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Lagoon-barrier system response to recent climate conditions and sea level rise, Mozambique, Africa

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ABSTRACT

Transitioning lagoon-barrier systems and coastal transgressive dunes offer the valuable opportunity to correlate their formation and interactions with seasonal dry and wet climate conditions, stepped relative sea-level rise of ~3.5 m, and sediment supply at various scales. This manuscript examines the Holocene sea level changes and recent climate conditions and controls on a 150 m-high coastal barrier system in Mozambique, southeastern Africa. The methodological approach was based on the use of 7 kyr B.P. relative sea-level curve; 37 years of wind records from 1979 to 2016; 52 years of rainfall records from 1960 to 2012; and 56 years of average recorded temperatures from 1960 to 2016. Local dunefield migrations were monitored and the sand transport rate was measured from 2016 to 2017. The combined effects of the relative sea-level rise and sediment supply indicate the formation of the lagoon-barrier system in southern Mozambique. While the recent dry and wet climate conditions suggest that they might be a controlling factor on the generation of transgressive dunefields that migrate landward. This migration is reflected on the sand transport rate of 1.4 kg m^{-1} s^{-1}, which is controlled by winds from the SSW, the S and the SSE quadrants. The active parabolic dunes monitored, indicated a SE-NW migration rate of 22.5 m yr^{-1}, which rapidly buries lakes and lagoons systems. The formation of different geomorphological features on the transgressive paleodunes and modern dunes reflect their exposure to prevailing S, SSE, SE, E and N winds, the annual rainfall of 1600 mm yr^{-1}, and the absence of rain for 7 months yr^{-1}. The stepped Holocene sea-level changes combined with high sediment supply and persistent acting of seasonal dry and wet climatic conditions led on the sedimentation and definition of transgressive dunefields morphology in southern Mozambique coast.

1. Introduction

The origin of barriers is associated to relative sea level changes and sediment supply that often accompany passive margin shores and other aggradational coasts (Otvos, 2012). Coastal barrier systems may be formed in different ways (Boyd et al., 1992) and could be occupied by coastal dunefields. In fact, Dillenburg and Hesp (2009) defined the dunefield barriers as landward-migrated foredunes, backshore dunes, and associated aeolian sand sheets derived from the backshore and foreshore zones. These coastal dunefields and continental systems occupy ~10% of the Earth's surface (Thomas and Wiggs, 2008). Aeolian processes in these fields generate active transgressive dunes and semi-active or fixed dunes (Thomas and Wiggs, 2008; McKenna-Neuman et al., 1996; Argaman et al., 2006; Ashkenazy et al., 2012; Tsoar, 2013; Kinast et al., 2013). Active or semi-active dunes occur when wind speed is greater than 6 m s^{-1} (Castro, 2005; Fryberger, 1979), with considerable annual precipitation and when vegetation coverage is less than 30% (Ash and Wasson, 1983).

The remobilization and migration of coastal dunes usually depends on: meteorological conditions (Tsoar, 2005; Kilibarda and Shillinglaw, 2014); coastal erosion (Aagard et al., 2007); relative sea-level changes and sediment supply (Boyd et al., 1992; Ramsay,

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1995; Argaman et al,. 2006); vegetation coverage (Pye, 1993); topography (Hesp et al., 2005); sand supply (Hesp, 2013); grain size, sand surface humidity (Wiggs et al., 2004); anthropogenic activities and the interactions of these factors. The influence of aeolian activity on these coastal dunes is sensitive to climatic conditions, mainly wind and rainfall (Yizhaq et al., 2013; Tsoar, 2013). Nevertheless, their interdependent interactions are still an open discussion and require more research to provide better understanding (Thomas and Wiggs, 2008).

Extensive studies on the importance of aeolian processes in both continental and coastal environments have been conducted throughout the world (Hesp, 1982; Fryberger, 1979; Hesp and Thom, 1990; Rust, 1990; Pye, 1993; Castro, 2005; Aagard et al., 2007; Yizhaq et al., 2013; Tsoar, 2013). These studies agree that the formation of coastal transgressive dunes depends on the effects of topography variation, vegetation coverage, rainfall, wind patterns, dune mobility index, sediment supply, existing accommodation spaces, water table levels and relative sea-level changes.

Despite the availability of various physical and mathematical models applied to continental aeolian environments (Mesbahzadeh and Ahmadi, 2005; Bullard, 1997; Tsoar and Blumberg, 2002; Pearce and Walker, 2005), their adaptations to coastal environments are relatively inconsistent due to the associated oceanographic and meteorological effects. Some of the literature about environmental reconstruction and evolution of coastal barrier systems (Armitage et al., 2006; Anthony et al., 2007; Arens, 1996, 1997; Arens et al., 1995; Saye et al., 2005; Hesp, 1982; Hesp and Short, 1999; Cooper and Pilkey, 2002; Davis, 1974), describes with a certain effectiveness the aeolian activity processes in short and medium term periods. According to these studies, there are large gaps in the existing researches, in particular those that focus on dune migration, mobility, orientation features and aeolian transportation of transgressive coastal dunes in Mozambique, on the southeastern coast of Africa.

Although there are regional studies that have described the evolution of coastal geomorphology in southern Africa (Armitage et al., 2006; Hobday, 1977; Cooper and Pilkey, 2002; Maud and Botha, 2000; Botha et al., 2003), the lack of research focused on coastal aeolian processes governed by relative sea level changes and environmental conditions is quite evident. Moreover, these studies of coastal dunes studies do not provide enough information about the absolute ages of the dunes studied their relationship with recent environmental data or with relative sea-level changes. The purpose of this research is to examine relative sea level changes and environmental patterns, and their control on the formation of dune-barrier system in Mozambique, southeastern Africa.

1.1. Regional setting

The coastal barrier system and transgressive dunefields described in this study are those that form a parallel system between coastal lagoons and lakes and the sea along the Mozambique coast (Fig. 1). The exposure of the southwest-northeast sand barrier ridge to environmental factors formed a set of modern transgressive dunefields that migrate landward and are orientated perpendicularly to the shoreline. Meanwhile, the fixed inner paleodunes are the result of paleo-environmental patterns related to the last maximum sea level that occurred during the Pleistocene. According to Cooper and Pilkey (2002) and Botha et al. (2003), these are among the highest coastal dunes in Africa and indeed the world. These coastal dunes extend along the coastline from Durban in the Republic of South Africa to Beira in the Republic of Mozambique, and are characterized by fixed paleo-dunes, small embryo foredunes, blowouts and modern transgressive parabolic dunes. The modern dunefields can reach heights of approximately 150 m.

The region's climate is tropical humid according to the Köppen classification, influenced by low pressure, anticyclonic tropical cells and somewhat by Antarctic polar fronts. The climate is distinctively seasonal, the summer between September and March and winter from April to August. According to Været et al. (2011), annual rainfall is roughly 1300 mm yr^{-1} with an average monthly temperature of ~23 °C. Været et al. (2011) state that mean annual evaporation exceeds 1100 mm yr^{-1} (evaporation data from 1954 to 2001). Maximum rainfall occurs between December and March, when the intertropical convergence zone with the precipitation belts reach the most meridional region (Moore et al., 2008). Moore et al. (2008), Ramsay (1995) and Armitage et al. (2006) reported that the annual seasons are influenced by the warm water current of the Mozambique Channel. The region has weak nebulosity and prevailing east quadrant maritime local winds and regional trade winds from the southeast quadrant.

According to Langa (2007) and Miguel et al. (2017), the local monthly wind regime (at a height of 10 m) averages between 3.5 $m^{-1} s^{-1}$ and 8.5 $m^{-1}s^{-1}$ with the main frequencies occurring from the NE, E, SE, S and SW. The persistent SE trade winds are the main factor in the generation of swell waves, which average of 1.5 m in height.

The region of interest is bounded by the Indian Ocean to the east with exposure to the north-south flowing Mozambique warm water current, which is characterized by periodic anti-cyclonic and cyclonic gyres (Halo et al., 2014). According to the National Institute of Hydrography and Navigation of Mozambique in 2015, the tidal regime is mesotidal with maximum amplitudes of 4 m during spring tides. The wave climate is predominantly from the southeast with a south-north longshore drift effect (Lutjeharms and Da Silva, 1987; Langa, 2007). A local longshore drift current is responsible for the dynamics of sediment transport alongshore and coastal hydrodynamic circulation.

1.2. Holocene relative sea level changes in southern Mozambique

Along the passive margins of southeast coastal Africa, a continuous coastal plain of about 800 km extends southward from Beira in Mozambique to Durban in South Africa (Armitage et al., 2006). Historical sea level changes on this coastline were previous studied by Ramsay and Cooper (2002), Ramsay (1995), Compton (2001), Jaritz et al. (1977), Gomes et al. (2017), Norstrom et al. (2011), Green et al. (2015) and De Lecea et al. (2017). These researches found sea-level transgression of 3.5 m recorded in back barrier estuarine fill sequences, diatom records, beachrocks and overstepped shoreline deposits on the submerged continental shelf.

The sea-level transgressions recorded brought about an elongated and shore-parallel sand ridges in southern Mozambique coast consisting of different geomorphic units, including beaches, paleo-dunes, modern dunefields, lagoons, lakes, tidal inlets and wash-overs at the mouth of the Limpopo River. This sand ridge is constituted by transgressive parabolic dunes, barchans and longitudinal dunes associated with coppice dunes. According to Armitage et al. (2006), the geological ages of these dunes are estimated to date sometime between the Pleistocene and Holocene. Their formation is associated with the sediment supply and relative sea level changes in southeastern Africa as presented by Jaritz et al. (1977), Ramsay (1995), Perry (2004) and Armitage et al. (2006) from 7 kyr B.P. to the present (Fig. 2).

