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Forecasting coastal dune mobility: A logistic regression model driven by meteorological data and climate indices

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Abstract

Predicting dune mobility under changing climatic conditions remains a challenge in aeolian geomorphology, particularly in data-scarce regions. This study presents a novel application of binomial logistic regression to forecast dune activation and migration using readily available meteorological data. We combine established dune mobility indices (Tsoar and Lancaster) into a new integrated index (TsoLa) and evaluate its performance against observed dune migration rates derived from satellite imagery. The model incorporates wind speed, precipitation, and the Southern Annular Mode (SAM) as predictors, achieving robust predictive accuracy (AUC > 0.75) for two distinct coastal dune fields in NE Patagonia, Argentina. Our results demonstrate that even with standard climatic inputs, logistic regression can effectively identify periods of dune activity, offering a low-cost tool for coastal management. The approach is transferable to other aeolian systems, providing a framework for assessing dune dynamics under current and future climate scenarios.

1. Introduction

Predicting the mobility of coastal dunes in response to climatic variability remains a significant challenge in aeolian geomorphology (Hugenholtz and Wolfe, 2005; Levin et al., 2014). Dune systems are dynamic landscapes that reflect complex interactions between wind energy, sediment supply, vegetation cover, and climatic oscillations (Hesp and Thom, 1990; Tsoar and Blumberg, 2002; Marcomini and Maidana, 2006; Yizhaq et al., 2007, 2013; Miot da Silva and Hesp 2013; Miot da Silva et al., 2013; Hoover et al., 2018; Louassa et al., 2018; Gao et al., 2023; Ren et al., 2024). While traditional approaches, such as drift potential calculations and mobility indices, provide valuable descriptors of wind-driven sediment transport (Fryberger and Dean, 1979; Lancaster, 1988; Tsoar, 2005), they offer limited predictive capacity for forecasting dune activation or stabilization over time. This methodological gap is particularly relevant in the context of climate change, where shifts in wind regimes, precipitation patterns, and storm frequency may alter dune behavior with consequences for coastal ecosystems and human infrastructure (Jackson et al., 2019a; Hesp et al., 2022).

Statistical modeling presents a promising pathway to bridge this gap. Binomial logistic regression is well-suited for predicting binary geomorphic outcomes—such as dune migration versus fixation—based on continuous environmental predictors. This method was first developed by Hosmer and Lemeshow, (1980) and Lemeshow and Hosmer (1982), and has been successfully applied in related environmental fields to model landslide susceptibility (Ohlmacher and Davis, 2003; Lombardo et al., 2015), soil distribution (Giasson et al., 2006; Abdel–Kader, 2011), vegetation dynamics (Rudgers and Maron, 2003; Andrew et al., 2012; Snedden and Steyer, 2013; Gallego–Fernández et al., 2015), and extreme climatic events on coastal environments (Koerth et al., 2013; Ozbas and Greenberg, 2013; Pour et al., 2014), yet its application to coastal dune mobility remains notably limited. The few existing studies that employ logistic regression in coastal contexts have focused primarily on habitat change (Brus et al., 2016) or storm damage (Ozbas and Greenberg, 2013), rather than on predicting dune activity from routine meteorological data.

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

The potential of logistic regression for dune studies lies in its ability to integrate multiple climatic variables, including wind speed, precipitation, and large-scale atmospheric indices into a single probabilistic framework (Hosmer et al., 2013; Sperandei, 2014). Unlike descriptive indices, a well-calibrated regression model can provide forecast probability of dune activation, offering a more dynamic tool for land management and risk assessment. Moreover, by relying on standard meteorological observations, such models can be applied in data-scarce regions where more complex numerical simulations are not feasible (Michel et al., 2018).

This study addresses this methodological opportunity by developing and validating a binomial logistic regression model to predict dune mobility in the coastal dunefields of northeastern Patagonia, Argentina. This region serves as an ideal natural laboratory due to its strong climatic forcing, well-documented aeolian activity (Carbone et al., 2007; Kokot and Favier–Dubois, 2017; Toffani et al., 2024), and availability of long-term meteorological records. The integration of the Southern Annular Mode (SAM), a key driver of extratropical climate variability in the Southern Hemisphere (Fogt and Marshall, 2020), further allows us to examine how regional atmospheric circulation patterns influence local dune dynamics.

The primary objectives of this work are 1) to develop a predictive logistic regression model that links meteorological variables and climate indices to the probability of dune activation; 2) to validate the model against multi-decadal records of dune migration derived from remote sensing, and 3) to assess the transferability of the modeling framework and its potential for application in other aeolian environments worldwide.

By framing our research around methodological innovation, we aim to provide a generalizable, accessible tool for forecasting dune activity—one that complements existing descriptive approaches and supports proactive coastal management in a changing climate. The study of these landforms is important because they constitute the first barrier against storm impacts, protecting coastal communities from extreme events and serving as freshwater reservoirs for nearby populations (Rusticucci et al., 2016; Portz et al., 2021).

2. Study area

2.1 Geographic and Demographic Context

The study area encompasses the northern coast of the San Matías Gulf, in northeastern Patagonia, Argentina, extending approximately 180 km from the mouth of the Negro River to the town of San Antonio Oeste (SAO) (Fig. 1). This area includes a series of villages and recreational areas, such as El Cóndor, La Lobería, Bahía Rosas, Bahía Creek, Caleta de los Loros, San Antonio Este and Oeste, and Las Grutas (Carbone et al., 2007; Kokot and Favier–Dubois, 2017). The combined permanent population of these towns was 22,205 inhabitants in 2010 (INDEC, 2010), with a significant seasonal increase due to tourism, particularly in Las Grutas, which averaged 118,000 visitors annually between 2006 and 2023 (INDEC, 2023). The area is connected by National Route No. 3 and Provincial Route No. 1, the latter running parallel to the coast. The presence of natural protected areas—Bahía de San Antonio, Punta Bermeja, and Pozo Salado–Caleta de Los Loros–Punta Mejillón—highlights the region's ecological value, hosting diverse flora

https://doi.org/10.5194/egusphere-2026-377
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and fauna, as well as archaeological sites evidencing human occupation since at least 6,000 yrs BCE (Favier–Dubois and Kokot, 2011; Marcos and Mancini, 2012; Favier–Dubois, 2013).

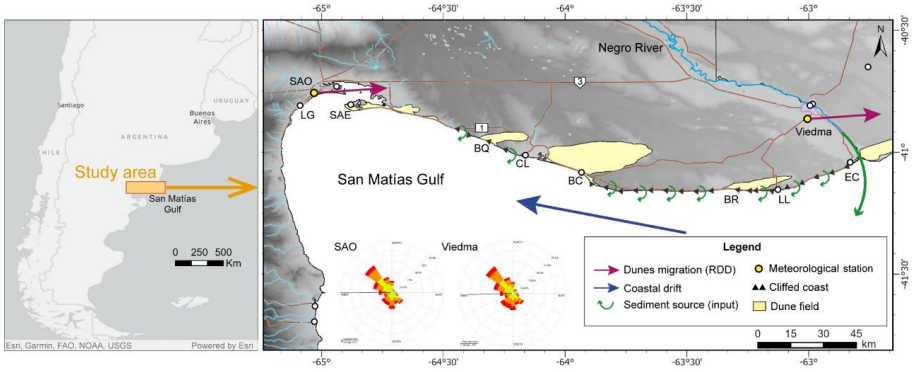

Figure 1. Study area. Meteorological stations, dune fields, and coastal villages. LG: Las Grutas, SAO: San Antonio Oeste, SAE: San Antonio Este, BQ: Bajo la Quinta, CL: Caleta de Los Loros, BC: Bahía Creek, BR: Bahía Rosas, LL: La Lobería, EC: El Cóndor. SAO and Viedma sand roses are present. Argentina map powered by Esri. DEM basemap from Instituto Geográfico Nacional.

