# Stabilization at Santinho-Ingleses dunefield, Southern Brazil: What will be the future of sediment input to Ingleses Beach?

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*Abstract— This paper describes the overpassing process using a case study from southern Brazil, that present a decadal pulse of sediment entering in the system. A transgressive dune field extends across a headland from Santinho beach to Ingleses beach. Analysis of precipitation data (1961-2014), wind direction and speed (1964-2014), aeolian drift potential (DP), aerial photographs/satellite images (between 1938 and 2016) and morphological data (2002, 2010 and 2014) make it possible to analyze the decadal-scale dune field evolution. The wind historical data showed southern wind as the stronger, moving the dune crests to north. The rainfall analysis presents an increasing trend leading to a decrease in drift potential and favors dune stabilization by vegetation growth. There is a decadal pulse of sediment inputs to the system, as well. The northern sector of Santinho beach has a positive budget and provides about 6,000m³/year of sediment to the foredune. Then, with southern winds, the sediment migrates into the dune field (about 3,000-5,000m³/year) reaches Ingleses by overpassing, ensuring a positive sediment budget for the system that occurs at east side of the Ingleses beach.*

## I. INTRODUCTION

Coastal dunes develop landward of areas with an ample unconsolidated sediment supply and the grain size is suitable for onshore aeolian transport [13, 15, 18, 31, 54]. Distributed worldwide in association with sandy beaches, they have a wide range of shapes and dimensions related to spatial and temporal variations in sediment input and wind regime [9, 15, 18, 44].

Several coastal dune systems have become increasingly vegetated in recent decades, for example in Africa [28], United Kingdom [43], Europe [12], China [56], Australia [7] and in Brazil [35] is not different.

Santa Catarina Island is located in southern Brazil. It contains numerous headlands, bays, and beaches with transgressive dune fields. Sediment overpassing by dunes is observed on this coast too [6,25, 26, 27, 41; 42].

The headland sediment bypassing (HSB) and overpassing (HSO) is a process in which sediment is transported by wind or waves from the updrift side of a headland to the downdrift side [26, 27]. Both, HSB and HSO are important components of regional sediment budget of some coasts [27, 34, 42].

[53] has shown a significant influence of overpassing on shoreline position, when the shoreline of the northern coast of Santinho accretes between 1 and > 5m/years-[1]

(1957-1978, 1998-2002, 2002-2007, 2010-2012) there is erosion on the Ingleses beach (between -1 and > -5m/years-¹). [6] had showed that this sediment that arrive in ingles dune as a result of overpassing, is transported by waves to the west direction.

The aim of this paper is quantify the overpassing process from Santinho's foredune (updrift) to Ingleses beach (downdrift) by aeolian transport and understand the vegetation cover influence in this process. A multi-decadal scale were used to analyze the overpassing process, based in aerial photography/satellite images, morphological and meteorological data.

## 1.1 The Santinho-Ingleses dunefield

Santa Catarina Island in Santa Catarina State, southern Brazil, lies at 27°S;48°W, in the Subtropical Zone [51]. The climate is humid subtropical (Cfa) or oceanic and subtropical highland (Cfb) with average temperatures in the coldest month below 18°C and in the warmest month above 22°C and hot summers with a trend to concentration of rainfall in these months, but with no dry season [10].

Most rain falls in the summer (36%) and spring (27%), followed by winter (19%) and autumn (18%) [35]. The main meteorological systems responsible for the rains on the state are the cold fronts, the cyclonic vortices, the tropical convection, the ZCAS (South Atlantic Convergence Zone) and the marine circulation [40].

The Santinho-Ingleses dune field migrates northward as a result of strong and frequent southerly winds [5, 19, 41, 54], providing a sediment input estimated around 3.000 m3/year to 10,000m³/year to Ingleses beach [6, 41]. In other words, sand overpassing by the dune field (Fig. 1) provides an important sediment supply to Ingleses beach. [25] analyzing the shore lines, between 1957 and 2012, showed a retraction at Ingleses (about -0,49±0,16 m/ano) and a progradation at Santinho (about 0,25±0,16 m/ano). [6] using a shoreline model show a retreat about 60 m over a period of 100 years on the eastern part of Ingleses were sediment input will stop and around 50 houses can be threatened by erosion. This dune field is the key fact in sediment budget of the study area.
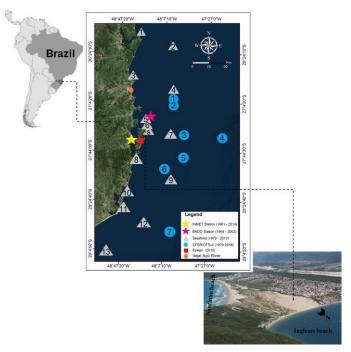


*Fig. 1: Study area location, southern Brazil, coast of Santa Catarina State, Santa Catarina Island. The left star indicates the position of the INMET Station which provided the rainfall data (1961-2014), the right star represents the BNDO data (1964-2002) collected hourly (1979-2016) and the square "A" is EPAGRI of the station 2027 ETE - Insular, "B" is EPAGRI of the station 1006 Florianópolis - Automatic (July to December 2010). The Santinho-Ingleses dunefield migrates northward and thus it is that the overpassing process occurs. Photo by Andrew Short/2014*

## II.    MATERIAL AND METHODS

### 2.1    Wind and Rainfall (1961-2014)

Wind and rainfall databases were compiled using observations and climate simulations from a global reanalysis and atmospheric downscaling. In situ wind speed and direction measurements were provided by the National Oceanographic Data Bank (BNDO), responsible for the meteorological station on Arvoredo Island (pink star in Fig.1). The historical time series from this station covers the period 1964- 2002 and provides values three times a day. The historical series of instrumental rainfall data, relating to 1961 to 2014, was obtained from the National Institute of Meteorology (INMET), represented by the yellow star.

