ref} values were highest (about 0.6–0.7) when the reference wind was aligned with the blowout axis (Fig. 7). The values gradually decreased to less than 0.2 for the most oblique conditions, suggesting that the wind then bypasses the notch almost completely. This also explains the dependence of the 50% activity contour on θ_A (Fig. 6a–d). Further landward in each notch, the reduction to these low values occurred within a narrower $\theta_{A,ref}$ range, while in N3 and N2 the maximum in U_{SA}/U_{ref} also shifted to more oblique wind directions, close to $\theta_{A,ref} = \pm 60^\circ$. At all sensors 03, but especially in N3 and N2, this resulted in a near-binary situation, with high (up to 0.8) or near zero values of U_{SA}/U_{ref} . When U_{SA}/U_{ref} was near zero and the notch was clearly always inactive, $\theta_{A,ref}$ was, as mentioned above, rather erratic (Fig. 8) and $\sqrt{tk_{eSA}}/U_{SA}$ increased rapidly, from less than 0.2 to well above 0.4 (Fig. 9). This implies that under these highly oblique conditions, the winds in the notches were always weak and dominated by vortices.

3.3 Flow speed-up

Fig. 7 already indicates that the wind accelerated in all three notches for most incident wind directions, given the generally higher values for U_{SA03}/U_{ref} than for U_{SA01}/U_{ref} . For example, in N3, U_{SA01}/U_{ref} was near 0.4 for $\theta_{A,ref} \approx -60^\circ$, while U_{SA03}/U_{ref} was then close to

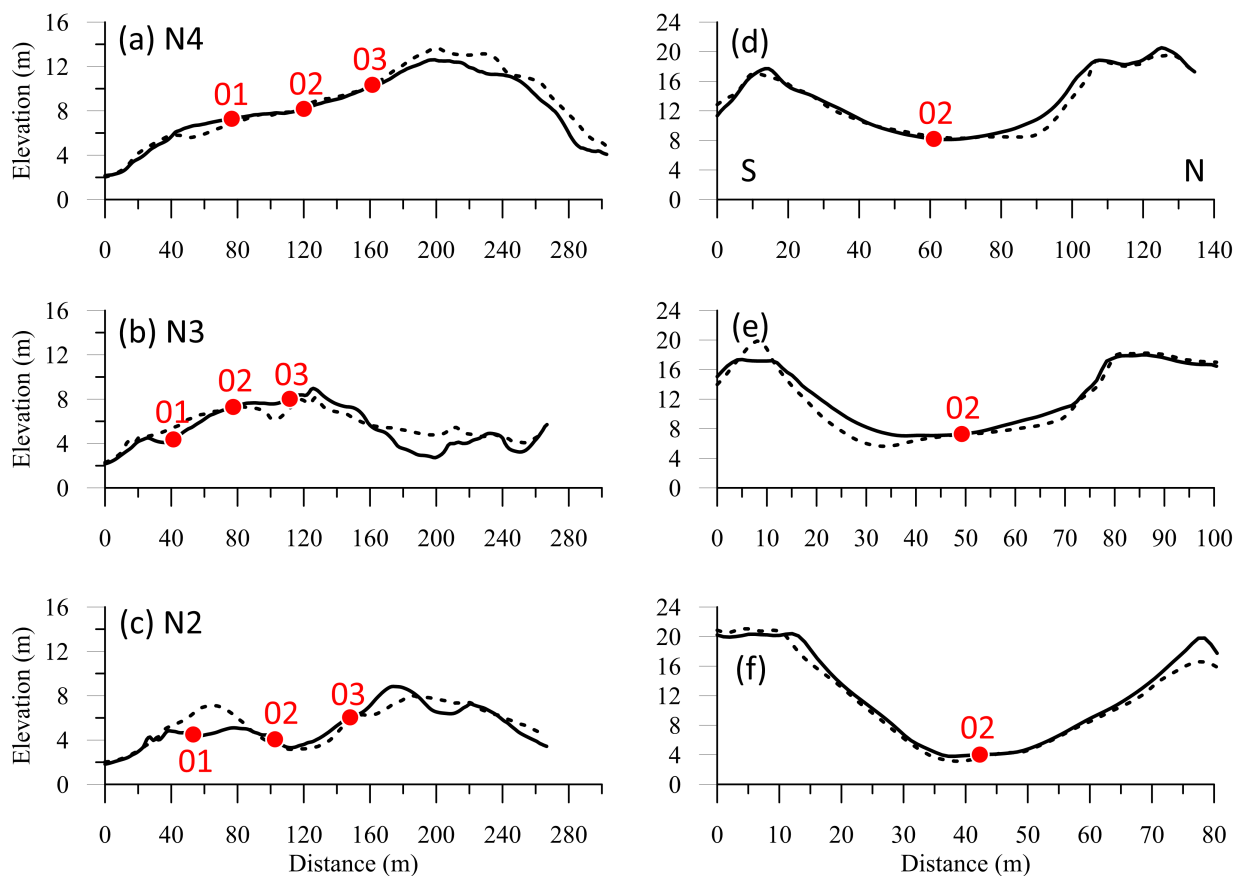


Figure 5 Elevation versus distance along the dune-normal (a–c; sea to land) and dune-parallel (d–f; south to north) transects shown in Figs 4a–c. In each panel, the solid line is the at the start of the deployment, and the dashed line at the end of the deployment. The ground location of the ultrasonic anemometers is shown in the start profile with the red symbols.

0.8, implying that the wind speed increased by a factor of 2 in N3 for this specific wind direction. To examine in more detail the dependence of flow speed-up on the incident wind direction, Fig. 10 displays the ratios U_{SA02}/U_{SA01} and U_{SA03}/U_{SA01} as a function of $\theta_{A,ref}$ for the three notches. It is obvious from this figure that the flow speed-up was highest in N3. Here, U_{SA02}/U_{SA01} was between 1.0 and 1.5 for $|\theta_{A,ref}| < \approx 75^\circ$, while U_{SA03}/U_{SA01} was even larger for the same $\theta_{A,ref}$ range, up to a factor of 2 for the more oblique directions. Figs 6b and 10 thus illustrate that the wind accelerated over the deflation basin of N3 for all wind directions that resulted in active conditions. Only for the most oblique, almost alongshore wind directions, when the notch was no longer active, the wind decelerated (Fig. 10; U_{SA02}/U_{SA01} and U_{SA03}/U_{SA01} are less than 1 for $|\theta_{A,ref}| > \approx 75^\circ$). This implies that we do not see that the $\theta_{A,ref}$ range with active conditions in N3 is divided into parts with an accelerating and decelerating wind, contrasting with the conceptual activation model inferred from Nguyen et al. (2021) (Fig. 1). The situation in N4 is comparable to that in N3, although the speed-up ratios were lower throughout (Fig. 10) and the wind decelerated for the most oblique winds with active conditions. Fig. 6 shows active conditions in N4 beyond $|\theta_{A,ref}| = 60^\circ$, while the speed-up ratios for such large $|\theta_{A,ref}|$ were below 1 (Fig. 10). Thus, the situation in N4 is more consistent with the conceptual model of Nguyen et al. (2021), although the $\theta_{A,ref}$ range with active conditions and decelerating wind is very narrow.