2.2 Climate

The climate is classified as cold semi-arid (BSk) according to the Köppen–Geiger system (Peel et al., 2007). Mean annual temperatures range from 14° C to 17° C, with maxima in January (22.2–23.6 ° C) and minima in July (7.1–7.5 °C) (Fig. 2). Annual precipitation increases from west to east, averaging 292 mm in SAO and 383 mm in Viedma for the 1991–2020 period, with higher values typically recorded in late summer and autumn (Servicio Meteorológico Nacional [SMN], 2024). Annual evapotranspiration ranges from 1,050 to 1,485 mm, and mean air humidity was 57 % during 1961–2000 (Genchi et al., 2010; Bohn et al., 2014).

https://doi.org/10.5194/egusphere-2026-377
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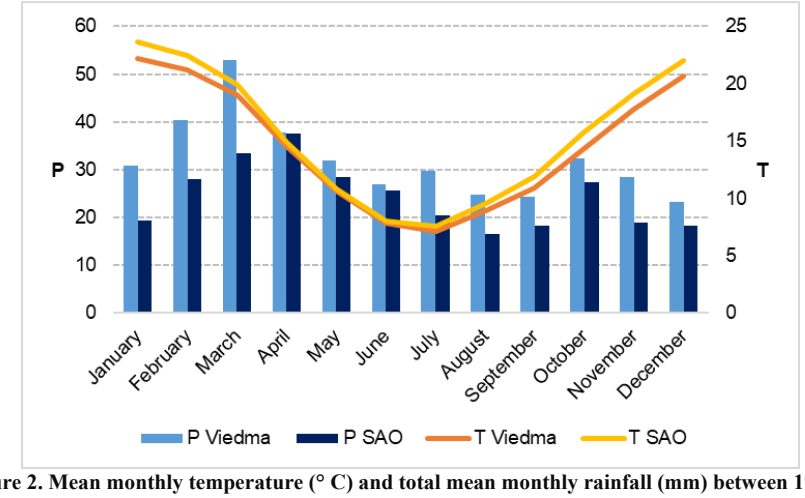

Figure 2. Mean monthly temperature (° C) and total mean monthly rainfall (mm) between 1991 and 2020 registered in Viedma Aero and San Antonio Oeste Aero meteorological stations. P: precipitation; T: temperature.

The region lies within the belt of mid-latitude westerlies, driven by the South Pacific and South Atlantic anticyclones and the subpolar low-pressure channel (del Valle et al., 2008; Rusticucci et al., 2016; Montes et al., 2017). These winds induce a mean surface circulation towards the E–ENE (Saavedra, 2011; Pisoni, 2012). Wind speeds are generally highest during the austral summer, exacerbating aridity in an already dry environment shaped by the rain-shadow effect of the Andes (Montes et al., 2017). Dominant summer wind directions are W, SW, and NW. Easterly winds, associated with sea breezes, are more frequent in winter, bringing moisture, cloud cover, and dew (López Alfonsín et al., 2012; Agosta et al., 2019).

The Southern Annular Mode (SAM) is the dominant mode of extratropical climate variability in the Southern Hemisphere. Its positive phase is associated with a poleward contraction and intensification of the westerly wind belt, leading to warmer, drier conditions at mid-latitudes (~40° S). Conversely, the negative phase is characterized by increased precipitation, cooler temperatures, and a northward expansion of storm tracks (Berman et al., 2012; Fogt and Marshall, 2020). A positive trend in the SAM index has been observed since the mid-20th century, particularly in summer, linked to greenhouse gas increases and stratospheric ozone depletion (Fogt and Marshall, 2020).

The El Niño–Southern Oscillation (ENSO) also influences regional climate. El Niño events are typically associated with increased annual precipitation (up to +50 mm) and higher autumn-winter temperatures in the study area, while La Niña phases correlate with reduced precipitation and cooler summers (SMN, 2014). The interplay between SAM and ENSO can amplify or attenuate their individual climatic signals (Rusticucci et al., 2016).

The tides in the San Matías Gulf are semidiurnal, with a mean range of 6.67 m at San Antonio Este and 3.35 m near the Negro River mouth. The maximum high tide reaches 9.62 m and the minimum low tide is 0.14 m (SHN, 2024). Typical wave heights range from 0.5 to1.5, reaching up to 3 m during storms, with periods of 7-10 s (Wörner et al., 2019).

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

2.3 Geology and geomorphology

San Matías Gulf covers approximately 18,000 km² with a maximum depth of 160 m (Isla, 2013). The gulf was flooded around 11,000 yrs BCE, with the post-glacial marine transgression peak (~6,000 yrs BCE) reaching about 6 m above present sea level, flooding depressions that now form coastal inlets and tidal flats (Isla, 1989; Mancini et al., 2005; Favier–Dubois and Kokot, 2011). A subsequent sea-level drop of 2–4 m, coupled with abundant sand supply and persistent westerlies, favored the development of extensive transgressive dunefields (Isla, 2013, 2017; Sander et al., 2018). Sand availability has also been linked to humidity fluctuations over the last 7,500 yrs (Marcos et al., 2014), consistent with typical formation mechanisms for transgressive coastal dunefields (Hesp, 2013).

The northern coast of the gulf features active sea cliffs fronted by beaches, backed by cliff-top dunes where cliffs are present, and transgressive dunefields where cliffs are absent (Toffani, 2020). Major dune fields include Bahía Rosas (largely stabilized), Bahía Creek, Bajo la Quinta, San Antonio Este/Oeste, and El Cóndor-Villa 7 de Marzo (Table 1, Fig. 3) (Carbone et al., 2007; Cortizo and Isla, 2012; Kokot and Favier–Dubois, 2017; Vergara Dal Pont et al., 2017; Sander et al., 2018).

The cliffs are composed of sedimentary formations ranging from Oligocene to Holocene age, including the Gran Bajo del Gualicho, Río Negro, Baliza San Matías, Tehuelche, and San Antonio formations (Andreis, 1965; Angulo et al., 1978; Lizuain and Sepúlveda, 1978; Sepúlveda, 1983). These deposits, representing continental and marine facies, are the primary sediment source for the dunes, via cliff erosion, beach/tidal flat reworking, and dune recycling (Gelós et al., 1990; Zavala and Freije, 2005; Fucks et al., 2012; Toffani et al., 2020). Sandstone compositions indicate a dominant volcaniclastic contribution from the North Patagonian Cordillera, mixed with quartz-rich sand derived from the Holocene transgression and fluvial input from the Negro and Colorado rivers (Gelós et al., 1990).

Table 1. Presence or absence of spits, maximum dune width and height, dune migration rate, and direction of the transgressive dune fields within the study area. * No data available. Data sources: San Antonio Oeste (SAO)- San Antonio Este (SAE) (Carbone et al., 2007; Kokot and Favier–Dubois, 2017); Bajo la Quinta (Favier–Dubois and Kokot, 2011); Bahía Creek (Sander et al., 2018; Toffani, 2020). El Cóndor (Vergara Dal Pont et al., 2017); and Villa 7 de Marzo (Cortizo and Isla, 2012).

	SAO-SAE	Bajo la Quinta	Bahía Creek	El Cóndor	7 de Marzo
Max width (km)	4	3	14	1	4.5
Max height (m)	10	20	16	6	11
Migration direction	E-NE	ENE	ENE	NE-ENE	NE-ENE
Migration rate (m yr^{-1})	4	*	10	7	5-9
Spits	Yes	No	Yes	Yes	Yes

The dunefields exhibit significant spatial variability in morphology, size, and activity (Table 1, Fig. 3):

San Antonio Oeste/Este (SAO/SAE): The dunefield extends up to 4 km in width, featuring barchanoid and transverse ridges, and blowouts. Dune heights reach up to 10 m, composed of fine to

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

medium sand, migrating at an average rate of 4 m yr^{-1} towards the E–NE (Carbone et al., 2007; Kokot and Favier–Dubois, 2017).