Near-surface wind time series at seven locations were analyzed by the global reanalysis dataset CFSR (Climate Forecast System Reanalysis, [46]), available for the period from 1979 to 2010 and CFSv2 (from 2011 onwards), the blue circles in Fig.1. This reanalysis represents an

improvement in the field of global climate modelling due to this high resolution and advanced data-assimilation techniques. The CFSR global atmosphere resolution is about 0.3 degrees (approximately 32km) for hourly wind data. Beginning in 2011, CFSR has been extended by NCEP's Climate Forecast System Version 2 - CFSv2 [47] operational model.

Meteorological data were also provided by the SeaWind dataset (13 silver triangles), a dynamic downscaling of the atmospheric conditions over the Brazilian Santa Catarina state. This data ware developed to providing the best marine surface wind fields following the methodology of [37]. Using the atmospheric limited-area model WR–ARW (Weather Research and Forecasting model with the Advanced Research dynamic solver, [50], the SeaWind wind and rain data were downscaled from the CFSR global model (1979-2010). The model's resolution were define with 42 vertical hybrid levels (14 first levels below the first 1,000 m) and 3km horizontal resolution. This atmospheric database was validated by means of the data from seven stations: two on Florianópolis island, one offshore on an oil platform (which contains records of winds up to 78 meter altitude) and four pluviometers located along the Itajaí-Açú river (orange circle).

The comparison of SeaWind rainfall (in situ observations) indicates that SeaWind data provide a reliable estimation of daily rainfall (Fig. 2).
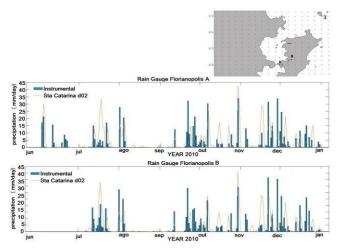


*Fig. 2: Comparison between SeaWind rainfall data (silver line) and gauges (blue bars).*

In order to check the performance of simulated wind data from the CFSR reanalysis and SeaWind dataset, they were compared with available wind measurements at one area closest to the Santinho-Ingleses dunefield, the 5 months record of the EPAGRI station. This area is at western side of the island, about 20km from the dune field, at 10 m height, therefore a higher spatial resolution would

be required to capture local inland wind anomalies between the mountains of the island.

Fig. 3 shows a comparison of the three wind datasets. A clear improvement of the SeaWind downscaling to global reanalysis is evident. It is possible to observe the SeaWind dataset represents wind anomalies in the study area. Local wind variations at high spatial resolution (e.g. hundreds of meters) would require a micro-scale modeling of the dune field and surrounding area.
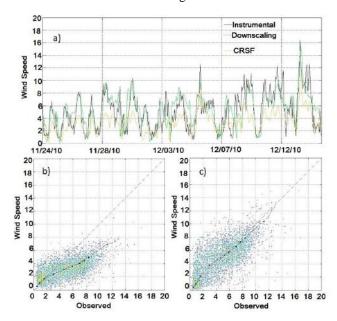


*Fig. 3: (A) Instrumental wind time series (red square in Fig. 1) in silver line, SeaWind with blue line and CFSR data at the inland station of Santa Catarina Island with orange line. (B and C) Scatter diagrams and qq plots of measured values (x-axis) versus CFSR (B) and SeaWind (C) simulated data.*

These different meteorological climate data were use to describe the wind pattern and the historical behavior of Santa Catarina State and the study area. The winds were divided into several other categories (0-3; 3-7; 7-10; 10-13; 13-16; 16-20, 20-25 and >25m/s).

Linear regression analysis was apply to estimate wind trends. The slope of the linear regression model was used to determine the magnitude of the wind speed trend in meters per second per decade (m s-1 dec-1). The nonparametric correlation coefficient of Mann-Kendall´s tau-b [24] was used to measure the statistical significance of annual and seasonal linear trends. The data period examined corresponds to the period covered by topographical surveys, aerial photographs and satellite images.

## 2.2 Aeolian Drift Potential (DP)

Aeolian drift potential was calculated using data for rainless windy days (with precipitation of less than 1 mm), because wet sediment hides the true results of DP. The equation used was developed by [28] (Equation 1). The results are expressed in vector units (u.v.).

$$q = \llbracket V \rrbracket^2 (V - V_t)*t, \tag{1}$$

where q is the amount of sand carried by the wind in a given period, V is the average speed of the wind at 10 m height, $V_t$ is the limiting impact threshold wind velocity at 10 m and t is the time during which the wind blew in one direction (the value is the percentile of frequencies for each wind direction).