In contrast to the findings for N3 and N4, the wind in the mouth of N2 decelerated for most $\theta_{A,ref}$. The ratio U_{SA02}/U_{SA01} was less than 1 for $\approx -45^\circ < \theta_{A,ref} < 60^\circ$, and above 1 for more oblique wind conditions (Fig. 10). Further landward in the notch, the wind increased in magnitude, especially for the winds that blew directly into the notch (U_{SA03}/U_{SA01} is higher than U_{SA02}/U_{SA01}), although for $\approx -30^\circ < \theta_{A,ref} < 0^\circ$ values of U_{SA03}/U_{SA01} were still around 1 (Fig. 10). Thus, the $\theta_{A,ref}$ range with active conditions in N2 is divided into parts with decelerating and accelerating winds. Yet, in contrast to the conceptual activation model of Nguyen et al. (2021), the winds that decelerate blow more or less directly into N2, while only the more oblique winds accelerate over its deflation basin.

Table 2 Annual landward sand transport rates Q^1 at sensor 03

Notch	Predicted with wind forcing during deployment in		
	N4	N3	N2
N4	232.8	268.0	228.0
N3	357.7	427.5	352.5
N2	274.2	292.0	271.3

¹ Values in boldface are based on measured U_{SA03} with missing values replaced by predictions (Section 3.4), while those in italics are based on predicted U_{SA03} (Section 4.2). All values are $\times 10^3$ kg/(m·year).

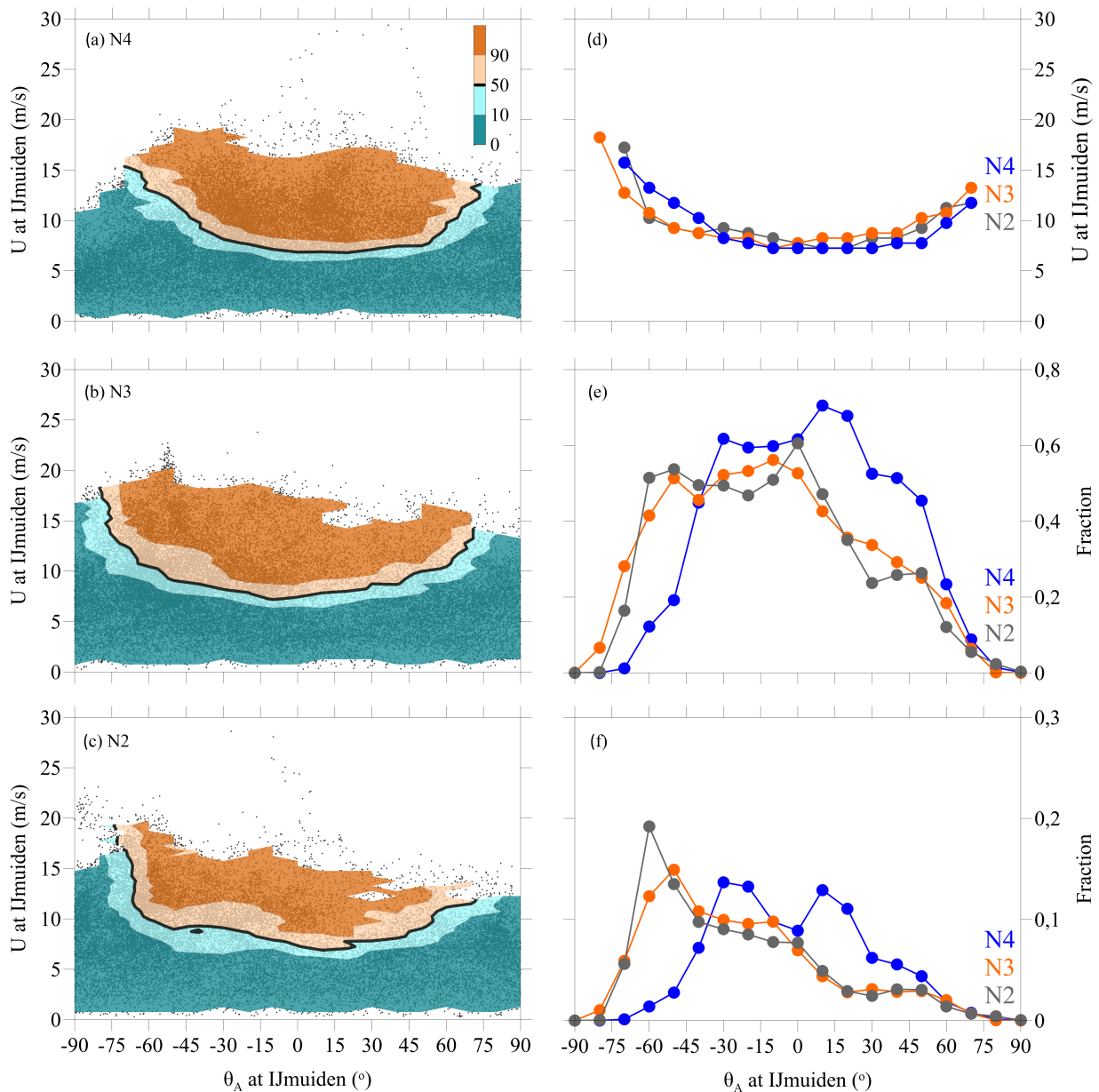


Figure 6 Estimated activation models in (a) N4, (b) N3, and (c) N2 as a function of the reference wind speed and direction. The colours represent the percentage of active conditions in the $(U, \theta_A)_{\text{ref}}$ bins (see Section 2.4). The black line is 50% activity contour, delineating the active part of $(U, \theta_A)_{\text{ref}}$ space. The small dots in (a)–(c) are the individual $(U, \theta_A)_{\text{ref}}$ observations when SA01, SA02 and SA03 were operational simultaneously. The 50% activity lines are repeated in (d) to allow a more direct comparison between N4 (blue circles), N3 (orange circles) and N2 (medium-gray circles). Panel (e) shows the fraction of active conditions in each direction bin. Panel (f) shows the ratio of the number of active conditions in a direction bin to the total number of active conditions.

3.4 Sand transport

For each deployment, the annual sand transport Q_{annual} beyond sensor 03 (that is, from the notch to the lobe) was estimated using the measured U_{SA03} as input into Eq. (1). The missing values in each U_{SA03} time series were replaced by predictions of U_{SA03} based on the dependence of $U_{\text{SA03}}/U_{\text{ref}}$ on the incident wind direction. The prediction approach and its accuracy is detailed in the Supplementary Text. As can be seen in Table 2, the Q_{annual} for the deployment in N4, N3, and N2 were 232.8 , 427.5 and $271.3 \times 10^3 \text{ kg}/(\text{m} \cdot \text{year})$, respectively. Thus, while the annual transport amounts for N4 and N2 were predicted to be approximately equal, the amount for N3 was about 70% higher. We return to this difference and its potential causes in the Discussion section.