Bajo la Quinta: An active dunefield buries Pleistocene-Holocene deposits. Dunes can reach 20 m in height and include barchanoid, transverse, and oblique forms (Favier–Dubois and Kokot, 2011).

Bahía Creek–Caleta de Los Loros: This is the largest dunefield in the study area, extending over 36 km in length and 5–14 km in width. It features a complex assemblage of crescentic, linear, parabolic, embryo, foredunes, cliff-top, and climbing dunes, with minor occurrences of oblique, reverse, and star dunes. Active dunes cover ~168 km^2, reach heights up to 16 m, migrate ENE at 6–10 m yr^{-1}, and are composed of medium to fine sand (Sander et al., 2018; Toffani, 2020). Vegetation patches, notably *Sporobolus rigens* and *Hyalis argentea*, form nebkhas.

El Cóndor–Villa 7 de Marzo: Near the Negro River mouth, this field consists of barchanoid and parabolic dunes extending 1–4.5 km inland. Migration is towards the NE–ENE at rates of 7 m yr^{-1} (El Cóndor) and 5–9 m yr^{-1} (Villa 7 de Marzo) (Cortizo and Isla, 2012; Vergara Dal Pont et al., 2017).

This diverse and dynamic coastal setting, with its well-defined climatic forcing, clear sediment sources, and varied dune morphologies, provides an optimal natural laboratory for developing and testing a predictive model of dune mobility based on meteorological parameters.

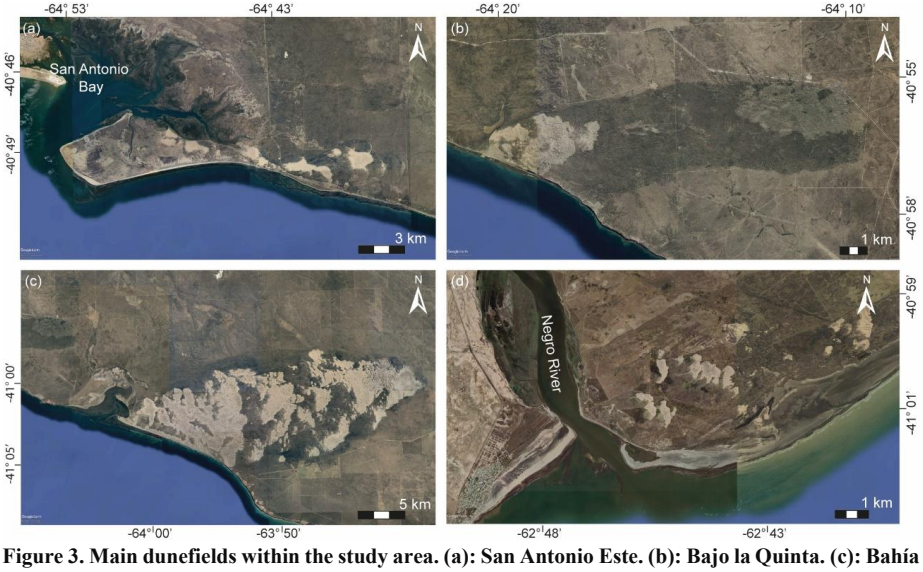

Figure 3. Main dunefields within the study area. (a): San Antonio Este. (b): Bajo la Quinta. (c): Bahía Creek. (d): El Cóndor-Villa 7 de Marzo. Imagery © 2025 Airbus, Map data © 2022-2024 Google.

3. Methods

Climatic data were obtained from the Viedma Aero and San Antonio Oeste Aero (SAO) meteorological stations operated by the SMN. The study period was 1991-2020, during which at least hourly records were collected from 6 a.m. to 11 p.m. This time frame corresponds to a standard reference

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

period for regional climatic studies, as recommended by the World Meteorological Organization (Wang, 2005). In Viedma, the data were recorded 7 m above the ground, while in SAO, they were recorded 20 m above the ground. Both datasets were normalized to 10 m standard acquisition data height (Touma, 1977; Robeson and Shein, 1997; Klink, 1999), according to the following Eq. (1) (Guevara Díaz, 2013):

$$Vz/Vref = (Z/Zref) \wedge a, \quad (1)$$

where V_Z is the wind speed to be estimated at the height (Z), where the measurement was taken; V_{ref} is the measured wind speed; Z_{ref} is the standardized height above the ground; and "a" is the wind shear exponent (a=0.2 in this study, corresponding to crops and bushes).

Hourly wind speed and direction (grouped monthly), total monthly precipitation, and mean monthly temperature data were analyzed. In addition, values for the SAM and the Southern Oscillation Index (SOI) were analyzed, obtained from the Natural Environment Research Council–British Antarctic Survey (NERC–BAS) and the National Oceanic and Atmospheric Administration (NOAA), respectively. Wave height data were downloaded from a Copernicus reanalysis, while cattle population was obtained from several censuses from the Instituto Nacional de Estadística y Censos (INDEC) between 1960 and 2018.

Wind speeds exceeding 6.17 m s^{-1} were considered sufficient for sediment transport, based on Toffani's (2020) calculations, which considered local grain size, environmental conditions, and Bagnold's (1954) equations for the friction speed threshold, when sediment transport begins and the minimum velocity threshold for grains to travel by saltation. Annual and seasonal DP were calculated according to the formula developed by Fryberger and Dean (1979):

$$Q \propto V^2(V - V_t) * t, \quad (2)$$

where Q represents transported sediments within a certain time t, V is the mean wind speed during t time, V_t is the minimum speed for wind saltation transport, and t is the wind blow time as a percentage. The Fryberger and Dean's (1979) method was applied using wind velocity data expressed in knots, with 16 directional classes based on geographic coordinates (each 22.5°). DP indicates wind energy environments classified as low (<200), mean (200–400), and high (>400). From these, the RDP and RDD were calculated. This approach is commonly used to assess regional wind intensity and sand transport in areas receiving more than 50 mm of annual rainfall (Levin et al., 2014).

The Lancaster (1988) and Tsoar (2005) mobility indices were calculated to estimate a measure of dune migration:

$$M = \frac{DP}{1000 - (750\frac{RDP}{DP})} \quad (3)$$

$$M = W/(P/PE) \quad (4)$$

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

Equation (3) represents the Tsoar index, which has been widely used to study dune fields across diverse environments worldwide, subjected to different climatic conditions. This index assumes that wind intensity is the most important factor in dune activity and is valid for sites with annual rainfall greater than 50 mm. Values below 1 represent fixed or vegetated dunes, whereas values above 1 correspond to dunes that are fully active or lack vegetation growth (Tsoar, 2005). Equation (4) represents the Lancaster index, where W is the wind percentage above the sand transport threshold, P is precipitation, and PE represents potential evapotranspiration, obtained using the Thornthwaite equation (Thornthwaite, 1948). This equation has also been successfully applied to assess dune behavior across different environments. According to Hugenholtz and Wolfe (2005), dunes are classified as inactive when $M<50$, as active crest dunes when $50<M<100$, as active dunes except the interdune area when $100<M<200$, and as fully active dunes when $M>200$. For this study, dunes were considered active only when both the Tsoar index exceeded 1 and the Lancaster index exceeded 50 at the same time. This new index is referred to here as the TsoLa index.