The combination of relative sea level changes, sediment supply, and climate conditions generated the barrier system underlain by landward facies similar to that deposited in local lakes, estuaries, lagoons and marshes during the transgression. The relationship between the formation of this barrier system and sea-level

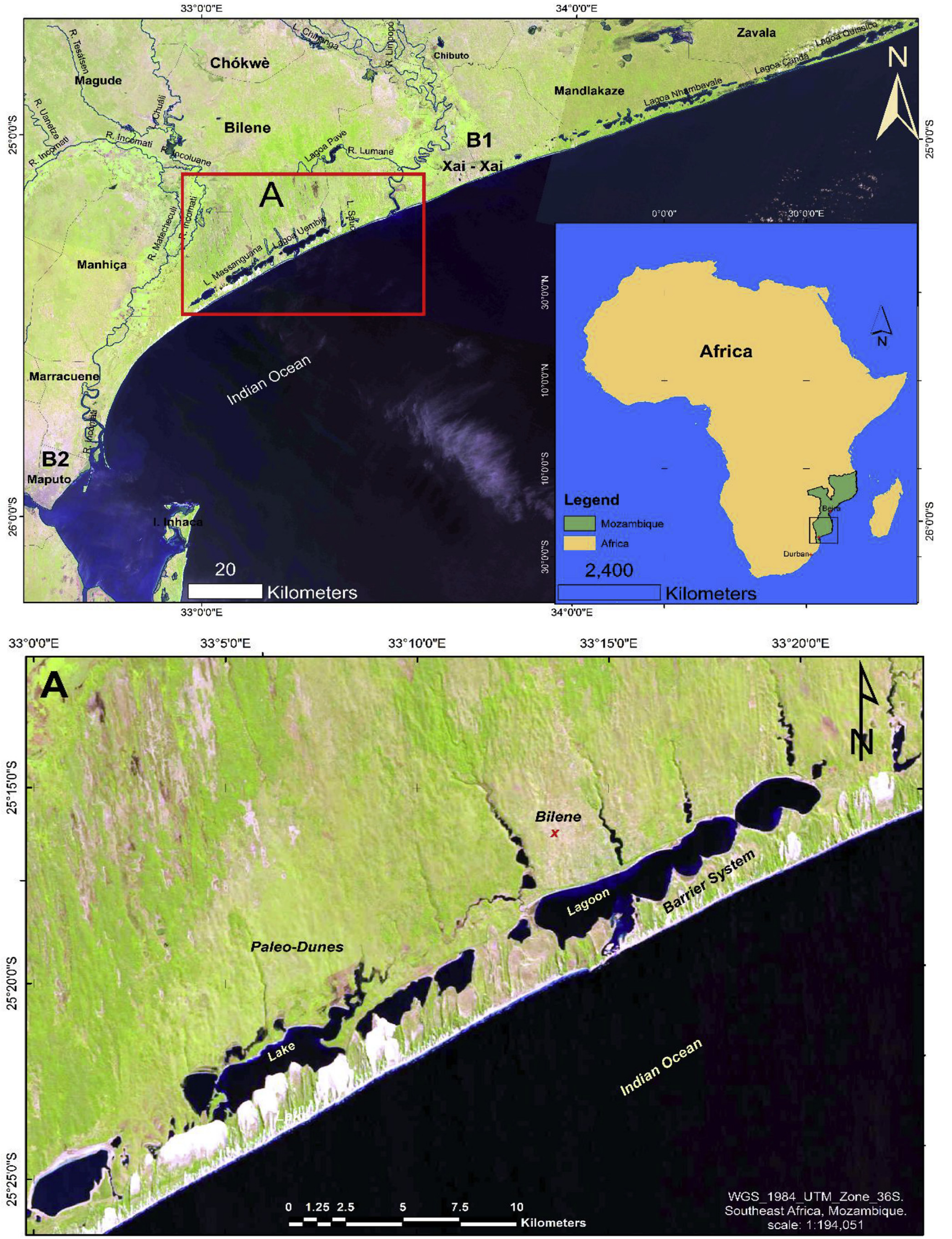

Fig. 1. Regional setting of coastal dunes in the lagoon-barrier system of southern Africa in Mozambique and the respective Maputo (B2) and Xai-Xai (B1) weather stations. The parallel lagoons and lakes are sheltered by a long sand barrier system formed by transgressive dunefields.

transgression was theoretically proposed by Boyd et al. (1992) and has been found in other parts of the world, including by Armitage et al. (2006) at Inhaca and Bazaruto Islands in Mozambique, and by Hesp et al. (2005) and Dillenburg et al. (2006) in Rio Grande do Sul state in southern Brazil, between 8 kyr B.P. and 7 kyr B.P., the same period referenced here.

Different estimates exist for sea-level changes and each presents slightly different sea levels during different periods of geological chronology (Fig. 2). Depending on which sea level estimation curve is used, the relative influence of sea-level change on the formation of barriers and dunefields differs. In this case, the four relative sea level curves for this coastal segment, curve (A) used an optically stimulated luminescence (OSL) method to date eolianites and sand deposits, while curves (B), (C) and (D) used the radiocarbon dating method (^{14}C) to date beachrock and shells. It is worth mentioning that Curve (A) is representative for the barrier islands of Inhaca and Bazaruto in Mozambique; Curve (B) is representative for the entire Mozambique coastline; Curve (C) is representative for the barrier islands of Southern Mozambique; and Curve (D) is representative for the southern Africa coastline including Southern Mozambique.

Different geological materials allow providing good documentation of the absolute ages of relative sea-level changes by using these methods. Indeed, Castro et al. (2014a,b) have recently dated vermetids using the radiocarbon method to determine sea-level fluctuations and coastal evolution in Rio de Janeiro State in southeastern Brazil, and obtained coherent results that allow important comparisons with previous studies. In this case, Angulo et al. (2006) in their review, refer to age misinterpretations that usually occur when using different sources of information about the paleo-sea level and its geochronology. The curves presented have different indicators with different approaches that can result in poor quality interpretations. For better interpretation of the formation of the inner paleo-dunes, the lagoons, the barrier system and the modern transgressive dunefields, curve (D) proved to be the best reference for adoption in the area studied.

Information on depositional processes in the region (Armitage et al., 2006; Botha et al., 2003), indicates that the sedimentary deposition occurred because of relative sea-level changes that began in the Pleistocene and continued through the Holocene. Curve (D) offers a good approximation of the marine transgression that occurred between 7 kyr B. P and 5 kyr B.P and the regression since 2 kyr B.P (Ramsay and Cooper, 2002; Ramsay, 1995) on the Mozambique coastline. These sea-level changes, combined with oceanographic and geologic processes, may have initiated different coastal barrier systems in southern Mozambique. Using a geologic-geomorphologic perspective, Dillenburg and Hesp (2009) summarize the reasonable hypotheses for how coastal barriers may be initiated. These include bar aggradation and emergence, spit elongation or progradation, and isolation of beach and beach-dune complexes caused by coastal submergence.

Barrier evolution may be controlled by a combination of various factors including shelf slope, sediment supply, wave and wind energy, tidal range, sea-level changes, tectonic events, longshore currents and climate changes. Among these factors, Boyd et al. (1992) combined the sea-level changes with rates of sediment supply to devise a classification for coastal depositional environments. This provides a better explanation for the generation of the present lagoon-barrier system caused by relative sea-level changes since 7 kyrB.P. This classification is particularly suitable for systems where the rate of sediment supply exceeds the rate of relative sea-level rise or the sediment accumulation during a relative sea-level fall; and where the relative rate of sea-level rise exceeds the rate of sediment supply such as that found in southern Mozambique.

2. Material and methods

A number of geological and geomorphological maps and environmental data sources were utilized in this investigation, including:

- The selection of a relative sea level curve (D) from Fig. 2 which presents better interpretation on the formation of the inner paleo-dunes, the lagoons, the barrier system and the modern transgressive dunefields;
- Digital geological maps depicting the lithologic features of the southern Mozambican coast (available and sold by the National Directorate of Mozambique Geology-DNGM for the period from 1975 to 2016);
- Altimetry data for the region in the Digital Elevation Model, available from the United States Geological Survey's (Earth Explorer Website Project) accessed in 2016;
- The temperature records from 1960 to 2012, wind speed and direction records from 1960 to 2015 and precipitation data from 1960 to 2012;
- The monitoring of dunefield migration and sand transport rate from January 2016 to February 2017.

The selected images were georeferenced in the ArcMap environment of the ArcGIS® program, version 10.2.2 in WGS1984 (UTM-Zone-36°S) geographic projection. The georeferencing process applied the control point's method, which included more than 10 geographic coordinate pairs. This process allowed a spatial statistical error of less than 7.0 m on the base map of coastal Mozambique. The lithostratigraphic map developed by DNGM in 2013 with a spatial resolution scale of 1:50,000 was selected and digitalized. Based on this information, a digital thematic map was designed that highlighted the transgressive paleo-dunes formed prior to the maximum Holocene sea level and the active-modern dunes formed after the maximum sea level, including the sedimentary deposits of lagoons, strand-plains, tidal flats, marshes and lakes.

Using the Digital Elevation Model, elevation profiles along six transects were sketched perpendicular to the coastline (Fig. 3). The sketched profiles included all the systems of interest: the beach environment, deflation plains, mobile and transgressive dunes, lacustrine-lagoon systems and the inner and fixed transgressive dunes. All of the elevation data were interpolated in a triangulated irregular network (TIN) dataset displayed as a modeled surface. The local water drainage system was also sketched and overlaid on the TIN dataset.