Fig. 11 shows that the winds from (or close to) the modal direction contributed the most to Q_{annual} in N3 and N2 ($\theta_{A,\text{ref}} \approx -55^\circ$). This is not surprising, as the winds from these directions were associated with the highest speeds (Fig. 3), resulted in the largest number of active conditions (Fig. 6f), and increased most in magnitude inside the notch (Fig. 10). Fig. 11 also shows that Q_{annual} in N4 resulted the most from winds with a direction that deviated less than about 30° from the long axis of N4. Although this $\theta_{A,\text{ref}}$ encompasses the modal direction ($\theta_{A,\text{ref}} \approx -25^\circ$), its contribution to Q_{annual} was much less pronounced than in the other two notches.

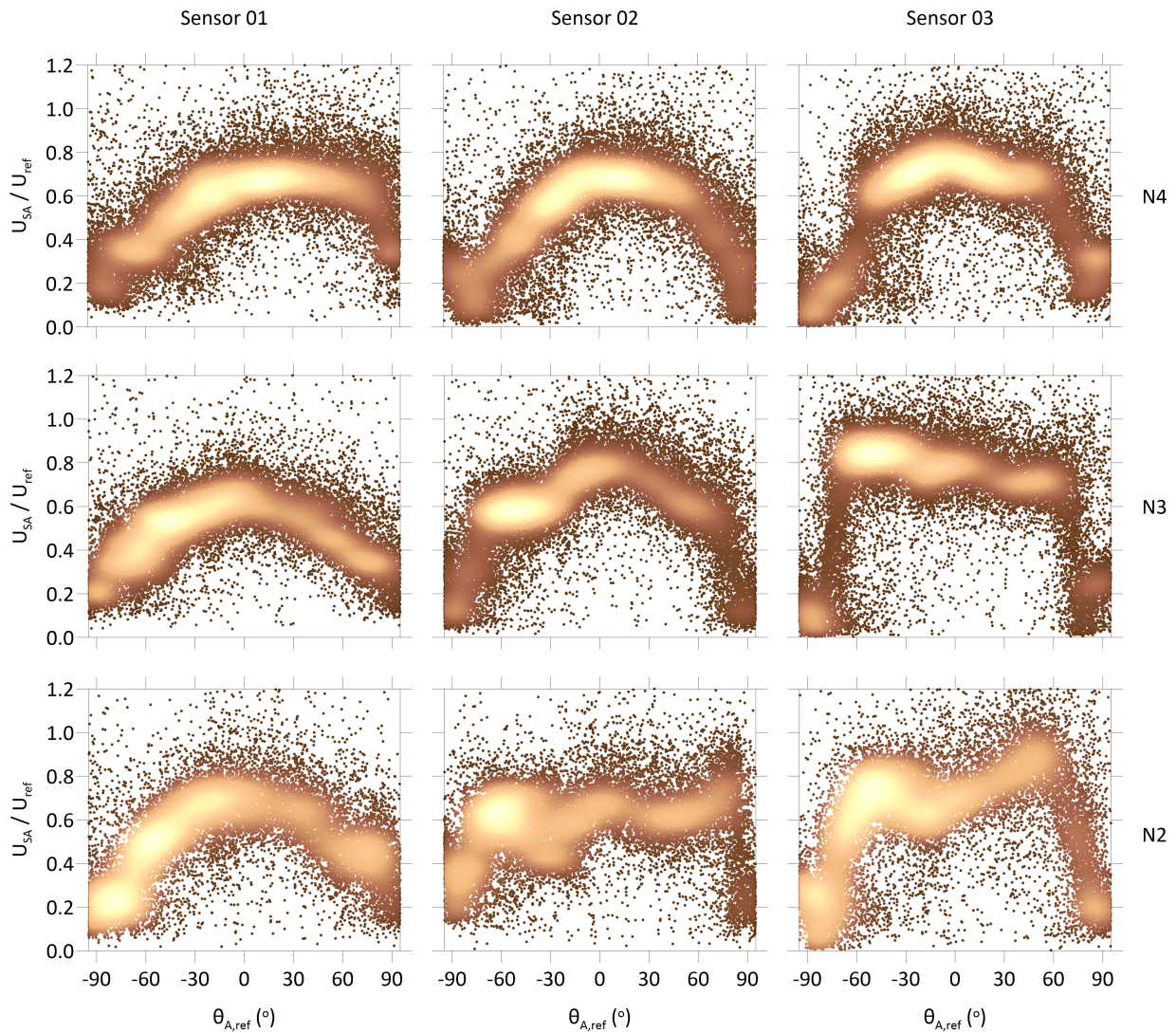


Figure 7 Ratios of the wind speed in a notch U_{SA} to the reference wind speed U_{ref} versus the reference wind direction relative to the long axis of each notch $\theta_{A,ref}$. Panels from left to right are sensors 01, 02, and 03, and panels from top to bottom are N4, N3, and N2. The dots are colored from brown to yellow with increasing frequency of occurrence (density).

4 Discussion

4.1 Notch activation model

We examined under which incident (reference) wind speeds and directions (U_{ref} and $\theta_{A,ref}$, respectively) sand is transported landward through foredune notches using multiannual data sets of wind speeds and directions at three locations on the deflation basin of three notches with different geometries. The notch-activation model proposed by [Nguyen et al. \(2021\)](#), which we generalised here with Fig. 1 to negative and positive angles relative to the notch long axis, served as the starting point for our analyses. Consistent with expectations, our data (Fig. 6) illustrate that the U_{ref} threshold for notch-activation increases with $|\theta_{A,ref}|$, here from 7.25 m/s (at 10 m height) when the incident wind blows parallel to the notch axis ($\theta_{A,ref} = 0^\circ$) to 15 m/s and more when the wind is highly oblique ($|\theta_{A,ref}| \approx 60 - 80^\circ$). Thus, winds from a wide range of incident directions ($\approx 130 - 150^\circ$) will produce landward sand transport, provided that the wind speed is sufficiently high. This is consistent with indications from airflow observations in natural trough

blowouts (e.g., [Hesp and Pringle, 2001](#)).

In contrast to expectations, we did not find a threshold $\theta_{A,ref}$ above which a notch remained active, yet the wind changed from accelerating to decelerating across the deflation basin. The flow speed-up values in N3 and N4 were above 1 for virtually all incident wind directions with notch-activation, while the incident wind decelerated in the mouth of N2 for $\approx -45 < \theta_{A,ref} < 60^\circ$ and accelerated under more oblique conditions (Fig. 10). These flow speed-up observations are consistent with the absence of sand deposition on the basin floor of N3 and N4, and the large deposition (almost 2.5 m) in the mouth of N2 during the deployment periods (Fig. 4d–f). Based on the work of [Pease and Gares \(2013\)](#), [Nguyen et al. \(2021\)](#) attributed the change from accelerating to decelerating airflow to a rapid increase in flow separation over the upwind lateral wall and weakening of the topographically steered flow over the basin. Our wind observations do not show such a change in airflow patterns under active conditions. Instead, the wind in N3 and N4 is redirected to the long axis, while in the narrower N2 the wind appears to deflect from the lateral wall to leave N2 in the opposite

