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Evolutionary stage, anthropogenic activities and evolution of the Itapeva dunefield (Torres-RS, Brazil)

Estágio evolutivo, atividades antrópicas e evolução do campo de dunas de Itapeva (Torres-RS, Brasil)

Gabriela Camboim Rockett[ae], Eduardo Guimarães Barboza[bf], Marina Refatti Fagundes[cg], Patrick Hesp[dh], Maria Luiza Correa da Câmara Rosa[bi]

[a]Centro de Estudos Costeiros, Limnológicos e Marinhos – CECLIMAR, UFRGS - Campus Litoral Norte, [b]Centro de Estudos de Geologia Costeira e Oceânica – CECO, UFRGS, [c]Instituto de Pesquisas Hidráulicas, Programa de Pós-Graduação em Recursos Hídricos e Saneamento Ambiental, [d]Flinders University, College of Science and Engineering Beach and Dune Systems (BeADS) Laboratory

[e]gabriela.rockett@ufrgs.br, [f]eduardo.barboza@ufrgs.br, [g]marinarf95@hotmail.com.br, [h]patrick.hesp@flinders.edu.au, [i]luiza.camara@ufrgs.br

Abstract

Transgressive coastal dunefields dominate the southern coast of Brazil, and few studies are investigating the factors driving their historical changes. The aim of this study is to investigate spatio-temporal changes over the last 60 years in the Itapeva coastal transgressive dunefield (northern coast of Rio Grande do Sul state) and also the factors influencing these changes. The dunefield is analyzed via various methods including (i) spatial and temporal analyses of the dunefield utilizing aerial photography, satellite imagery and Geographic Information System, (ii) climatic analysis from 1961 to present and (iii) sand drift calculations. The results show a significant decrease in the mobile dunes area since 1953, an increase in vegetation cover, and an increase in urbanization area. While anthropogenic factors have influenced the dunefield (e.g. sediment removal and urbanization development), results of this study show that an increase in rainfall and decrease in average wind velocity are also responsible for the main spatial changes, vegetation colonization and stabilization processes in the Itapeva dunefield. The dunefield has also evolved into a new stage where deflation basin development and enlargement has encouraged vegetation colonization and expansion.

Keywords: Transgressive dunefield; climate; dunefield evolution; vegetation cover; human impacts

Resumo

Campos de dunas costeiros transgressivos dominam a costa sul do Brasil, e existem poucos estudos investigando os fatores que impulsionaram suas mudanças históricas. O objetivo deste estudo é investigar as mudanças espaço-temporais nos últimos 60 anos no campo de dunas transgressivo de Itapeva (litoral norte do Estado do Rio Grande do Sul) e também os fatores que influenciam essas mudanças. O campo de dunas é analisado via vários métodos, incluindo (i) análises espaciais e temporais do campo de dunas utilizando fotografia aérea, imagens de satélite e Sistema de Informações Geográficas, (ii) análises climáticas de 1961 até o presente e (iii) cálculos do potencial de deriva de areia. Os resultados mostram uma diminuição significativa na área de dunas móveis desde 1953, um aumento na cobertura vegetal e um aumento na área urbanizada. Embora fatores antropogênicos tenham influenciado o campo de dunas (por exemplo, remoção de sedimentos e desenvolvimento da urbanização), os resultados deste estudo mostram que um aumento na precipitação e diminuição na velocidade média do vento também são responsáveis pelas principais mudanças espaciais, colonização da vegetação e processos de estabilização no campo de dunas de Itapeva. O campo de dunas também evoluiu para um novo estágio em que o desenvolvimento e o alargamento da bacia de deflação encorajou a colonização e expansão da vegetação.

Palavras-chave: Campo de dunas transgressivo; clima; evolução de campo de dunas; cobertura vegetal; impactos humanos

1. Introduction

Coastal dunefields may develop adjacent to sandy beaches where there is abundant sediment supply and adequate grain sizes to be transported by effective winds (Carter, 1988, Hesp & Thom, 1990). Sediment supply, wind regime, grain size, fetch, and surf zone beach type and coastline orientation are some factors that influence the size of coastal dunefields (Hesp & Walker, 2013; Moulton et al., 2021). Coastal dunes have a great physical and ecological importance due to their function as a protective barrier from storm erosion, in providing a sometimes significant freshwater storage, constitute ecological habitats for fauna and flora and are important as a natural intrinsic landform (Martínez et al. 2013).

Transgressive dunefields are defined as relatively large-scale aeolian sediment deposits formed by the landwards oblique to alongshore movement (or transgression) of sand over a prior terrain (Hesp, 2000). The dunefield surface morphology and vegetation cover may change through time as a result of natural processes and climate changes (Martinho et al. 2010, Miot da Silva & Hesp, 2013, Hesp, 2013, Miot da Silva et al. 2013, Mendes & Giannini, 2015, Pickart & Hesp, 2018), changes in sediment supply (Tomazelli, 1994, Aagard et al. 2007), or anthropogenic influences (Nordstrom, 1994, 2000, El Banna & Frihy, 2009, Moulton et al. 2018). Coastal transgressive dunefields may be mostly active (mobile), partly stabilized, or fully stabilized depending on the degree of vegetation cover and age and stage of development (Hesp & Thom, 1990, Hesp, 2013).

The southern Brazilian coastal plain, in Rio Grande do Sul state (RS), is approximately 600 km in length and characterized by multiple barrier-lagoon depositional systems, where four of these systems are preserved (Villwock et al. 1986; Rosa et al. 2011). These systems are characterized by a Quaternary coastal plain formed by sandy barriers and lagoons with “restinga” vegetation, in a temperate climate (Fernandez et al. 2019). This coastal plain is the emerged portion of the Pelotas sedimentary basin (Rosa et al., 2017), approximately 620 km in length. The four barrier-lagoon systems were formed during sea level highstands as identified by Villwock et al. (1986) and represent a high-frequency depositional sequence (Rosa et al. 2011, 2017). The ages of the barrier-lagoon systems I through IV are 325, 230, 125 and 8 ka to recent, respectively (Rosa et al. 2017). The Holocene barrier-lagoon is characterized by the formation and migration of a transgressive dunefield barrier, initiated in the final stages of the post-glacial marine transgression about 7-8 ka B.P. (Dillenburg et al. 2006). Studies show that simultaneous progradational and retrogradational patterns can be identified in distinct sectors of the RS coastal plain Holocene barrier (Dillenburg et al. 2000, 2009, Rosa et al. 2017, Barboza et al. 2011, 2018).

Many different geomorphological features have been developed in southern Brazil during the Holocene, such as dunefields, beach ridge and foredune plains, coastal lakes, and lagoons. The most common aeolian features are transgressive dunefields (Villwock, 1984, Villwock & Tomazelli, 1995, Hesp et al. 2005, 2007), and wide and/or large transgressive dunefields are present along all the RS coast (Tomazelli, 1990, Arejano, 1999, Ugri, 2004, Guimarães, 2005, Martinho et al. 2010). This development was due to the conjunction of favorable factors, such as a high sediment supply, appropriate wind regime, low topography, and dissipative beaches (Tomazelli et al. 2003, 2008). The Holocene coastal dunefields have developed on the RS northern coast over the past 7 ka B.P. (Martinho et al. 2008; Dillenburg & Barboza 2009; Dillenburg et al. 2009). In general, the sands in this coastal region are predominantly of quartz composition, fine-grained, well rounded, and characterized by high mineralogical maturity (Martins, 1967, Tomazelli, 1990).

Coastal dunefield evolution in RS is described by Tomazelli (1994), where transverse dunes evolve to barchanoid chains, and later to isolated barchans dunes. Studies demonstrate that the changes in dune morphology on the RS coast are due to a downwind decrease in sediment supply (Tomazelli, 1994), and climate changes (Martinho et al. 2010, Barboza et al. 2013). Martinho et al. (2008, 2010) examined nine dunefields on the northern coast of RS and showed that the variations in dimension, morphology, and distribution were due to differences in precipitation, sand drift potential, and sediment supply. Despite extensive studies along all the RS coastal plain, there are still few studies examining the recent evolution of the transgressive dunefields and none specifically of the Itapeva dunefield, a dunefield in a singular geological/environmental settings in the RS coastal plain. In this context, this study aimed to investigate spatial and temporal changes in the Itapeva transgressive dunefield over the last 60 years and investigate the factors influencing those changes.