Satellite and aerial images were processed to estimate dune migration rates between 1986 and 2023. Visible-spectrum images with a spatial resolution of 1.05 to 1.25 m and three bands, corresponding to the years 2003, 2004, 2009, 2010, 2013, 2016, 2019, 2020, and 2023, were obtained from Google Earth. Additionally, a 1986 aerial image with 2.35 m resolution and three bands was obtained from the Instituto Geográfico Nacional. Due to cloud cover, some dune fronts were not identified in the 2009 image from Viedma. The images were processed using ArcGIS Pro 3.4.0. They were georeferenced using control points, orthorectified, and projected to the WGS84 UTM Zone 20 S coordinate system. Dune fronts and selected precipitation ridges were drawn manually. To quantify migration rates, points were automatically placed at 50 m intervals along the reference line, and orthogonal distances between those points and the subsequent year's dune front position were measured to establish migration rates. The root mean square error (RMSE) values were always below the spatial resolution of the images, indicating minimal position error. Meteorological data from the SAO station were compared with dune activity in the San Antonio Este dunefield, located 13 km away. Likewise, data from the Viedma meteorological station were compared to the El Cóndor-Villa 7 de Marzo dunefield, located 26 km away, distances equal to or less than those considered acceptable by Hugenholtz and Wolfe (2005).

For the statistical analysis, RStudio software (version 2024.12.0), including the boot, broom, car, ggeffects, ggplot2, glm2, glm.predict, glmtoolbox, mosaic, ResourceSelection, ROCR, sjPlot, and vcd packages, was used to perform a multiple binary logistic regression, following the guidelines proposed by Hosmer and Lemeshow (1980), Kalil et al. (2010), and Stoltzfus (2011). This statistical method is used to establish the relationship between a set of continuous independent predictor variables and a binary categorical variable to model the probability of occurrence of an event, for which variables with $p<0.05$ were considered significant, represented as $Pr(>|z|)$ in the software calculations (Zhu, 2016).

To perform the logistic regression, the independence of the predictor variables was considered through statistical correlation tests using the "cor.test()" function, with significance defined as $p<0.05$ (Schober et al., 2018). Colinearity was evaluated to exclude correlated variables, seeking values closer to 1 (Daoud, 2017). Likewise, the less frequent results concerning the number of independent variables were considered to avoid overfitting (ratio equal to or greater than 10) (Kalil et al., 2010). The outliers were calculated based on the third quartile plus 1.5 times the interquartile range. However, they were retained in

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

the analysis as they were interpreted as valid extreme environmental values rather than measurement errors. Once the individual variables met the selection criteria, they were combined in the model, which was tested using the "stats::step(model)" function to identify if the overall model performed better with or without each variable. Thus, the final models included monthly values (1991–2020) of the SAM index, total monthly precipitation, and monthly average wind speed as independent predictor variables. Temperature, potential evapotranspiration, and soil moisture were excluded due to multicollinearity, while wave height, cattle population, and SOI and NDVI indices were excluded to improve the model performance. Moreover, monthly data for cattle and NDVI were considered unreliable due to limited availability and minimal temporal variability. The binary categorical variable was defined using a combination of the Tsoar and Lancaster indices and RDD values. A value of 0 was assigned when the dunes behaved as fixed in at least one index and/or when the RDD values ranged between 181° and 360°. Conversely, a value of 1 was assigned when they behaved as active in both indices and the RDD values ranged from 1° to 180°, consistent with the general drift direction for dunes along the coast.

The estimated probability for each model, known as the Logit function ($\hat{\boldsymbol{p}}$), is:

$$\hat{p} = (e\text{^}(\beta 0 + \beta 1X1 + \ldots + \beta nX))/(1 + e\text{^}(\beta 0 + \beta 1X1 + \ldots + \beta nX))$$

$$= ln\,(\hat{p}/(1 - \hat{p})) = \beta 0 + \beta 1X1 + \ldots + \beta nX, \quad (5)$$

where $X1$, $X2$, …, Xn are the different predictors and $\beta 1$, $\beta 2$, …, βn are their associated coefficients (Herrera Briones, 2023). If the regression coefficient $\boldsymbol{\beta i}$ is positive (negative), an increase in the explanatory variable $\boldsymbol{Xi}$ increases (decreases) the probability of the event ($\hat{\boldsymbol{p}}$) (Sperandei, 2014). The inverse function of the Logit is the cumulative distribution function, also known as the sigmoid function, which is used to plot the probabilities of occurrence of an event (Jansche, 2005).

To build the statistical model, the dataset was randomly split, allocating 70 % for training and 30 % for testing. The accuracy of the models for both subsets was evaluated by calculating the proportion of correct predictions made by the model relative to the total number of predictions made. To separate these classes, a threshold value was determined that maximized or minimized a specific metric (between 0 and 1). This optimal cut-off point was identified using the "opt.cut" function. In this study, priority was given to minimizing false negatives, which correspond to cases where dunes mobility is not predicted despite the actual movement, given the potential risks this poses to nearby coastal villages and for coastal management applications based on coastal dunes dynamics. To achieve this, the cut-off value that maximizes sensitivity (true positive rate) was selected. Additionally, the receiver operating characteristic curve (ROC) and the area under the curve (AUC) value were used to evaluate the model's performance. An AUC value greater than 0.5 indicates that the model performs better than random guessing. However, the model is overfitted when this value is close to 1 (Wei and Dunbrack, 2013).

The goodness of fit of the model was evaluated, i.e., how well it can predict whether a dune is fixed or mobile, using the chi-square regression test (with $p<0.05$ considered statistically significant) (Healy, 2006) and the Hosmer–Lemeshow test, where $p>0.05$ indicates adequate fit (Hosmer and Lemeshow, 1980). Finally, internal validation of the predictive values was also performed using a bootstrapping method (Steyerberg et al., 2001).

https://doi.org/10.5194/egusphere-2026-377
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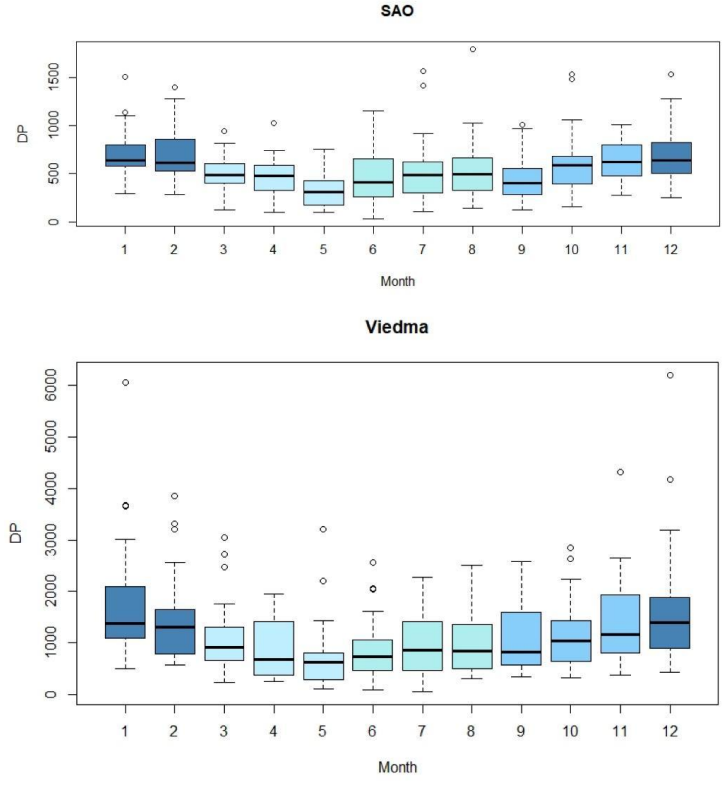
4. Results

