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Controls on blowout evolution in southern Portugal: A 49-year analysis

Lara Talavera [a,b,*], Susana Costas [b], Óscar Ferreira [b]

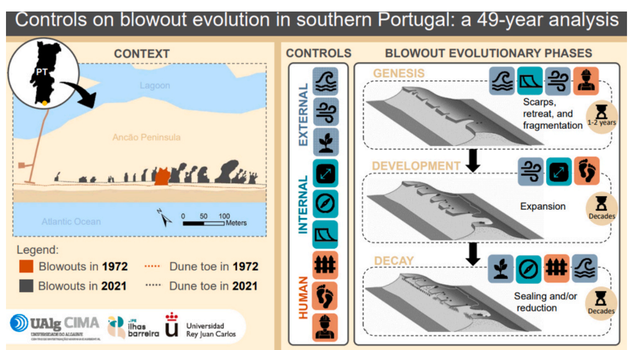
[a] Department of Biology, Geology, Physics and Inorganic Chemistry, School of Experimental Sciences and Technology (ESCET), Rey Juan Carlos University, C/Tulipán s/n, Móstoles, 28933 Madrid, Spain

[b] Centre for Marine and Environmental Research (CIMA), Building 7, Faculty of Science and Technology, Gambelas Campus, University of Algarve, 8005-139 Faro, Portugal

HIGHLIGHTS

- Blowout genesis requires an initial dune scarp and winds during 1 or 2 years.
- Blowout development involves physical and human forcings for decades.
- Elongation and sealing are faster in large and shore-oblique blowouts, respectively.
- Blowout natural and artificial decay can take around 30 and 4 years, respectively.
- Blowout lifetimes can take up to >50 years.

GRAPHICAL ABSTRACT



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ABSTRACT

Blowouts are wind-formed depressions that help maintain the sediment budget and enhance biodiversity in coastal dunes. However, the drivers controlling their evolution and the temporal scales associated to their genesis, development and decay phases remain unclear. To address this, the morphometric characteristics of a series of blowouts on the Ancão Peninsula (South Portugal) were digitized using imagery from 1972 to 2021, and used to analyse changes in the number of blowouts, total area, morphometric characteristics (width, length, orientation), and elongation rate over time. These data were compared with metocean time series and human activities, allowing the identification of blowout phases, drivers, and associated temporal scales. This work revealed that the blowout genesis phase primarily arised from the impact of physical external factors (e.g., non-storm low-to-moderate winds blowing out sand from dune scarp irregularities formerly created by extreme wave events), creating incisions across the foredune crest, and lasted 1 or 2 years. The blowout development phase, still ongoing, was characterized mainly by blowout expansion and rotation of large blowouts from North-northeast (NNE) to the East-northeast (ENE) controlled by external physical forces at specific times (e.g., low-to-moderate winds) and blowout internal factors (e.g., size and orientation). Complete blowout decay phases were not observed, except the complete artificial sealing of some blowouts due to fencing, which lasted 4 years. These findings suggest that a complete and natural blowout genesis-development-decay cycle could likely take more than five decades, with complex and spatiotemporally variable ecogeomorphic feedbacks driving their

* Corresponding author at: Department of Biology, Geology, Physics and Inorganic Chemistry, School of Experimental Sciences and Technology (ESCET), Rey Juan Carlos University, C/Tulipán s/n, Móstoles, 28933, Madrid, Spain.

E-mail addresses: lara.talavera@urjc.es (L. Talavera), scotero@ualg.pt (S. Costas), oferreir@ualg.pt (Ó. Ferreira).

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evolution. The only phase reversal documented was the reactivation of the artificially sealed blowouts, due to storm impacts. Allowing the dune and blowouts to evolve naturally appears to be the current best approach for the dune management at the studied area.

1. Introduction

Coastal foredunes are dynamic sedimentary landforms ubiquitous in almost any sandy coast of the world (Hesp, 2011; Psuty, 2008) that provide numerous and invaluable ecosystem services to society (e.g., protection against storms and flooding, recreation, habitat provision) (Martínez et al., 2013; Richardson and Nicholls, 2021). Their formation, dynamics and evolution are strongly determined by complex site-specific interactions between the sediment budget and aeolian (e.g., wind direction and intensity), biological (e.g., vegetation types and density), and marine (e.g., waves, tides, storms) forcing, as well as anthropogenic pressures, acting at a wide range of spatiotemporal scales (Costas et al., 2024; Delgado-Fernandez, 2011; Hesp et al., 2015; Ruggiero et al., 2018). Threatened by climate change and rising sea-levels (Jackson et al., 2019; Wong et al., 2014) among others, the future survival of these landforms will rely on their ability to maintain (naturally or artificially) their sediment budget while migrating inland (Davidson-Arnott, 2005; Ollerhead et al., 2013).

Several aeolian transport pathways are known to facilitate foredune inland migration supplying sand from the beach to the foredune: transfers of sediment from the stoss slope, over the dune crest, and onto the lee slope (Davidson-Arnott, 2005; Kombiadou et al., 2023; Ollerhead et al., 2013), or transfers through erosive features named blowouts (Castelle et al., 2019; Laporte-Fauret et al., 2022; Pethick, 1984). Blowouts are sandy depressions of different shapes formed by wind-induced erosion of foredune cavities formerly excavated by natural (e.g., wind and wave action) and/or anthropogenic (e.g., trampling, sand extraction) disturbances (Baird et al., 2021; Carter et al., 1990; Hesp, 2002; Hesp and Hyde, 1996). The transferred sand can also positively impact biodiversity at the back-dune (Gares and Nordstrom, 1991; Martínez et al., 2001), enhancing the overall dune system resilience (van Kuik et al., 2022). Therefore, these landforms emerge from intricate interactions among atmospheric, marine, terrestrial, and human processes (Schwarz et al., 2018), and serve as important and distinctive indicators of climatic, environmental and anthropogenic conditions that shape coastal dunes (Hesp, 2002).

The evolution of a blowout is governed by a non-linear and spatio-temporally variable interplay of abiotic and biotic factors (Gares and Nordstrom, 1991; Laporte-Fauret et al., 2022; Pye and Blott, 2017; Walker et al., 2017), complexity that is further exacerbated by environmental changes and/or the eventual crossing of tipping points (van Kuik et al., 2022). Schwarz et al. (2018) proposed that blowout evolution is dominated by geomorphological, bio-geomorphological and biological processes depending on if blowouts are at an initial, development or closure phase, respectively. Understanding the drivers modulating the blowout transition through these phases and deciphering each phase associated timescales are crucial not only to shed light on possible foredune's evolutionary pathways (Hesp, 2002), but also to implement adequate management and conservation measures that ensure the dune system resilience to for example, sea-level rise. For that, long-term and detailed spatiotemporal analyses able to identify blowout variability and trends are paramount. However, only a few studies have attempted to do so. For instance, Bolles (2012) examined 58-year topographic changes in blowout morphologies and vegetation coverage and species in Northwest Ireland from 1951 to 2009, finding a cycle of eco-geomorphic feedbacks controlling blowout evolution, with wind triggering blowout initiation and growth. Van Kuik et al. (2022) developed an algorithm using multi-spectral imagery available in Google Earth Engine and extracted 36-year changes in blowout surface area and width-to-length ratio from 1984 to 2020 in the coasts of three European countries and the USA. These authors identified phases of blowout initiation, development and closure over time, finding blowout lifetimes of at least multiple decades. Similarly, McKeehan and Arbogast (2023) mapped blowout morphologies applying an unsupervised machine learning classification to aerial images. After applying a landscape change model, they found that most of the blowouts they analysed in the southern coast of Lake Michigan (USA) had contracted in the last decades, supporting the observed regional and global trends of coastal dune stabilization (Jackson et al., 2019).