1.1 Study area

The Itapeva dunefield is located in Torres municipality (Figure 1), in the northern coastal plain of Rio Grande do Sul state, southern Brazil. There are somewhat unique characteristics in this area, which are different from other coastal sectors on the Southern Brazil coastal plain, such as the presence of basement outcrops from the Serra Geral and Botucatu formations (Paraná Basin); in terms of aeolian deposits and evolution, it is another case study that fits within other studies of historical dunefield evolution in Southern Brazil (Tomazelli et al., 2008; Martinho et al., 2008; 2010; Miot da Silva & Hesp, 2013; Miot da Silva et al., 2013; Oliveira et al., 2017). The Itapeva dunefield is approximately 4 km in length and varies from 300 m to 1 km wide, confined between the basement outcrops and headlands. According to Tomazelli (2001) this is one of the few dunefields in Rio Grande do Sul that has maintained characteristics very close to the original natural system. The creation of a protected area in 2002 in the Itapeva region has partially acted to keep this coastal sector protected since that time.

The Itapeva dunefield is an active aeolian system and is part of barrier-lagoon system IV of the RS coastal plain. It is characterized as a transgressive dunefield (Hesp et al. 2005; Tomazelli et al. 2008) developed as a progradational barrier type (Rockett et al., 2014). It is typical of many transgressive dunefields; it has broad aeolian sand deposits formed by the downwind, oblique or alongshore movement of sand sheets and dunefields over an area with or without vegetation, and is bordered by precipitation ridges, and fronted by deflation basins and plains (Hesp & Thom, 1990).

The Itapeva dunefield is a transgressive dunefield abutted on both sides by basement outcrops and headlands. In the northern portion there are basement outcrops that form cliffs about 40-50 m high on the Torres coast ("Morro das Furnas" and "Morro do Farol" hills), "Torre Sul" and "Guarita" towers, as well as in the southern portion of the dunefield, where a lower altitude outcrop occurs close to the beach (the "Itapeva rock") and becomes higher landward ("Itapeva hill") (Figure 1A).

Moreover, another outcrop called "Pedra Vermelha" occurs close to the largest washout (an ephemeral stream that flows out to the coast following high rainfall events) in the central region of the dunefield and becomes more visible during winter. The Serra Geral formations outcrops only occur in this sector of the Rio Grande do Sul coast. All these basement outcrops and the low thickness of sediment over the basement (varying from 2 to 22 m in the main central drainage area and in the deflation plain (Rockett et al. 2013, 2014) may influence the Itapeva dunefield dynamics.

On the west side of the dunefield, there is a wetland area with swamp forest, and sandy forest on the precipitation ridge forming the dunefield boundary (Itapeva State Park management plan - SEMA, 2006). This humid area extends from the center to the northern sector of the dunefield. From the central sector of the dunefield until Itapeva rock, there is native grassland vegetation.

The coastline orientation in this area is NE-SW. Figure 1B shows that there are both vegetated, partially vegetated and active portions of the dunefield today.

1.2 Climate setting

According to Köppen's classification (Alvares et al. 2014), the climate is warm temperate or humid subtropical (Cfa), with generally warm to hot temperatures in the summer. The average annual temperature is between 18 and 20ºC. NE winds are dominant, particularly from September to March. From April to August, winds from the south and SW are dominant. The annual rainfall ranges from 1600 to 1900 mm and is evenly distributed throughout the year. Higher precipitation occurs in the northern littoral of RS (Torres to Tramandaí) due to the influence of the highlands (500–700 m high), which are close to the coast (within15–20 km), causing a local increase in rainfall (Dillenburg & Barboza, 2014).

2. Methods

The materials used and methods adopted are described below. The methods were performed in three steps: (i) Spatial and temporal analysis; (ii) climate data analysis; and (iii) sand drift potential calculations.

2.1 Spatial and temporal analysis

Aerial photographs and satellite imagery were analyzed in a GIS environment to determine spatial and temporal variations of the Itapeva dunefield and associated landforms. Spatial changes in the Itapeva dunefield and its vicinity were examined by comparing vertical aerial photographs from 1953, 1965, 1974, 1989 and 1996 and high-resolution satellite images from 2006 and 2013. The photographs' scales vary from 1:20,000 to 1:60,000. Aerial photographs from 1989 and 1996 do not cover the total dunefield area. In these cases, some analyses were performed only in the northern region of the dunefield, focusing on the urbanization advance over this area.

The photos are from the Autonomous Department of Highways of Rio Grande do Sul State (Departamento Autônomo de Estradas de Rodagem - DAER-RS), the Geological Survey of Brazil (Companhia de Pesquisa de Recursos Minerais – CPRM, Serviço Geológico do Brasil) and the Torres municipality government (Secretary of the Environment). The high-resolution satellite image comprised an orthorectified IKONOS panchromatic image for the year 2006 (Rovedder, 2007), and an image from Google™ Earth for the year 2013.

The use of remote sensing techniques to analyze a dunefield's morphology and vegetation cover is very common (Hugenholtz et al. 2012), and on the southern coast of Brazil some studies were performed by Seeliger et al. (2000), Tomazelli et al. (2008), Martinho et al. (2010) and Miot da Silva et al. (2013). A decadal analysis was performed, beginning in 1953, using the available remote sensing products. The aerial photos were scanned, and for each photograph/image a geometric correction was performed, referenced to a UTM projection, zone 22 S, WGS-84 datum. Images were photo-interpreted and the features and landform units delimitation was performed using a Geographic Information System (GIS). The transgressive dunefield was defined, as well as the vegetated deflation plain and the urban areas, allowing the delimitation for each feature/landform unit type and the preparation of thematic maps. The main aeolian landforms or units in the years 1953, 1974 and 2006 were also identified and described in terms of type, dimensions and spatial distribution.

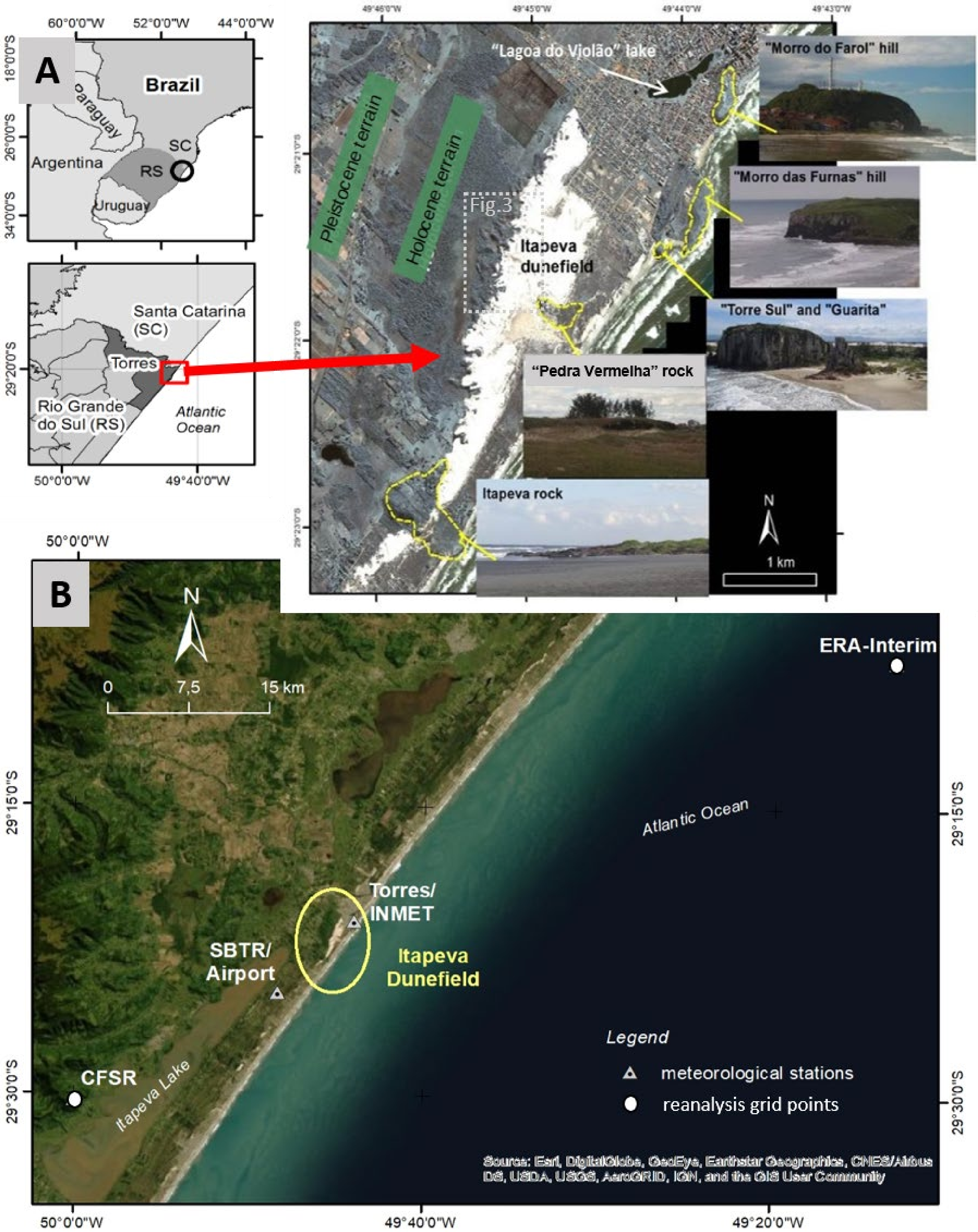

Figure 1: Location of the study area: Itapeva dunefield, Rio Grande do Sul, southern Brazil. A) Satellite image of the Itapeva dunefield and location and imagery of basement outcrops close to, and within the dunefield; and B) Location of the two meteorological stations and the two reanalysis grid points used in this study (ESRI basemap satellite image).