To characterize the recent aeolian activity on the study area, historical wind records from three meteorological stations were investigated: One in Gaza province at Xai-Xai (B1); One in Maputo Province (B2); And another from the NASA weather station (25° 20′00″ S - 33° 10′ 00″ E). Additionally, daily wind dataset for the period from 1960 to 2015, provided by the National Institute of Meteorology of Mozambique (INAM) for the Xai-Xai station of Gaza Province (25° 02′ 24″S; 33° 38′ 24″ E) and the Maputo station (25° 57′ 36″ S; 32° 27′36″ E) were analyzed. We also used the daily wind speed and direction dataset measured hourly at a height of 10-m by the NASA meteorological station from 1979 to 2016 at 25° 20′00″ S - 33° 10′ 00″ E. There were no significant differences between the meteorological database from NASA and the local measured data. Hence, no calibration was necessary for the analyses conducted in this study. Based on the historical dataset record of wind speed and directions, only wind speeds greater than 6 m s^{-1} were selected according to the threshold velocity established by Castro (2001) and Tsoar (2005, 2013). We selected a dataset greater than the threshold velocity because it is believed that sand transport takes

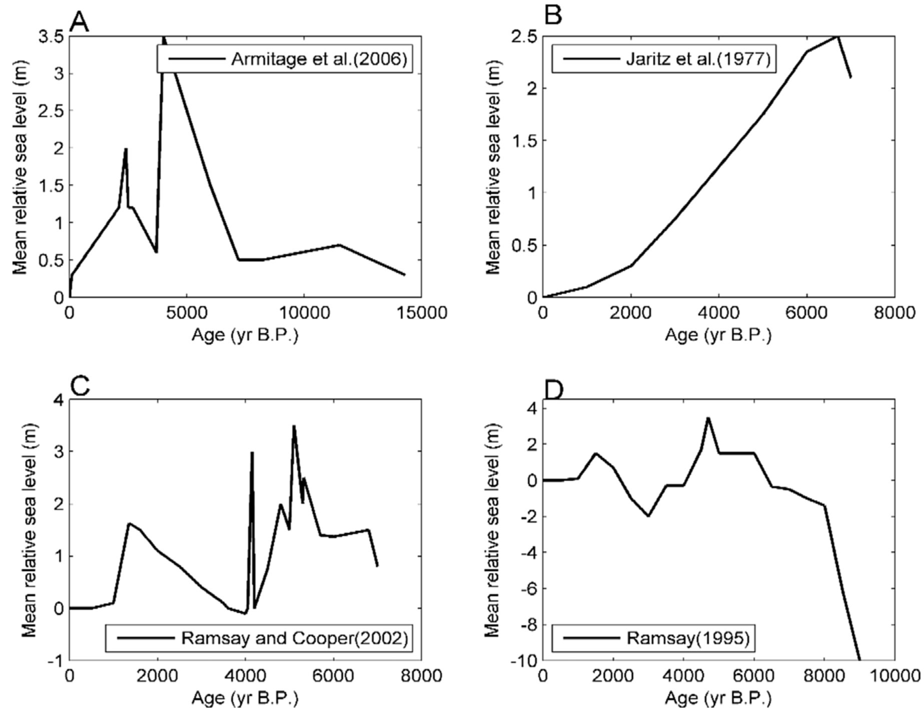

Fig. 2. Relative sea level curves for the Mozambique coastline, southeastern Africa.

place (Liu et al., 2005) for dune formation. This database record was processed in periods of 10-year patterns between 1979 and 2016 in wind sector orientations: N, NNW, NW, WNW, W, WSW, SW, SSW, S, SE, ESE, E, NNE and NE. To estimate the sand transport rate (Q in kg $m^{-1}s^{-1}$), the model proposed by Lettau and Lettau (1978) was used:

$$Q = C_b\sqrt{\frac{d}{D}}\,\frac{\rho}{g}\left(w - w_{ref}\right)w^2 \qquad (1)$$

where C_b is constant ($C_b = 6.7$; Lettau and Lettau, 1978); d indicates the average grain size of the dune system studied (0.375 mm; Fig. 1); D is a reference grain size (0.250 mm); q is the air density (1.22 kg m^{-3}); g is the gravity acceleration (9.81 m s^{-2}); w is the hourly recorded wind speed at the station at 25° 20′00″ S - 33° 10′ 00″ E; and w_{ref} indicates the threshold friction velocity (6 m s^{-1}).

To compare the calculated sand transport rate, an 80 m-high transgressive parabolic dune at the specific geographic coordinate position (25.36°S and 33.14°E) was selected. This transgressive dune was monitored from January 2016 until February 2017. The monitoring process consisted in the identification of three references in the geographic coordinated system for this dune, including: 50 m from the middle front of the dune, 50 m from the lateral dune and 50 m from the right of the dune. The average of the dune movement was calculated according to the sand transport distance advanced after one year in the three positions monitored.

The drift potential (DP) was calculated by using Fryberger (1979) equation:

$$DP = w^2\left(w - w_{ref}\right)t \qquad (2)$$

where w is the recorded velocity greater than 6 m s^{-1}; $w_{ref} = 6$ m s^{-1} and t is the time increment relative to the annual wind data record measurements in percent. A sand mobility index (M) was calculated using Lancaster (1988) equation:

$$M = W\frac{ETP}{P} \qquad (3)$$

In which W is the annual percent of wind greater than 6 m s^{-1} (from 1979 to 2016), P is the annual precipitation average from 1960 to 2012; and the annual evapotranspiration (ETP) average is 1100 $mm^{-1}yr^{-1}$ (Været et al., 2011).

Parallel analyses were taken for the historical rainfall record dataset from 1960 to 2012 at the Xai-Xai and Maputo meteorological stations. The dataset records were statistically analyzed to obtain monthly and yearly averages, in series grouped into 10-year periods for the 52 years studied. Da Silva et al. (2008) used same method and obtained good comparative results related to ENSO events in short and long periods in coastal barrier system of Rio Grande do Sul State, Brazil. Despite the simplicity of this technique, is effective in identifying possible anomalies caused by ENSO events, which can accelerate aeolian transport in dry periods or decelerate in rainy and humid periods. Based on the monthly series averages, the standard deviation for each determined period was calculated. During this analysis, the number of rainy and rainless days for each year were determined.

The historical air temperature dataset record between 1960 and 2012 was collected at the Maputo and Xai-Xai meteorological stations in the study region. These data were analyzed similarly to the precipitation datasets. The episodic data was separated into maximum daily temperatures and their peaks were related to the occurrence of *El Niño*, while the minimum daily temperatures were related to *Lã Niña* phenomena.

3. Results and discussion

3.1. Analyses of lagoon-barrier system and geomorphological evolution

The formation of the southern Mozambique barrier systems as

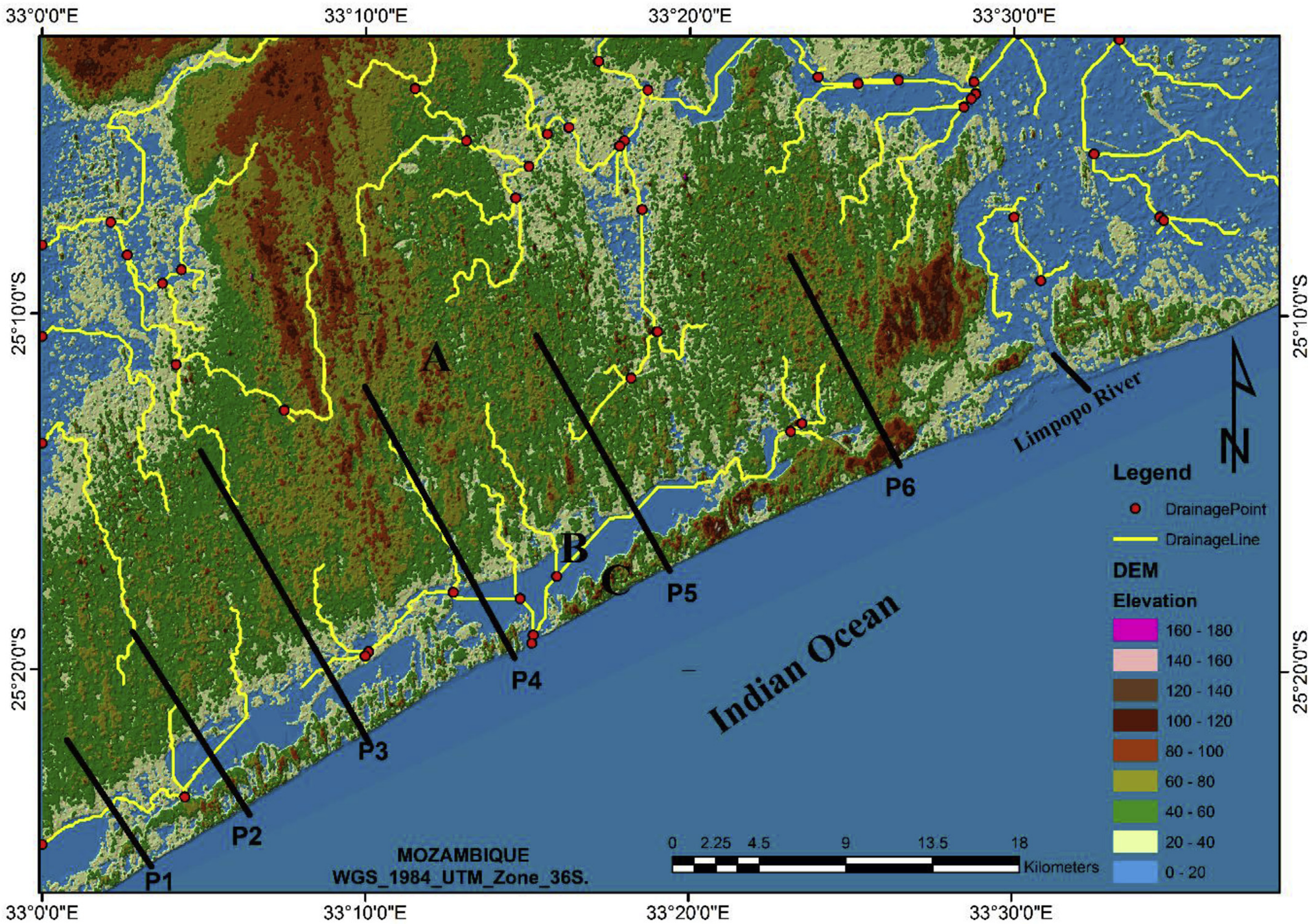

Fig. 3. Sketched cross-sections of the lagoon-barrier system: P1, P2, P3, P4, P5 and P6. A-indicates the inner paleo-dunes; B-indicates the lacustrine and lagoon systems; C-indicates the transgressive dunefields.

response to sea-level transgression was theoretically proposed by Boyd et al. (1992) and has been found in other parts of the world (Armitage et al., 2006; Hesp et al., 2005; Martinho et al., 2008; Gomes et al., 2017; De Lecea et al., 2017; Dillenburg et al., 2006). In fact, a variety of ways exist by which coastal geological and geomorphological features may be initiated or formed, including wind power, wave climate, littoral currents, sediments supply, climatic fluctuations, antecedent topography, beach morphodynamics type, and relative sea-level changes. From a coastal geomorphological perspective, the Boyd et al. (1992) classification presents a plausible interpretation of the present lagoon-barrier system formation, which is the consequence of relative sea-level changes and sediment supply. These relative sea-level changes were previously reported by Ramsay (1995) and provide a suitable interpretation of the formation and evolution of the inner paleodunes, brackish systems, and the modern dunefields studied. The proposed relative sea-level changes indicate evidence that inner transgressive paleodunes were formed between 7 kyr B.P. and 5 kyr B.P., when the sea level maximum was approximately +2.5 m above the current level. On the other hand, the modern dunefields were formed similarly to the paleodunes in the last 5 kyr B.P., displaying well documented geomorphologic evidences indicating that the seasonal dry and wet climate conditions may be controlling their evolution.