The goal of this work is to investigate, for the first time, the spatio-temporal evolution and associated drivers of a series of blowouts present in the currently fragmented and retreating foredune of Ancão Peninsula (South Portugal) over a 49-year period (from 1972 to 2021). Specifically, this research aims to identify blowout evolutionary phases, determine the timescales associated to each phase, explore blowout possible trajectories, and pinpoint what external and/or internal factors control the blowout transition through each phase, from the initiation and maintenance, to their decay. To achieve this, possible links were examined between the observed changes in number of blowouts, extent, and morphometric characteristics over time and the changes in the metocean conditions (e.g., storms and Aeolian capacity), shoreline position, and anthropogenic interventions in the area. This study enhances the understanding of atmospheric, marine, biological and human processes as key agents controlling blowout evolution and sheds light on the implications for the foredune's evolutionary response over time. It also provides valuable insights for effective management and conservation strategies to ensure the future adaptability of foredunes to climate change and increasing anthropogenic pressures. Lastly, this research offers a comprehensive long-term dataset of various morphometric parameters from numerous blowouts, covering several decades of their evolution. This dataset greatly enriches the currently scarce research on blowout variability and evolutionary trends, providing important insights into these dynamic processes.

2. Study area

Ria Formosa is a multi-inlet barrier system, located in South Portugal (Fig. 1a). This system, declared Natural Park in 1987, comprises beaches, dunes, marshes, and tidal flats of high ecological and socio-economic value. These environments are protected under the Ramsar convention and included in the list of protected areas within the EU Natura 2000 network. Ria Formosa is a cuspate-shaped system consisting of five barrier islands and two sandy peninsulas separated by six tidal inlets that connect the lagoon with the Atlantic Ocean (Fig. 1a). The multi-barrier system is located at a maximum distance of 6 km from the mainland and extends along 55 km, having Santa Maria Cape (located in Barreta Island) as the southern-most point (Fig. 1a).

The average annual significant wave height is 0.92 m while the mean annual peak period is 8.2 s (Costa et al., 2001). Waves reach the area from the west-southwest (W-SW) and the east-southeast (E-SE) directions, with 71 % and 23 % occurrence, respectively (Costa et al., 2001). This duality in the wave direction is also reflected in the wind regime, which is dominated by winds from the west (W), northwest (NW) and southwest (SW) directions (Fig. 1b). Eastern winds are less frequent, although they can be intense and may affect this region, mostly during spring and autumn (Andrade, 1990). The most frequent storms impacting the area come from the W-SW and are associated with low-pressure Atlantic systems typical of the winter, with wave heights up to 7 m (Almeida et al., 2011). The less frequent E-SE storms are linked to Levante winds originated in the Strait of Gibraltar, between October and

May, and they generate smaller waves due to the limited fetch (Almeida et al., 2011). Accordingly, the western flank of the barrier system concentrates higher wave power than its eastern counterpart (Vila-Concejo et al., 2002). The tides in this region are semidiurnal, with neap and spring tides presenting average ranges of 1.3 and 2.8 m, respectively. Maximum spring tidal range can reach up to 3.5 m (Pacheco et al., 2008). The main source of sediment in the system comes from the cliffs located up-drift, whose material is eroded and then transported eastwards by the longshore currents (Alveirinho Dias and Neal, 1992). The regional climate falls within the Mediterranean hot summer Koppen

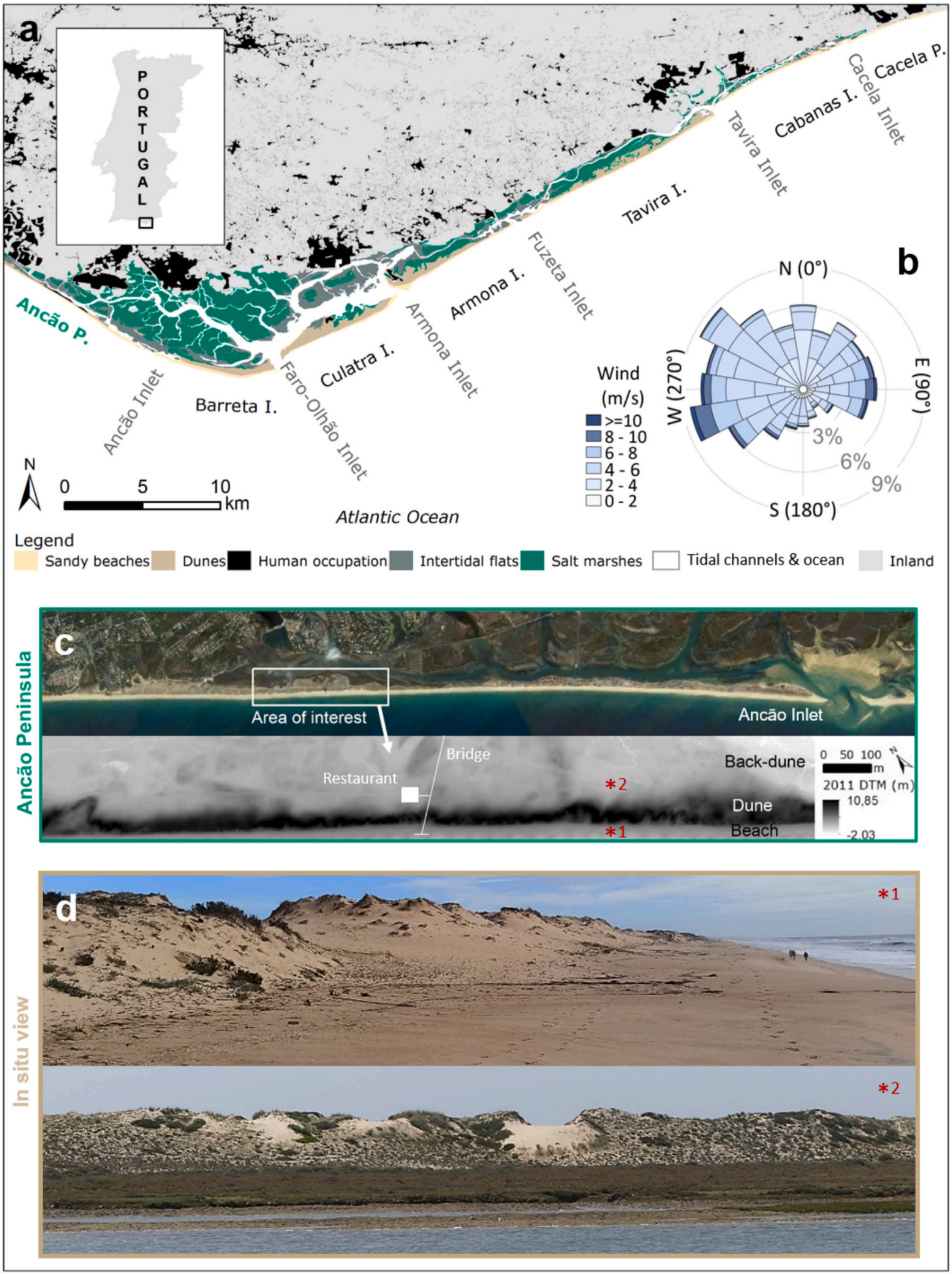

Fig. 1. (a) Location of the Ancão Peninsula (South Portugal) showing the distribution of ecosystems within the Ria Formosa Natural Park, (b) wind distribution data (source: Faro airport, 1997–2017), (c) Aerial image of Ancão Peninsula highlighting in white the area under analysis (top panel: source Google Earth), a Digital Terrain Model (DTM) of the area in 2011 (bottom panel) and location of the two in situ photographs shown in (d), represented by red asterisks and a number, and (d) In situ photographs showing a view of the blowouts from the dune windward (top panel) and lee (bottom panel) sides, respectively.

type (Csa) according to the Portuguese Institute for Sea and Atmosphere, I.P. (IPMA, 2019), characterized by a humid (October to April) and a dry (May to September) season. During the former, the lowest average temperature is 10 °C and the average precipitation values are 50 mm/month. During the latter the average temperature is 20 °C, and the precipitation is often close to zero mm/month (IPMA, 2019).