According to the established procedures, the optimal model for each location included the Southern Annular Mode (SAM), precipitation, and wind speed as predictor variables. A total of 360 data measurements per variable were used for each meteorological station to develop the models. Overfitting was assessed based on the frequency of the least common outcome relative to the number of independent variables (n=3), resulting in at least 30 events of each possible outcome (0 and 1). Variance Inflation Factor (VIF) values were below 1.08 in SAO and below 1.16 in Viedma, indicating no multicollinearity. Precipitation ranged from 122 mm to 578 mm in SAO and from 214 mm to 653 mm in Viedma, while SAM index values varied between -5.77 and 4.92. For wind, a more exhaustive analysis was performed. Winds exceeding the minimum threshold accounted for 33.7 % of the total observations for the 1991–2020 period in SAO and 30.6 % in Viedma, mainly blowing from the NW and SW in both cases. According to the Tsoar index, dunes were identified as active in 119 months (33.1 %) in SAO and in 268 months (74.4 %) in Viedma. Using the Lancaster index, dunes were classified as mobile during 254 months (70.6 %) in SAO and during 247 months (68.6 %) in Viedma. When both indices were considered simultaneously, active dune conditions were recorded in 82 months (22.8 %) in SAO and in 160 months (44.4 %) in Viedma. Monthly DP values in SAO ranged from 30 to 1,976, averaging 549. In Viedma, DP values ranged from 55 to 6,203, with a mean of 1,176 (Fig. 4). Overall, higher DP values were recorded during the austral summer, with NW, SW, and SE as main components, while lower values were typical in autumn. During the remainder of the year, most records correspond to the NW component, with the addition of the SW component during spring in Viedma, where in general stronger winds were registered (Fig. 5). The RDD values suggest a general trend of dune migration toward the east. Over the full study period, the mean RDD was 90° in SAO and 89° in Viedma. A decreasing trend in DP values was observed in Viedma over time (Fig. 6). In contrast, although fluctuations were recorded in SAO, DP values remained relatively stable over the study period (Fig. 6). RDP values generally follow these tendencies.

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026



346 **Figure 4. Boxplots showing the monthly Drift Potential values obtained from SAO and Viedma**
347 **meteorological stations during the 1991–2020 period.**
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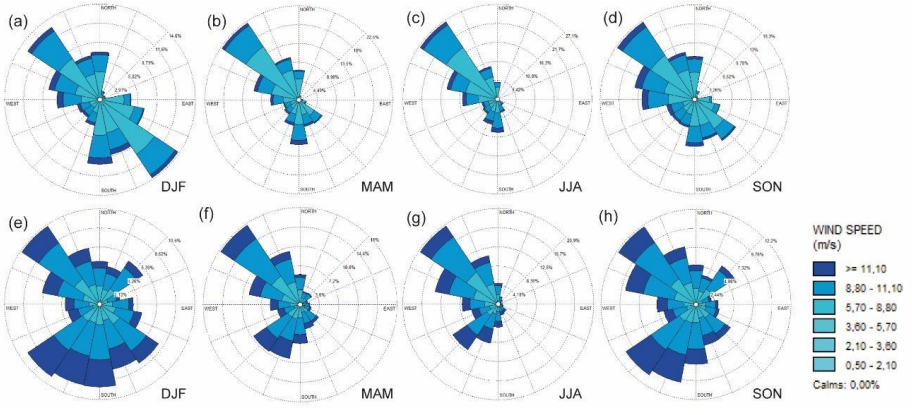


349
350 **Figure 5. Seasonal winds above the sediment transport threshold for the 1991-2020 period. (a-**
351 **d): San Antonio Oeste, (a): summer, (b): fall, (c): Winter, (d): spring. (e-h): Viedma, (e): summer, (f):**
352 **fall, (g): winter, (h): spring.**

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

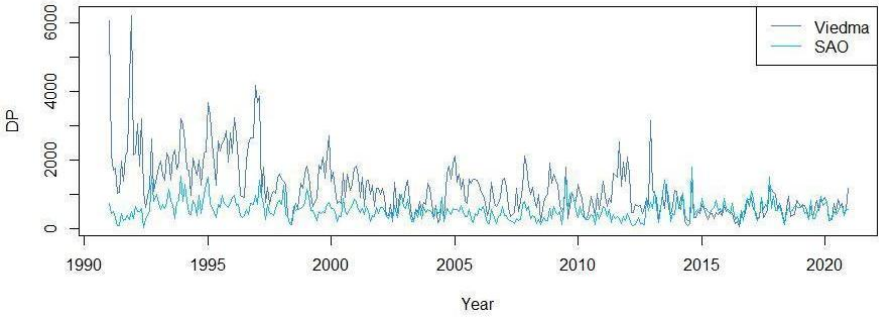


Figure 6. Drift Potential variation between 1991 and 2020, according to the recorded winds in Viedma and SAO.

For both study areas, the logistic regression model identified three significant predictors of dune migration: SAM, precipitation (P), and wind speed (Wind) (Table 2). In the SAO region, significance levels were $p = 0.01$ for SAM, $p = 0.001$ for precipitation, and $p < 0.001$ for wind speed. In Viedma, all three predictors also showed statistical significance ($p = 0.04$ for SAM, $p < 0.001$ for precipitation, and $p < 0.001$ for wind speed). The estimated coefficients indicate that SAM and precipitation have a negative effect on dune migration probability, while wind speed has a positive effect. This suggests that the probability of dune migration (i.e., the event coded as 1) increases when wind speeds are higher or if precipitation and SAM index values decrease. Coefficient values further support this interpretation: in the SAO region, estimates were –0.3 for SAM, –0.04 for precipitation, and 0.64 for wind speed; in Viedma, the values were –0.2, –0.04, and 0.32, respectively. The combined influence of these three variables determines the final predicted probability of dune migration for each observation (Table 2). A response curve was generated to visualize these relationships (Fig. 7), illustrating that dune migration is unlikely when precipitation exceeds 150 mm, wind speeds fall below 20 km h^{-1}, or SAM values are high.

Table 2. SAO and Viedma logistic regression estimates (log-odds), 95% confidence intervals (CI), and p-values are shown for each predictor. p < 0.05 values result significant to the model.

TsoLa San Antonio Oeste			
Predictors	*Estimate*	*CI*	*p*
(Intercept)	-14.52	-19.17 – -10.57	**<0.001**
SAM	-0.30	-0.54 – -0.07	**0.011**
Precipitation	-0.04	-0.06 – -0.02	**0.001**
Wind	0.64	0.46 – 0.84	**<0.001**

TsoLa Viedma			
Predictors	*Estimate*	*CI*	*p*
(Intercept)	-5.15	-7.03 – -3.42	**<0.001**
SAM	-0.20	-0.39 – -0.01	**0.040**
Precipitation	-0.04	-0.06 – -0.03	**<0.001**