To calculate the shear stress related to wind speed requires the grain size data (0.199mm to the dune field) and Equation 2 proposed by [1] was used with logarithmic speed distribution:

$$V_{((10))} = 5.75*(V*t)*\log Z/(Z') + (V't), \tag{2}$$

where V (10) is the impact threshold wind velocity (measured at 10 m height); (V*t) is the threshold shear stress (m.s-1); Z is the standard height of the wind data (10 m); Z' = 10*d (mm) is the roughness factor of the sand grain surface determined by [2], considered as a plane surface; and V't is the shear speed (= 894 *d (mm)) proposed by [55]. The result is given in cm/s, converted into m/s. The impact threshold wind velocity was (V(10m)) of 6.16m/s.

To calculate the shear stress threshold, Equation 3, as proposed by [1], was used:

$$V*t = A\sqrt{((\rho s - \rho a)/\rho a \, gd)}, \tag{3}$$

where A is a constant equal to 0.1 [1], ρs is sand grain density (2650 kg.m-3), ρa is air density (1.2 kg.m-3), g is gravity (9.8 m.s-2) and d is the median grain diameter (mm), used 0.199mm. The threshold of shear stress (V * t) of 0.206 m/s.

The drift potential result was classified by [13] is: low energy wind (present values up to 200 u.v.), moderate energy wind (between 200 u.v. – 399 u.v.) and high energy wind (more than 400 u.v.).

## 2.3 Remote sensing – Analysis of Aerial Photograph and Satellite Image (1938 - 2014)

The Table 1, presents the data used to analyze the dune field evolution.

*Table 1: Information about Remote Sensing data.*

| Data | Year | Provide by |
|---|---|---|
| Vertical Aerial Photographs | 1938, 1957, 1978, 1994, 1998, 2002 and 2007 | Urban Planning Institute of Florianópolis (IPUF) |
| Satellite Images | 2003, 2004, 2009, 2010, 2011, 2012, 2013, 2014, 2016 and 2018 | Google Earth PRO |

All images were rectified using GIS software (Root Mean Square between 1.4 and 7.2). The boundaries of the dune field, vegetation, water and urbanization were digitalized manually. The occupied areas by these four categories were measured for all the years analyzed. In addition, the location of the dune crest was measured in each aerial photograph/satellite image and compared with the position in previous years.

## 2.4 Morphological data (2002, 2010 and 2014)

Topographical data are important to understand the sediment budget and to make volume calculations. Thus, altimetry data of study area were derived from aerial photographs of 2002 by the Urban Planning Institute of Florianópolis. In 2010, a digital terrain model were also derived from aerial photographs (with altimetric error about 0.66m), from the Department of Sustainable Development of the State of Santa Catarina. In 2014 field surveys were conducted using a GPS in RTK mode, configured to collect data every 0.5m and transects were spaced at 15 m (on 21, 29 and 30/5/2014). Transects, parallel to Ingleses beach, were also collected every 0.5m with intervals at 30m for the whole dunefield on 14/08/2014 (Fig.4-A).

Once the sediment originates on the Santinho foredune coast, perpendicular profiles were measured every 30m (Fig.4-B) along the beach with transverse lines on the crest and the base of the foredune. The survey data were interpolated to allow volumetric calculations.
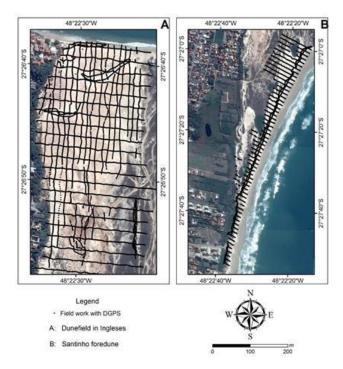
Fig. 4: Survey with GPS collecting data each 0.5m on the (A) dune field and (B) Santinho foredune to analyze the dune crest's migration and the volume.
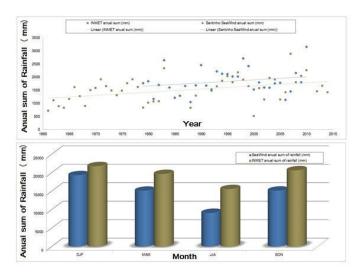


Fig. 5: In (A), an interannual analysis of INMET rainfall data (1961–2014) and SeaWind model (1979-2010), showed an increasing linear trend over the years. In (B), the columns present the rainfall data for summer (D,J,F), autumn (M,A,M), winter (J,J,A) and spring (S,O,N).

The interpolation with Inverse Distance Weighting (IDW) were use because presented the lowest RMS (0.08) and the best representation the study environment, presenting a realistic morphology. The dune field volume calculation used the zero level as 1.26m in comparing to the sea level, in order to obtain a same beginning date for the whole area.

## III.    RESULTS

### 3.1. Environmental and Anthropogenic Factors

The annual rainfall index, based on the historical series (INMET) and numerical model (SeaWind), showed an upward trend over the years, as well as, for seasonal analysis. The higher values occurred during the summer (DJF) with 20% and 8% respectively, followed by spring (SON) with 19% and 7%, autumn (MAM) 18% and 6%, and winter (JJA) with 15% and 5% (Fig. 5).