2.2 Climate data analysis

Precipitation data were obtained for Torres station (Figure 1B) from the meteorological database of the National Institute of Meteorology (Instituto Nacional de Meteorologia – INMET). The database extends from 1961 to 2014, with total monthly precipitation measurements in millimeters (mm). For the analysis of this climatological variable, the years that had failures in more than two months of data were disregarded (1984, 1986, 1987 and 1990). The missing data could not be complemented due to the lack of other weather stations nearby that would allow a correlation of the data to complete the historical series. For cases in which only one or two months of the year were missing, the average values of that month over all the period were used to complete the series. After data organization, precipitation analysis was then conducted considering annual total values and annual averages. In order to verify the existence of some variation of precipitation over the years, the Mann-Kendall hypothesis test was employed. This method was chosen because it is recommended by the World Meteorological Organization (WMO) for assessing the presence of trends in time series (mainly temperature, precipitation and flow data) and has been applied in several studies (eg. Xu & Zhang 2006, Karmeshu 2012, Lopes *et al*. 2013, Sanches *et al*. 2013, Soares *et al*. 2018). The basic principle of the test is to compare each time series value with the remaining values in sequential order. Thus, it can be verified whether the next term is longer or shorter than the previous term. In addition, it also allows to identify the starting point of a certain trend in the historical series under study (Back, 2001). As it is a nonparametric test, it is not necessary for the distribution to be normal or linear, being considered very robust regarding the normality and non-stationary deviations of the values of a series. However, the series must be independent and there can be no autocorrelation between the data. For a given time series (x1, ..., xn) to be analyzed to prove the null hypothesis (H0), where there is no positive or negative trend in the series, the Mann-Kendall test uses the statistics of Equation 1.

$$S = \sum_{j=i+1}^{n} sign(x_j - x_i) \qquad \text{Equation (1)}$$

Where:
x_j are the estimated data of the sequence of values
n is the size of the time series
It is determined that the value of $sign(x_j - x_i)$ is equal to -1 for $(x_j - x_i) < 0$, equal to zero when $(x_j - x_i) = 0$ and equal to 1 when $(x_j - x_i) > 0$.

Assuming the null hypothesis is true, the S statistic follows a Gaussian distribution, with zero mean and variance determined by Equation 2.

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \qquad \text{Equation (2)}$$

Finally, the value of the Mann-Kendall coefficient (MK) can be determined using Equation 3.

$$MK = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} \; if\ S > 0 \\ 0\ if\ S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} \; if\ S < 0 \end{cases} \qquad \text{Equation (3)}$$

The MK factor sign indicates whether the series has positive (MK> 0) or negative (MK <0) variation. However, to find out if the trend found is significant, the magnitude of the p-value determined by the statistical test must be less than 0.05 when considering a 95% confidence interval (Marengo et al. 2007).

2.3 Aeolian drift potentials

Sand drift potentials were calculated for each station and for each season based on historical wind data from two meteorological stations: Torres/INMET (1961-2019), SBTR/Airport (2002-2014) (Rockett et al. 2017) and two reanalysis grid points CFSR (1979-2010, onshore) and ERA-Interim (1979-2019, offshore). Furthermore, Fryberger & Dean (1979) sand roses were created following the technique described in Miot da Silva & Hesp (2010). Torres/INMET station is located 1km from the northern boundary of the Itapeva dunefield (in the northeast direction); the Airport station is located 5 km from the southern boundary of the dunefield (in the southwest direction), in the coastal plain region; CFSR station is located about 25 km far from the southern boundary of the dunefield (in the southwest direction), in low land very close to the Serra Geral scraps; ERA-Interim station is located offshore, 55 km distant in the northeast direction from Itapeva dunefield (Figure 1B).

The offshore wind data (ERA) can clarify the regional setting with no topographic interference, while local wind data (Torres, Airport and CSFR) can show the topographic effect in the Itapeva region/dunefield.

Seven wind speed classes were chosen for this study; three of them are according to Pearce & Walker (2005) - wind speeds higher than 14.31 m/s were condensed into one class – and, in addition, four complementary classes were used, due to the specific wind data characteristics (Table 1).

Table 1: wind velocity classes used in this study (according to Miot da Silva et al., 2013).

Wind velocity classes (m/s)						
0.0 - 3.0	3.01- 5.6	5.61- 7.0	7.01 - 8.7	8.71 - 11.3	11.31 - 14.3	> 14.31

The average grain size for the Itapeva dunefield sands is 0.177 mm and the wind data calculations were in m s^{-1}.

3. Results

3.1 Spatio-temporal changes in the Itapeva dunefield

Significant changes in the dunefield were detected from 1953 to 2013 as shown in Figure 2. The 1953 aerial photograph (Figure 2A) shows the dunefield length was wide relative to today, extended approximately 4.5 km from the north until Itapeva rock, and from Itapeva rock to the south a narrower area of mobile transgressive dunes occurs. The mobile dunes area extended from just behind the backshore (defined as the point where the upper beach meets the dune toe), and the total mobile dunes area up to the Itapeva rock was 4.55 km².

The northern boundary of the dunefield was about 220 m in a southerly direction from the “Lagoa do Violão” lake, which is a low topographic area. From this region behind the “Morro do Farol” hill, vegetation can be observed. A more humid area (the “Riacho Doce” drainage) can be observed in the northern region of the dunefield, which flows from the dunefield toward the sea (NW-SE direction) on the southern side of “Torre Sul” hill. In the landward, western margin of the dunefield, an active precipitation ridge is present and in places is actively migrating onto or over a former vegetated precipitation ridge (related to earlier dunefield phase). In the northern sector, the dunefield advances landwards over low Holocene terraces.

Dune forest is present on the dunefield western boundary. There are also some active, U-shaped parabolic depositional lobes present on the older, more landward digitate precipitation ridge (Figure 3). In the northern portion of the dunefield, the lobes are oriented to the NW direction, and just south of them (in the central portion of the dunefield), the depositional lobes are oriented to the SW direction. Possibly the basement outcrops (“Morro das Furnas” hill) act to deflect the NW wind in the northern portion of the dunefield, influencing the wind dynamics and sand transport in this region. These depositional lobes are characterized by unvegetated dune crests and vegetated deflation plains and basins. In these deflation areas, the grey tone is lighter in the photo and indicates grassland vegetation (Figures 2A and 3).

Between “Torre das Furnas” and “Torre do Farol” hills there is a beach (“Praia da Cal”). In 1953, there was a connection between “Praia da Cal” beach and the Itapeva dunefield northern area. There was also a dunefield between the “Morro do Farol” hill and the “Lagoa do Violão” lake (Figure 2A).