Ancão Peninsula is the westernmost barrier of the system. The barrier is narrow with widths up to 300 m and dune heights reaching up to 9.3 m above mean sea level, respectively (Kombiadou et al., 2019) (Fig. 1c). The sediments in the beach-dune system of Ancão Peninsula are primarily composed of well-sorted medium to coarse quartz sands. The beach is reflective, with mean grain sizes ranging from 0.35 mm to 0.80 mm (Costas et al., 2018), while at the dune, the mean gain size is around 0.50 mm (Costas et al., 2020). The evolution of this barrier is dominated by the eastward migration of the Ancão Inlet (Fig. 1c), whose migration rates range from 40 to 100 m/yr (Vila-Concejo et al., 2002). According to the analyses of cross-shore shoreline rates, barrier and dune width evolution performed by Kombiadou et al. (2019), shoreline erosion affects the west-central part of Ancão Peninsula with barrier widths decreasing by 0.53 m/yr for the past six decades, while shoreline accretion and dune construction are dominant processes in the east. Additionally, this barrier is also characterized by the presence of blowouts, which are the biggest and more developed of the entire Ria Formosa barrier system (Fig. 1d).

Several engineering and soft interventions have affected the evolution of the Ancão Peninsula, including the jetties of Vilamoura marina, constructed 10 km west from the study area in 1972, which contributed to increase the retreat rates at the study area (Ferreira et al., 2006). Several nourishment actions have been carried out in the area (1998, 1999, 2000, 2010, and 2012) following extreme events (Pinto et al., 2018), along with dune fencing (2001 and 2005). Lastly, facilities are also installed during summer, namely wooden walkways nearby the beach access and parallel to the dune toe, as well as beach umbrellas. Human trampling is also common, not only in the areas with high affluence of visitors but also further away and across the dune, blowouts, and back-dune areas.

3. Materials and methods

3.1. Analyses of metocean conditions

Time series of wind data (1997–2017) were retrieved from the Faro airport meteorological station. Winds with speeds exceeding 9 m/s and directions within a 90-degree range from the shore-normal were filtered in both directions and accumulated every month to obtain the optimal aeolian transport capacity using Bagnold's equation (Bagnold, 1936) (Fig. 2).

Time series of wave data (1962–2021) were retrieved from a near-shore point of the hindcast model Marine Environment Information System (SIMAR) (SIMAR_5017021) run by Puertos del Estado (The Spanish Port Authority), close to the area of interest. Storm waves were detected using a Peak Over Threshold method, defining them as events where the significant wave height (Hs) exceeded the 95th percentile of the wave time series, for at least 6 h (Fig. 2). The obtained storms were used as a qualitative approach to define differences on the wave energy hitting the coast along the studied period. Additionally, due to the low image temporal resolution during the first half of the study period (from 1972 to 2005), information of observed and reported past extreme events (those that caused damages) present in the literature was also consulted (Almeida et al., 2012; RISCKIT Storm Impact database: http://risckit.cloudapp.net/risckit/#/map) (Fig. 2).

3.2. Image collection and mapping of blowout characteristics

The aerial photographs (1972, 1989 and 1996) and orthophotos (2001, 2005, 2008, 2009 and 2014) used in this work were provided by the Portuguese Direção-Geral do Território (DGT) and were originally compiled and georeferenced when needed in the frame of the EVEREST project (Kombiadou et al., 2019).The Google Earth Pro images (2013, 2017, 2019 and 2021) were downloaded with the highest resolution

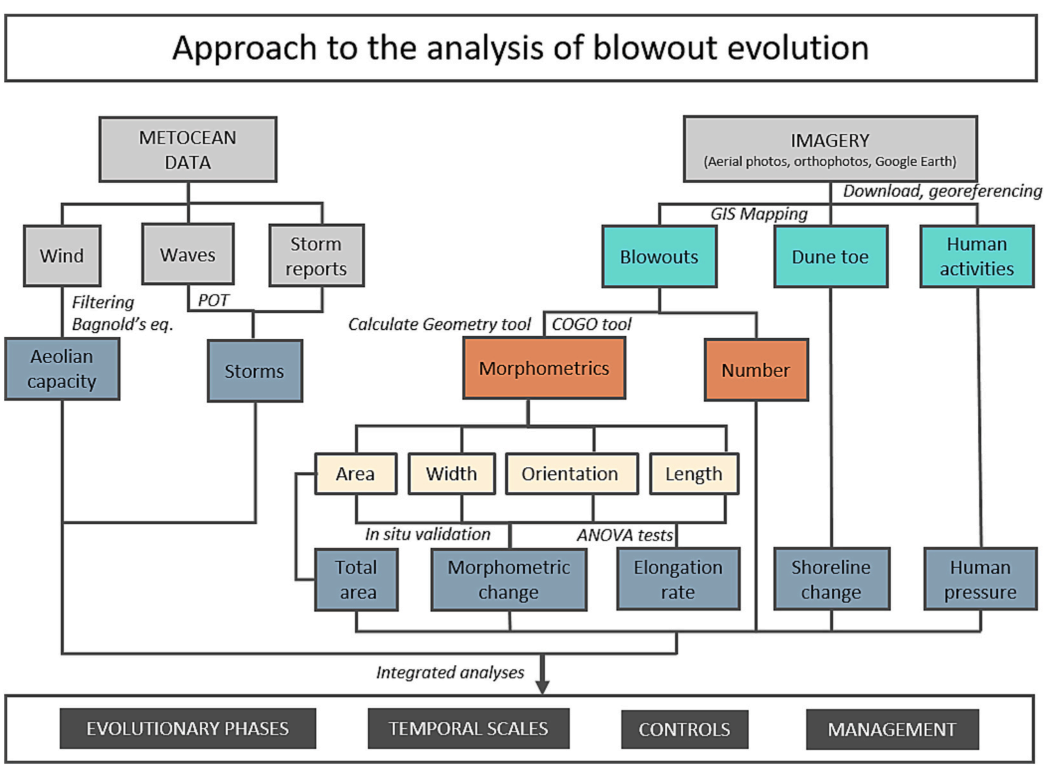

Fig. 2. Flowchart diagram detailing the progression of the work-flow followed in this study, from initial data collection through intermediate steps and final outcomes.

available (4800 × 2869), and carefully georeferenced using invariable features, as well as the temporally closest orthophoto as basemap (georeference error below 0.5 m) (Fig. 2 and Fig. S1). The resolution of the images ranged from 0.10 to 0.5 m (Table S1), allowing a detailed examination of the blowout contours and their morphologies (e.g., mouth, deflation basin, walls, lobe), which were visually validated during field campaigns in 2019 and 2021.

The blowout contours and dune toe position were manually digitized from all the imagery (except the areas nearby a restaurant; Fig. 1c) using ArcMap (®ESRI) GIS software, and stored as polygons and polylines, respectively (Fig. 2). The blowout areas were estimated using the Calculate Geometry Tool while their morphometric characteristics (width, length, and orientation) were measured using the COGO Report Tool (Fig. 2).. Blowout sizes below 100 m^2 were considered as dune notches indicative of early stages in blowout formation given that the majority of their morphologies were initial incisions appearing after storm events, typically lacking lobes, which may or may not develop over time. Sizes exceeding 100 m^2 were referred to as blowouts. The definition of the morphometric characteristics depends on the type of blowout configuration. Specifically, those characteristics can be measured in a different way if the blowouts exhibited a unique lobe or if their branches were parallel or oblique (see Fig. 3 as example of the measured morphometric characteristics for different blowouts). The measurements allowed the investigation of the overall spatiotemporal changes of the median blowout morphometric characteristics as well as the total blowout area, the number of blowouts, as well as changes in the shoreline position (Fig. 2). Besides, human occupation (e.g. summer facilities, trampling paths) and management activities observable in the imagery (e.g., fencing) or compiled from the literature (e.g. up-drift jetty construction, nourishments) were also digitized or taken into consideration for assessing their possible influence on the morphodynamics and evolution of the blowouts (Fig. 2).