In general, the analysis of wind roses for the coast of Santa Catarina State (Fig. 6) presented two striking directions: north-northeast and south-southwest. The wind velocity was higher at the southern than the northern extremities of the island. Around 80% of the data were in the category 3-7m/s.
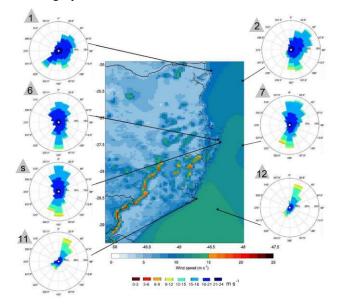


Fig. 6: Wind roses for seven of twenty-one points on the coast of Santa Catarina Island. Warmer colors symbolize higher speeds, as seems usual in southerly and south-southwesterly directions for northern points and a strong northerly wind for southern points (11 and 12).

The wind pattern was similar for those points in the north of Santa Catarina Island. The winds from the south quadrant were stronger and those from the north quadrant were the most frequent. At locations in the south of the island, the pattern is the opposite: the stronger and most frequent winds come from the north quadrant. At the Arvoredo meteorological station, the winds are similar to the pattern observed at CFSR and SeaWind.

As shown in Fig. 7, the most important result from the trend analysis is the increase in southerly winds (shown in yellow/orange). These southerly winds impact the whole study area but have their greatest impact on the Santinho shore.
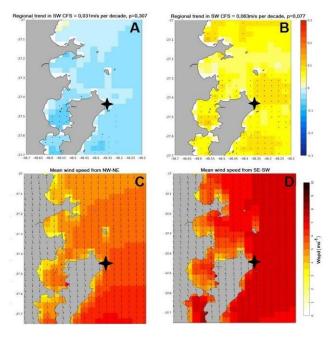


*Fig. 7: The black star indicates the dune field place. In A and B, the dots show significant trends in wind direction. Estimated linear trends to the period 1979-2010, using the SeaWind dataset, on the left (A) with northerly winds (sector between 300º and 45º) and on the right (B) with southerly winds (sector between 210º and 135º). Above (in C and D), the wind regime (average wind speed and direction) obtained for the directional sector between north wind (left side) and south wind (right side) under rainless conditions for the same period.*

In order to describe the variations of historical wind speed, changes in the Seawind hindcast were analyzed over a region around the target area. Northerly (300-45º) and southerly (135-210º) wind speed anomalies under rainless conditions were selected at each grid-point and trends, yearly and seasonally, were assessed. Results indicate that the variations of historical wind speed, changes in the Seawind hindcast over a region around the target are changes during autumn (MAM months) with an

increase in southerly winds and a decrease in northerly ones. Nevertheless, an evident interannual variability is observed, especially for southerly winds (Fig.8).

Analyzing the seasonal wind roses at the grid-point of SeaWind near Santinho (Fig. 8), the winds from the northern quadrant were more frequent and the southerly winds the strongest, the same patterns observed in Fig. 6.
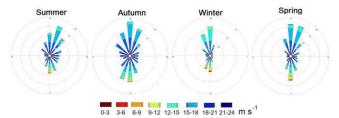


*Fig. 8: Wind rose for SeaWind "S", seasonal: Summer (D,J,F), Autumn (M,A,M), Winter (J,J,A), and Spring (S,O,N).*

The Fig. 9, present southerly winds showed peaks in the years: 1983-1984, 1987-1988, 1990-1991, 1993-1994, 1995-1996 and 2003-2004.
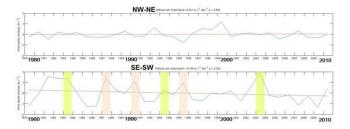


*Fig. 9: Annual high wind speed conditions (95-percentile anomaly of wind speed without rain).*

The Fig. 10-B, evidence the vegetation grow between 1938 and 2018 (80 years). Visual observation in the field shows that the growth of vegetation (grasses and small shrubs) usually occurs quickly after the rainy period in the lowest areas. T (Fig. 10-C) showed an increase from 1957 to 1978 (about 10,000m²), with a decrease in 2004 (about 100,000m²), and another significant increase happened at 2007 (about 120,000m²) and 2014 (about 150,000m²) until 2018. Usually this evident grow happened each decade, the same pattern observed with the sediment pulse.
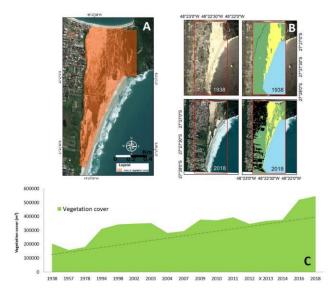
*Fig. 10: (A) The delimited area (in orange) on the dune field, represents the location of vegetation cover analyze. (B) Vertical Aerial Photograph from 1938 above and satellite image from 2018 below. (C) Graph represent the temporal change in vegetation cover since 1938-2018, the dotted line is the trend grow.*

In 1938, in the western portion of the dune field, were well-preserved vegetated plains, with no houses, streets, resorts, tourists or paths for passages; was possible to see only one road. At 1978 there had arisen a large and growing urban area that persists to the present day (Fig. 11, graph).