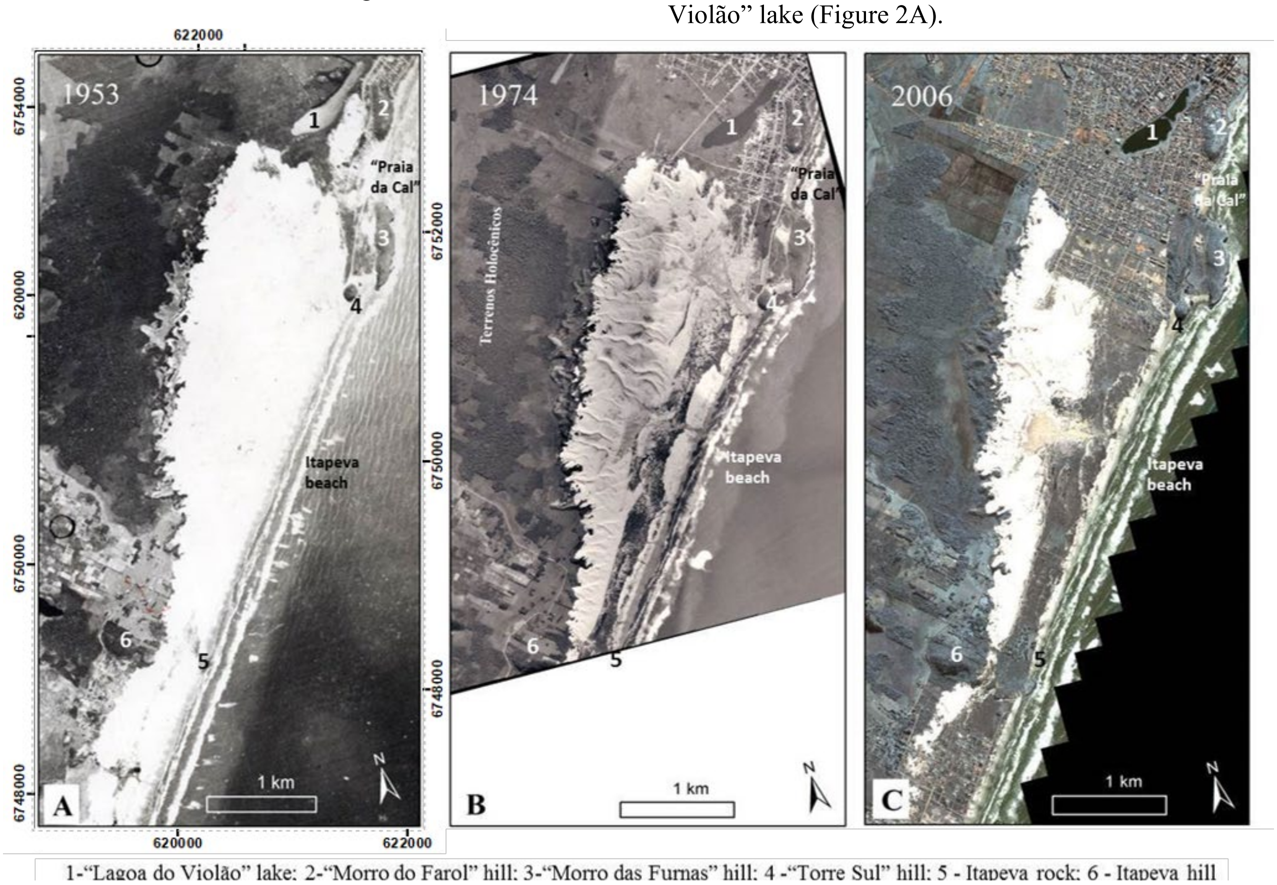

Figure 2: Spatio-temporal changes in the Itapeva dunefield: (A) Aerial photo from 1953; (B) aerial photo from 1974; and (C) IKONOS satellite image from 2006. A reduction in active dunefield area, expansion of the deflation plain, and urban area can be seen. (UTM Zone 22S, datum WGS84)

A slightly higher topography around the “Morro do Farol” hill, in the northern portion of “Praia da Cal” beach (Figure 2A) constitutes a physical barrier for aeolian sediment transport from the beach. An aerial photograph from 1934 illustrates this area in another perspective (Figure 4), showing the environment at that time. Although there is a connection between “Praia da Cal” beach and the northern portion of the Itapeva dunefield, sediment supply from this beach does not seem to be significant. In general, the mobile dune area is elongated in the SSW-NNE direction, with a convex edge that suggests a migration from the south to the north direction (Figure 2).

The urbanized area in Torres is clearly defined in the oblique aerial photograph (Figure 4), from the “Morro do Farol” hill to the northern direction. Some roads are oriented towards the beach direction, in a direction towards “Guarita” hill, but no significant urbanization was detected from “Morro do Farol” hill towards the southern direction in that year.

The dune morphology within the active dunefield could not be analyzed, due to a lack of contrast in the aerial photographs. However, the 1930 aerial photograph (Figure 4) clearly shows transverse dunes were dominant at least in the northern section of the dunefield, and the digitate precipitation ridge bounding the western margin of the dunefield was active.

The 1974 aerial photograph covers the northern region of the Itapeva dunefield (Figure 2B) and shows a small decrease in the dunes area in the northern portion. New roads have been built around the “Lagoa do Violão” lake, facilitating access to the southern region of the city. Many new roads and urbanization have developed from the city center to the south, until “Praia da Cal” beach. No more dunes are observed in this area as they were covered by urbanization.

Two large drainage channels are present in the northern region of the dunefield. One of them is the “Riacho Doce” drainage and the other significant drainage area can be observed 1 km to the south and flows from the dunefield toward the sea on the southern side of the red rock outcrop (“Pedra Vermelha” rock). On the western edge of the Itapeva dunefield, the parabolic depositional lobes oriented in the N-NW and SW directions are now mostly vegetated and stabilized. In 1974, a vegetated deflation plain, with a maximum width of 330 m, developed in the northern region. Transgressive sand sheets are also present, with no vegetation. These features are about 180 m in width, advancing landwards from the beach, over the deflation plain. This represents a new phase of initial transgressive sand sheet development. The presence of wetter interdune areas and the formation of washouts segmenting the sand sheets and dunes can be observed in the northern region of the dunefield by 1974.

The 2006 satellite image covers the entire dunefield (Figure 2C) and it may be observed that Itapeva dunefield extends about 4.15 km from the north until the Itapeva rock and that from the Itapeva rock to the south, the mobile dunes extend about 670 m.

Figure 3: Detail of the digitate precipitation ridge with parabolic depositional lobes landward of the principal active precipitation ridge on the margin of the Itapeva dunefield in 1953. Location indicated in Figure 1.

In the northern region of the dunefield, new urbanization, covering about 1,000 linear meters over the dunefield and the “Riacho Doce” drainage channel, was developed, with a loss in dune area of about 1.08 km². The distance between the “Lagoa do Violão” lake and the northern portion of the dunefield is about 700 m. The drainage area that developed about 1 km distant in the southern direction from the “Riacho Doce” drainage now occupies a larger low area (previously occupied by dunes), and the main drainage channel appears to have become more stable and deeper (Figure 2C).

By 2006, the mobile dune area is separated from the beach line by a foredune and a vegetated deflation plain continued developing parallel to the coast. The maximum width of the deflation plain is 430 m. The maximum mobile dunes width is about 830 m in the northern region of the dunefield and comprises reversing transverse dunes, some with sinuous crests. On the dunefield landward margin, precipitation ridges advance into wetland areas, small lakes, and vegetation, and in the central sector it advances over the grassland.

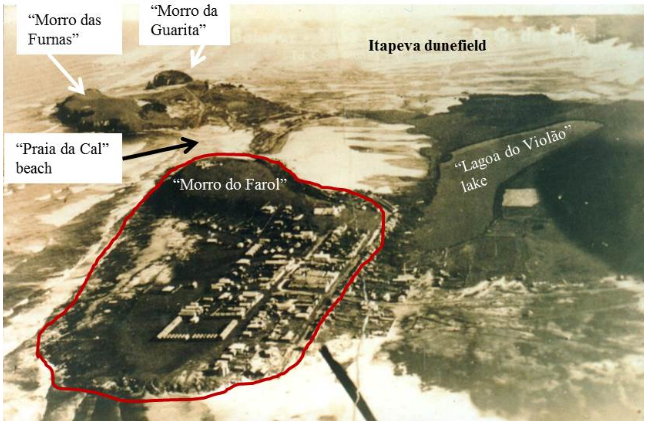

Figure 4: Oblique aerial photograph from the 1930's (view from north to south). The red line surrounds the higher topography and urbanized terrain in Torres, around "Morro do Farol" hill (Source: "Historiadores de Torres" community at Facebook)

The significant anthropogenic occupation can be observed on the northern boundary (Figure 2C). Since the creation of the protected area (Itapeva state park) in 2002, and the delimitation of its boundaries, new occupation areas were not identified in the image. This is verified by analyzing a satellite image of 2013 and comparing it to the image from 2006.

The deflation plain is completely vegetated by 2006 and has increased in width, reaching about 600 m in width in the northern portion of the dunefield. Transgressive sand sheets occur over this area and are now completely vegetated. The aerial photo from 1989 already shows vegetation growth over the sand sheets. The distance from the sand sheets precipitation ridges up to the vegetated foredunes western boundaries ranges from 80 to 160 m. Irregularly spaced washouts are present along the entire dunefield. The vegetation cover increased significantly between the mobile dunes area and the foredune line (Figure 2C) between 1074 and 2006. These analyses of spatial changes in the Itapeva dunefield over ~60 years are shown in Table 2 and Figure 5.

In summary, the original mobile dunes area between "Morro da Itapeva" hill and the "Lagoa do Violão" lake decreased from 4.55 km² in 1953 to 1.89 km² in 2006. At the same time that the dunefield moved landward, a deflation plain developed, and the vegetation cover in this area increased. An area of 0.45 km² of vegetation developed from 1953 to 1964, and continued increasing up to 1974, when it reached a coverage of 1.22 km². From 1974 until the year 2006, the vegetation cover increase was much less. Also, on the landward margin, vegetation cover increases during these years and became denser.