A selected 10-blowout sub-set (blowouts persisting over the period of study) was used to analyse the blowout elongation rate over the years using the mapped blowout lengths (see asterisks in the bottom panel on Fig. S2) (Fig. 2). Positive values indicate blowout elongation inland (i.e., the lobe of the blowout is extending and advancing landwards) while negative values represent a reduction in the blowout length, usually promoted by lobe sealing. One-way ANOVA ("analysis of variance") was performed separately on the positive and negative blowout elongation rate values to understand if the morphometric characteristics of the selected blowouts (independent variables such as size, orientation and width-length ratio) affect both inland elongation (positive) and lobe sealing (negative) rates (dependent variables) (Fig. 2). When ANOVA showed significant differences ($p < 0.05$), pairwise comparisons, applying a Tukey's Honest Significant Difference (HSD) test, were done to explore significant differences between all pairs of independent variables.

It should be noted that the inconsistent and low temporal resolution at the beginning of the time series complicates the comparison of blowout spatial changes with atmospheric and marine forcing.

4. Results

4.1. Metocean and dune toe changes

The extreme events impacting the study area included sporadic occurrences (1 or 2 per year) as in 1979, around 1990, and in 2018, and patterns of consecutive extreme storms and/or storm clusters (Fig. 4a). Notable examples of consecutive extreme storms and storm clusters include those reported in the periods spanning from 1994 to 1998, 2000 to 2003, 2008 to 2010, and 2013 to 2014 (Fig. 4a). The latter caused significant damage in the nearby coasts of Ria Formosa (Almeida et al., 2012). These extreme storms were often accompanied by moderate to high aeolian transport capacity peaks, especially the extreme storms occurring from 2000 to 2003, with aeolian transport capacity peaks of nearly 9 m^3/m, or those occurring from 2008 to 2010, during which the aeolian transport capacity reached up to 13 m^3/m (Fig. 4b). Conversely, high and moderate aeolian transport capacity peaks were also found, such as the ones observed in 1999 (nearly 20 m^3/m) or in 2011 (4 m^3/m), which were not linked to either extreme events or storm clusters (Fig. 4a and b).

Lastly, the shoreline in Ancão Peninsula experienced a net retreat of 8 m over the analysed period (Fig. 4c). This retreat did not occur progressively but rather in two main abrupt steps. The first one took place from 1996 to 2005, during which the dune toe retreated approximately 4 m (Fig. 4c). The previous led to nourishment actions (1998, 1999, and 2000) and dune fencing in the area (2001 and 2005). The second dune toe shift occurred from 2008 to 2011, and it was characterized by a significant retreat of nearly 7 m (Fig. 4c). These retreat phases were concomitant with the impact of extreme storms reported between 1997 and 2003, as well as from 2008 to 2010 (Fig. 4a), with the first one causing the destruction of some of the fences previously installed (2001 and 2005). The lack of a natural source of sediment led to new nourishments in 2010 and 2012 (Fig. 4c). Besides, the dune toe also exhibited periods of relative stability from 2011 to 2021 and even slight progradation during the years 1972–1996, 2005–2008, and 2011–2017 (Fig. 4c).

4.2. Overall blowout changes

Over the course of the 49-year study period, the net change in the total number of notches and blowouts tripled, rising from 8 in 1972 to 26 in 2021 (Fig. 5a and Fig. S2). During this time, the number of notches and blowouts oscillated. There were two distinct growth phases: one from 1972 to 1996 and another from 2005 to 2011, both characterized by peaks of 36 notches and blowouts. Following these increments, there were two subsequent declines (Fig. 5a and Fig. S2). These fluctuations

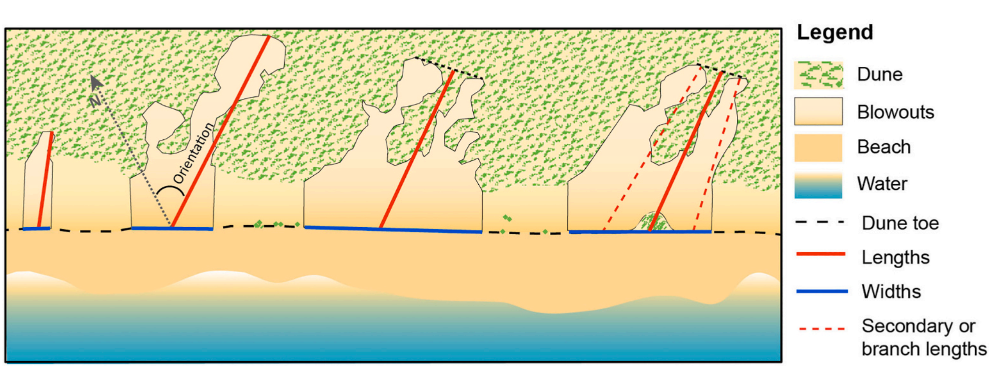

Fig. 3. Mapping criteria followed to map the blowout morphometric characteristics over different blowout configurations (Note: The angle between the blowout length and the North is the blowout orientation).

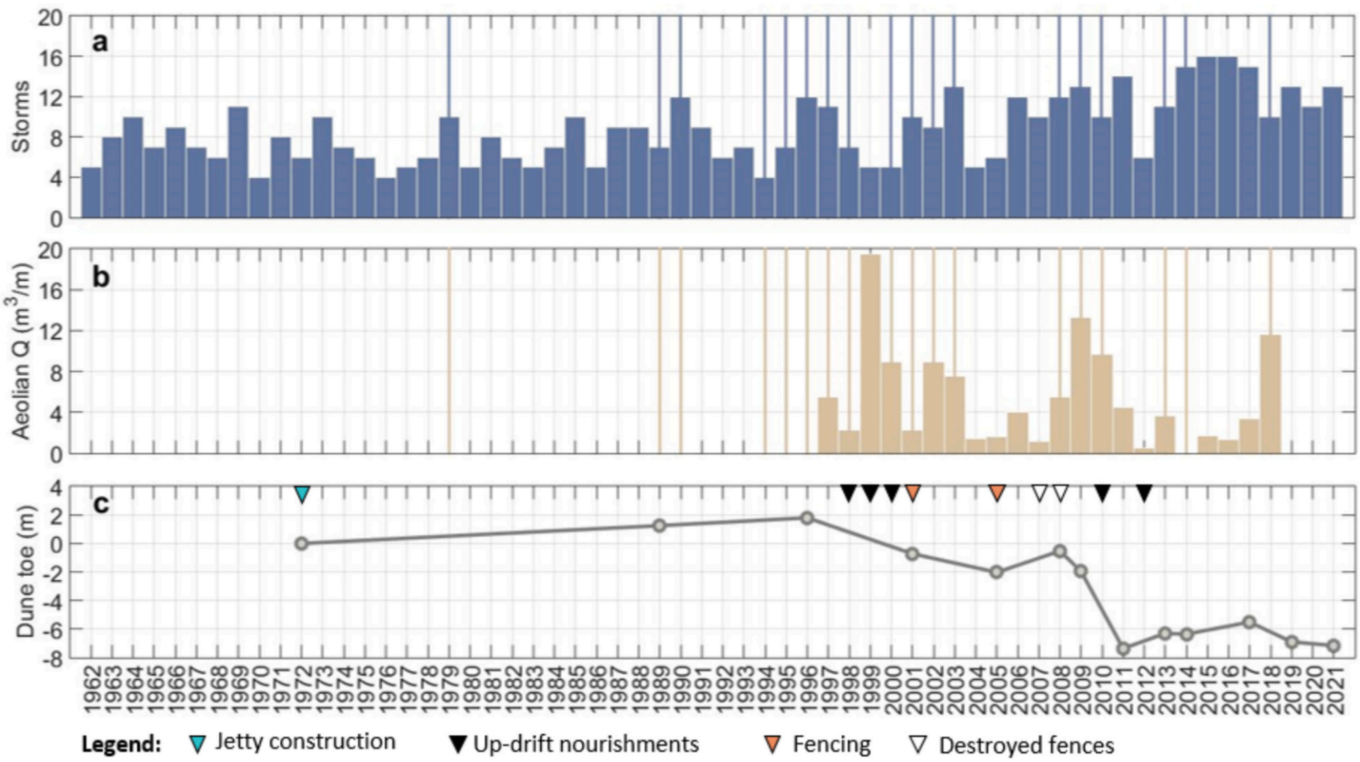

Fig. 4. Metocean conditions, shoreline changes and human interventions during the analysed period: (a) Number of storms per year (1962–2021), (b) Aeolian transport capacity per year (1997–2017), and (c) Cumulative dune toe evolution after the first image, where negative represents erosion and positive progradation, as well as human interventions (triangles). (Note: Extreme storms reported in the area are represented by vertical lines).

were primarily driven by notable variations in the number of notches (dune cavities with size below 100 m^2) (Fig. 5a). Specifically, these notches experienced a significant initial increase from 1972 (5) to 1989 (28), followed by a gradual decrease to 13 by 2005. By 2011, the count of notches doubled, reaching 20, before declining again to only six by 2019 (Fig. 5a).