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

Wind	0.32	0.23 – 0.42	**<0.001**

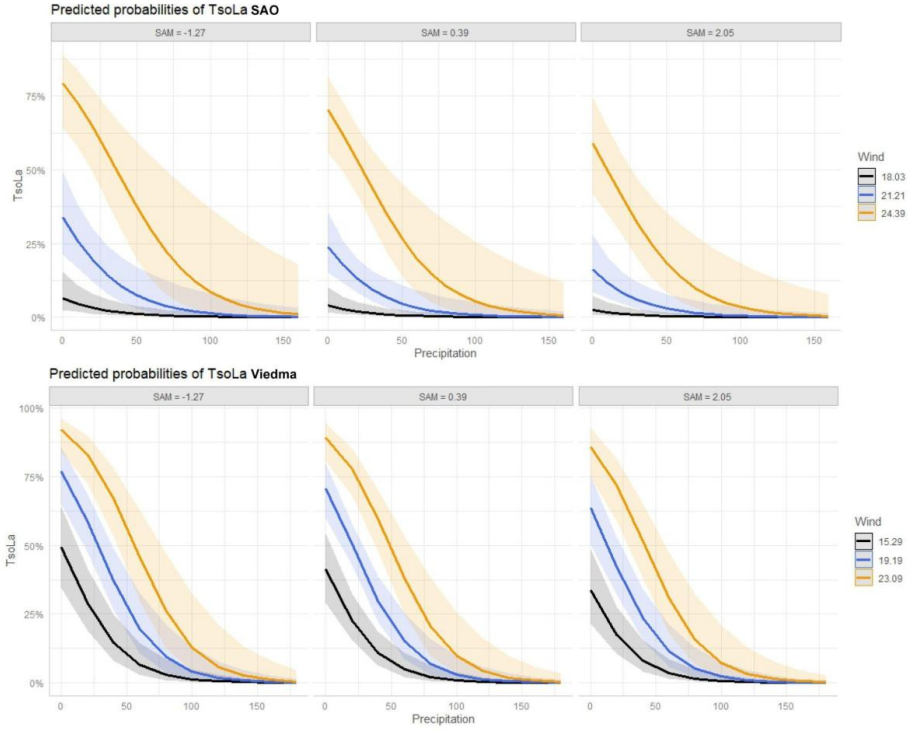
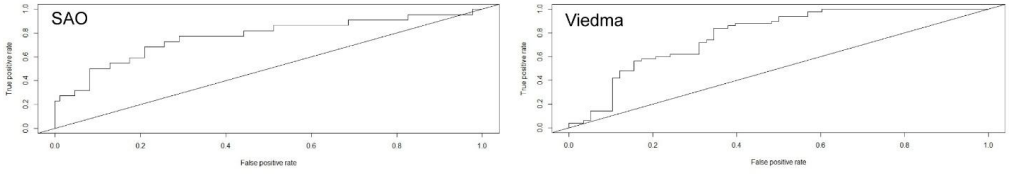


Figure 7. The plots show how the TsoLa probability diminishes when precipitation increases and wind speed is slower for different SAM values in both meteorological stations. SAO curves on top, Viedma curves at the bottom.

The logistic regression models demonstrated a good fit, as indicated by the likelihood ratio test ($p < 0.001$) and the Hosmer–Lemeshow goodness-of-fit test ($p > 0.05$). These results suggest that the models adequately represent the relationship between the predictor variables and dune migration probability. Model discrimination was further assessed using the Area Under the Receiver Operating Characteristic Curve (AUC-ROC), which yielded values of 0.77 for SAO and 0.78 for Viedma, indicating acceptable predictive performance. The optimal classification thresholds (cut-points) were determined to be 0.8 for SAO and 0.4 for Viedma (Fig. 8).



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Preprint. Discussion started: 2 March 2026

Figure 8. Area Under the Receiver Operating Characteristic (AUC-ROC) curves for SAO (left) and Viedma (right).

The models also showed consistent classification performance. In SAO, the model correctly classified 77 % of the training data and 73 % of the test data, while in Viedma, 75 % of the training and 74% of the test observations were correctly predicted (Figs. 9–10). A breakdown of classification performance shows that, for the training data, in SAO, predictions included 57 % true negatives, 20 % true positives, 19 % false positives, and 4 % false negatives (Fig. 9). In Viedma, the distribution was 39 % true negatives, 36 % true positives, 17 % false positives, and 8% false negatives (Fig. 9). For the test data in SAO, dunes were correctly classified as active in 15 % of cases and as fixed in 58 %. False positives accounted for 21 %, and false negatives for 5 % (Fig. 10). In Viedma, dunes were correctly predicted as active in 39 % of cases and fixed in 35 %. False positives represented 7 %, while false negatives reached 19 % (Fig. 10).

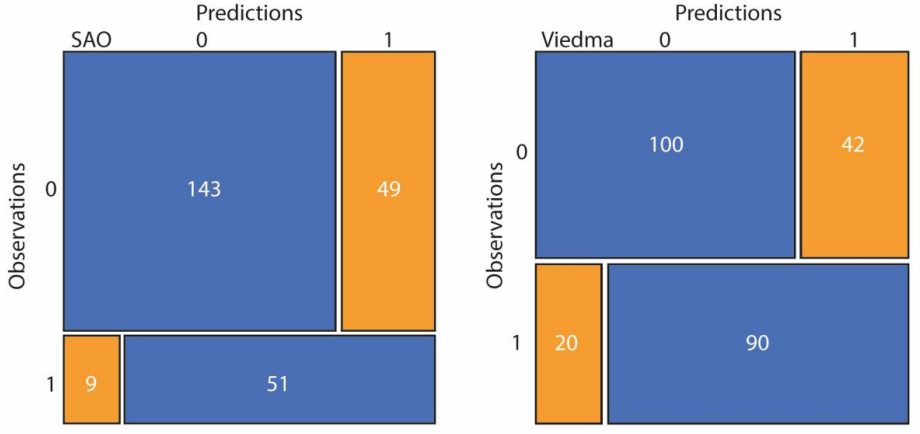

Figure 9. Confusion matrix for the training data in SAO (left) and Viedma (right).

A bootstrap analysis with 1,000 resample attempts with replacement was performed to validate the stability of the fitted logistic regression model. The model coefficients were estimated in each iteration. In SAO, the coefficient associated with the variable Wind had a mean value of 0.635, with a 95 % confidence interval (percentile method) of [0.421, 0.806], suggesting a positive and consistent effect on the probability of TsoLa occurrence. In contrast, SAM and Precipitation showed negative effects, with average bootstrap coefficients of –0.296 and -0.037, and respective 95 % confidence intervals of [-0.553, -0.035] and [-0.060, -0.017]. In Viedma, the coefficient associated with the variable Wind had a mean value of 0.318, with a 95 % confidence interval (percentile method) of [0.218, 0.427]; the coefficient associated with the variable SAM had a mean value of -0.196, with a 95 % confidence interval of [-0.379, -0.035]; and the coefficient related to the variable Precipitation showed a mean value of -0.044, with a 95 % confidence interval of [-0.059, -0.029]. This non-parametric approach enabled a robust assessment of predictor significance without relying on classical model assumptions.

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Preprint. Discussion started: 2 March 2026