The grey tones in the 1953 aerial photo allow the identification of understory vegetation covering the older precipitation ridge, and some shrubby vegetation (sandy forest) growing on the active precipitation ridges. In the 1974 photo, new precipitation ridges covering the shrubby vegetation in some areas may be identified, and there is an increase of vegetation in other parts of the landward margin/precipitation ridge. Active sand sheets were present at that moment. In 2006, shrubby vegetation has established on the older precipitation ridge and other parts of the dunefield landward margin. Urbanization takes place in the northern dunes area after the year 1974. In 1989, 0.35 km² of the Itapeva dunefield was occupied by urban structures, and by 1996 the urbanized area increased to 0.67 km². From this year until 2006, an additional area of 0.41 km² was occupied by urbanization over the dunefield.

Table 2: Spatial and temporal changes in the mobile dunes area, vegetation cover in the deflation plain area, and urbanization over the original dunes area, between 1953 and 2013.

Years	**1953**	**1964**	**1974**	**1989**	**1996**	**2006**	**2013**
Mobile dunes area (km²)	4.55	3.84	3.42	No data	No data	1.89	1.89
Vegetation cover in the deflation plain (km²)	0	0.45	1.22	No data	No data	1.23	1.21
Urbanization over the original (1953) mobile dunes area (km²) in the northern dunefield area	0	0	0	0.35	0.67	1.08	1.09

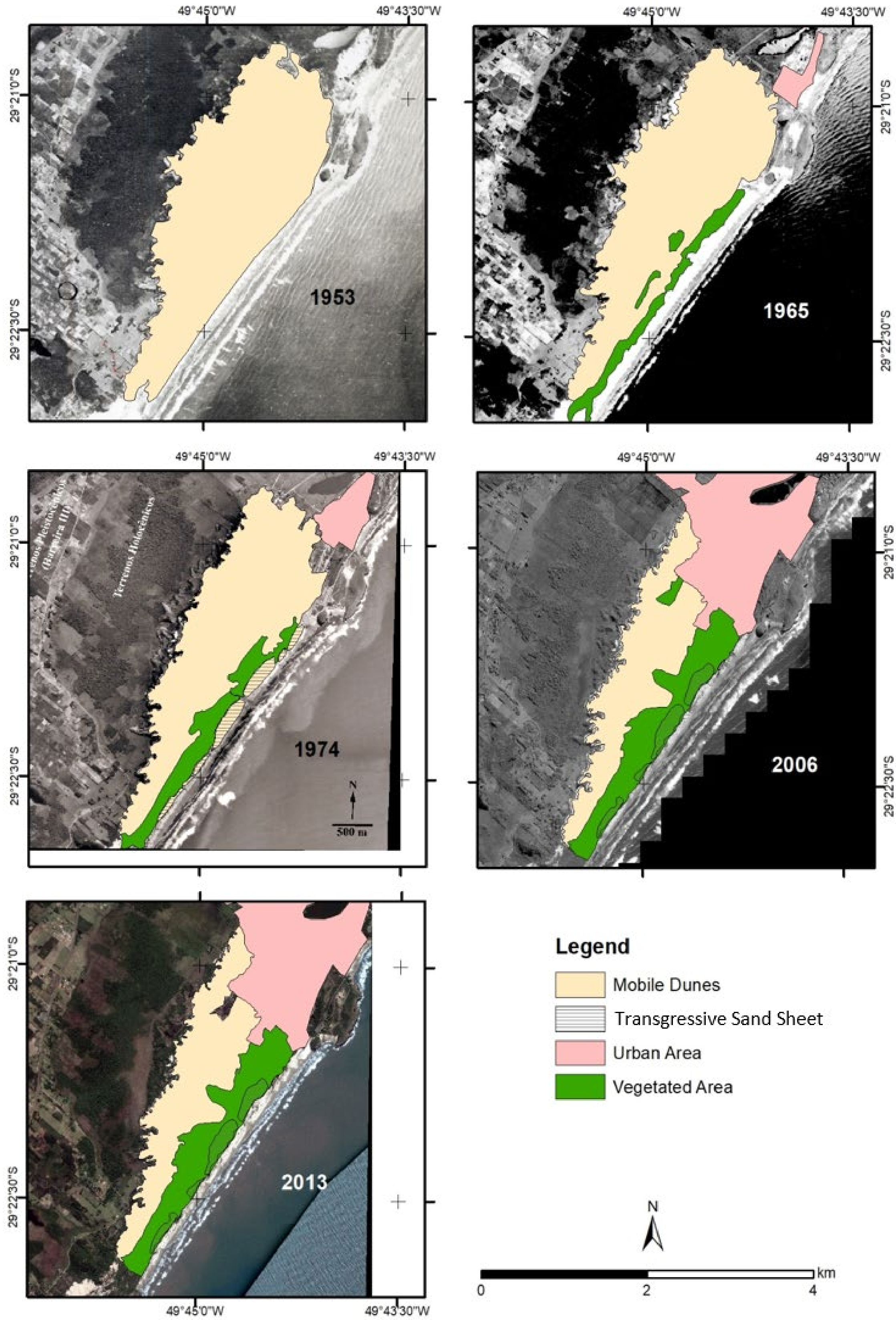

Figure 5: Spatio-temporal changes in the Itapeva dunefield from 1953 to 2013 showing the changes in mobile dunes, vegetated area and urban area.

3.2 Precipitation analysis

In the last 53 years, some variations in average yearly precipitation were observed (Figure 6). The lowest minimum precipitation occurred in 1962 (47 mm) and a maximum occurred in 1983 (179 mm). The same "dry" year (1962) was detected by Martinho (2008) on the southern Brazilian coast, for Imbé station (57 mm), which is located 80km from the Torres station to the south.

Despite the high variability during the period examined, the data show a tendency of increasing rainfall (Figure 6A), and since the year 2002, no annual average below 100 mm occurred. Evaluation of the historical series in order to look for possible evidence of variations in precipitation values over the years, the Mann-Kendall test was applied to the annual total values. Analyzing the results obtained from MK methodology, it was found that there have been significant changes in the behavioral patterns of this meteorological variable in recent decades, with a significant increase in precipitation values. The p-value found by the statistical test was 0.0015. Thus, the null hypothesis (that there are no trends in the series) should be rejected. The resulting Mann-Kendall coefficient value was 3.17, showing an increase in total annual rainfall in the region from the analysis of this historical series.

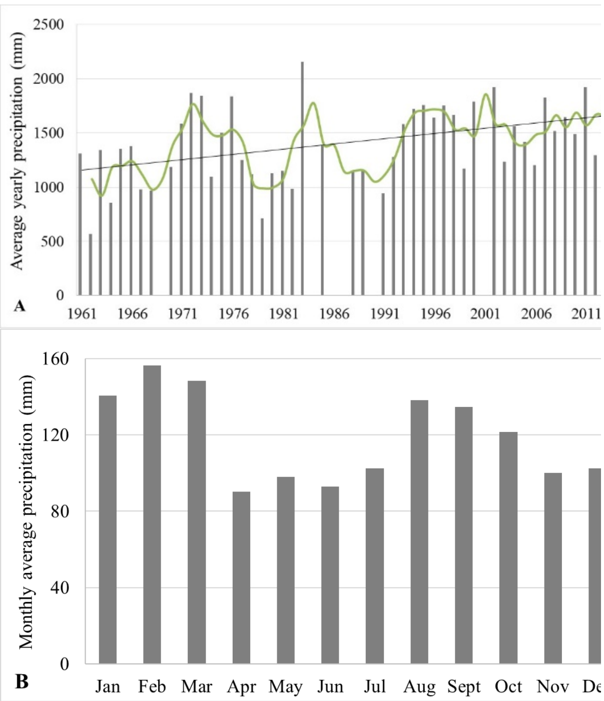

Figure 6: A) Yearly average precipitation for Torres meteorological station for 53 years of data. The black trend line shows an increase in the precipitation from 1961 to 2014. The green line is the 3 years moving average. B) Monthly average precipitation for Torres station for the period from 1961 to 2014.

3.3 Aeolian drift potentials

The regional winds are bimodal from the NE and S (Rockett et al. 2017). According to Fryberger and Deans' classification (1979) and Bullard's considerations (1997), the ERA data indicates a high wind-energy environment (offshore); the Torres meteorological station indicates a intermediate wind-energy environment (very close to Itapeva dunefield); and the CSFR data and Airport meteorological station indicate a low wind-energy environment (close to the dunefield and inland).

The analysis of the variation of the Drift Potential (DP) over the years shows a trend of declining values, mainly for Torres station and for the Airport station (Figure 7). Although there is considerable dispersion in the data, Pearson's correlation coefficient for these meteorological stations showed values of -0.86 and -0.68, respectively. The trend towards a reduction in DP values is corroborated when analyzing the results of the statistical tests for these stations. In both cases the value of the MK coefficient was negative (-6.41 and -2.34) and the p-values were below 0.05 (approximately zero and 0.019). The ERA INTERIM data also showed a negative correlation, but in this case, the values obtained indicated a weak correlation (-0.25). In this case the p-value is equal to 0.13, indicating that there are no significant reduction trends. Only the CSFR estimates showed a positive linear correlation; however, the value of Pearson's coefficient obtained these estimates also indicated a weak correlation. This non-significant tendency is confirmed when evaluating the p-value for this historical series (0.52)

The data shows that wind velocities have decreased over the last decades for the meteorological stations and reanalysis grid points (Figure 7).