On the other hand, the overall blowout area across the dune at the study site has seen substantial growth during the past 49 years. By 2021, it had expanded to more than four times its extent in 1972 (Fig. 5b). Two significant jumps in total blowout area were observed, each followed by periods of relative stability. The first jump nearly doubled the total blowout area, increasing from 2655 m^2 in 1989 to 5059 m^2 in 1996, and then again to 6274 m^2 in 2001. It remained relatively stable for the next 15 years (until 2011). The second jump occurred from 2011 to 2013, during which the total blowout area rose again to 7956 m^2 (Fig. 5b), with minor fluctuations continuing until 2021. A significant portion of the total blowout area (especially from 2013 onward) was attributed to large blowouts (size equal or above 500 m^2) (Fig. 5b).

The blowouts (size above 100 m^2) also experienced substantial morphometric transformations over time. In general, the net median blowout widths decreased by over half, shrinking from 33 m in 1972 to 15 m in 2021 (Fig. 5c). In contrast, the net median blowout lengths nearly tripled, expanding from 18 m 1972 to 30 m in 2021 (Fig. 5d). The blowouts also experienced a net 15° rotation towards the ENE (Fig. 5e). However, these net blowout changes were not linear. Throughout the study period, the blowout widths and lengths exhibited fluctuations with periods in which both increased or decreased, or periods in which they showed opposite behaviours. For instance, between 1972 and 1989, the median blowout width significantly decreased by 27 m (from 33 m to 6 m), while the length increased by 10 m (from 18 m to 28 m) (Fig. 5c and d). This trend reversed from 1989 to 1996, with median widths increasing by 5 m, but lengths decreasing by 8 m (Fig. 5c and d). Increases in both dimensions were also observed. For instance, between 1996 and 2005, blowout widths expanded slightly from 9 m to 12 m, while lengths also increased from 20 to nearly 29 m (Fig. 5c and d). Another example occurred from 2009 to 2011, when widths increased by 4 m and lengths by 3 m (Fig. 5c and d). Conversely, there were periods during which both blowout widths and lengths decreased. The most significant of these occurred between 2014 and 2017. During this time, the widths decreased slightly from 13 m to 11.5 m (a reduction of 1.5 m), while the lengths experienced a substantial decline of 8.5 m (from 34 m to 2.5 m) (Fig. 5c and d). Lastly, regarding blowout orientation, the blowouts displayed a significant rotation towards the ENE direction (Fig. 5e). The most pronounced shift occurred between 1989 and 2005, during which the median blowout orientation changed from 43° to 58°. Subsequently, after 2005, the blowout orientation remained relatively stable, with only minor fluctuations within an 8-degree range until the end of the studied period.

4.3. Blowout dynamics

The average elongation rate of the 10-blowout subset was not constant but rather it exhibited variations over the analysed period. Initially, it fluctuated subtly, ranging from 0.5 to 1.5 m/yr during the first 25 years until 2011 (Fig. 6a). Afterwards, there were two distinct periods of sudden accelerations followed by a drop in the rate of elongation. The first acceleration occurred between 2011 and 2014, during which the elongation rate rose up to 3.3 m/yr from 2011 to 2013, and then to 3.6 by 2014—almost tripling the 2011 rate (Fig. 6a). After three years, by 2017, elongation rate dropped back to 0.5 m/yr, which suffered a new rise, reaching values of 3 m/yr in 2019. Once again, a new drop followed this acceleration to −1 m/yr by 2021 (Fig. 6a).

In general, most blowouts exhibited inland elongation (positive elongation rates), but some also experienced lobe sealing (negative elongation rates), leading to a reduction in their lengths (Fig. 6b and c). During the initial 13 years analysed, only a few blowouts showed low negative elongation rates (−0.5 to −1 m/yr), suggesting slight lobe sealing (Fig. 6b and c). From 2009 onwards, lobe sealing rates