In Fig. 11, the red arrow indicates the buildings that are threatened by dune migration. Several houses and restaurants already have sediment inside them, and satellite images indicate areas where others have been completely covered.
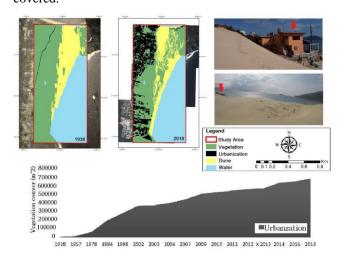


*Fig. 11: Satellite image (1938 and 2018) classification (urban area in black). Graph of annual urban growth (m²) between 1938 and 2018. The arrows indicate buildings and remnants in the dune field.*

### 3.2. Environmental and Anthropogenic Factors

Drift potential at location marked as SeaWind "S" (Fig. 1) on Santinho beach, shows the dominance of southerly winds in the potential transport (Fig. 12-A) and the red arrow shows the direction of dune field migration (Fig. 12-B).



*Fig. 12: (A) the Drift Potential shows the most efficient wind comes from the south/south-southwest and in (B) the resulting Drift Potential direction (indicated by the red arrow).*

Seasonally, the spring results showed the strongest DP (305); followed by winter (246), summer (234) and autumn (207). Southerly winds are at their most powerful in spring, and weakest in autumn (Fig.13).



*Fig. 13: Seasonal DP and DP separated by direction during each season in Santinho's beach.*

In Fig. 14 the seasonal pattern about resulting northward Drift Direction is showed.



*Fig. 14: DRD for each season (red arrow). The greatest DRD occurring in spring and the worst in autumn. All seasons showed a higher occurrence during periods of southerly winds.*

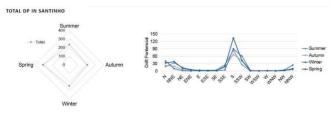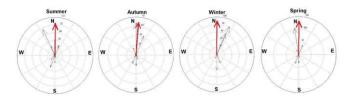Several features were monitored during the fieldwork and on aerial photographs/satellite images. They include parabolic dunes, gegenwalle ridges, blowout, remnant knobs, interdune plains, barcanoid chains, linear extensions and depositional lobes.

During 2002 and 2003, four well-defined crests on the satellite images were analyze and show a northward displacement with a migration rate between 15 and 42m/year and an average of 30m/year. In 2003 and 2004, three dune crests were analyzed, the migration rates being 16-28m/year with an average of 21m/year. Ten years after, 2013 and 2014, the migration rate of six crests ranged were 5 to 40m/year and had the lowest average of the three periods analyzed, 18m/year. Using the 2014 GPS data, an average of 4m/3 months was observed. This estimate is close to the average found for the years 2013 and 2014 (18m/year). At 2016 the average rate was 3,8/year and to 2018 the migration average rate was 4,5/year. Showing an important trend about crest migration is decreasing.

The volume results for the dune field show a decay (reduction) over the years (Fig. 15). In 2002, the demarcated area covered about 3,066,695m³. After a further eight years, this decreased to 2,840,979m³ (7%) and four years later, in 2014, the volume was 2,542,653m³, giving an overall 17% reduction.
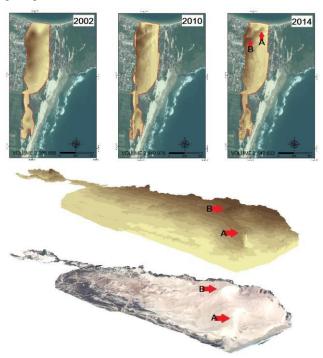


*Fig. 15: On the left, interpolations with altimetry data of IPUF-2002, in the middle the digital terrain model of SDS-2010 and at right side GPS collected on the dune field in 2014. The red arrow A and B, show the crests whose volumes were analyzed.*

The data collected in 2014 with GPS provided a 3D model for the analysis of the sediment input from the dune field of Santinhos-Ingleses (Fig. 16). Feature A, contained about 87,000m³ of sediment and B about 51,000m³; in 2014 the crests' migration was about 16-18m/year, dividing the volume per migration rate, the sediment input to Ingleses beach was 3,000-5,000m³/year.

According to the results shown in Fig. 17, the foredune area does not show a large variations in total volume. Thus, was necessary to analyze the foredune by sector (north, center and south) to better understand the input of sediment into the system.
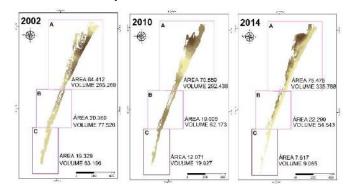


*Fig. 16: Santinho foredune shows no large overall variations. When considered in three sectors, however, it is evident where sediment input occurs. The 3D model shows higher volumes, in the darker colors, which represent greater volumes, in the north.*

Sector A showed the highest sediment volume in the years 2002, 2010 and 2014 (265,269m³, 292,438m³ and 335,788m³, respectively) compared with sectors B (77,526m³, 62,173m³ and 54,543m³, respectively) and C (63,196m³ and 19,927m³ 9,065m³, respectively) as observed at Fig. 17.