The directional variability index for the four datasets show a high variability of sand-transporting winds in the region (RDP/DP ratios: Torres station = 0.26; ERA-Interim station = 0.16; CSFR station = 0.09; and SBTR/Airport station = 0.27). Wind data from ERA and CSFR can be classified as obtuse bimodal flow regimes, while Torres and Airport data can be classified as complex flow regimes.

Results show that the total drift potential (DP) at Torres station is 42.6 v.u., at the ERA-Interim station it is 118.8 v.u, at the CSFR station is 17.4 v.u. and at the SBTR/Airport station it is 23.1 v.u. (Figure 8).

The ERA dataset (offshore) shows the potential sand transport from the NNE and NE winds are the highest (25.4 v.u. and 22.7 v.u., respectively), followed by the potential sand transport from SW winds (15.4 v.u.), resulting in a resultant drift potential (RDP) of 18.8 v.u. to the SSW direction (196º).

At Torres station, the potential sand transport from NE winds are the highest (14.3 v.u.), followed by the potential sand transport from S winds (10.3 v.u.), which play a significant role resulting in a resultant drift potential (RDP) of 11 v.u. to the NW direction (RDD = 316º).

At the Airport/SBTR station, sand transport potentials are from ENE and E winds (4.9 and 3.4 v.u., respectively), followed by SW winds (2.7 v.u.), resulting in a resultant drift potential (RDP) of 5.9 v.u. to the W-NW direction (309º).

From the CSFR data, sand transport potentials are from NE and ENE winds (4.1 and 3.2 v.u., respectively), followed by WSW winds (2.2 v.u.), resulting in a resultant drift potential (RDP) of 1.5 v.u. to the ~N direction (358º).

Datasets for the ERA, CSFR and Airport stations utilize discrete wind data in 16 directions, while for Torres station the wind data is classified in eight directions, and this could have influenced the sand drift potentials as indicated by Pearce and Walker (2005). Further, ERA and CSFR datasets provide four observations per day (0000, 0600, 1200, 1800), and the Torres dataset provides three observations per day (0000, 1200, 1800) and the Airport dataset shows intermittent hourly data and do not show data for all days during the years. Even so, the results are complementary, showing that (i) the regional resultant drift potential inland in the Itapeva region is to the NW-N quadrant direction (ii) NE, NNE, ENE and SW, S winds play a significant role in the regional wind pattern and sand drift potentials at the Itapeva Region (ERA, Torres and Airport stations), (iii) the N-E quadrant DP is higher at Torres station (14.3 v.u. NE) than at the SBTR/Airport station (4.9 v.u. ENE), (iv) winds from the S direction have great sand transport potential at Torres station (10.3 v.u.) and from SW at ERA station (15.4 v.u.) and the Airport station (3.0 v.u.), (v) the RDP from offshore winds is peculiar, when comparing to the onshore data; the onshore wind data show a regional/local wind transport pattern, which influence the aeolian forms in the Itapeva region, although the offshore dataset is free of topographic influence.

The DP data show that the strongest winds occur at the Torres station compared to the Airport and CSFR stations. Torres station is located in a coastal area very close to the dunefield, which is surrounded by basement outcrops; Airport is located in a flat area close to a lake and the CSFR is very close to the lake and the highlands.

Seasonal sand drift potentials for Torres station, which is closer to the Itapeva dunefield and is the object of this study, are shown in Figure 9. High RDP data occur during spring, due to the strong NE winds acting in the area, which provides a significant sand transport potential (56.6 v.u.) with resultant drift potential (RDP) of 20.2 v.u. into the W-NW direction (277º).

During summer, NE winds play a significant role together with S winds, resulting in a sand transport potential of 37.8 v.u., and a RDP of 15.17 v.u. to the WNW direction (283º). In the autumn season, winds are responsible for lower DP’s in the area (33.0 v.u.), and winds from the SW and S play a significant role resulting in a RDP of 12.3 v.u. into the ~Ñ direction (10º). In winter season, the SW and S winds are the most significant for sand transport, with a RDP of 15.0 v.u. into the ~N direction (16º).

Winter and spring seasons have the higher sand transport potential in the Itapeva region, with resultant drift potentials to the Ñ direction and to the W-NW direction, respectively.

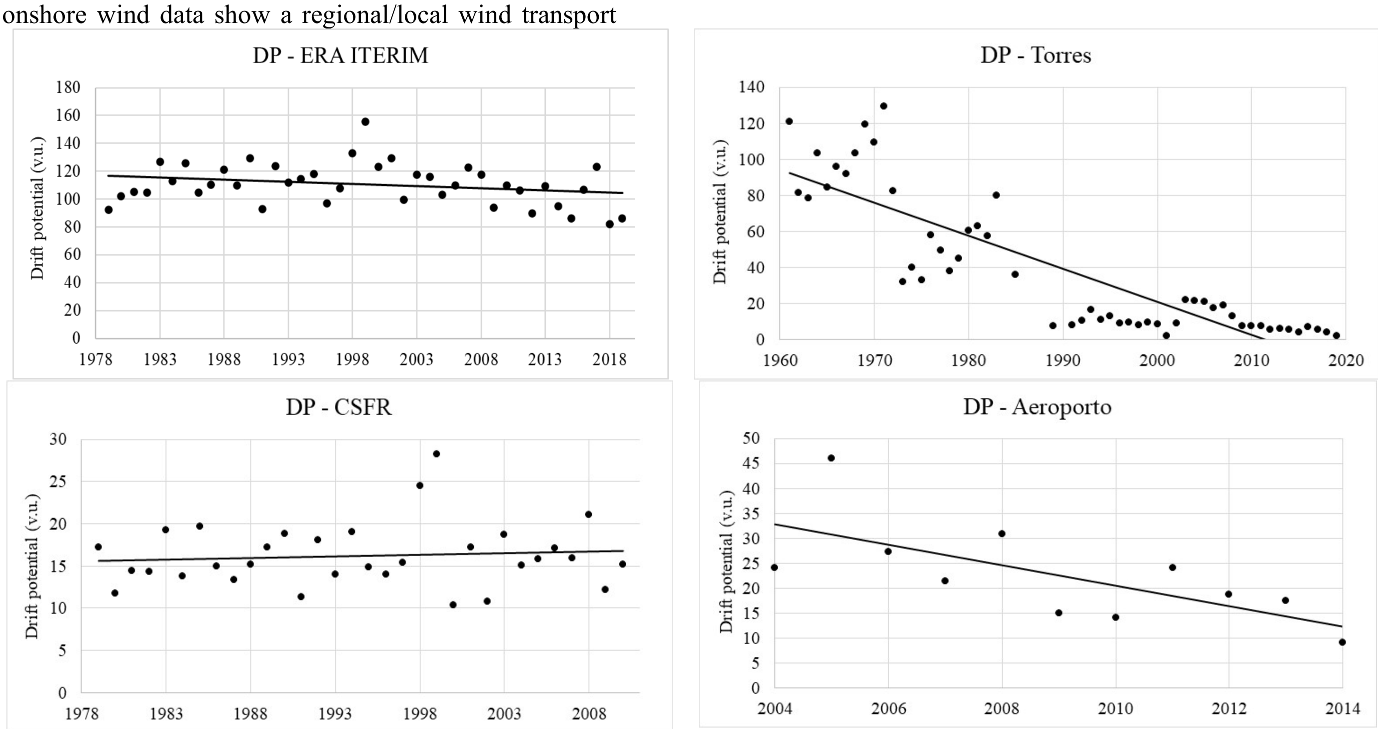

Figure 7: Drift Potential for the analyzed meteorological stations and reanalysis. Data source: INMET- BDMEP and ERA.