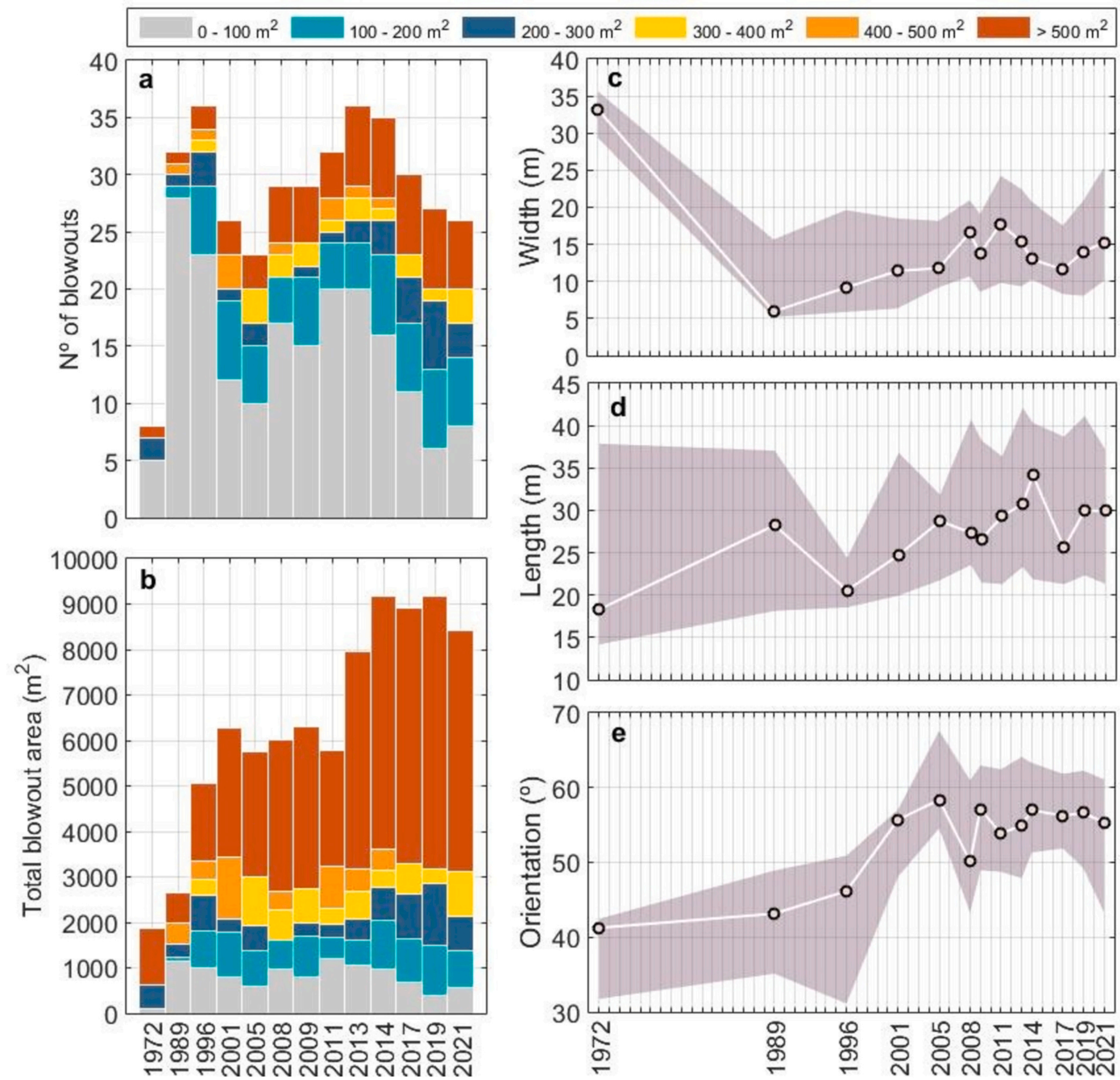

Fig. 5. Overall changes in (a) Number of notches and blowouts, (b) Total area of notches (< 100 m^2) and blowouts, (c) Median width, (d) Median length, and (e) Median blowout orientation (0° is North, and 90° is East). [Note 1: the notches, or dune cavities below 100 m^2, were removed from morphometric analyses to avoid noise and help the interpretation of results. Note 2: white lines represent the median values while the lower and upper bounds of the purple area correspond to the 25th and 75th percentile values, respectively. Note 3: For better visualization the years 2009 and 2013 were removed from the X axis in Fig. 5c, d, and e].

accelerated substantially, reaching −2.5 m/yr by 2014 and − 4 m/yr by 2021 (Fig. 6b and c). However, lobe sealing was only dominant over elongation after 2019.

The ANOVA tests revealed that, among all the independent variables analysed (i.e., blowout size, orientation, and width-length ratio), size and orientation significantly affected the positive (inland elongation) and negative (lobe sealing) elongation rate of the blowouts (dependent variable), respectively. On one hand, the results showed that blowouts larger than 400 m^2 exhibited faster inland elongation rates (2.7 m/yr; positive boxplot in Fig. 6b) compared to blowouts smaller than 200 m^2 (0.6 m/yr; positive boxplot in Fig. 6b). The difference between these two groups was statistically significant (F = 6.53, $p < 0.01$). The intermediate size group (200–400 m^2) did not differ significantly from either of the other two groups (see positive boxplot in Fig. 6b). No significant differences were observed in the inland elongation rates based on blowout orientation (F = 1.96, $p = 0.15$) or width-length ratio (F = 0.19, $p = 0.83$) groups. Regarding lobe sealing (negative elongation rates), blowouts with more oblique orientations relative to the coast (> 60°) exhibited high lobe sealing rates (−2.45 m/yr) and showed statistically significant differences compared to the other two groups (F = 12.91, p < 0.01) (see negative boxplot in Fig. 6c). No significant differences were observed in lobe sealing rates based on blowout size (F = 0.86, $p = 0.37$) or width-length ratio (F = 0.54, $p = 0.59$) groups.

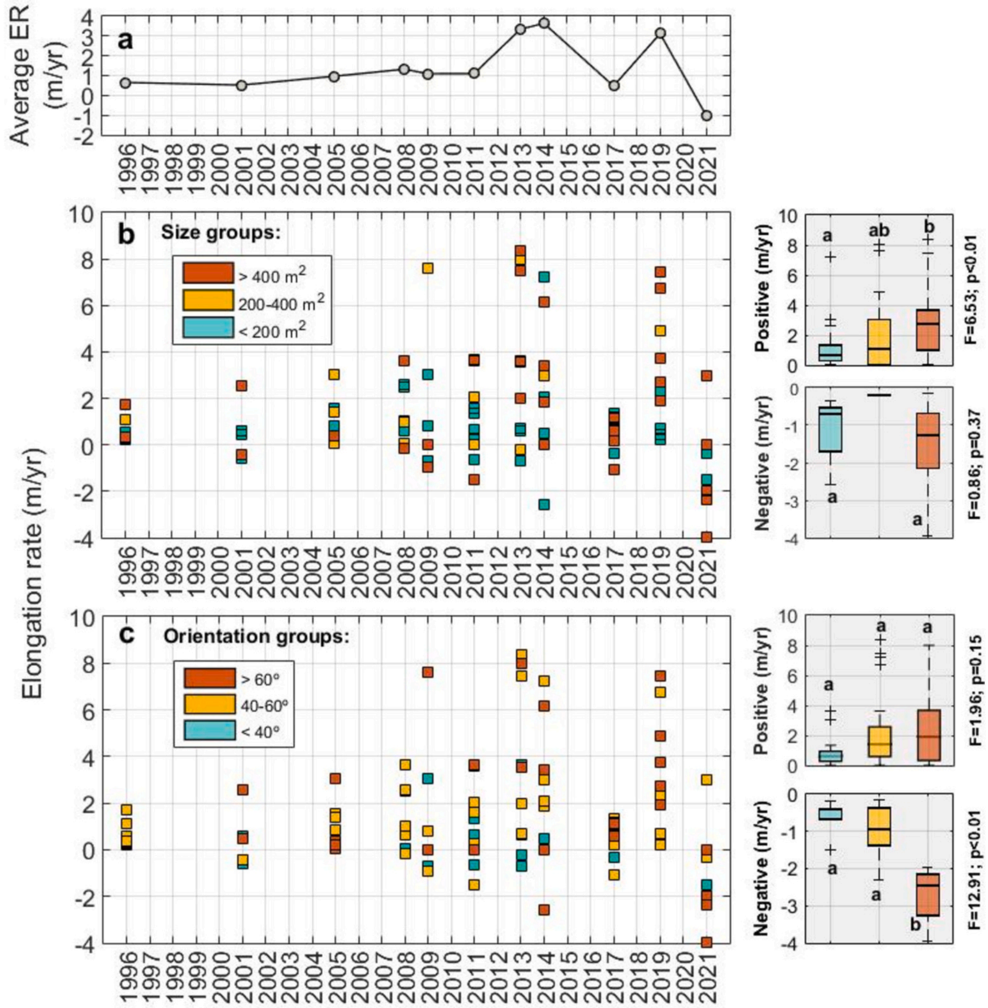

Fig. 6. (a) Average elongation rates (ER) of the blowouts, (b) elongation rate of the individual blowouts (squares) groups by size, and associated boxplots, and (c) elongation rate of the individual blowouts (squares) groups by orientation, and associated boxplots. Note: the non-capital letters show the results of the pair-wise comparison.

5. Discussion

5.1. Phases of blowout evolution, controls involved and blowout lifetimes in Ancão Peninsula

The integration of all findings allowed the definition of three phases of blowout evolution in Ancão Peninsula, designated as Genesis, Development and Decay (Fig. 7), similarly to what was observed by other authors in other coastal settings (e.g., van Kuik et al., 2022). It also allowed the identification of the temporal scales associated to each phase and the external and internal controls involved.

Firstly, blowout genesis phases correspond to periods exhibiting a sudden increase in dune notch number (Fig. 7). Notch formation (e.g., 2005–2008 or 2009–2011; Fig. 5a and Fig. S2) was always preceded by periods with extreme storms (e.g., 2000–2003 or 2008–2010; Fig. 4a) causing foredune retreat (e.g., 2001–2005 or 2008–2010; Fig. 4c), scarping, slumping, and general dune debilitation. The aforementioned is the result of the long-term chronic retreat identified by Kombiadou et al. (2019), although it does not necessarily occur continuously over time but rather in pulses, that usually coincide with storm periods. Additionally, following storm events, calm periods with low-to-moderate aeolian transport potential occurred (e.g., 2004–2007 or 2011; Fig. 4b). These conditions appear to trigger the subsequent wind-driven excavation of notches (Fig. 7). These processes have been described in multiple investigations in the literature (Bolles, 2012; Castelle et al., 2017; Delgado-Fernandez, 2011; Gares and Nordstrom, 1988; Hesp, 2002). When favourable conditions exist (e.g., storms followed by adequate aeolian capacity), the blowout genesis phase can occur rapidly. Here we observed that dune notch formation can occur as early as 1 or 2 years after the debilitation or scarping of the foredune. For instance, the notch formation observed between 2009 and 2011 (Fig. 5a) resulted from storm-induced foredune retreat during that period, as well as non-storm moderate winds in 2011 (Fig. 4a, b and c). Nevertheless, this temporal scale may extend beyond that or even notch formation fail to occur if the necessary conditions are not present. The blowout genesis phase resembles to the geomorphological stage outlined in Schwarz et al. (2018) conceptual model for blowout evolution. According to this model, blowout initiation is primarily influenced by physical processes (e.g., wave magnitude and direction, tides, aeolian sediment transport, among others), as observed here.