Many studies agree that Holocene transgression started since 7 kyr B.P., and caused partially enclosed estuaries and bays dominated by strong tidal currents. Further, this was followed by sea level Highstand of about 3.5 m above the current sea level. This transgression is interpreted in southern Africa as the main factor that caused the development of sheltered back barrier environments associated with marches and tidal flats (Gomes et al., 2017; De Lecea et al., 2017). Besides the formation of these back environments, formed sheltered lacustrine-lagoon systems and inner paleodunes in the site studied. Gomes et al. (2017) suggest as well, the formation of barriers washovers associated with the higher sea level and increased storminess in southern African.

The Highstand was followed by sea level fall and stepped sea level rise/fall between ~5.2 kyr B.P. and ~3.5 kyr B.P., which according to Gomes et al. (2017) and Green et al. (2015) resulted on the formation of back-barriers development and infilling process. This event conditioned the continued construction of sandy barriers and washovers such as those of southern Mozambique coast, confirmed with De Lecea et al. (2017) and Green et al. (2015) in Maputo Bay, and Armitage et al. (2006) at Inhaca Island and Vilanculos' barrier islands. The stepped sea level changes recorded since 2 kyr B.P., conditioned barrier accretion and the formation of shallow brackish systems and lacustrine-lagoon systems, including Bilene lagoon-barrier system (studied site), Lake Lungué (Sitóe et al., 2017), Inharrime estuarine system (In Inhambane Province), Maputo Bay, and Saint Lucia estuarine system.

There is a good agreement that periodic marine incursions associated with storm surges and over wash, remained prevalent until at least ~1.2 kyr B.P. Sitóe et al. (2014), Siesser (1974), Ramsay (1995), Armitage et al. (2006), and Sitóe et al. (2017) reported similar ages with unanimity in beachrocks, eolianites and estuarine sediments by radiocarbon dating (^{14}C) and OSL. Recent radiocarbon ages recorded in Lake Lungué (southern Mozambique) by Sitóe et al. (2017), suggest late Holocene sea-level changes and paleoclimate fluctuations since 1.4 kyr B.P. to the present. These data support possible coastal dune accretion that formed mobile barriers occupied by transgressive dunes along the southern Mozambique coast.

Although the petrographic analyses indicate high-energy conditions, which disagree with the law-energy that caused the barrier growth and inlet closure at approximately 6.2 kyr B.P (Benallack et al., 2016) in South Africa, the growth of the barrier studied is supported by high sediment supply from the continental shelf and the Limpopo river (Ramsay, 1995). The sediment supply and the stepped sea-level changes, conditioned the formation of the barrier growth of 150 m-high and inlet closure by dune progradation. It is believed that the inner paleodunes studied had been reworked and modified by periodic incursions related to sea level highstands (Gomes et al., 2017; Compton, 2001; Ramsay, 1995) occurred between 7.5 kyr B.P and 5.8 kyr B.P. These highstands reported are in good agreement with those of Castro et al. (2014a,b) and Angulo et al. (2006) in Rio de Janeiro coast, and Martinho et al. (2008) in Rio Grande do Sul barrier system. This sea level transgression conditioned the formation of parallel back-barriers or sand ridges to the coastline.

The inner paleodunes and the modern dune-barrier geomorphology may be reworded with the strong storms occurred from the mid through the late Holocene period. This storminess period was reported by Dixon (2016) in South Africa, and somewhere around the world by Billeaud et al. (2009) and Sorrel et al. (2012). The storminess periods bring about the formation of strong positive dipole anomalies such as that reported by Dixon (2016) in Indian Ocean. Webster et al. (2005) state in their work that these anomalies are strongly related to warming sea surface temperatures (ENSO events) and the increase in cyclonic intensity and frequency. The cyclonic intensification and high frequencies are confirmed in recent strong cyclones that usually affect Mozambique coastline (e.g.: Dineo cyclone in 2017, Jókwè cyclone in 2008, Fávio in 2007, Claude in 1966 and many others). These in turn, cause strong storm surges that generate strong waves, which modify abruptly the coastal geomorphology, and thus, intense sand transport may be registered in the back-barriers and dunefields. Other major sand transport may be driven by extreme climatic fluctuations, such as those registered by Humphries et al. (2016) in southern Africa. These climate anomalies are related to droughts in southern Mozambique, and cause intense sand transport in non-vegetated coastal dunefields.

A variety of ways exist by which coastal dunefields may be generated, and their mechanisms of formation involve seasonal climate changes, availability of sediments in the surf zone and in the tidal plain, wind regime, sea level changes, water table levels, destabilization of frontal dunes, coastal erosion, disturbance or destruction of vegetation cover, and coalescence of parabolic dunes (Castro et al., 2017; Castro, 2001; Martinho et al., 2008; Hesp, 2013; Dillemburg and Hesp et al., 2009; Pye, 1983; Tsoar et al., 2009). According to the coastal geomorphic features presented and previous results related in studies of the region (Armitage et al., 2006; De Lecea et al., 2017; Gomes et al., 2017; Ramsay, 1995; Sitóe et al., 2017), all these factors mentioned take the role on the generation of coastal dunefields studied. Despite the time scale limitation, the Boyd et al. (1992) hypotheses explain well the formation of the inner paleodunes and modern dunefields considering the relation between the relative sea-level changes and the availability of sediment source supply. Indeed, the presence of maritime material, shell deposits and old eolianites is evident in the stabilized paleodunes. The approach based on the relative sea-level changes and sediment supply in southern Mozambique coast is valuable since the regional paleo-environment conditions since the Pleistocene are still little known. These conditions are reflected in the inner parabolic paleodunes and blowouts stabilized by vegetation and compacted sand, which have blocked the aeolian activity, the same found in Maputaland and Saint Lucia estuary by Botha et al. (2003) and Gomes et al. (2017). The stabilization of vegetation was reinforced by annual rainfall of over 1600 mm yr^{-1}, which increased from 7.5 kyr B.P. to 5.1 kyr B.P. (Partridge, 1997; Tyson, 1999; Tyson and Partridge, 2000), less evaporation of 1100 mm yr^{-1} and a water-table rise. These inner transgressive paleodunes system consist of fixed SE-NW projection old-dunes with tonalities varying from orange, white to brown sand.

According to the sea-level changes reported by Ramsay (1995), the rapid drop of sea-level from +4 m to 0 m between 4.5 kyr B.P. and 3 kyr B.P., led the formation of a lacustrine-lagoon systems parallel to the coastline (Sitóe et al., 2014, 2017), the same that formed the Saint Lucia at South Africa (Gomes et al., 2017). These lagoons and lakes extend from Inhambane Province in Mozambique to Maputaland in South Africa, and are generally constituted by cemented sand, black organic matter, shell-deposits, animal remains and decomposed vegetation (trunks). This organic matter was the outcome of the change in preterit paleo-environment conditions that occurred during the drop in sea level (Botha et al., 2003; Sitóe et al., 2014).

Despite the debate about the regional sea-level highstands reported between 2.5 kyr B.P. and 1.5 kyr B.P. by Ramsay (1995), Gomes et al. (2017), Compton (2001), Ramsay and Cooper (2002) and Armitage et al. (2006), the sea-level rise controlled the formation of the current major transgressive dunefields that migrate landward with a southeast-northwest orientation. The subsequent falling of the sea level created the present beach, local estuaries, strand-plains and tidal flats as theoretically proposed by Boyd et al. (1992). In fact, Sitóe et al. (2017) in Lake Lungué along the Limpopo River, De Lecea et al. (2017) in Maputo Bay, Gomes et al. (2017) and Humphries et al. (2016) at Saint Lucia estuary reported these environments in the same region.

The modern dunefields system is active, has a SE-NW orientation and migrates landward burying part of the lacustrine and lagoon water bodies. These dunefields display different tonalities of sandy colors, highlighted generally by yellow and white. The sand cover of the geomorphic dunefields lack the natural exposure that displays the stratigraphic relationships between dune sand bodies. The local inner and sand barrier ridge compaction revealed a coastline erosion process reflected in sliding margins.

In regard to the lagoon-barrier system studied, an effective simple classification is presented in Fig. 4. The geologic and geomorphologic dune features depicted were based on the classification proposed by Boyd et al. (1992), including lagoons, lakes, abandoned channels, marshes or brackish, inner transgressive paleo-dunes, middle transgressive dunes, strand plains, tidal flats and modern mobile dunefields, semi-fixed modern transgressive dunefields and eolianites. The lagoons, lakes, abandoned channels and marshes are salt water, fresh water or mixed water bodies. While the inner transgressive paleodunes, middle transgressive dunes, strand plains, semi-fixed modern transgressive dunefields, tidal flats, modern mobile dunefields and eolianites are sand bodies that constitute the main strand plains and dunes.