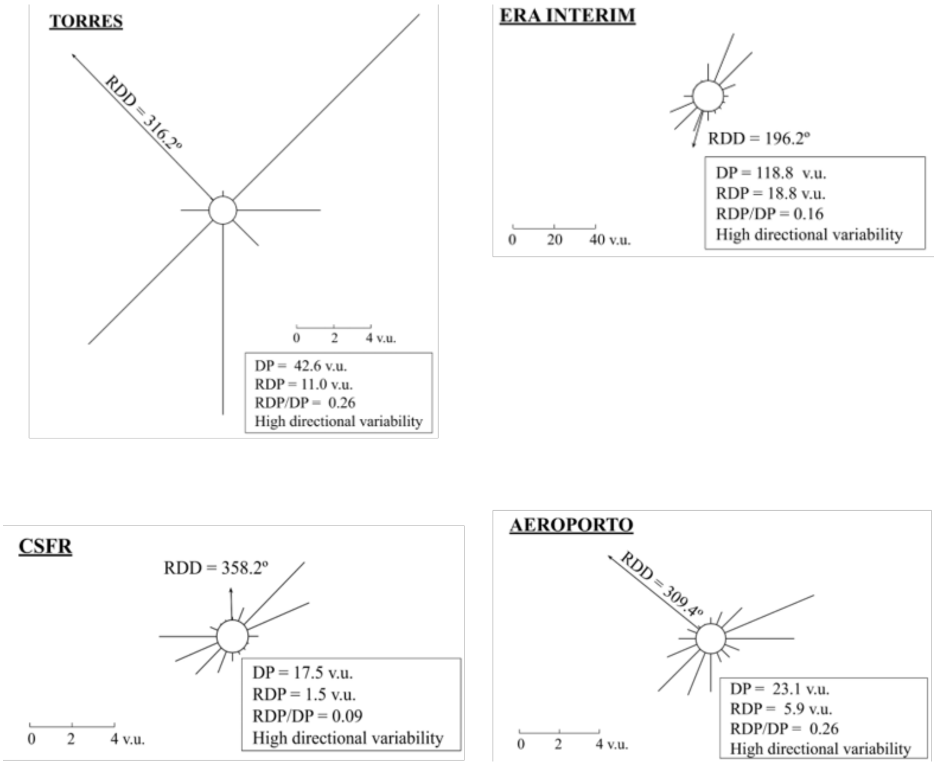

Figure 8: Sand roses for ERA-Interim, Torres, CSFR and SBTR/Airport meteorological stations, showing the annual DP for each. The arrow represents the RDP, and the RDD is also indicated. Vector units calculated based on wind velocities in m s-1.

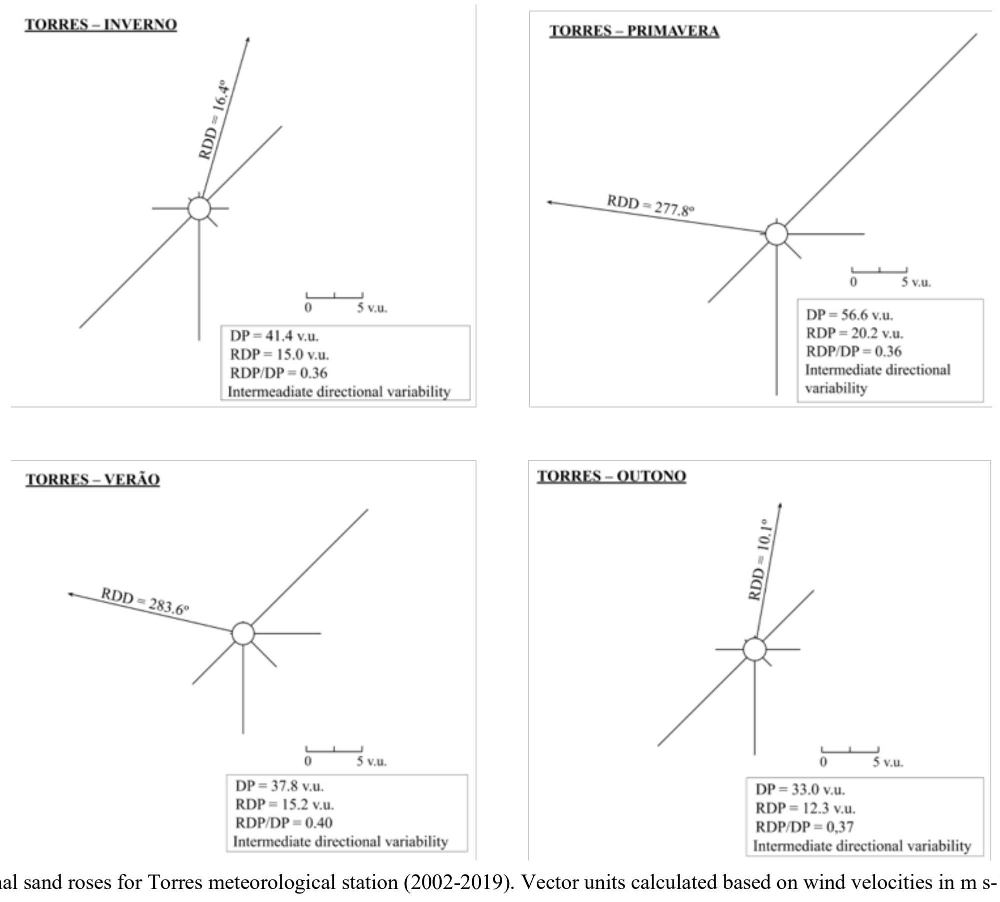

Figure 9: Seasonal sand roses for Torres meteorological station (2002-2019). Vector units calculated based on wind velocities in m s-1.

4. Discussion

4.1 Climate and vegetation cover

An increase in yearly average precipitation over the last 50-60 years has been found in other coastal studies in southern Brazil (e.g. Miot da Silva and Hesp, 2013, Miot da Silva et al. 2013). For the Florianópolis station (located 280 km north of Torres) an increase of 60 mm over the last 50 years was found by Miot da Silva & Hesp (2013), and for Imbé station (located 80 km south from Torres) an increase in average precipitation of 20 mm was found by Martinho et al. (2010). Despite being more distant from Torres, Florianópolis station presented an average increase in precipitation closer to the values found for Torres station compared to the ones for Imbé station. This result can be associated with the close proximity of Torres and Florianopolis to the Serra Geral and Serra do Mar mountains, which act as a physical barrier in the rainfall regime/humidity. Khan et al. (1998) analyzed historical rainfall data from 13 meteorological stations in Rio Grande do Sul and Santa Catarina states, and showed that Torres and Florianopolis stations data (the only two stations located close to the coast) do not correlate significantly with the other ones, and suggested that they are under the influence of a coastal effect. Besides similar in variable trends for precipitation and total wind power, the two stations (Florianópolis and Torres) showed a clear difference when Drift Potentials from southern and northern winds were analyzed (Mendes & Giannini, 2015). The effect of the South Atlantic Summer Monsoon-SASM (and the South Atlantic Convergence Zone) was detected when comparing the directional wind data from Florianópolis and Torres stations. In Torres station, the increase of the SASM probably weakens both the north and the south winds, and this results in a strong correlation between the two wind directions (in Florianópolis SASM affects north winds more intensely).

The increase in precipitation over time would lead to an increase in the height of the water table which could have a significant effect on vegetation colonization and growth particularly within, and near the deflation plain, and as shown for other dunefields (e.g., Marcomini & Maidana, 2006, Jackson et al., 2019).

Spatial changes in the Itapeva dunefield and its vicinity were observed and quantified from aerial photos from 1953 to 2013, and a drier environment in 1953 changed to a more humid environment over the years until the present. The increasing moisture influenced dunefield morphologies during the last decades (from 1953), with the appearance of drainage areas (washouts) along the coast that were not present in the region before, although this is likely, in part, influenced by the stage of dunefield evolutionary development. It appears that more washouts or local drainages are formed once the deflation basins are well developed and the water table is close to the surface. The water table level could be closer to the surface due to the aeolian deflation processes in the region. The more humid climate during the last decades, may have influenced the vegetation cover increase in the Itapeva region, together with the decrease in average wind velocities since 1961 (Figure 7), as also occurred in nearby regions and other coastal dunefields (Bigarella, 2000, Hesp et al. 2009, Martinho et al. 2010, Miot da Silva & Hesp 2013, Miot da Silva et al. 2013, Mendes & Giannini, 2015). Considering the typical subtropical climate of the Itapeva region, and according to Tsoar (2005) and Yizhaq et al. (2009), for an annual rainfall greater than 800 mm, the main factor controlling the mobility of the dunes is the effective wind. Possibly in the Itapeva region the main factor for vegetation increase could be the decrease in wind velocities during the last decades, although given the concurrent increase in rainfall, it is uncertain which of these factors (rainfall or winds) are the most critical in driving change.

Note also that the Holocene sediment thickness in the Itapeva dunefield region is relatively thin (a maximum of 22 m in the central region of the area, according to Rockett et al. 2014, and minimum 0 m – basement outcrops), compared with the other southerly dunefields This minimal thickness of sediment overlying impervious basement rocks may contribute to water confinement and possibly a faster rise of the water table in this region, thereby contributing to the increase of subsurface humidity and vegetation growth. The development of tropical forest vegetation and its increase in density over the years in the Itapeva region is also rather unique, due to its singular more "tropical-like" climatic characteristics (Hesp, 2004). A deflation plain has developed over this 60-year period, and vegetation growth began in this region in the late 1950's/early 1960's, and this is now fully vegetated. Minimal grass vegetation and midsize shrubby vegetation cover were present in 1953, as observed in the aerial photographs, and became denser after the 1990's. The active precipitation ridges continued advancing landwards. The new transgressive sand sheet phase, not very clear or obvious in the 1965 picture but quite obvious by 1974 (Figure 7), failed to develop further and largely stabilized as the continuing change in precipitation and decline in windiness continued. In more recent times the sand sheet has disconnected from Itapeva beach, and there is no sand feed to the sand sheet mobile dunes or deflation plain. The sand is being trapped close to the beach forming foredunes.