Human trampling is, together with an assortment of drivers such as animal grazing or land-use practices, an additional external and physical factor contributing to notch formation and dune fragmentation (Baird et al., 2021; Hesp and Hyde, 1996; Jewell et al., 2017; McKeehan and Arbogast, 2023; Mir-Gual et al., 2013; Mir-Gual and Pons, 2011). Trampling is particularly relevant in the area of interest, where multiple trampling signs and paths have been observed not only at the foredune stoss but also across the dune crest and lee, especially in the last images

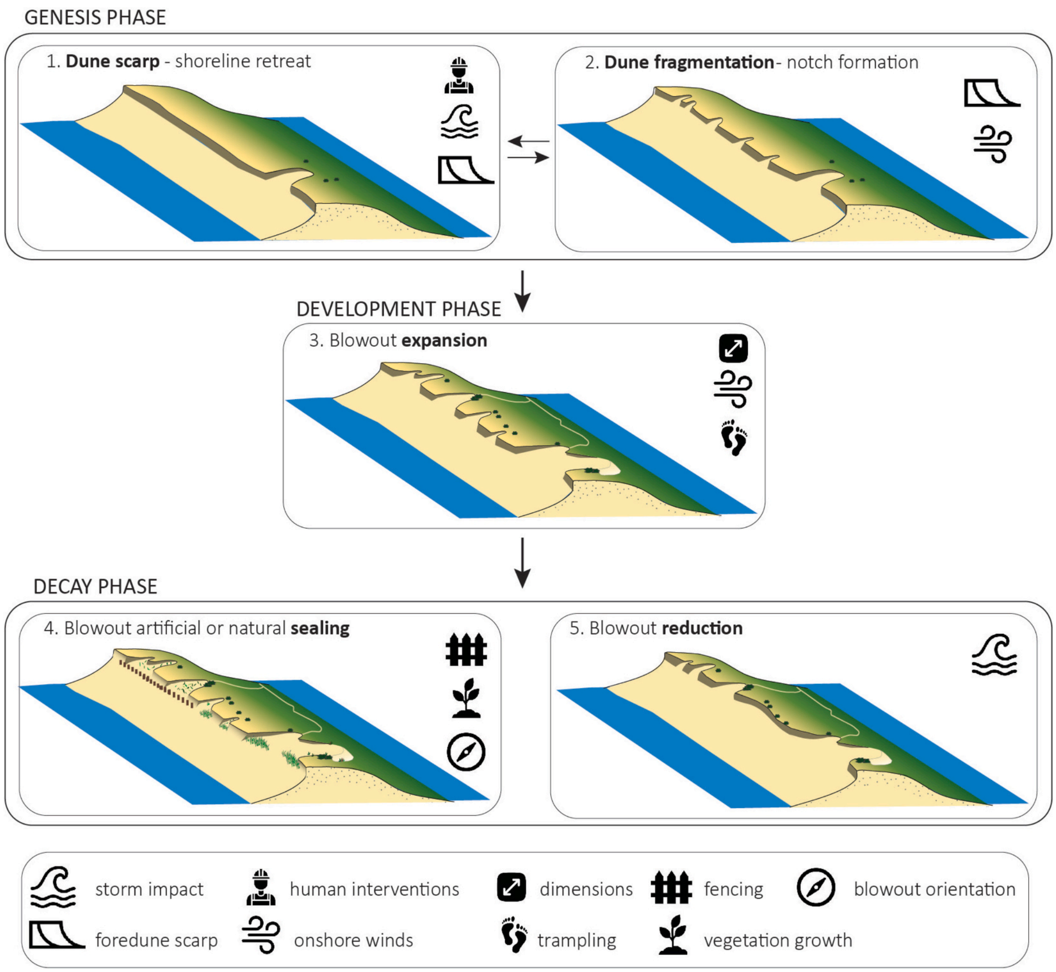

Fig. 7. Conceptual model illustrating the different blowout evolutionary phases, processes and changes to the system that may induce blowout formation, as observed in Ancão Peninsula during the past 49 years.

analysed (see Fig. S2). In fact, sometimes the trampling paths cross blowouts suggesting they are used as ways to cross the dune from the beach to the lee. Despite this, it is unlikely that human activity alone caused the initial formation of notches (Bate and Ferguson, 1996) as these cavities existed historically before human affluence became significant along this coastal stretch.

The development phase was characterized mainly by expansion (growth) of most of the notches and blowouts, from small to large, although some were also experiencing reduction (shrink), occurring at different time scales (Fig. 7). van Kuik et al. (2022) documented that blowout area varied on multi-annual, seasonal and event-scale time scales. Blowout expansion and average acceleration in inland elongation rates in the study area, similarly to notch formation, occurred during calm periods without extreme storms and with low-to-moderate winds. For instance, absence of extreme storms and low-to-moderate wind periods (e.g., 1999 and 2011–2012; Fig. 4b) preceded the expansion shifts observed in the total blowout area (1996–2001 and 2011–2013; Fig. 5b), median blowout lengths (1996–2001 and 2011–2013; Fig. 4d) and the increase in inland elongation rates from 2011 to 2013 (Fig. 6a). Additionally, the largest blowouts (size above 400 m^2) elongated at faster rates than the small ones (positive boxplot in Fig. 6b). Some authors stated that large blowouts have transport dynamics very different from small blowouts (Delgado-Fernandez et al., 2017). Van Kuik et al. (2022) observed that blowout elongation was more pronounced with a low width-length ratio. However, in this work no significant differences were observed in the inland elongation rates based on width-length ratio. Large blowouts also contributed the most to the overall increase in total blowout area (Fig. 5b). The temporal scales associated with the blowout development phase can span several decades, as observed here. Nevertheless, we observed that around 3 or 4 years were needed for a dune notch to develop into a small blowout (see Fig. S2). We also documented a notch present in 1989 developed over the following 32 years and became the largest blowout of the entire period by 2021 (Fig. S2). This development phase results mainly from external physical factors such as wind intensity acting under pulses. In our case, and contrary to Schwarz et al.'s (2018) conceptual model, biological processes controlling blowout development were not observed.

The decline in the number of pre-existing dune notches or even small blowouts, or their reduction in size, were interpreted as a phase of blowout decay (Fig. 7), and it was observed during specific time intervals (e.g., 1996–2001 or 2001–2005; see Fig. 5a). These periods were simultaneous with either external physical controls such as high-energy storm events (e.g., 1996–2001; Fig. 4a), resulting in event-scale blowout reduction or disappearance due to foredune erosion and retreat; or human controls such as dune fencing (e.g., 2001–2005; Fig. 4c; Fig. 7). Dune fencing along the dune toe and blowout entrances promoted vegetation growth on the blowout deflation basins causing the complete artificial sealing of notches and blowouts (Fig. S2), a phenomenon observed to last 4 years approximately, from 2001 to 2005. The previous falls within the timescale of blowout re-vegetation observed by Leege and Kilgore (2014). Nevertheless, the gradual long-term natural sealing of the largest blowout in 1972 was also observed, which appeared almost completely re-vegetated 29 years later, by 2001 (Fig. S2). Sealing rates may vary regionally depending on atmospheric factors such as precipitation or temperature, among others (McKeehan and Arbogast, 2023). Lobe sealing rates were faster in blowouts obliquely oriented to the shoreline (> 60°) than in blowouts oriented perpendicular to it (< 60°) (see negative boxplot in Fig. 6c). These blowouts with faster lobe sealing rates were also typically the largest (size above 400 m^2; Fig. 6b). The largest blowouts also exhibited the fastest inland elongation rates (positive boxplot in Fig. 6b), as mentioned above. This apparent contradiction can be understood considering the overall blowout evolution. As blowouts elongate and mature, they tend to rotate from NNE (<40°) towards the ENE (>60°; Fig. 5e), aligning with the dominant SW winds in the area (Fig. 1b). When there is insufficient aeolian transport capacity and the blowout lobe reaches a lower position in the dune lee, sediment transport to the lobes decreases, leading to re-vegetation and gradual sealing. Whether natural or artificial, it seems that the blowout decay phase shows similarities with the blowout closure stage defined by Schwarz et al.'s (2018) conceptual model, which states that blowout closure is primarily governed by vegetation re-colonization. However, as stated, reductions in size or disappearance can also be triggered solely by physical factors (e.g., foredune retreat caused by storms) (Fig. 7).