The process of sand deposition and dune formation presented in geomorphologic features (Fig. 4), similar to that depicted by Rebelo

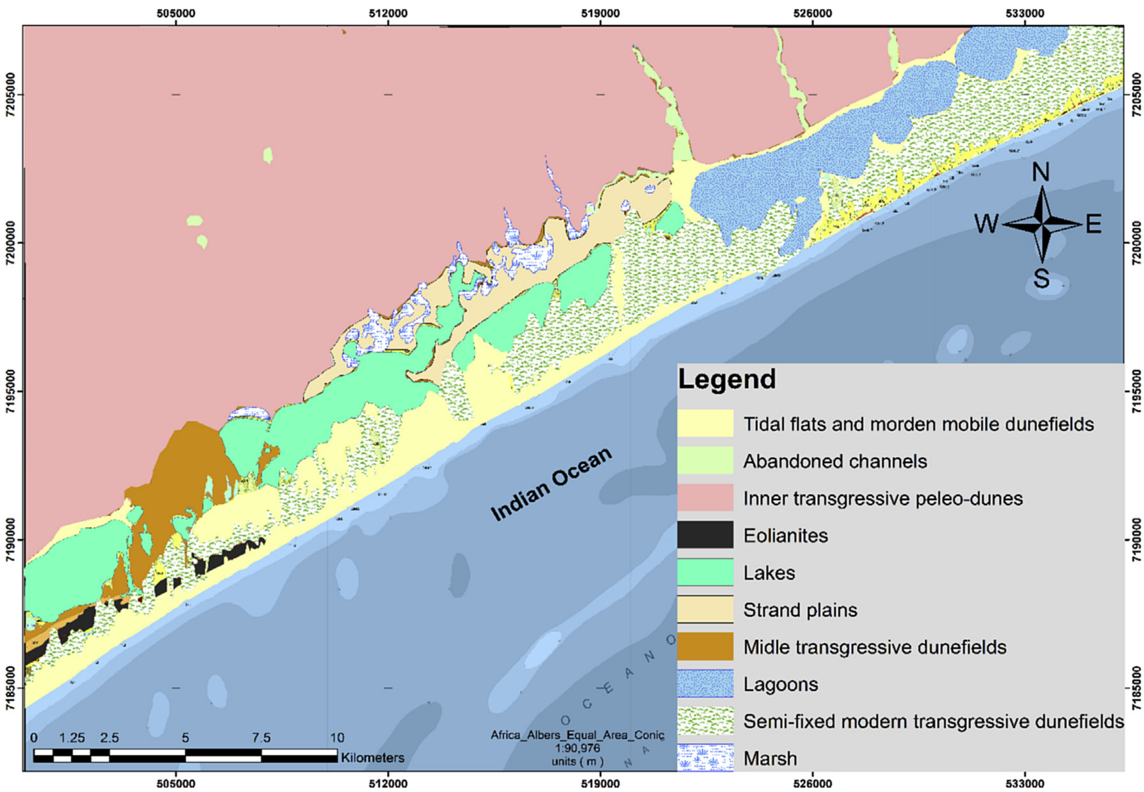

Fig. 4. Geologic and geomorphologic dune features and the lagoon-barrier system in southern Mozambique, Africa.

et al. (2012), are in good agreement with the sea level hypotheses proposed by Ramsay (1995); Botha and Porat (2000) and Botha et al. (2003). These studies also reported issues related to sediment transport from the inner continental shelf induced by waves and 3 m tides as factors fundamental to the strand plains and tidal flats formation. On the other hand, the SE-NW dune projections reflect exposure to the sea-level changes and paleo-environmental changes, which led to formation of the barrier-lagoon system. Although we did not analyze all possible factors, those that were studied - wind, precipitation and relative sea-level variation - suggest that the coastal dune features reflect the exposure to the relatively significant changes of environmental conditions since the Pleistocene.

The lithology mapped in Fig. 4 indicates a sedimentary deposition process of aeolian sand, which constructed the barrier-lagoon system in two phases: A) In the first phase the deposition of aeolian sand occurred during the maximum sea-level conditions > 2 m higher than the present (between 7 kyr B.P. and 5 kyr B.P.), previously identified by Ramsay (1995), Ramsay and Cooper (2002); and B) the second phase was characterized by the subsequent falling of the relative sea level, which formed the lacustrine-lagoon systems protected by current transgressive sandy ridges. The sea-level falling was subsequently followed by rapid raising that generated the barrier and modern dunefields. The dunefield construction model with a coarsening upward sequence type had been previously described by Armitage et al. (2006), Maud and Botha (2000).

The lithology depicted in Fig. 4 consists of eolianites, isolated beachrocks and mature quartz sands of various colorations found in the deposits, including lakes, lagoons and in the barrier system. After applying the vertical geology sketches on the specific sedimentary deposits at the positions (25.35°S, 33.14°E), (25.32°S, 33.24°E) and (25.30°S, 33.21°E), the production of large-scale tabular units trough cross-beds, buried by modern aeolian sand was quite evident. The exposed marine sediments mixed by dead shells under the sand tabular units come close to the coarsening upward sequence model. The lagoons, lakes and abandoned drainages rivulets found behind the sand barrier ridge are rich in mud and accumulated peat from decayed local vegetation and dead shells. In the local tidal flats, the sand deposits consist of poorly sorted medium and very coarse sand. These environments presented facies organized sequentially according to the common barrier systems sequences that include the shore-facies, backshore facies composed of well-sorted fine-grained sand, medium sand and some coarse sand. The analysis of eolianites and beachrocks facies found in the outcrops, helped us to recognize an abundance of primary structures exhibiting cross-ripples and some smoothly inclined plane-parallel laminations.

Ramsay (1995) offers the plausible theory that the sediment source is the inner continental shelf transported by wave action, littoral currents and tides driven by the prevailing southeast trade winds. The transported material and an existing accommodation space offered conditions for sediment disposition, increased by the material erosion/sliding of continental alluvial deposits and consolidated long-existing dunes. Field observations in these deposits have revealed sand structures of large-scale tabular crossing beds of marine sediments buried largely by modern aeolian sands. Some specific sedimentary structures found in the aeolian deposits indicate the evident formation and evolution of the sand deposits to 150 m-tall transgressive dunefields with different morphology features consisting of parabolic dunes, barchan dunes, isolated transverse and coppice dunes. These deposits contain some important geologic units of eolianites and beachrocks that date between 7 kyr B.P. and 5 kyr B.P. (Ramsay, 1995; Ramsay and Cooper, 2002). These current lacustrine deposits and seashells indicate the sedimentary deposits dated about 5 kyr B.P. (Norstrom et al., 2011), when the relative sea level was +2 m above the present.

A variety of ways exist by which the color tonalities of these units may be produced, these include the source rock and the local pedogenetic processes on the deposits. The combination of these factors with oxidation, lixiviation, temperature variation, water evaporation, soil humidity and water table changes (Kocurek et al., 2001), produced the different sand tonalities found in the system. Rebelo et al. (2012) described the different sand colors and the mineral composition of the deposits. Their results suggested that the currently varied composition of sand minerals reflects the source rock, such as continental granites (main Quartz source), continental alluvial sands and marine carbonate sediments mixed with shells. These sediments were carried out from the inner continental shelf (Ramsay, 1995; Botha and Porat, 2000; Botha et al., 2003) and were added to the ancient local sediments to generate the mineral composition of the lagoon barrier system of the region. The sediments exposed on the deposits (lakes, lagoons, tidal flats and barrier system), passed through a long and persistent action of aeolian activity, climate changes and hydraulic action to define the current sediment lithology. On the other hand, the associated preterit paleo-environmental conditions combined with hydrodynamic action on the sedimentary deposits of the actual lakes and lagoons defined the mineral composition of black sand, which is rich in mud and accumulated peat from decayed local vegetation and dead shells. The depositional accumulation process associated with compaction and lithification processes generated the formation of well-documented geologic units such as cemented mature sand, eolianites and beachrocks in the system sketched.

According to the topographic profiles sketched (see Fig. 3), three evident evolutionary stages of dunefields associated to the lagoon-barrier system were observed: (A) inner transgressive paleodunes that extend back to the lagoons; (B) parallel shoreline lagoons and lacustrine systems; and (C) modern mobile transgressive dunefields (Fig. 5).

These stages and the geomorphological classifications of the aeolian systems studied are well correlated to the regional sea-level tendencies, sediment supply, existing accommodation space and deposition processes discussed by Norstrom et al. (2011); Botha and Porat (2000); Botha et al. (2003), Maud and Botha (2000), Armitage et al. (2006), Hobday (1977), Boyd et al. (1992), and Cooper and Pilkey (2002). Indeed, a difference in height is quite evident between the paleodunes, which are relatively shorter, and the 150 m-high modern dunefields caused by sand erosion, sediment supply and compaction process.

The modern dunefields with maximum height of 150 m migrate landward, transporting aeolian sand volumes from the tidal flats and strand plains. These modern transgressive dunefields move landward with SE-NW projection burying local vegetation, lakes and lagoons in the extension of 3 km from the sea to land. Details of these modern dunes matched geomorphological features with the paleodunes, suggesting the result of long periods of aeolian action due to the relative sea-level changes and climate condition changes since the last maximum sea level in the Pleistocene.

3.2. Wind impact on the dune migration

The monthly average wind speeds were greater than $6\,m\,s^{-1}$ between 1979 and 2016, while the observed decadal dataset displays the wind speed variations from $5\,m\,s^{-1}$ to $8.5\,m\,s^{-1}$ (Fig. 6). The displayed wind speeds higher than $6\,m\,s^{-1}$, the threshold speed established by Fryberger (1979) and Castro (2001), indicate the persistent wind activity on the aeolian sedimentary system throughout the year. This is the main factor conditioning the formation of different geomorphic features in the modern dunefields system. Castro et al. (2017) reported similar results in northern Brazil coast, which sustain such aeolian activity occurrence in tropical areas. The features of the dunefields reflect their exposure to aeolian activity given that the current sand transport is in a direction similar to the wind.

Wind speed and direction frequency between 1979 and 2016, with maximum wind speed of $22\,m\,s^{-1}$ were registered (Fig. 7). Monthly wind speeds above $6\,m\,s^{-1}$ are predominantly from the south, southeast and east quadrants. However, the wind with the lowest average speed and lower frequencies blows from the southwest, west and northwest, while north and northeast winds had moderate wind speed frequencies. These two wind speed groups have revealed their seasonal action on the dunefields and defined the dune orientation and progradation projection to SE-NW. Despite records that wind speeds above $6\,m\,s^{-1}$ have come from different directions in all months, winds mostly from the S, SSE, SE, E and N directions were observed, which occur persistently each year between July and November.