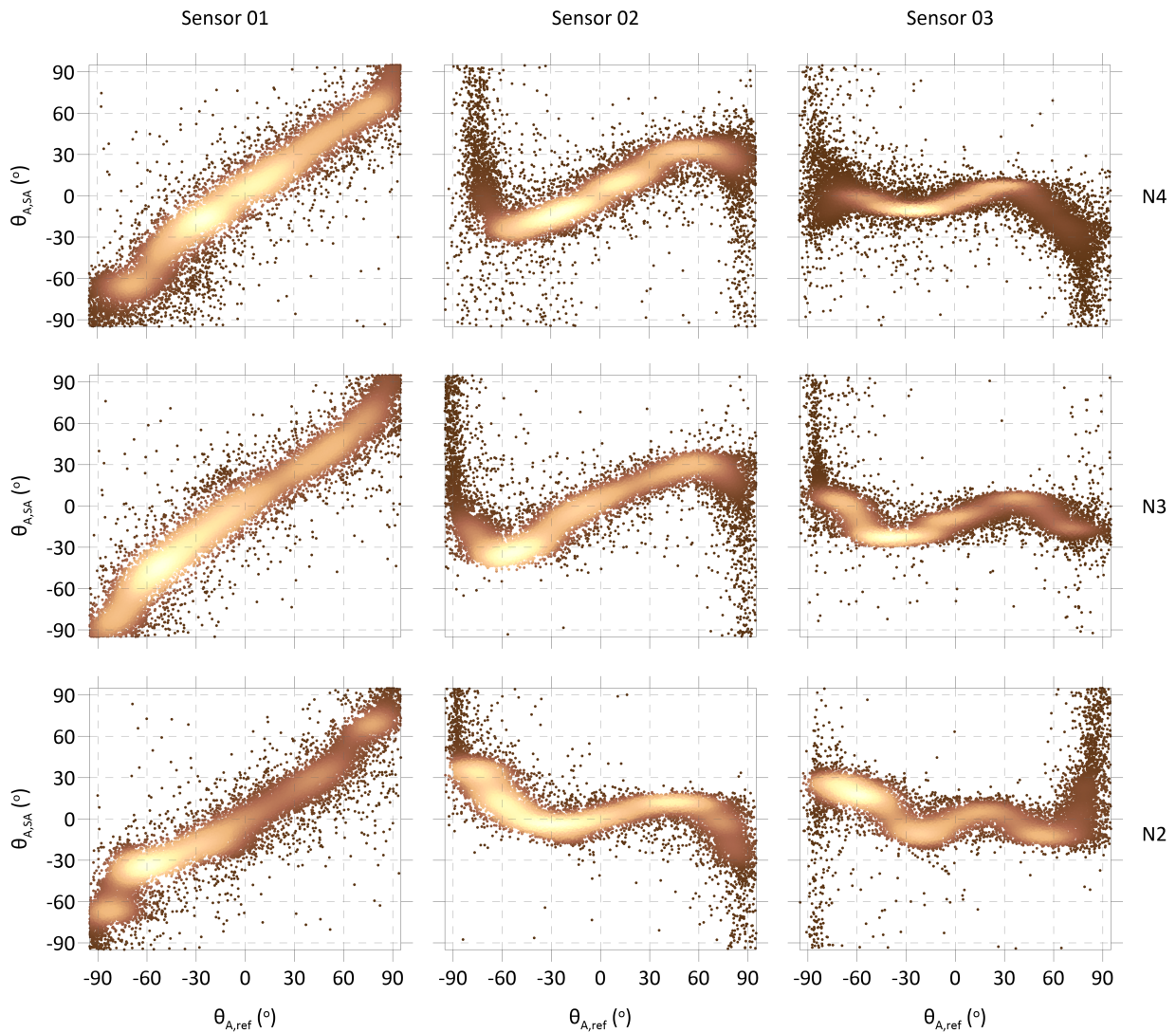


Figure 8 Wind direction in a notch $\theta_{A,SA}$ versus the reference wind direction $\theta_{A,ref}$, both relative to the long axis of each notch. Panels from left to right are sensors 01, 02, and 03, and panels from top to bottom are N4, N3 and N2. The dots are colored from brown to yellow with increasing frequency of occurrence (density).

direction once $|\theta_{A,ref}|$ exceeds approximately 40° . In our data, vortices appear only to be prominent during the most oblique incident winds (Fig. 9), associated with near-zero wind speeds within a notch (Fig. 7), in other words, under conditions that a notch is inactive. Possibly, the substantially larger width of the notches in our study area (50–100 m) compared to those in [Nguyen et al. \(2021\)](#) (6.5 m) explains the difference in airflow. Although there may be flow separation over the upwind lateral walls in our study site during oblique conditions, it remains a local effect, and the wind over the basin remains topographically steered and accelerating. Air-flow simulations with Computational Fluid Dynamics (CFD; [Smyth \(2016\)](#)) could help evaluate this suggestion. The complicated dependence of flow speed-up on $|\theta_{A,ref}|$ in N2, with a deceleration flow for winds parallel to the notch axis, presumably resulted from the complicated topography in its mouth.

4.2 Differences between notches

Although the estimated activation models for the three notches are similar (Figs 6a–d), other aspects of the re-

sults are different. For example, the percentage of active conditions in N2 was $\approx 10\%$ lower than in N4 (Table 1), and the estimated annual landward sand transport rate in N3 was $\approx 70\%$ higher than in N2 and N4 (Table 2). In this subsection, we explore whether such differences are due to geometrical differences or are caused by the (slightly) different reference wind conditions during the three consecutive deployments (Fig. 3).

To assess the percentage of active conditions, missing U_{SA} values at sensors 01, 02 and 03 (Section 2.3) were first replaced by predicted values (Supplementary Text), and the percentages were recomputed from the gap-filled data set. As shown in Table 1 (column ‘Gap filled’), the percentages are more consistent, with the difference between N4 and N2 reduced to less than 5%. To investigate the influence of the different reference wind conditions between deployments, wind speeds at SA01, SA02, and SA03 in a given notch were also predicted (Supplementary Text) when the three sensors were deployed in another notch. The resulting percentages are presented in Table 1, columns ‘Predicted with forcing from’. As shown, the percentage of active conditions in N3 remains nearly unchanged relative to the gap-