The area of the Santinho foredune have the same pattern behavior to all historical data: sector A with biggest area, after B and the C were always the smallest. Another observed patter was at 2002, 2003, 2004 and 10 years later, 2012, 2013 and 2014. During 2002 and 2012, the graph shows a grow at sector A, 2003 and 2013 a decay, 2004 and 2014 another grows, indicating a tendency to a new sediment rate, i.e. a large volume of sediment input occurs each 10 years in the northern sector of Santinho's beach (Fig. 18). The data of 1994 present a high value too, this means, 10 years before the first volume pattern observed at 2004. Thus, over 10 years (from 1994, 2004 and 2014) sector A received at least 70,000m³ (6,000 m3/year), indicating an import sediment pulse in the system.
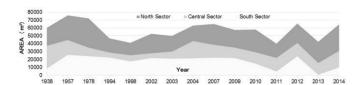
*Fig. 17: Difference between Northern, Central and Southern areas (m²) of Santinho foredune.*

## IV. DISCUSSION

4.1. Relationship between environmental factors and dunefield migration

Rainfall has great influence on the dunefield, favoring the increase of the vegetation cover, the stabilization of the system and the reduction of aeolian sediment transport [33]. [45], studying the effect of relief on the formation of convection and rainfall in southern Brazil, showed that the most irregular topography resulted in heavier rainfall. As the dune field is located between two hills, it is subject to heavy rainfall.

The precipitation data showed an increase over the years analyzed (Fig. 5), also observed by [33] and [35]. This trend is due not only to local or regional factors, but is a global condition that influences the weather and climate all over the world, as El Niño and La Niña [35].

[16] explain that during El Niño the precipitation tends to be greater than in La Niña periods. As observed in southern Brazil, during the El Niño years the rainfall is above the normal climatic range, while in the years of La Niña, the opposite is true: dry periods predominate in the south [22].

However, [10] show others two important factors affecting rainfall in Santa Catarina, the South American Monsoon System (SAMS) which is related to the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ) which becomes more intense during the summer and accounts about 60% of the rainfall in state of Santa Catarina. The other factor is the cold fronts, responsible for the winter rains.

There are many consequences of an increase in rainfall on the island of Santa Catarina, among them being: with more moisture in the sediment, the threshold velocity increases, the aeolian drift potential in the region is reduced, the migration rate is also reduced and the growth of vegetation favored (between 1978 and 2014 the growth was about 65%); so over the years vegetation encroachment and the consequent stabilization of the dune field are inevitable, as possible to observe at dune field.

Overall, it is possible to observe two general patterns, as may be seen in Fig. 6. The first is the behavior of wind components showed at roses as between the northern half

and the southern half. The points located in the north presented a scattering component for all directions, which happens because the area is slightly warmer, thus generating convection effects. The convective clouds result in winds from all directions due to the consequent convergence the air. The points in the southern position suffer the influence of a barocline system, resulting, for example, in cold fronts and extratropical cyclones, presenting dominant and more clearly defined components (NE-SW).

The second pattern observed relates the most frequent (north/northeast) and the strongest winds (south/south-southwest), agreeing with [3, 4, 5], Vintem et al. (2006), [19]. However, at the points situated near the coast, below the southernmost point of the island (in SW-8, 10 and 11), the pattern is the opposite. The winds from the north quadrant were the most frequent and stronger than the southerly ones, as observed by [19].

There are several influences that affect winds along their trajectory; [3, 4] explains how the topography, headlands and mountain ranges of Santa Catarina Island can produce changes in wind flows, thus providing some protection against the north wind.

[3] described the topographical protection from the north and northeast winds, suggesting this as the reason for the effectiveness of winds from the south and southeast quadrants. This is consistent with the behavior of the data analyzed, as well as the direction of the migration of the dunefield.

Several studies have described dunefield stabilization in southern Brazil [5, 20, 32, 33, 35, 36, 38, 41, 48], as well as in Argentina [30] and the northern hemisphere [23, 43]

[39], analyzing the Moçambique dunefield, to the west of their study area, showed an increase (about 70%) of vegetation area between 1938 and 1976 and attributed it to the level of the water table, decreasing sediment supply and local changes in both wind power and precipitation.

A natural stabilization of dune fields as an environmental response and/or as due to climatic factors such as rainfall and level of the water table, wind regimes and waves, sediment supply and variations in relative sea level [17, 21, 49].

The vegetation cover mapped in 1957 and 2014 shows a growth in the vegetation during that period close to the edge of the Santinho beach (on the east side of the dune field). This region is lower and likely offered favorable conditions for vegetation growth, the increase in whose area was of about 40%.

South of Santinho beach, in the subaerial zone, the water table often rises, presenting a moist region; however, this process cannot possibly occur on the dunefield due to the thick accumulation of sediment above the water table.

According to the Catarinense Water and Sanitation Company reports (CASAN; personal communication???), the groundwater has two distinct levels: static (the distance from the surface of the ground to the water level inside the well, located about 12m from the surface) and the second, a dynamic level (the distance between the surface of the ground and the level of the water inside the well when pumped, which can attain 17m). The average time for the water level to return to its static level during its summer use is around 3 hours. Then, in the Santinho/Ingleses system the water table have less significant influence on the vegetation cover.

Urbanization in the study area began in 1980, particularly near the coastal areas. The spread of urbanization promotes changes in the system such, for example, that impermeable surfaces prevent the infiltration of rainwater, making it difficult to replenish the water table and thus reactivating stabilized dunes, leading to a new migration of sediment, demonstrating not only the impact of human occupation on the dunes but also the impact of the occupation on the dynamics of the dune field.