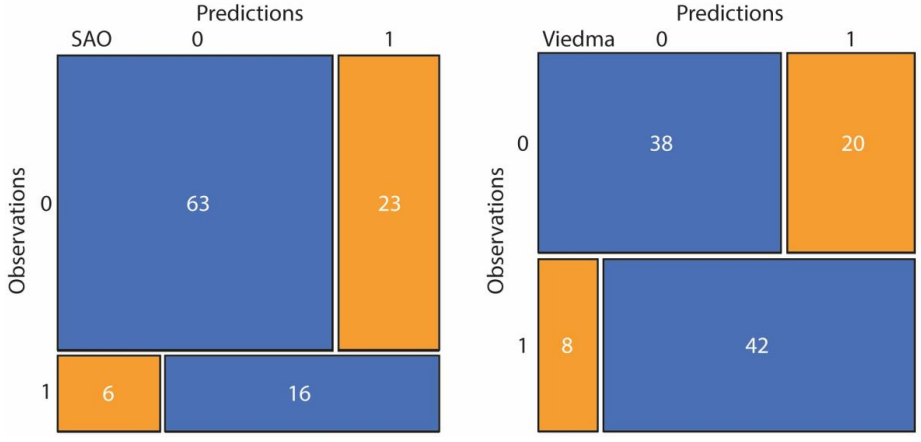
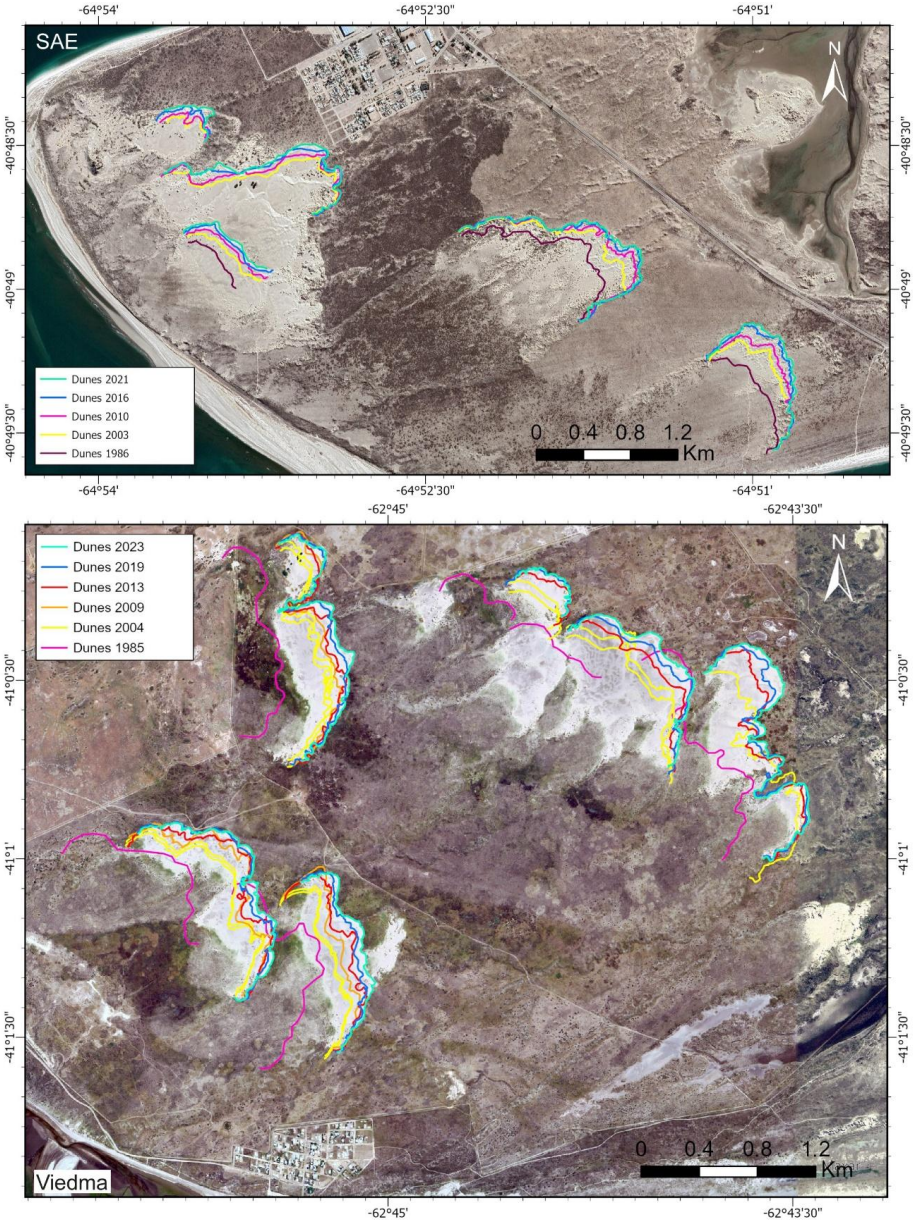


Figure 10. Confusion matrix for the test data in SAO (left) and Viedma (right).

To estimate dune migration over time, different dune fronts from the San Antonio area (1986–2021) and the Viedma/El Cóndor-Villa 7 de Marzo area (2003–2023) were studied (Fig. 11). The dune precipitation ridge was measured at a minimum of 20 points per dune/dunefield for each specific time period. In San Antonio, average migration rates ranged from 2.51 to 6.01 m yr^{-1} (Table 3), with no significant correlation to RDP values, except for one dune (R=0.71). In contrast, in Viedma, the average migration ranged from 2.92 to 10.12 m yr^{-1} (Table 3), showing a general decreasing trend over time and a positive correlation with RDP values for the same periods, R = 0.84 (Table 3). The RDP values were selected because they better represent the wind intensity in relation to the direction of dune migration.

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026



426 **Figure 11. Dune migration between 1985 and 2023 in the San Antonio Este (SAE) area and the**
427 **Viedma–Villa 7 de Marzo areas. Imagery © 2025-2026 CNES/Airbus and Maxar Technologies, Map**
428 **data © 2003-2023 Google.**

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430 **Table 3. Dune migration rates and average RDP values for the 1991-2020 period.**

SAO		1986-2003	2003-2010	2010-2016	2016-2021	R2
	Dune 1	-	2.43	4.45	3.66	0.71

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

	Dune 2	-	3.29	4.11		1.63	0.12
	Dune 3	5.85	5.85	5.22		4.55	0.18
	Dune 4	5.31	3.52	2.43		0.82	0.01
	Dune 5	6.86	3.81	5.40		1.90	0.07
	Mean	**6.01**	**3.78**	**4.32**		**2.51**	**0.07**
	RDP	276.75	233.3	264.92		271.73	-
		1985-2004	2004-2009	2009-2013	2013-2019	2019-2023	R2
	Dune 1	12.26	8.39	2.53	2.42	2.16	0.74
	Dune 2	9	9.37	4.3	3.57	2.31	0.54
	Dune 3	9.52	9.97	4.32	4.02	5.19	0.46
Viedma	Dune 4	8.22	5.01		5.26	4.06	0.81
	Dune 5	8.73	5.77		2.56	0.42	0.84
	Dune 6	13.02	3.6		2.94	3.37	0.88
	Mean	**10.12**	**7.02**	**4.26**	**3.46**	**2.92**	**0.84**
	RDP	718.84	483.94	503.83	336.07	374.65	-

5. Discussion

The statistical significance of wind speed as a predictor of the binomial outcomes of the TsoLa mobility index supports the model's validity. Ultimately, the values of this index are related to this parameter through the DP and RDP values, as defined by the formula used in its calculation. Furthermore, the dominance of the westerlies is reflected in the RDD values. The observed negative relationship between precipitation and dune migration direction may be attributed to increased soil moisture resulting from higher precipitation levels, which restricts dune mobility and promotes their fixation. Additionally, easterly winds (SE) of oceanic origin are typically associated with greater moisture influx inland and increased precipitation. This pattern is consistent with the findings reported by Agosta et al. (2019), especially during austral fall and winter. Both factors influence general dune migration towards ENE, because easterly wind components are less frequent and are usually associated with rainfall, which decelerates dune migration. Finally, the negative estimate value of the SAM in the model can be attributed to its climatological implications. Negative SAM phases are associated with a northward displacement of the mid-latitude westerlies, bringing stronger winds, lower temperatures, and increased precipitation to regions around 40° S. Although precipitation increases slightly, heightened storm activity and lower temperatures are often associated with greater instability in coastal dune fields and the destabilization of vegetated dunes (Jackson et al., 2019a; 2019b). Conversely, during positive SAM phases, the atmospheric circulation shifts southward, leading to more stable weather, weaker winds, higher temperatures, and reduced precipitation in the study area. These conditions generally favor vegetation growth and dune stabilization (Toffani et al., 2024). This highlights the dominant role of wind over precipitation in controlling sediment transport, reinforcing wind as the primary driver of dune mobility. It is also worth to mention that the DP shows a tendency toward higher values during warmer months, likely reflecting periods with longer daylight hours, higher temperatures, and stronger winds. These features favor the drying of the material that may be transported by winds, even though torrential rains can occur.