The reported wind speed and directions are in good agreement with that of Langa (2007) and Miguel et al. (2017) in the same region. These wind dynamics type proved around the world that their blowing effect on the beach might transport loose sediments from the surface and move them to the interior of the continent. Thus, originating large coastal dunes such as that found on the southern Mozambique coast (Armitage et al., 2006), Oregon and California (Cooper, 1958, 1967), Peru (Finkel, 1959), Namibia (Lancaster, 1988), Natal (Orme, 1973), East Australia (Pye, 1982), Southern Brazil (Dillenburg et al., 2009), and northeastern Brazil (Castro et al., 2017).

Based on the classification proposed by Fryberger (1979), the results indicate the intermediate drift potential (DP) as a result of winds from the N, NNW, NW, WNW, W, WSW, SE, ESE, E, NNE and NE directions, while winds from the SW, SSW, S and SSE indicated high drift potential (Fig. 8).

Winds from the SW, SSW, S, SSE and SE all indicated a high frequency of occurrence above 15%, which explains the highest DP over the 37 years. Decadal results of drift potential decreased smoothly between 1979 and 1989 and averaged 200 in this period; followed by a steady increase from 1990 to 2000 with an average of 300 for this period; the drift potential increased between 2000 and 2010, and averaged 513 in the period, which slight decreasing until 2016 with an average of 407.

The drift potential in this period averaged 365, which fits well into the coastal dune model proposed by Tsoar (2005) for Israeli coastal dunes and stabilized Europe coastal dunes. The dune type indicates the large percentage (70%) of vegetation cover that reduces the dune mobility index. Indeed, Yizhaq et al. (2008); Tsoar et al. (2009); Hein et al. (2012) and Castro et al. (2017) found that vegetation growth rates of up to 20% could greatly reduce the transport of aeolian sediments on coastal dune surfaces. Although the vegetation growth is important for dune stabilization by reducing sediment flux, is not included in Goldsmith (1978) parameters defined for the presence of coastal dunes, these include: availability of loose sediments, wind action with reasonable force to rework and transport the sediment, as well as appropriate storage spaces.

Despite the total drift potential obtained, predominant winds from the S occurred only 14% of the time, compared to 21% for SSE winds. The S trade winds are strong throughout the year but have a shorter active period than those from the SSE, which blow persistently throughout the year. The total drift potential presented a high percentage from the SE, ESE, E, N, NNE, NE and ENE. The SSE and S winds had strong speeds but persist for a short time and are associated with relatively high sand mobility and transport, while the remaining sectors had weaker speeds but persist for a longer time during the year and are associated with relatively weak sand

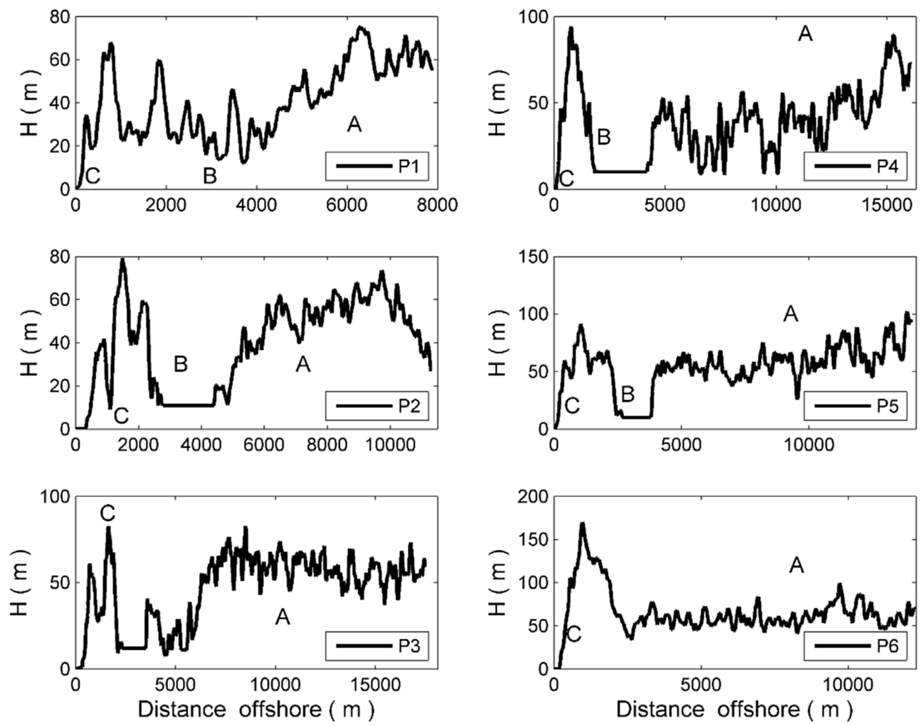

Fig. 5. Sketched profiles illustrating the geomorphic units of the coastal lagoon-barrier system. (A) Indicates inner paleodunes. (B) Indicates lagoons and lacustrine systems. (C) Indicates modern mobile and fixed transgressive dunes.

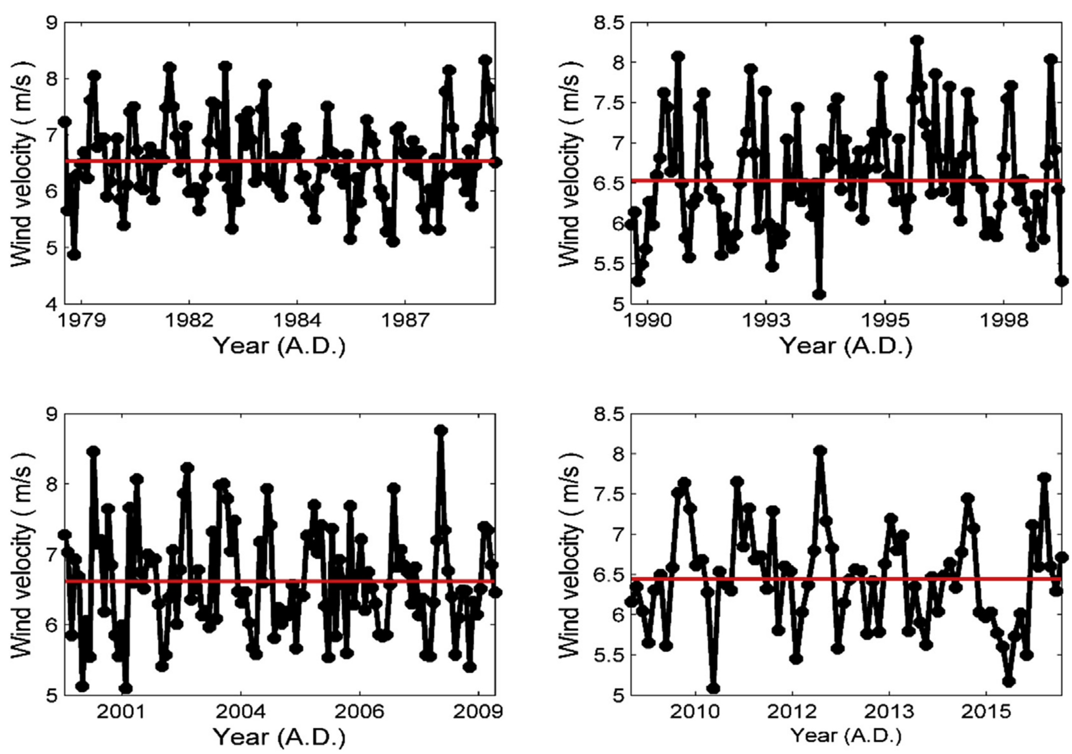

Fig. 6. Monthly distribution of wind speed at the NASA station (25° 20′00″ S - 33° 10′ 00″ E) divided into ten-year periods from 1979 to 2015. The red line highlights the mean wind speed. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

mobility. Relatively high values for drift potential were found in July, August, October and November, while weak wind drift potential was recorded in March, April and May.

Although the DP reflects aeolian sand mobility, the relation between them is not linear since other factors contribute to sand mobility (transport), such as precipitation, water table, soil humidity, evaporation and vegetation coverage (Castro et al., 2017; Yizhaq et al., 2008; Tsoar et al., 2009). Although these results are

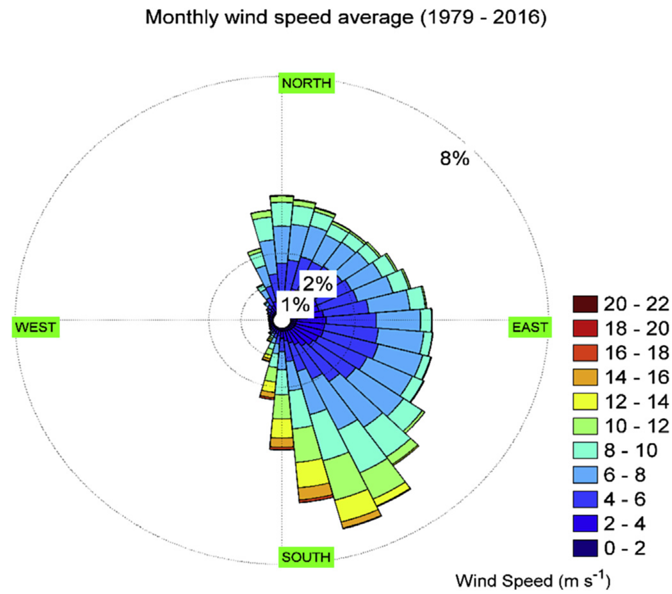

Fig. 7. Monthly wind speed averages and direction frequencies between 1979 and 2016 at the Xai − Xai weather station (25° 02′ 24″S; 33° 38′ 24″ E).

relatively significant, the sand mobility index varied between 50 and 200, which indicates semi-active dunes in southern Africa (Lancaster, 1988; Yizhaq et al., 2008), composed of vegetation cover that blocks the aeolian activity.