[52] comment that urbanization in inappropriate places has been responsible for the direct/indirect extinction of some dunefields in Rio Grande do Sul. Direct extinction occurs when building occupies the dunes and indirect extinction occurs when the input of sediment ceases, usually on adjacent beaches.

Studies conducted on the Canary Islands have shown an increase of up to 35% in wind speed, sediment deficit and pressure from users, thus reducing the size and modifying the features of the dunefield [8].

The urbanization adjacent to the transgressive dune system of Santinho / Ingleses does not present a big impact, due to the expansion's occurring mainly to the side of the dune field. The shoreline position thus permits the input of sand without any influence of urbanization; even during the strongest (southerly) winds as there is no anthropogenic barrier that affects aeolian sediment transport, on the contrary to Moçambique dune field.

The coastline of Ingleses beach from 1978 to 2012 showed a tendency to equilibrium with short episodes of erosion [53]. Between 1957 and 1978 (when the urbanized area was minimal as well as the vegetated cover) the coastline was stable with occasional accretion [53], showing that the urbanization near the dune field did not greatly affect the aeolian transport. Thus, the factor that most affects the aeolian sediment transport in this dune

field is the vegetation cover and temporal changes in wind velocity, as well the sediment supply in waves.

Vintem et al. (2006) and [5] studying the migration of several dunefields in Santa Catarina state calculated that the DP at Moçambique (to the west of our present study area) was 330 u.v., using the superficial wind data corresponding from Platform PVIX, concluding that these dunes, according to [13], had moderate energy winds (200 u.v. – 399 u.v.), similarly to the results achieved in this present study (249). Using the Arvoredo data, the DP was 70 u.v. Both results were different from those observed by [38] who showed an annual average DP from 1964 to 1998 between 100 and 150 u.v.

In autumn months, the drift potential presented lower values (207 u.v.) than in other seasons; the Spring had the greatest drift potential with 305 u.v. (Fig. 14).

[39] concluded that the Moçambique dunefield shows a decreasing trend in DP coincident with above average rainfall in the early 1970s, thus explaining the initial growth of the vegetation cover, as observed at Santinho/Ingleses dunefield.

According to [13], the values obtained from the DP calculation are not necessarily real, but represent a transport trend. It should be understood that the local environmental features such as vegetation, topographical features, moisture and the coastline, affect the amount of sediment transport significantly.

The drift potential values must be considered a wind energy index for a particular region, and the efficiency of sediment transport will depend on the local surface characteristics of the area in which the wind blows [13], according to this autors the study area has moderate energy winds (200 u.v. – 399 u.v.).

Regarding the resultant drift direction (DRD), the applied method was suited to the Santinho/Ingleses dunefield, resulting in DRD diagrams concordant with the general direction of system migration and with the results of previous studies.

The Santinho-Ingleses dunefield presents different kinds of aeolian deposits such as parabolic dunes, barchans and gegenwalle. There are few studies of gegenwalle in the Santa Catarina dunefields; however, these features were often cited by [14, 32, 33] in the transgressive dunefields of Rio Grande do Sul, as proof of dune migration, as they develop behind barchan dunes.

Northward dune migration under southerly winds yields sediment for the Ingleses beach. This northerly migration was also evident from the analysis of the wind rose (Fig 6) and the resulting drift direction (Fig 12), both agree with the expected pattern on the coast: southerly

winds were the strongest but northerly winds the most frequent.

The data obtained during the fieldwork (16m/year), even though the method of analysis was different, the values obtained approximated to the migration rate observed by Satellite Images (18m/year), as identify at Table 2.

[5] showed the dune migration rate (also on Santa Catarina Island) was of only 2.5m/year. [6] studying a dune field at west side of the study area and about three times bigger), presented migration values between 2.5 and 5 m/year.

The rate of crest migration in Rio Grande do Sul was between 15 and 40 m/year from 1974 to 1999 [33]. According to [35], the dunefields in Santa Catarina state (Moçambique, Lagoa da Conceição, Pinheira, Garopaba and Ouvidor) presented a migration rate of between 4 and 41m/year from 1938 to 2009.

*Table 2: Resume about migration rate of dune field in south of Brazil.*

| Localization | Migration Rate | Average value | Date | Author | Data |
|---|---|---|---|---|---|
| Santinho/Ingleses (SC State) | 16-28m/year | 21m/year | 2003-2004 | [41] | Satellite Images |
| Santinho/Ingleses (SC State) | 5-40m/year | 18m/year | 2013-2014 | [41] | Satellite Images |
| Santinho/Ingleses (SC State) | 4m/3 months | 16m/year | 2014 | [41] | Topographic measurements |
| Lagoa da Conceição (SC State) | 49.7m | 2.5 m/year | 1975-2004 | [5] | Satellite Images + Topographic measurements |
| Moçambique (SC State) | 2.5-5m/year | - | 1938-2007 | [6] | Satellite Images |
| Rio Grande do Sul (RS State) | 15-40m/year | - | 1974-199 9 | [33] | Satellite Images |
| Moçambique, Lagoa da Conceição, Pinheira, Garopaba,Ouvidor (SC State) | 4-41m/year | - | 1938-2009 | [35] | Satellite Images |

The dunefield presents a higher elevation as well as greater sediment volume in the western and northern portions. The crests located in this region showed higher migration rates than those on the eastern side which were in a lower region, both moister and under the influence of vegetation. Over the years the average rate of system migration is declining and this implies a lower sediment input to Ingleses beach. [11] explains that the position of the beach influences the dominant wind, favoring both waves and winds from the south and southeast at Santinho beach, moving the active dunes towards the north and providing an input of sediment at Ingleses. Recent studies have also shown that the largest input to Ingleses comes from the dunefield, not by longshore drift, thus bringing out the importance of this system [53].