The previous evolutionary phases occurred concurrently in Ancão Peninsula and affected different blowouts at different times. Blowout phase concurrency and spatial heterogeneity align with observations made by van Kuik et al. (2022), further supporting that each feature can have its own dynamics and evolve differently from the surrounding ones. Determining the factors controlling blowout transitions through the various evolutionary phases (genesis, development, decay) is challenging due to infrequent observations, especially during the initial decades of this study. On the other hand, most blowouts in Ancão Peninsula did not exhibit a complete cycle (including genesis, development, and decay) during the 49-year analysis. Based on the concurrent 32-year blowout development phase and the 29-year blowout decay phase observed in this work, it is hypothesized that blowout lifetimes in the Ancão Peninsula could extend beyond the analysed period resulting on an overall life cycle of more than five decades, which agrees with other works in the literature (e.g., Dech et al., 2005; Gares and Nordstrom, 1995; Hesp, 2002; Jewell et al., 2017; van Kuik et al., 2022). Phase reversals were limited to the reactivation of the artificially sealed notches and blowouts as it happened in 2011 due to the 2008–2009 storms impacting the area and destroying the fences (Fig. 4c and Fig. S2). This agrees with the study from van Kuik et al. (2022) were phase reversals were not observed.

Contrary to other areas where blowouts and dunes are being naturally stabilized (da Silva et al., 2013; Jackson et al., 2019; McKeehan and Arbogast, 2023; Osswald et al., 2019; Van Boxel et al., 1997), the blowouts present in Ancão Peninsula are experiencing an ongoing trend of development and expansion up to this day, which agrees with results shown in other works (Smyth et al., 2020).

5.2. *Implications for dune management under climate change and rising seas*

The potential management measures applicable to ensure the future adaptability of the receding dune in the Ancão Peninsula must be evaluated carefully. Attempting to stabilize both the dune and the blowouts with fences would probably be counterproductive, given the recent evolution of this coastal segment (dominated by retreating rates; Kombiadou et al., 2019) and the narrow beach that facilitates winter waves reaching the dune toe during high-tide (Fig. 1d). This diverges from the historical management practices that placed fences on the area, which have been destroyed by the sea. On the other hand, the existing periodic nourishments performed up-drift are necessary to impede an accelerated foredune retreat in this sector of the Ancão Peninsula that would cause the full erosion of the dune ridge (see Ferreira et al., 2006). The past nourishment in up-drift sectors prevented further shoreline retreat but have not led to dune recovery on the study area, since this sector mostly functions as a bypass zone for longshore transport directed towards the Ancão Inlet at the eastern end of the Ancão Peninsula (Fig. 1c).

As a consequence of the natural stabilization of coastal dunes observed in recent decades (Jackson et al., 2019), alternative practices to dune stabilization involve artificially excavating dune notches to promote onshore sand transport and to restore dune aeolian dynamics (Castelle et al., 2019; Ruessink et al., 2018; van Kuik et al., 2022) while enhancing back-dune plant biodiversity. However, some authors expressed clear opposition to interfering with dune natural evolutionary processes if not proven its necessity and possible side effects (Delgado-Fernandez et al., 2019). In our case, finding a conclusive solution for the foredune retreat in the Ancão Peninsula is challenging. Due to a narrow beach and winds unable to transfer sand up the stoss and down to the lee, the blowouts are the only mechanism in this barrier that have successfully transferred sand inland at specific points, enhancing the dune's resilience in targeted areas. Considering this, it may be prudent to allow the dune and blowouts to evolve naturally, as stated by Delgado-Fernandez et al. (2019). However, as a downside to the continuity of transfers of sediment inland through the blowouts, if these blowouts continue to develop, the dune crest will keep lowering, increasing the vulnerability of these areas to overwash.

Any solution would require a comprehensive understanding of the dune behaviour. Firstly, it would be important to better understand whether the sediment transferred through the blowouts originates from the beach, the dune, or both, before any intervention is made. Secondly, the solution must carefully consider the rate of blowout development or elongation (around 1 m/year) in relation to the current rate of foredune retreat in the area where the blowouts are located (around 0.3 m/year over the last six decades; Kombiadou et al., 2019). Thirdly, solutions would need to account for the expected increase in sea-level attributed to climate change. If the retreat rates would be to increase (no nourishment or additional effects of sea-level rise) the dune ridge and the blowouts would probably be destroyed (as suggested by Ferreira et al. (2006). However, if the area is let to evolve, with added sediment sources (up-drift nourishments) and dynamic blowouts, it would naturally adapt to sea-level rise by slightly migrating inland (dune rollover by blowout action), without no major consequences. A resilient dune, adapted to sea-level rise, will need to have active blowouts delivering sediment inland, and promoting vertical accretion of the back-barrier. Nevertheless, to mitigate excessive dune fragmentation, informative panels could be placed contributing to minimize human pressure and uncontrolled trampling in the area.

6. Conclusions

This work analysed the evolution of a series of blowouts located on Ancão Peninsula (south Portugal) from 1972 to 2021. Over the past 49 years, these blowouts have undergone significant spatiotemporal changes and displayed a net gradual expansion trend arising from the interplay of atmospheric, marine, biological and human processes. The study identified several blowout evolutionary phases as well as the triggers involved and the associated temporal scales. On one hand, the blowout genesis phase (notch formation) primarily resulted from physical external factors, such as non-storm low-to-moderate winds eroding sand from dune scarp irregularities formerly created during extreme events. This initial phase lasted around 1 or 2 years. The blowout development phase mainly involves expansion and rotation of the most developed blowouts towards the ENE direction. It was controlled by external physical and human forcing (e.g., winds, fencing), and blowout internal factors such as size and orientation (large blowouts elongated inland faster than medium and small blowouts, while lobe sealing occurred more rapidly in shore-oblique blowouts compared to shore-normal ones). This development phase is still ongoing and has persisted for more than three decades in some blowouts. While a complete blowout decay phase was not observed, natural re-vegetation and sealing occurred over 29 years in a large blowout. Additionally, artificial sealing induced by fencing occurred in small blowouts and notches, lasting for 4 years, being the only phase reversal observed over the entire period. These findings also revealed that the blowout evolutionary phases identified can be concurrent and affect each blowout differently, and that a full blowout life cycle (including genesis, development, and decay) did not occur within the 49-year period. Furthermore, based on the expressed results it can be concluded that blowout lifetimes in Ancão Peninsula are likely to extend for more than five decades.

The retreating foredune on the Ancão Peninsula (materialized in the formation of dune scarps and localized incisions during storm periods) seems to be already adapting to rising sea levels and storm impacts by transferring sediment inland through the blowouts. Since the back-barrier is a natural area without immediate human infrastructure or services at risk, allowing the system to evolve naturally including the development of blowouts would probably be the most appropriate management measure for the area.

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CRediT authorship contribution statement

Lara Talavera: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Susana Costas:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Data curation, Conceptualization. **Óscar Ferreira:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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