The wind speeds from all sectors resulted in estimated average sand transport of 1.38 kg m^{-1} s^{-1}, with predominant sand transport from the SW (0.13 kg m^{-1} s^{-1}), SSW (0.28 kg m^{-1} s^{-1}), S (0.27 kg m^{-1} s^{-1}) and SSE (0.17 kg m^{-1} s^{-1}). The exposure to these specific sand transports is reflected in the dunefield factures and with the sand burying the back lacustrine and lagoon systems. The local monitoring from January 2016 to February 2017 indicates average transgressive parabolic dune progradation rate of 22.5 m yr^{-1}, which is higher than the 11 m yr^{-1} estimated by Castro (2001, 2017) in Brazil, 17.5 m yr^{-1} by Jimenez et al. (1999), and that by Levin (2010) in Australia. The progradation of the parabolic dune monitored is very high and is locally reflected in the rapid burying of the lakes, lagoon and the evident SE-SW vertical position of the local vegetation.

Wind speeds on Africa's southeastern coast in Mozambique were summarized into frequencies predominantly from the S, SE, E, NE and N, as also found and reported by Langa (2007) and Miguel et al. (2017). These frequencies confirm that the persistent wind direction that generates the SE to NW dune features is the same as the direction of sand transport. The prevailing direction of the local winds is similar to the orientation of local sand dune movements and suggest that wind forcing is the mechanism that generates the geomorphological features and the southeast-northwest direction of the regions' parabolic, transverse, coppice, isolated barchan and barchanoids dunes. The exposure to persistent aeolian activity mobilizes the sand transport on the transgressive dunefields into the lake and lagoon systems, confirming the depositional hypothesis proposed by Botha and Porat (2000) for this region.

The temporal examination of wind variability since 1979 demonstrated that the winds have a strong influence on sand transport during the entire year. This hypothesis may fail to explain the dune mobility index (DMI) if the aeolian activity is considered to have a single determining factor, since the sand transport rate involves many environmental conditions, such as precipitation, air humidity, water table, sand source, temperature, ENSO phenomena and vegetation. The effect of these variables differs, however, the correlation between dune mobility index and precipitation fitted well with a strong exponential regression of $R^2 = 0.91$ (p-value $= 8.3 \times 10^{-12}$ and n = 325,776 h observed) (Fig. 9). This indicates with a certain effectiveness that the high precipitation reduces the sand mobility, and may controls on the formation of mobile dunes and vegetated and fixed dunes (Tsoar et al., 2009; Yizhaq et al., 2008).

The estimated critical dune mobility index-DMI (Fig. 9) varied between 50 and 200, explains the expected effect of climate change on the dunefields studied. These climate changes may correlate well or poorly with dune mobility. In the specific case presented in Fig. 9, all other annual climate conditions correlated poorly with dune mobility demonstrating that they are independent variables. This independence is due to the statistical error made when combining the winter and summer data to estimate the annual wind average and drift potential. Hence, the annual wind speed average has a low statistical level of significance and fails statically to explain the dune mobility index.

3.3. *Rainfall and temperature dataset analysis*

Decadal means of monthly average rainfall were found to be 71 mm $month^{-1}$ between 1969 and 1979, 63 mm $month^{-1}$ from

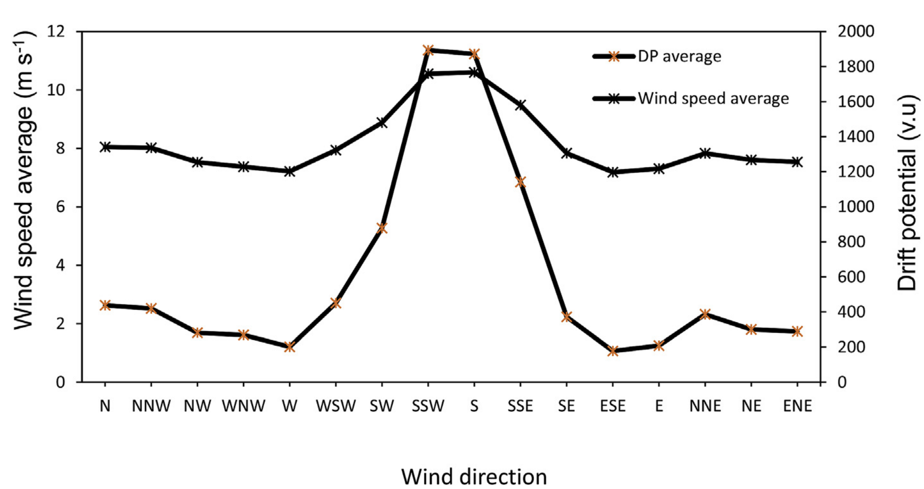

Fig. 8. Drift potential and wind speed averages between 1960 and 2015 at the Xai-Xai weather station (25° 02′ 24″S; 33° 38′ 24″ E).

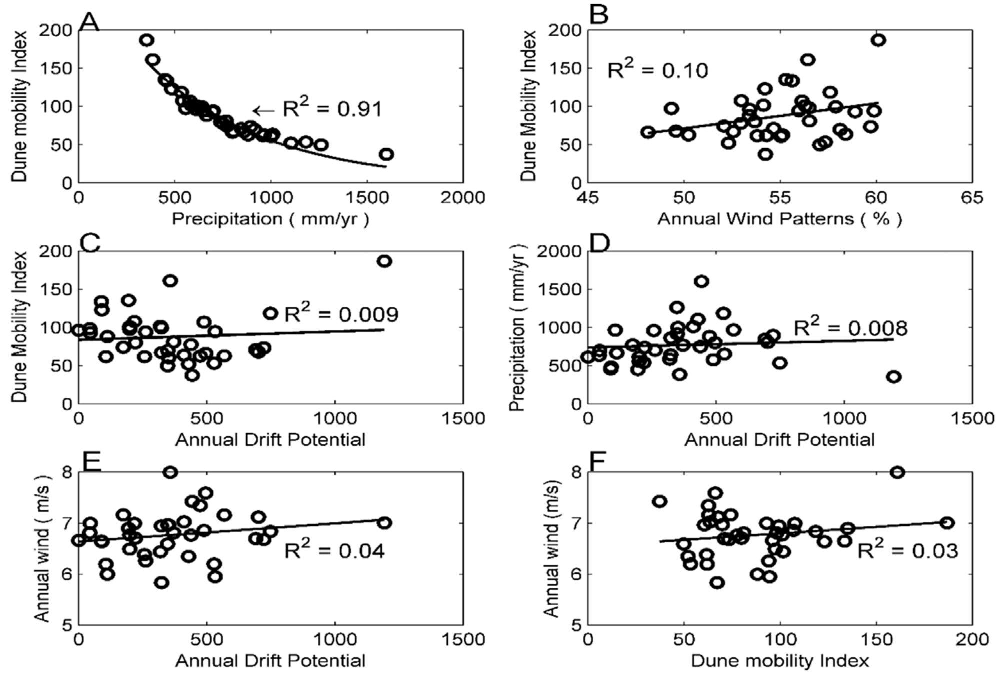

Fig. 9. A - annual dune mobility index vs. precipitation; B - wind patterns vs. DMI; C – DP vs. DMI; D – DP vs. precipitation; E – annual wind averages vs. DP; and F - dune mobility vs. annual wind averages between 1979 and 2016 at the weather station 25° 20′00″ S - 33° 10′ 00″ E.

1980 to 1989, 65.44 mm $month^{-1}$ from 1990 to 1999 and 65 mm $month^{-1}$ from 2000 to 2012, respectively (Fig. 10). This indicates a relatively significant monthly rainfall that stimulated considerable colonization of vegetation above 30%, which stabilized much of the dunes in the aeolian system. These findings are in accordance with those of Ash and Wasson (1983), Yizhaq et al. (2013) and Tsoar (2005, 2013), in similar aeolian systems around the world. On the other hand, it was found that precipitation reduced dune mobility because the monthly average wind speed was less than the 13.0 m s^{-1} limit proposed by Anthonsen et al. (1995), which is not sufficient for mobilizing dunes with wet surfaces. These results corroborate those reported in other similar coastal systems worldwide (Pye, 1993; Yizhaq et al., 2013; Tsoar, 2013; Da Silva el. al., 2008; Castro, 2001).

The *El Niño* effects were observed in: 1982, 1983, 1991,1992, 2004, 2005 and 2006, while *Lã Nina* indicators were recorded in 1975, 1981, 1984, 1994, 1995, 2000, 2007, 2009 and 2011 (Fig. 11). Regarding precipitation, an average of 280 non-rain days and 80 rainy days were found (Fig. 11). The results exhibited high rainfall in summer between December and April, while the reverse was found in winter. Rainfall above 1000 mm yr^{-1} was recorded in 1972, 1973, 1975, 1977, 1978, 1981, 1984, 1985, 1997, 1998, 2000 and 2010. Years with the number of rainless days below the average of 280 were recorded in 1970, 1978, 1982, 1986, 1988–1992, 1994, 1996, 1998, 2001 2004 and 2006–2012. These records are similar to those found for the *El Niño* and *Lã Niña* phenomena events obtained by Kumar et al. (2014) for southern Africa. Castro et al. (2017) reported similar results on the northern and northeastern coast of Brazil, which were associated to the occurrence of *El Niño* and *Lã Niña*. These events probably occurred in conjunction with wind intensities higher than 6 m s^{-1} between July and November, which conditioned larger drift potential, high aeolian activity, dune mobility and intense sand transport.

Years with above average accumulated rainfall suggest lower wind activity, lower mobility and lower dune field movement and consequently low sand transport. It was found that the average prevailing southeast wind speed exceeded 6 m s^{-1}, which is higher than the limit proposed by Anthonsen et al. (1995). The observed rainfall regime suggests that the modern dunefields projection and orientation have been induced by persistent wind activity and precipitation regime.

Despite the time scale limitation on the rainfall observation, the paleodunes geomorphic features reflect the paleo-environmental conditions since the displayed paleo-climate data of southern Africa (Partridge, 1997; Tyson, 1999; Tyson and Partridge, 2000; Holmgren et al., 2003; Partridge et al., 1999; Scott and Lee-Thorp, 2004) indicates the relatively high precipitation and temperature rise of 1 °C (6° C to 7° C) from 7.5 kyr B.P. to 5.1 kyr B.P., when annual rainfall was up to 10% above the present. Certainly, the increased precipitation decreased the aeolian activity on the paleodunes generated by the relative sea-level rise in the same period, while the rising temperature increased evaporation and aeolian activity. Actually, the annual average maximum temperature was found to be 28 ± 2 °C between 1960 and 2015, while the annual average minimum temperature was 19 ± 3 °C.