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

Considering these parameters together with the general decline in dune migration rates, the observed trend can be linked to a progressive greening of the landscape. This process is characterized by increasing vegetation cover and dune fixation due to weaker winds (reflected in lower values of DP and RDP), higher temperatures, and a trend to more positive SAM index values (Toffani et al., 2024). These changes are more pronounced in Viedma. In San Antonio, the slower dune migration rates may be related to dune morphology and sand supply: shorter and "worm-like" dunes there appear to experience faster vegetation colonization (Toffani et al., 2024). Combined with lower sediment supply and wind intensity, vegetation colonization may result in slower dune migration rates not necessarily directly related to the RDP. Therefore, dune stabilization can occur over decadal timescales (i.e., 10 to 20 years) (Delgado–Fernández et al., 2019; Jackson et al., 2019a). Even if wind speed increases, enhanced vegetation cover and dune fixation may prevent increases in dune migration, indicating that the RDP value alone does not fully reflect dune mobility dynamics, being dune mobility also limited by sediment supply. Contrarily, the Viedma area has a greater sand supply due to its proximity to the mouth of the Negro River, allowing the growth of larger transverse dunes, with their migration controlled by transport capability, reflected in the correlation to RDP values. San Antonio receives sand primarily from its narrow adjacent beach and the San Antonio Bay, resulting in a more limited sand budget (Carbone et al., 2007). This contrast highlights the importance of integrating geological and geomorphological variables into predictive models. In addition, mean dune migration rate values are higher in Viedma than in SAE, related to more intensive winds and higher DP and RDP values in the region.

The absence of a significant effect of the regional climate index SOI and the relatively minor influence of SAM compared to precipitation and wind speed in the models may be attributed to a stronger influence of local-scale phenomena driving dune dynamics. The exclusion of SOI is justified by its negligible contribution to the model. SOI reflects conditions associated with El Niño and La Niña events, which in the study area result in relatively minor climatic anomalies: annual precipitation variations of no more than 50 mm and temperature deviations typically below ±0.5° C. However, some authors have reported delayed effects of El Niño over southeastern South America, which may help explain the limited influence of this variable in the current analysis. The reported lag period varies between 5 months in Buenos Aires and 8-13 months in southernmost Patagonia (Schneider and Gies, 2004; Pasquini et al., 2008). Further work is needed to obtain a correct lag period for the SAO and Viedma areas.

The AUC values obtained for the model, 0.77 for SAO and 0.78 for Viedma, indicate a good fit and suggest that the selected predictors can be considered reliable indicators of dune migration dynamics. The distribution of true positives and true negatives confirms that the models perform reasonably well, particularly in identifying stable dune conditions. The Viedma model shows a higher rate of false positives in the test dataset, indicating some limitations in detecting fixed dunes. This reflects the chosen optimum cut value, which prioritizes minimizing false negatives. Despite these strengths, model performance is constrained by the limited number of observations, i.e., 360 records per station. While this sample dataset is sufficient to detect general patterns, the lower number of positive cases in SAO restricts the model's robustness. For those cases, data covering more years can help to improve it. Furthermore, given the values of each variable, it is possible to estimate what values of the remaining variables are needed to get a higher or lower chance of dune migration.

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

With improved datasets, such as higher-resolution livestock data, vegetation index, sediment supply, or wave dynamics, a more accurate and representative model could be developed, allowing for better predictive capabilities. In this study, wave data were obtained from reanalysis sources; however, this variable could be refined using data from nearby buoys. Livestock data are limited to annual records at different governmental agencies, rather than at localized scales near the dune fields. Monthly vegetation indices have poor spatial resolution, with similar values for each month. This lack of variation may be associated with the low resolution or minimal change in vegetation cover over time. Finally, the absence of a reliable method to estimate monthly sediment supply remains a significant gap and its inclusion would substantially improve the model performance. Nevertheless, the current model demonstrates that even with basic meteorological data from standard weather stations, a Binomial Logistic Regression Model can provide a reasonably robust prediction of dune mobility. The development and application of such models is crucial, given that these phenomena already impact, and will continue to impact, nearby populations. Predictive modeling supports more informed and proactive land-use planning and decision-making policies, particularly in coastal areas experiencing population growth and infrastructure expansion. These models gain even greater relevance when combined with field-based observations of dune migration. Incorporating data from additional meteorological stations, integrating reanalysis datasets, and/or adding adjusted early mentioned parameters would further refine and strengthen the model's accuracy. Building comparable models for other coastal or inland regions and including other phenomena may enhance their validity.

The results derived from the DP analysis herein are consistent with findings from other areas along the Argentine coast and Patagonia, including those obtained by Cortizo and Isla (2012) in the south of the Buenos Aires province, where westerly winds also predominate. There, spring and summer exhibit the highest wind intensity, with average DP values around 900 units. Del Valle et al. (2008), in Peninsula Valdés, obtained higher DP values, comparable to the highest values observed at the Viedma meteorological station. The RDD values also suggest predominantly westerly winds throughout the entire year, particularly influenced by the SW and N components. In southern Patagonia, Montes et al. (2015) analyzed the migration rate and direction of certain dunes, which were between 29.6 and 70 m yr^{-1} and towards the E (86° N) between 2003 and 2013 in the central area of the San Jorge Gulf. Additionally, at a site adjacent to Colhué Huapi Lake, Montes et al. (2017) recorded an average dune advance of 45 m yr^{-1} towards the E (95° N). These places exhibit similar dynamics and could serve to upgrade the model and extend it to inland dunes.

6. Conclusions

This study demonstrates that binomial logistic regression provides a robust and transferable methodological framework for predicting coastal dune mobility based on standard meteorological variables. By integrating established wind-based indices (DP, RDP) with a novel mobility index (TsoLa), we developed a probabilistic model that successfully links climatic drivers to discrete geomorphic states (active vs. fixed). The model's strong performance (AUC > 0.75) across two distinct dunefields in NE Patagonia validates its core premise: even with readily available climatic data, it is possible to move beyond

https://doi.org/10.5194/egusphere-2026-377
Preprint. Discussion started: 2 March 2026

descriptive wind roses and mobility indices toward a predictive, probabilistic understanding of dune activity.

Our analysis identified wind speed as the primary and most consistent predictor of dune activation, a finding that reinforces the fundamental role of aeolian forcing in dune dynamics while also providing internal validation for the model's logical coherence. The negative relationships with both precipitation and the Southern Annular Mode (SAM) highlight the moderating effects of moisture availability and large-scale atmospheric circulation. Specifically, the SAM's significant role underscores how regional climate modes can exert a measurable, predictable influence on local-scale geomorphic processes—an important linkage for forecasting dune behavior under future climate scenarios.

The use of common meteorological parameters (wind speed, precipitation) and globally available climate indices (e.g., SAM, ENSO) means the framework can be adapted to other coastal and inland aeolian systems with minimal modification. While applied here in a semi-arid, wind-driven setting, the model structure can accommodate additional site-specific variables such as vegetation indices (NDVI), sediment supply estimates, or anthropogenic factors where data resolution permits.

Notably, the model offers a practical, low-cost tool for land-use planning and proactive coastal zone management. By outputting a probability of dune activation, it enables early identification of periods and locations with higher erosion or encroachment risk, supporting decision-making for infrastructure protection, especially in developing coastal regions vulnerable to climate pressures.

Future research should focus on enhancing the model's spatial and temporal resolution, testing its performance in diverse climatic and geomorphic settings (e.g., temperate coastal dunes, arid continental ergs), and incorporating lagged effects of climate oscillations. The integration of higher-frequency remote sensing data, improved sediment budget constraints, and process-based validation using computational fluid dynamics or cellular automata models will further strengthen the predictive power and physical grounding of this statistical approach. Ultimately, this work establishes a scalable pathway for integrating climatic forecasting with geomorphic hazard assessment, contributing to more resilient management of dynamic dune landscapes worldwide.

Author contribution:

MT conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, and writing (original draft preparation). SC funding acquisition, investigation, resources, supervision, validation, and writing (review and editing).

The authors declare that they have no conflict of interest.

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