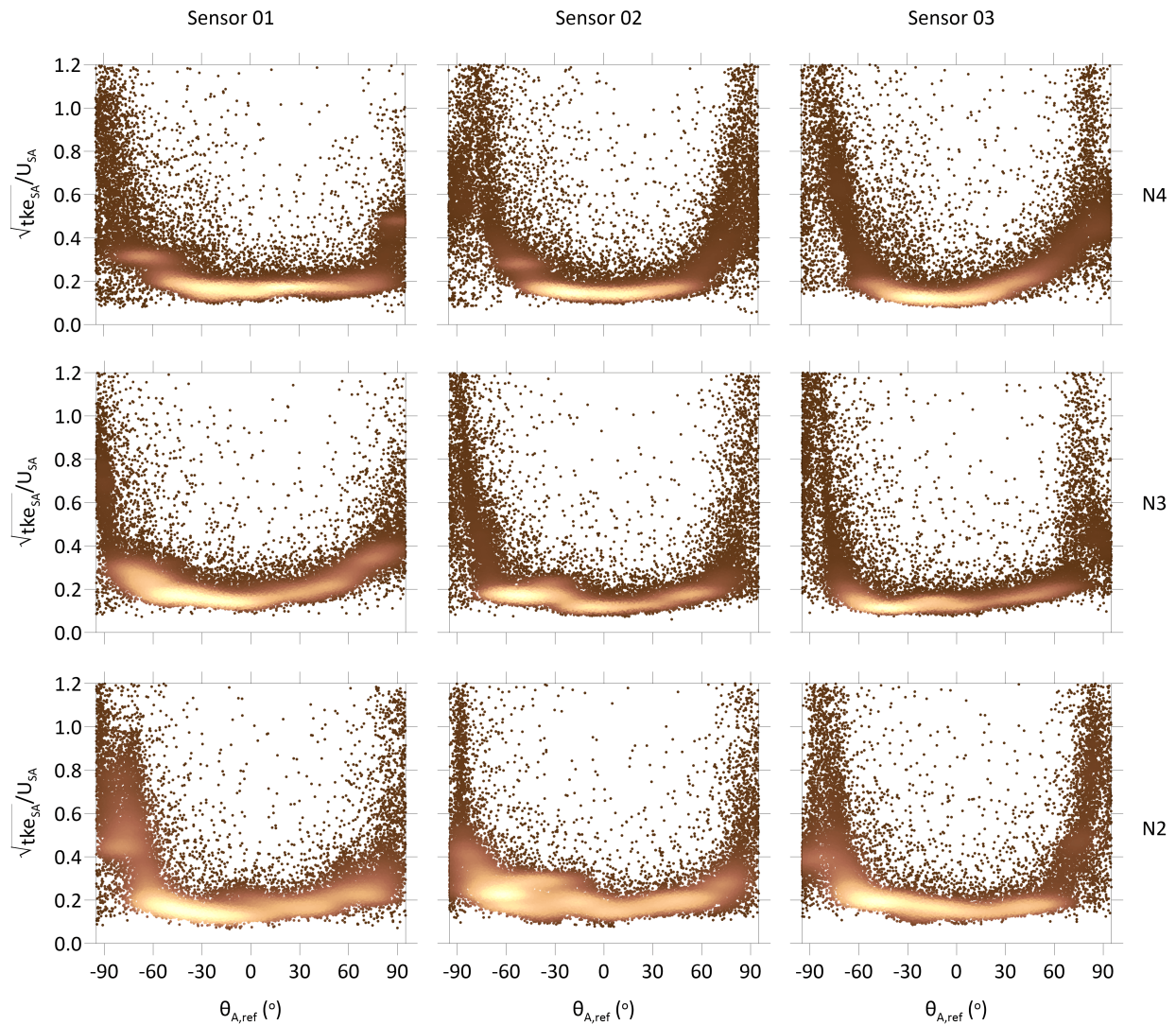


Figure 9 Ratio of the square-root of the turbulent kinetic energy to the wind speed in a notch $\sqrt{tke_{SA}}/U_{SA}$ versus the reference wind direction relative to the long axis of each notch $\theta_{A,ref}$. Panels from left to right are sensors 01, 02, and 03, and panels from top to bottom are N4, N3, and N2. The dots are colored from brown to yellow with increasing frequency of occurrence (density).

filled observations (38.9%) under both N4 (39.2%) and N2 (39.3%) forcing. N4 shows moderate sensitivity (37.7 vs. 40.1%), while N2 is most affected: N3 wind forcing increases the percentage from 34.1% to 47.6%. Overall, no notch consistently exhibits higher activity, indicating that the differences in Table 1 arise mainly from wind forcing rather than geometry.

A consistent difference emerges in the predicted annual landward sand transport rates at sensor 03, with rates in N3 always exceeding those in N2, which in turn are slightly higher than in N4 (Table 2). For instance, under N4 wind forcing, the estimated annual Q at sensor 03 in N3 is 357.7×10^3 kg/(m-year), compared with 274.2×10^3 kg/(m-year) in N2 and 232.8×10^3 kg/(m-year) in N4. Although these estimates should be interpreted with caution (Section 2.5), they suggest that N3 favours greater sand transport behind the foredune than the other two notches. This outcome is consistent with the wind data: the N3 ratio U_{SA03}/U_{ref} , particularly at the modal wind direction, exceeds the corresponding N2 and N4 ratios (Fig. 7), indicating that under the same reference wind conditions, wind speed at SA03 in N3 is generally higher than in the other notches. We attribute

the larger annual transports in N3 to its slightly steeper basin-floor slope (1:20, $\approx 3^\circ$), which enhances airflow acceleration relative to N2 and N4 (Fig.10).

4.3 Management implications

Foredune notching is increasingly applied in dynamic dune management to enhance landward sand transport, with anticipated benefits for biodiversity and coastal resilience. ‘Learning by doing’ (Gann et al., 2019) initiatives have supported dune managers in addressing governance (e.g., stakeholder participation, policy frameworks) and capacity-building challenges (e.g., awareness-raising) associated with implementation (Geelen et al., 2024; Denning et al., 2024). Widespread adoption and upscaling, however, remain constrained by knowledge gaps in notch design. A key uncertainty includes the optimal notch geometry for sustaining the geomorphological and biogeomorphological stages of notch development to maximise sand deposition behind the foredune.

As emphasised by Pye and Blott (2016) and Smyth et al. (2025), understanding airflow is essential to iden-