The 56-year temperature anomalies indicated the occurrence of *El Niño* and *Lã Niña* with relatively low or moderate intensities. The recent recorded temperatures suggest that the aeolian system studied reflects the role of persistent *El Niño* events, characterized by relatively long periods of low rainfall in the region. This causes increased evaporation and water drought, which caused a higher dune mobility than estimated. The results obtained are in good agreement with the discussion presented by Castro et al. (2017) and Tsoar et al. (2009), who found that the occurrence of *El Niño* increased the aeolian activity in northern Brazil and sand transport. Both compared regions have similar environmental conditions since they are located in tropical regions where exposure to persistent droughts caused by *El Niño* events and wind blowing is quite evident. In fact, Castro et al. (2017) and Otvos (2012) concluded that when these environmental conditions are associated to relative sea-level changes, sediment supply, water droughts and water-table variation may be the major factors in the dune

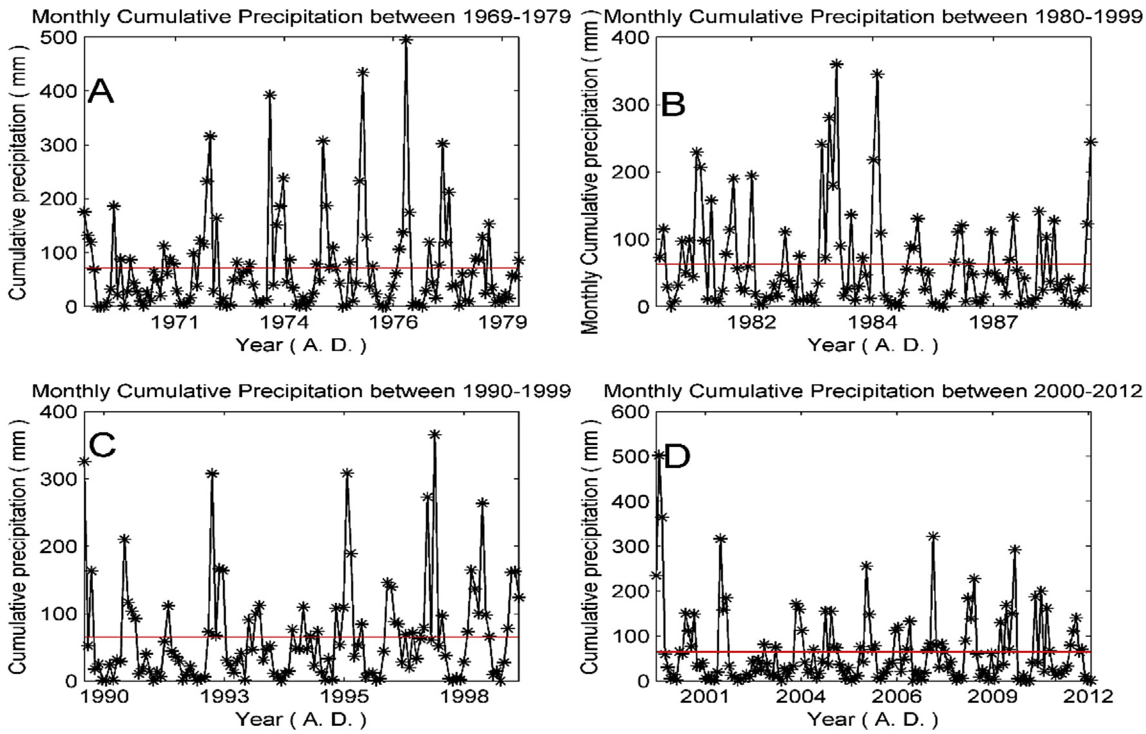

Fig. 10. Decadal monthly cumulative precipitation regime for southern Mozambique from 1960 to 2012 at the Xai-Xai weather station (25° 02′ 24″S; 33° 38′ 24″ E).

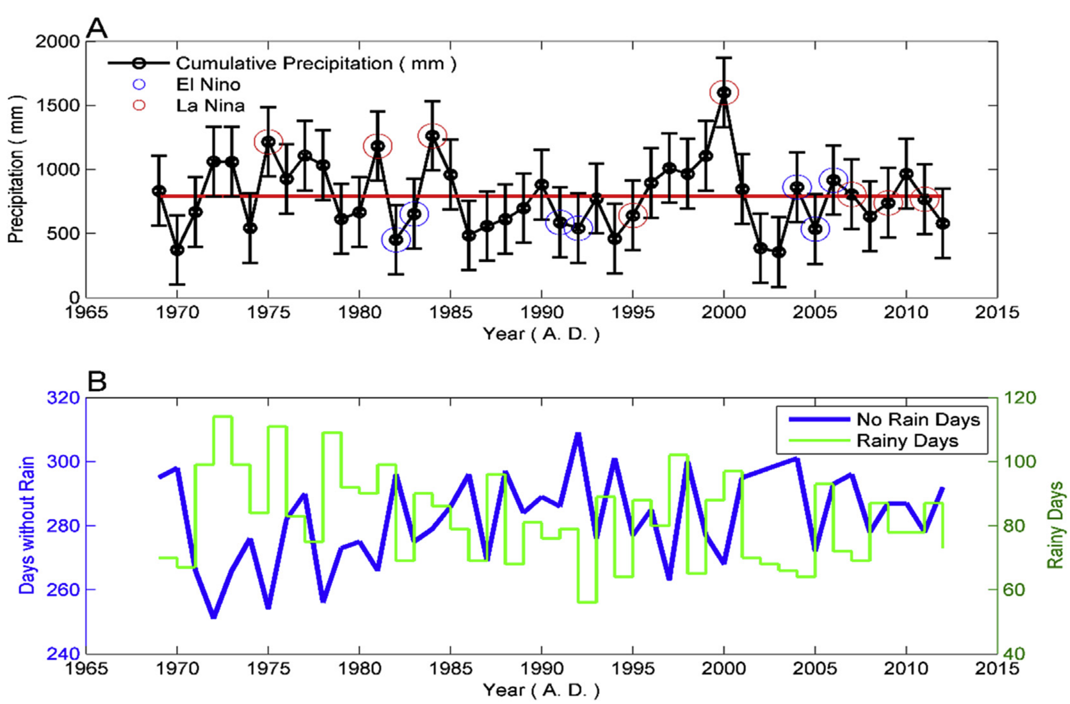

Fig. 11. Average annual precipitation in the region between 1960 and 2012 at the Xai-Xai station (25° 02′ 24″S; 33° 38′ 24″ E). Lower precipitation peaks and high non-rain days highlight *El Niño* events.

formation and progradation.

The ENSO anomalies are relevant to the sand transport and dune migration in areas where they may cause droughts. The droughts are connected by strong ENSO anomalies and may drive strongly the dune migration, example that previous detected by Maia et al. (2005) in Ceará-Brazil. In addition, Hastenrath (2006) found that ENSO events have not only led to increased drought periods but in some cases to increased periods of rain. In this case, any relationship of ENSO to drought is uncertain and has a low statistical level of significance (Gasques and Magalhes, 1987). In this perspective, a single ENSO effect fails to explain the dune migration in Mozambique, nevertheless it may be important when considered in relation with other environmental conditions.

The relative temperature increase found between 1960 and 2016 agreed with those discussed by Kumar et al. (2014) in a historical study of southeast Africa. The data presented is in agreement with the displayed paleo-climate data for southern Africa (Partridge, 1997; Tyson, 1999; Tyson and Partridge, 2000; Holmgren et al., 2003), which suggests the relationship between warm climate and wet conditions while cooling conditions are related to drought. The relatively historically high precipitation and temperature found in the region is confirmed by the rise from 6° C to 7° C from 7.5 kyr B.P. to 5.1 kyr B.P. and by the increased annual rainfall up-to 5–10% above the present (Partridge, 1997; Partridge et al., 1999; Scott and Lee-Thorp, 2004). Indeed, the transgressive paleo-dunes studied reflect exposure to paleo-climate changes that allowed stabilization of vegetation, while the persistent modern climate changes and relative sea-level trends have generated the modern dunefields of up to 150 m-high, characterized by parabolic, barchan and coppice dunes.

4. Conclusions

The combined influence of sediment supply, the existing accommodation spaces, climate conditions, and relative sea-level changes that have occurred since 7 kyr B.P. on the Mozambique coast, generated the present complex of an elongated, shore-parallel, lagoon-barrier system consisting of modern transgressive dunes, paleodunes, lacustrine-lagoon systems, strand plains and tidal flats.

The geomorphological features indicated that ~30% of aeolian sediments are exposed and without vegetation coverage. Are dominated by aeolian activity resulting in sand transport of 22.5 m^{-1} yr^{-1} that have buried the local lacustrine-lagoon systems, and all frontal material. The aeolian sand transport average was estimated to be 1.4 kg m^{-1} s^{-1}, with a major contribution from the SSW (0.28 $kgm^{-1}s^{-1}$), S (0.27 $kgm^{-1}s^{-1}$) and SSE (0.17 $kgm^{-1}s^{-1}$). However, the sand mobility between 50 and 200 from 1979 to 2016 combined with drift potential average of 365 v.u are reflected on the dunefields vegetation coverage of about 70%, which strongly blocks the aeolian activity.

The 56-year temperature anomalies indicated the occurrence of ENSO events with relatively low or moderate intensities that may be linked to similar events that occurred when precipitation rose 10% and temperatures of 1° C from 7.5 kyr BP to 5.1 kyr B.P. These ENSO events connected to temperature, precipitation, vegetation coverage, sediment supply, and wind regime may be good indicators that explain the migration of the paleodunes and modern dunefields of southern Mozambique coast.

Many environmental factors influence sand transport, however, the accumulated average annual rainfall of 1600 mm yr^{-1} found, which intensifies between December and March, contributed negatively to the dune mobility. However, have conditioned to stabilizing process of the modern dunefields with over 70% vegetation coverage. Indeed, the annual average of 80 days with rain and 280 days without rain identified the episodic *El Niño* and *Lã Niña* phenomena in the region, which contributed to strong aeolian activity in the system.

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