Rainfall is increasing and thus aeolian sediment transport is being reduced, making the growth of vegetation possible, thus stabilizing and encroaching the dunefield, explaining the reduction of the migration rate.

4.2. Sediment budget and overpassing

[35] identified three evolutionary morphological stages in dunefields in Santa Catarina state. In the Santinho/Ingleses system, it was possible to identify these three stages by the analysis of aerial photographs/satellite images. The first stage between 1938 and 1957 shows an increase in the area occupied by aeolian sediment, suggesting an increase in the system's volume. The second phase was characterized by an acceleration of depositional lobe migration between 1957 and 1978. The third stage began in 1978 and continues until today, with system stabilization and reduction of migration rates.

The morphological stages involve changes in the environment directly related to the sediment budget, i.e., the difference between the input and removal of sediment. For the system to accumulate sediment, aeolian transport requires a strong wind and available sediment [1].

The sediment volume of the dunefield has been reduced over the years. In 2002, the common area defined for the analysis of the volume was of about 3,066,695m³, after twelve years it had shrunk to 2,542,653m³; i.e., it had lost around 44,000m³/year of sediment (to Ingleses beach).

Different methods of data acquisition (orthorectification and RTK, respectively), and the various errors committed, however, urge caution regarding this conclusion. In order to present data with greater accuracy, sediment volume has been calculated for two major crests in the system using GPS data.

The sediment volume values calculated for two crests in the dunefield were consistent with the rates published by [6], showing that the dunefield supplies about 3.000-5.000m³/year to Ingleses beach.

[6] calculated that the dunefield contributes around 10,000 m3/year of sediment to Ingleses using the length and the angle of the slip face whereas this study used a more accurate GPS survey method.

The sediment budget also estimated the volume that enters the system through the northern sector of Santinho beach. [53] utilizing shoreline variations showed that, when the northern part of Santinho has presented an accumulation, Ingleses has retreated. The sector A of the foredunes which are more exposed to swell and wind action, presents the greatest width and volume, as compared with sector C. Volume changes in the northern sector of Santinho indicate an input to the dunefield of approximately 70,000m³ of sediment in 12 years (6,000m³/year, assuming that none is lost to marine erosion). This dunefield provides 3,000-5,000m³/year of sediment to Ingleses, showing a positive budget indicating the maintenance of the dunefield; as the sediment input is bigger than the output to Ingleses, the system will continue over the years to provide sediment to the beach without suffering any loss.

Regarding the sediment pulse, in 2002 the northern part of Santinho presented lower volume and area, suggesting that a previous pulse of sand had already entered the dune system. In 2010 the volume was getting higher, suggesting a new pulse was imminent. In 2014, the input was confirmed, by the higher volume in sector A than in previous years (2002, 2010 and 2014, 265,269m³, 292,438m³ and 335,788m³, respectively).

Figure 9 shows a selection of high wind speed conditions, marked in yellow (95-percentile anomaly), that corroborates with the years when sediment pulses entered in the system (Fig. 17), as well as high values of volume during the years: 1983-1984, 1993-1994, 2003-2004. [6] noted too, a sediment pulse in Moçambique dunefield (on the west side of Santinho beach), but occurs every 14 years, at Santinho/Ingleses the data show about ten years, for being a smaller dunefield system.

## V. CONCLUSION

The Santinho/Ingleses dunefield presents a significant growth of vegetation, an increase of a 40% over the 76 years analyzed, thus changing from a large active dune field to a system with increased stability.

The reduction in the crest migration rate over the years is a result of three factors: the tendency to increasing rainfall, a decreasing trend in drift potential and the stabilization of the dune field by an increase in vegetation. However, this is controlled by the wave of sand that is entering to the coast.

There is a decadal sediment pulse into the system from the north of Santinho beach that provides an overpassing process which the input volume (6,000m³/year) is bigger than the output to Ingleses beach (3,000-5,000m³/year), ensuring a positive sediment budget for the system (Fig 18).
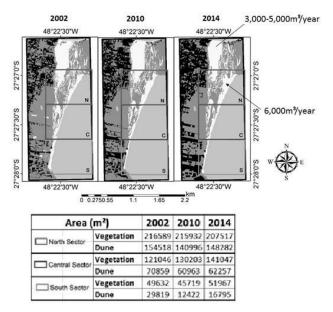


| Area (m²) | | 2002 | 2010 | 2014 |
|---|---|---|---|---|
| North Sector | Vegetation | 216589 | 215932 | 207517 |
| | Dune | 154518 | 140996 | 148282 |
| Central Sector | Vegetation | 121046 | 130203 | 141047 |
| | Dune | 70859 | 60963 | 62257 |
| South Sector | Vegetation | 49632 | 45719 | 51967 |
| | Dune | 29819 | 12422 | 16795 |

*Fig. 18: Illustration of the system with volume data for each sector and sediment pulse rate.*

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