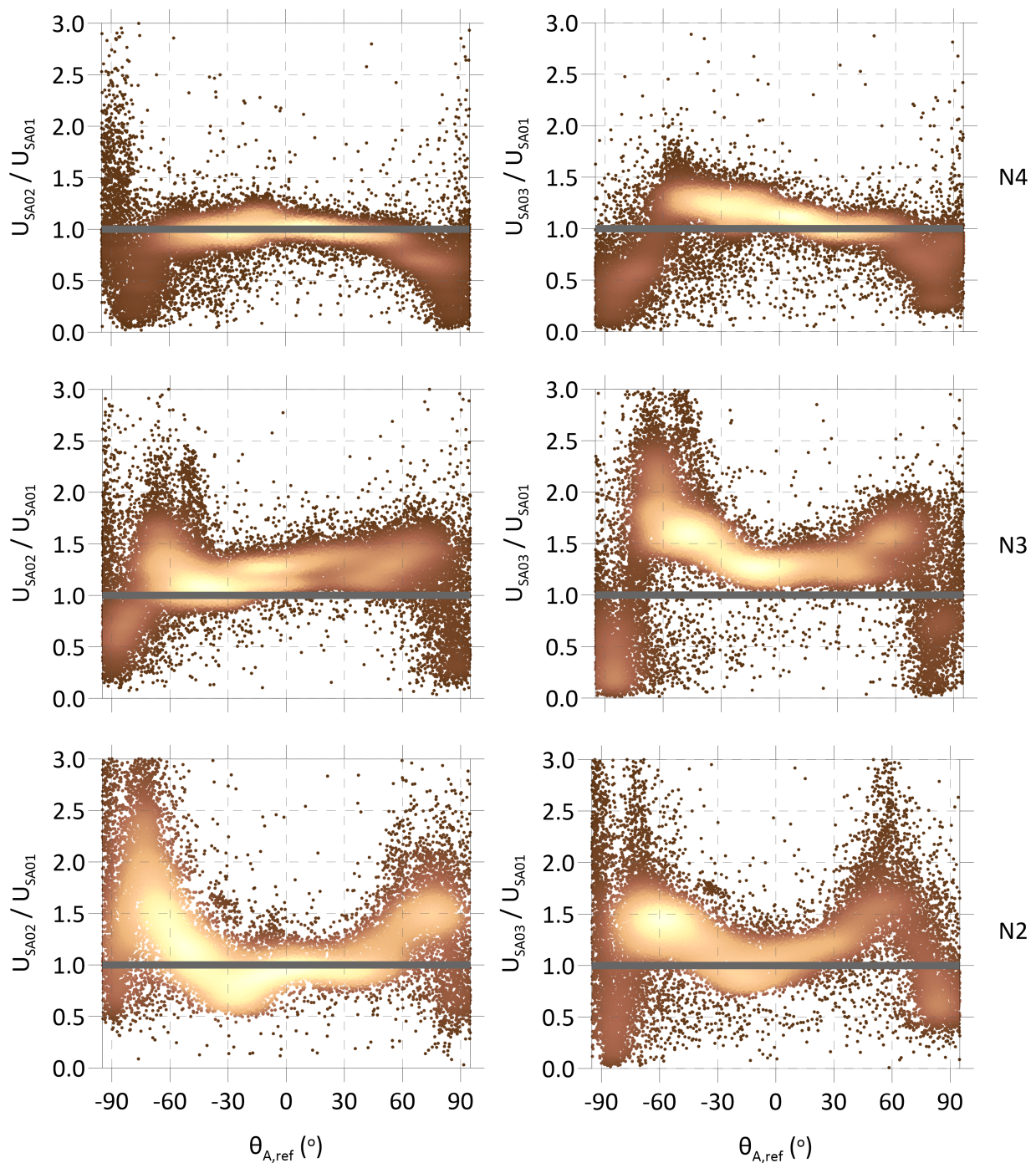


Figure 10 Values of flow speed-up (left column, U_{SA02}/U_{SA01} ; right column, U_{SA03}/U_{SA01} versus the reference wind direction relative to the long axis of each notch $\theta_{A,ref}$. Panels from top to bottom are N4, N3, and N2. The dots are colored from brown to yellow with increasing frequency of occurrence (density). The thick gray horizontal line in each panel corresponds to no speed-up.

tify which aspects of notch geometry most strongly influence long-term aeolian transport. Our results indicate that notch width and deflation basin slope are important aspects, as reflected in the differences between the conceptual and observed activation models and in the estimated annual sand transport rates (Sections 4.1 and 4.2, respectively). If a notch is excavated too narrowly, flow separation and deceleration may extend across the deflation basin, leading to rapid infilling and inhibiting the development of an effective corridor for landward transport. In such a case, part II in Fig.1 would occupy a large part of the wind conditions under which a notch is active. For the notches examined here

(50–100 m wide), part II is effectively absent.

Our suggestion that N3 is the most favourable notch for long-term landward transport, due to its steeper basin floor, is consistent with [Pye and Blott \(2016\)](#). Their analysis of foredune notches in Wales indicated that notches with a convex long profile or a steep linear slope resulted in sand deposition over a larger area behind the foredune than notches with a nearly horizontal basin floor. They also attributed this greater transport effectiveness to more pronounced slope-induced flow acceleration. However, our suggestion contradicts [Smyth et al. \(2025\)](#), who, based on airflow simulations with CFD, suggested that a notch aligned with the prevail-

ing wind direction and not too wide (25 m, rather than 50 or 100 m) should provide the most favourable conditions for landward transport. At our study site, the most favourable notch is neither the one that is best aligned with the wind climate (N4) nor the narrowest (N2). This suggests that the effect of the bed slope outweighs that of orientation and width, at least for the range of conditions in our study.

The inferred positive relationship between deflation basin slope and landward aeolian transport contrasts with the CFD results of [Nguyen et al. \(2025\)](#), who found that steeper basin slopes (10–25°) reduce bed shear velocity and, consequently, transport effectiveness. In their simulations, increased slope also decreased the notch depth, which limited the deflection of the wind and the flow acceleration—an effect they termed ‘blowout depth-induced flow acceleration’. At our site, where the basin floor slopes are gentler, slope-induced acceleration appears to still dominate. These contrasting results imply that the suggested positive relationship cannot be generalised and that an optimal slope likely lies between 3 and 10°. It is plausible that the optimal slope depends on the foredune height. In [Nguyen et al. \(2025\)](#) the foredune was 11 m high, roughly half the height observed at our site (Section 2.1). With a higher foredune, increasing the bed slope would have a smaller impact on notch depth. Consequently, the ‘blowout depth-induced flow acceleration’ effect would be weaker, allowing the slope-induced acceleration to dominate on steeper slopes. Observations at other field sites and CFD simulations that explore a range of foredune heights are necessary to test this suggestion. Finally, [Regtien \(2023\)](#)’s CFD simulations showed that slopes exceeding $\sim 5^\circ$ may induce a wind stagnation zone between the upper beach and the notch, similar to flow separation observed on foredune stoss slopes (e.g., [Hesp, 2002](#); [De Winter et al., 2020](#)). Such stagnation would interrupt landward aeolian transport, providing a second mechanism by which too steep basin floors reduce transport effectiveness.

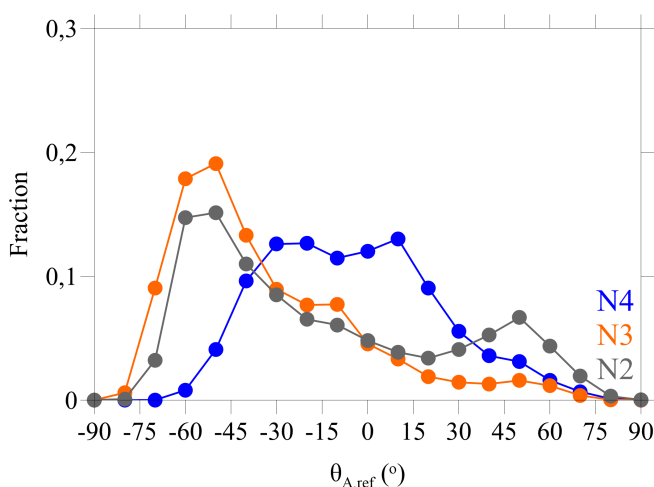


Figure 11 Ratio of the sand transport Q_{annual} at SA03 in 10° wide bins of the reference wind direction $\theta_{A,ref}$ to the total sand transport Q_{annual} at SA03 in N4 (blue circles), N3 (orange circles) and N2 (medium gray circles).

5 Conclusions

We evaluated the conceptual model for landward aeolian sand transport through foredune notches proposed by [Nguyen et al. \(2021\)](#) using a multiannual data set of near-bed wind measurements from three geometrically distinct notches in Bloemendaal, the Netherlands. The notches were found to be active across a wide range of incident wind directions (130–150°), with higher wind speeds required as the angle between the incident wind and the notch increased (7.25–15 m/s at 10 m height). Contrary to the conceptual model, no critical angle was found beyond which the notch remains active, yet the flow decelerates. Instead, wind consistently accelerated over the deflation basin (except in the case with complicated topography in the mouth of the notch), likely due to the relatively wide notches (50–100 m) at our site. Although the fraction of active conditions did not vary systematically between notches, the results suggest a positive relationship between deflation basin slope and annual landward sand transport due to stronger slope-induced flow acceleration. Together with evidence from airflow modelling in the literature, our findings indicate that notches with moderate deflation basin slopes (3–10°) and relatively large widths (≥ 50 m) optimise long-term sand transport beyond the foredune.