4.2 Sand drift potential, sediment supply and aeolian geomorphology

Despite the fact that NE winds are the most frequent during spring and summer, southerly winds (S and SW) play a very significant role over the four seasons regarding sand transport potential across the Itapeva dunefield. Southerly winds, originating as cold fronts from the south pole, show more frequent higher velocities (>12m.s-1) and they strongly contribute to sand drift potential in the Torres/Itapeva region. In a historical wind analysis, Rockett et al. (2017) showed that from April to September the high frequency of high velocity (>5m/s) winds from W-S quadrant predominate in the region. These winds occur together with lower precipitation months at the studied region (Figure 6B). Based on the historical wind data analyzed in this study, the annual resultant drift direction (RDD) at the Torres meteorological station is to the NW direction (316º).

Winds responsible for dunefield development are decreasing. Historical data from ERA, and the Torres and Airport stations show that sand drift potential have decreased along the decades. The ERA station is very close to Torres but offshore so it is free of any topographic influence or interference. The Itapeva dunefield is also controlled by topographic influence, which can be observed in Torres, Airport and CSFR data.

ERA offshore data shows a RDD pointing to the ~SW, which fits with the pattern seen in other dunefields in Rio Grande do Sul coast, but in the Itapeva dunefield the pattern is different, due to its location in a peculiar geological setting in the Rio Grande do Sul coastal plain (confined between basement outcrops and very close to the Serra Geral high hills) and the topography influences the sand drift and aeolian forms. As we can observe in Torres, Airport and CSFR data, the calculated RDD is approximately towards the NW/N direction, driven by stronger southerly winds that act in the region frequently. As a future work, field observations and measurements are required to investigate if this RDD is confirmed at a dunefield scale.

Seasonal analysis for the Torres station, shows the resultant drift direction during winter and autumn is into the ~N, and during spring and summer is into W-NW. The resultant sand drift direction (RDD) in the Torres region has a very different pattern when compared to the Imbé region (Tomazelli, 1993, Martinho et al. 2010), in which the resultant sand drift potential direction is to the SW almost throughout the year (spring, summer and autumn – except in winter, when the RDD is in the SE direction), driven by NE winds. Furthermore, the northern region of Rio Grande do Sul coastal plain is in the temperate climatic zone, and the climate in this region can be defined as mild mesothermal, super humid without a dry season (Nimer, 1977), and in the northern coast of RS, higher altitudes are responsible for the rainiest period during the summer months (Grimm et al. 1998), different from the mid and south coast of RS where the rainiest period is in the winter months. The historical precipitation data from Torres meteorological station shows that the periods of higher rainfall are in summer/beginning of autumn (January to March), and the end of winter/beginning of spring (August to October). These higher rainfall periods coincide with the growing season, and also with the highest wind period. Both would act to potentially increase the degree of vegetation growth and colonization rates as the rainfall gradually increases over time in the Itapeva dunefield/Torres region.

The analysis of the climate data and the aerial photograph from 1953, indicate that the sediment supply to the Itapeva dunefields was mostly from Itapeva Beach, which is very exposed to southerly winds, together with a contribution from “Praia Grande” beach driven by NE winds during spring. Alongshore sediment transport on the Rio Grande do Sul coast is from S to N, and so, the hills located just north of Itapeva (“Morro das Furnas” hill) could also have contributed to sediment trapping in the Itapeva beach embayment during the Holocene. Also, a recent study indicated that the Torres coastal sector presents the highest azimuth (41.3 °) of the Rio Grande do Sul northern littoral (Vianna & Calliari, 2019), and together with other variables, has unique environmental features.

Martinho et al. (2009) calculated longshore sediment transport for different coastal sectors in RS, and for the Torres region it is classified as low, compared to other sectors up to Chuí beach (extreme south of the RS coast). Longshore transport in Torres can be observed nowadays at Molhes beach (South side of Mampituba river mouth), due to the sediment trap on the southern side of the river after jetty construction. Zasso et al. (2013) studied and quantified erosion and accretion on Molhes beach, before and after the jetties installation. The coastline orientation of Molhes Beach and Itapeva Beach is the same, so, “Torre Sul” and “Morro das Furnas” hills possibly act the same way that the jetties do to the south trapping sand and making it available to the dunefield. The sediment supply in Itapeva beach can be observed nowadays in the foredunes since they have significantly developed since the formation and stabilization of the most recent transgressive dunefield/dune sheet phase.

Overall, the evolution and morphologies present in the Itapeva dunefield, indicate that this dunefield has developed from the backshore, and is currently at stage III in transgressive dunefield development (Hesp, 2013). At this stage, the dunefield gradually migrates inland and a larger deflation plain forms in the upwind region. Vegetated aeolian forms such as nebkha and gegenwalle ridges are present, and wetlands (aka wet slacks) have formed. The precipitation ridge at this stage is commonly undulate (wavy), and digitate especially where it is migrating into dense or high vegetation.

4.3 Urbanization and sediment supply

In the 1970s, urbanization was intensified in the Torres municipality, and the human occupation of land adjacent to Torres advanced towards, and into the southern dunefield region, with an increase in road development in the southern part of the city center. From 1989 to 1996, human occupation and urban infrastructure in the Itapeva dunes area increased 100%. All of this development and expansion was illegal, but not policed or restricted by authorities. This fact is explained by Graciano (2004), who states that during the 1990’s, the tourism industry crisis resulted in a reduction of available jobs and together with the lack of urban planning in Torres, the illegal settlement called "Riacho Doce" formed in the northern sector of the Itapeva dunefield. Occupation continued growing contributing to environmental degradation and pollution until the Conservation unit was created in the Itapeva region in 2002. Even if sediments from Praia Grande beach and the Mampituba river could have contributed to the formation of the Itapeva dunefield, driven by NE winds in the past, since the human occupation and urbanization of Torres city, NE winds do not contribute any more to sediment supply to the Itapeva dunefield.

In addition, some sand removal from the aeolian system and dunefield for construction due to human occupation since the 1970's until 2002 has contributed to the decrease in sediment volume in the dunefield and possibly affected the aeolian landforms and dune types now present. A global review study indicates dunefield stabilization around the world, showing loss of bare sand area due to increase in vegetation cover and urbanization expansion (Gao et al., 2020).

5. Conclusions

In this study, spatio-temporal and climatic analyses were performed in a sector of the southern Brazilian coast, the Itapeva dunefield region in Rio Grande do Sul state, to understand its historical evolution over the previous ~60 years, and to identify factors influencing the changes observed. The Itapeva dunefield is confined in an area with basement outcrops and a locally different wind pattern than adjacent regions. Dunefield spatial changes over the last 60 years described in this study are related to an increase in vegetation cover, a decrease in the dune area, and an increase in drainage and urbanized area. Despite the fact that human factors have influenced the dunefield to some degree by the removal of sediment and by covering a significant portion of the dunefield due to urbanization, the results also indicate that evolutionary factors, particularly the development of a significant deflation plain whose height is strongly controlled by the water table, and natural factors (an increase in rainfall and vegetation colonization, and a decrease in wind velocities and consequently in sediment supply) are responsible for the main spatial changes and stabilization process of the Itapeva dunefield. An increase in rainfall and decrease in wind velocities and sand transport into the dunefield over the last decades (as opposed to into the foredune formed in more recent times), combined with the evolution of a significant deflation plain which is relatively easily colonized by vegetation once deflation occurs down to, or near the surface of the water table zone contributed to the establishment of vegetation and the beginning of the stabilization process of the Itapeva dunefield. This study corroborates the results found by others in Santa Catarina, the next State to the north (Miot da Silva et al., 2013; Miot da Silva & Hesp, 2013, Mendes & Giannini, 2015, Leal & Barboza, 2017). Further, there is a worldwide trend of dune stabilization - 93% of the more than 160 dunefield sites analyzed (Gao et al., 2020).

The main findings of this study, when comparing images from 1953 to 2013, is that in the past there was no or little vegetation in the Itapeva dunefield. The area covered with mobile dunes was greater in the 1950's, when beach sediment directly fed the dunefield. Since the area became more humid due to increasing rainfall and a deflation plain developed, followed by the vegetation growth since the 1960's-70's, sediment from the Itapeva beach driven by southerly winds could not move into the dunefield (natural evolution). In the last decades, the influence of human occupation also isolated or covered a significant area of sand within the Itapeva dunefield system.

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