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Land Recognition

After consulting relevant resources and checking with the relevant local communities, the authors have confirmed that the lands containing their institutions and all work sites associated with this study do not have cultural or historical significance to a particular indigenous group.

Data and Codes Availability

The measured wind data have been archived on Zenodo, available at <https://doi.org/10.5281/zenodo.17256373>, under the title “Wind observations in three excavated foredune notches of the Noordwest Natu-

urkern project” (version 1.0). Similarly, the topographic data can be accessed via Zenodo at <https://doi.org/10.5281/zenodo.7010095>, and are titled ”Topographic data and orthomosaics of the Noordwest Natuurfkern project” (version v2.1.0).

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Conflict of Interest Disclosure

The authors declare no conflict of interest.

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Declaration on Artificial Intelligence Use

The feedforward neural networks described in the Supplementary Text were implemented in MATLAB R2024b (The MathWorks, Inc., Natick, Massachusetts, USA) using the Deep Learning Toolbox. The authors used Write-Full and OpenAI’s ChatGPT to assist with improving grammar and clarity during manuscript preparation. No new content was generated by these large language models.

References

- Bakker, J. P., Baas, A. C. W., Bartholdy, J., Jones, L., Ruessink, G., Temmerman, S., and van de Pol, M. *Environmental Impacts - Coastal Ecosystems*, chapter 8, pages 275–314. Springer, 2016.
- Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R. The value of estuarine and coastal ecosystem services. *Ecological Monographs*, 81(2):169–183, 2011.
- Barth, S. Comparison of OWEZ wind speed and wind direction measurements with Meetpost Noordwijk, IJmuiden and K13: linear regression and long term wind climate. Technical report, ECN Windenergie, ECN-E-08-024, 2008.
- Castelle, B., Bujan, S., Ferreira, S., and Dodet, G. Foredune morphological changes and beach recovery from the extreme 2013/2014 winter at a high-energy sandy Coast. *Marine Geology*, 385:41–55, 2017.
- De Jong, J. De geologische geschiedenis van de Kennemerduinen - Hoe en wanneer zijn de duinen ontstaan? *Natura*, 102:163–166, 2005. (in Dutch).
- De Winter, R. C. and Ruessink, B. G. Sensitivity analysis of climate change impacts on dune erosion: case study for the Dutch Holland coast. *Climatic Change*, 141:685–701, 2017.
- De Winter, W., Donker, J., Sterk, G., Van Beem, J., and Ruessink, G. Regional versus local wind speed and direction at a narrow beach with a high and steep foredune. *PLOS ONE*, 15(1), 2020.
- Denning, L., Pugh, M., Pitts, V., and partners, D. D. The Sand Dune Managers Handbook. Version 2. Technical report, Dynamic Dunescape (DuneLIFE) project, 2024.
- Everard, M., Jones, L., and Watts, B. Have we neglected the societal importance of sand dunes? An ecosystem services perspective. *Aquatic conservation: marine and freshwater ecosystems*, 20:476–487, 2010.
- Farrell, E. J., Delgado Fernandez, I., Smyth, T., Li, B., and Swann, C. Contemporary research in coastal dunes and aeolian processes. *Earth Surface Processes and Landforms*, 49:108–116, 2024.
- Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., Hallett, J. G., Eisenberg, C., Guariguata, M. R., Liu, J., Hua, F., Echeverria, C., Gonzales, E., Shaw, N., Decler, K., and Dixon, K. W. International principles and standards for the practice of ecological restoration. Second edition. *Restoration Ecology*, 27:S1–S46, 2019.
- Gao, J., Kennedy, D. M., and Konlechner, T. M. Coastal dune mobility over the past century: A global review. *Progress in Physical Geography*, 44:814–836, 2020.
- Geelen, L., Arens, S. M., Oost, A., Pye, K., Houston, J., and many others. Foredune dynamisation manual for The Netherlands. Technical report, OBN natuurfkennis, 2024.
- Hesp, P. A. Foredunes and blowouts: Initiation, geomorphology and dynamics. *Geomorphology*, 48:245–268, 2002.
- Hesp, P. A. and Hyde, R. Flow dynamics and geomorphology of a trough blowout. *Sedimentology*, 43:505–525, 1996.
- Hesp, P. A. and Pringle, A. Wind flow and topographic steering within a trough blowout. *Journal of Coastal Research*, Special Issue 34:597–601, 2001.
- Hesp, P. A., Hilton, M., and Konlecher, T. Flow and sediment transport dynamics in a slot and cauldron blowout and over a foredune, Mason Bay, Stewart Island (Rikiura), NZ. *Geomorphology*, 29:598–610, 2017.
- Houser, C., Wernette, P., Rentschlar, E., Jones, H., Hammond, B., and Trimble, S. Post-storm beach and dune recovery: implications for barrier island resilience. *Geomorphology*, 234:54–63, 2015.
- Jackson, D. W. T., Costas, S., González-Villanueva, R., and Cooper, A. A global ‘greening’ of coastal dunes: An integrated consequence of climate change? *Global and Planetary Change*, 182: 103026, 2019.
- Jelgersma, S., De Jong, J., Zagwijn, W. H., and Van Regteren Altena, J. F. The coastal dunes of the western Netherlands; geology, vegetational history and archeology. Technical report, Mededelingen Rijks Geologische Dienst, 1970.
- Keijsers, J. G. S., Poortinga, A., Riksen, M. J. P. M., and Maroulis, J. Spatio-temporal variability in accretion and erosion of coastal foredunes in the Netherlands: Regional climate and local topography. *PLOS ONE*, 9, 2014.
- Kok, J. F., Partell, E. J. R., Michaels, T. I., and Karam, D. B. The physics of wind-blown sand and dust. *Reports on Progress in Physics*, 75:106901, 2012.
- Konlechner, T. M., Ryu, W., Hilton, M. J., and Sherman, D. J. Evolution of foredune texture following dynamic restoration, Doughboy Bay, Stewart Island, New Zealand. *Aeolian Research*, 19: 208–214, 2015.
- Kooijman, A. M. *Environmental problems and restoration measures in coastal dunes in The Netherlands*, chapter 15, pages 243–258. Springer, 2004.
- Kroon, A., De Schipper, M., De Vries, S., and Aarninkhof, S. Subaqueous and subaerial beach changes after implementation of a mega nourishment in front of a sea dike. *Journal of Marine Science and Engineering*, 10:1152, 2022.
- Kuipers, M. The daring Dutch: restoring the dynamic dunes. In *Coastal dunes management strategies and practices: perspectives and case studies*, edited by Favennac, J. and Battiau-

- Queney, Y., volume 33 of *Dynamiques environnementales*, pages 132–138, 2014.
- Laporte-Fauret, Q., Castelle, B., Michalet, R., Marieu, V., Bujan, S., and Rosebery, D. Morphological and ecological responses of a managed coastal sand dune to experimental notches. *Science of the Total Environment*, 782(146813), 2021.
- Masselink, G., Brooks, S., Poate, T., Stokes, C., and Scott, T. Coastal dune dynamics in embayed settings with sea-level rise - Examples from the exposed and macrotidal north coast of SW England. *Marine Geology*, 450:106853, 2022.
- Matzke, S. and Leege, L. M. Measuring success: plant growth and sand movement in a coastal dune restoration on Tybee Island, USA. *Ecological Restoration*, 43:102–115, 2025.
- Maun, M. A. Adaptations of plants to burial in coastal sand dunes. *Can. J. Bot.*, 76:713–738, 1998.
- Nguyen, D., Hilton, M., Wakes, S., and Simons-Smith, T. Incident wind angle and topographic steering through excavated fore-dune notches. *Geomorphology*, 395:107982, 2021.
- Nguyen, D., Hilton, M., and Wakes, S. Aeolian sand transport thresholds in excavated fore-dune notches. *Earth Surface Processes and Landforms*, 47(2):553–568, 2022.
- Nguyen, D., Wakes, S., and Hilton, M. Controls on geomorphological stage of trough blowout evolution: Evidence from computational fluid dynamics (CFD) airflow modelling. *Earth Surface Processes and Landforms*, 50:50:e70095, 2025.
- Nolet, C., van Puijenbroek, M., Suomalainen, J., Limpens, J., and Riksen, M. UAV-imaging to model growth response of marram grass to sand burial: Implications for coastal dune development. *Aeolian Research*, 31:50–61, 2018.
- Nordstrom, K. F. and Jackson, N. L. *Beach and dune restoration - Second Edition*. Cambridge University Press, Cambridge, United Kingdom, 2021.
- Pagon, T., Smyth, T., Wilson, R., and Fox, B. Distribution and constructed morphology of artificial fore-dune notches. *Earth Surface Processes and Landforms*, 50:50:e70094, 2025.
- Pease, P. and Gares, P. The influence of topography and approach angles on local deflections of airflow within a coastal blowout. *Earth Surface Processes and Landforms*, 38:1160–1169, 2013.
- Petrova, P. G., De Jong, S. M., and Ruessink, G. A global remote-sensing assessment of the intersite variability in the greening of coastal dunes. *Remote Sensing*, 15:1491, 2023.
- Pickart, A. J., Miller, L. M., and Duebendorfer, T. E. Yellow Bush Lupine invasion in northern California coastal dunes. I. Ecological impacts and manual restoration techniques. *Restoration Ecology*, 6:59–68, 2002.
- Pye, K. and Blott, S. J. Dune rejuvenation trials: overview report. Report to Natural Resources Wales. Technical Report KPAL Report 19099, Kenneth Pye Associates Ltd., 2016.
- Raman, M., De Haeck, A., De Knijf, G., Maebe, K., Maes, D., Paredis, R., Provoost, S., Saerens, A., Sioen, G., Speybroeck, J., Thomaes, A., Thoonen, M., Tuerlings, T., Vandekerckhove, K., Vangansbeke, P., Van Braeckel, A., Van Doorn, L., Van den Broeck, A., Van Hecke, F., Van Ryckegem, G., and Wouters, J. *Habitats en soorten in een veranderend klimaat: Een selectie van kennis voor de periode 2015-2025*. Number 48 in Rapporten van het Instituut voor Natuur- en Bosonderzoek. Instituut voor Natuur- en Bosonderzoek, België, 2025.
- Regtien, J. Modelling the airflow in fore-dune blowouts using Computational Fluid Dynamics. MSc thesis, Utrecht University, 2023. Available from <https://studenttheses.uu.nl/handle/20.500.12932/47131>.
- Rene, C., Robin, N., Smyth, T. A. G., Hesp, P. A., Lamy, A., Raynal, O., and Heurtefeux, H. Dynamics and sediment transport in a path-induced blowout in opposing wind conditions. *Science of The Total Environment*, 978:179340, 2025.
- Rozé, F. and Lemauiel, S. Sand dune restoration in North Brittany, France: A 10-year monitoring study. *Restoration Ecology*, 12:29–35, 2004.
- Ruessink, B. G., Arens, S. M., Kuipers, M., and Donker, J. J. A. Coastal dune dynamics in response to excavated fore-dune notches. *Aeolian Research*, 31:3–17, 2018.
- Ruessink, G., Groenendijk, D., and Arens, B. Digital Elevation Models and Orthomosaics of the Dutch Noordwest Natuurfok Fore-dune Restoration Project. *Data*, 9(2), 2024.
- Schuring, N. The observations of aeolian sediment transport in the mouth of an excavated fore-dune notch. MSc thesis, Utrecht University, 2023. Available from <https://studenttheses.uu.nl/handle/20.500.12932/44023>.
- Schwarz, C., Brinkkemper, J., and Ruessink, G. Feedbacks between biotic and abiotic processes governing the development of fore-dune blowouts: a review. *Journal of Marine Science and Engineering*, 7:2, 2019.
- Schwarz, C., Van Starrenburg, C., Donker, J., and Ruessink, G. Wind and sand transport across a vegetated fore-dune slope. *Journal of Geophysical Research - Earth Surface*, 125(e2020JF005732): 18, 2021.
- Shao, Y. P. and Lu, H. A simple expression for wind erosion threshold friction velocity. *Journal of Geophysical Research*, 105: 22437–22443, 2000.
- Smyth, T. A. G. A review of computational Fluid Dynamics (CFD) airflow modelling over aeolian landforms. *Aeolian Research*, 22: 153–164, 2016.
- Smyth, T. A. G., Jackson, D. W. T., and Cooper, J. A. G. Three dimensional airflow patterns within a coastal trough-bowl blowout during fresh breeze to hurricane force winds. *Aeolian Research*, 9:111–123, 2013.
- Smyth, T. A. G., Delgado-Fernandez, I., Jackson, D. W. T., Yurk, B., and Rooney, P. Greedy parabolics: Wind flow direction within the deflation basin of parabolic dunes is governed by deflation basin width and depth. *Progress in Physical Geography*, 44(5): 643–660, 2020.
- Smyth, T. A. G., Pagon, T., and Walker, I. J. Exploring wind flow dynamics in fore-dune notches using Computational Fluid Dynamics (CFD). *Coastal Engineering*, 195:104646, 2025.
- Talavera, L., Costas, S., and Ferreira, O. Controls on blowout evolution in southern Portugal: A 49-year analysis. *Science of the Total Environment*, 955:176759, 2024.
- Van der Wal, D. Effects of fetch and surface texture on aeolian sand transport on two nourished beaches. *Journal of Arid Environments*, 39:533–547, 1998.
- Van Hateren, J. A., Van Buuren, U., Arens, S. M., Van Balen, R. T., and Prins, M. A. Identifying sediment transport mechanisms from grain size-shape distributions, applied to aeolian sediments. *Earth Surface Dynamics*, 8:527–553, 2020.
- Van Kuik, N., De Vries, J., Schwarz, C., and Ruessink, G. Surface-area development of fore-dune trough blowouts and associated parabolic dunes quantified from time series of satellite imagery. *Aeolian Research*, 57:100812, 2022.

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