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Artigo

CLIMATE VARIABILITY AND ANTHROPOGENIC ACTIONS AS DRIVERS FOR AEOLIAN ACTIVITY DURING THE LAST MILLENNIUM IN SOUTH-WESTERN EUROPE:
A CASE STUDY ON THE PORTUGUESE COAST

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ABSTRACT – The building of dunes and sand drifts along the European coastline are generally related to climatic variability and sea-level fluctuation. The last phase of dunes formation in south-western Europe coincides with the Little Ice Age (LIA) period characterized by pronounced climate variability. Historical sources retrieved from archives also report sand-drift events along the Portuguese coast. The sand invaded many agricultural fields, and settlements, forcing the inhabitants to move elsewhere. The article explores the temporal relationships between sand drift occurrences and climate, as a principal trigger for coastal dune migration. We used historical sources about sand-drift events as documentary proxies to infer the past climate variability on the Portuguese coast. Three spatial scales of climate variability were considered: i) the global climatic variability induced by the cold abrupt events over the last Millennium (LIA); ii) the regional (mesoscale) climate variability (NAO index), and iii) the local climate variability (extreme meteorological events). The paleoclimatic interpretation indicates that drifts in Portugal are related to both NAO modes, providing new insights into coastal dunes dynamics, as a response to natural drivers. However, the analysis of human activity on the coast also allowed us to better understand the relation of the local populations with their environments, highlighting those anthropogenic actions caused an additional disturbance on coastal dune dynamics.

Keywords: Sand-drift events; climate fluctuation; LIA; NAO index variability; Portugal.

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RESUMO – VARIABILIDADE CLIMÁTICA E AÇÕES ANTRÓPICAS COMO IMPULSIONADORES DA ATIVIDADE EÓLICA DURANTE O ÚLTIMO MILÉNIO NO SUDOESTE DA EUROPA. UM CASO DE ESTUDO DA COSTA PORTUGUESA. A construção de dunas e os movimentos de areia ao longo da costa europeia estão geralmente relacionados com a variabilidade climática e com a flutuação do nível do mar. A última fase da formação de dunas no sudoeste da Europa coincide com o período da Pequena Idade do Gelo (LIA), caracterizado por uma pronunciada variabilidade climática. Fontes históricas extraídas de arquivos referem ocorrências de invasão de areia ao longo da costa portuguesa. A areia invadiu muitos campos agrícolas e povoações, forçando os habitantes a mudarem-se para outros lugares. O artigo explora as relações temporais entre as ocorrências de invasão das areias dunares devido ao vento e o clima, como principal impulsionador para a migração das dunas costeiras. Foram utilizadas fontes históricas sobre eventos de deriva de areia como *proxies* documentais para inferir a variabilidade climática passada na costa portuguesa. Três escalas espaciais de variabilidade climática foram consideradas: i) a variabilidade climática global induzida pelos eventos abruptos frios ao longo do último milénio (LIA); ii) a variabilidade climática regional (de mesoescala – índice NAO); e iii) a variabilidade do clima local (eventos meteorológicos extremos). A interpretação paleoclimática indica que os movimentos de areia em Portugal estão relacionados com ambos os modos do índice NAO, proporcionando novos conhecimentos sobre a dinâmica das dunas costeiras, em resposta às condicionantes naturais. No entanto, a avaliação da atividade humana no litoral também nos permitiu compreender melhor a relação das populações locais com os seus ambientes, destacando que as ações antrópicas causaram um distúrbio adicional na dinâmica das dunas costeiras.

Palavras-chave: Eventos de deriva de areia; flutuação climática; LIA; variabilidade do índice NAO; Portugal.

RÉSUMÉ – LA VARIABILITÉ CLIMATIQUE ET LES ACTIONS ANTHROPIQUES COMME DÉCLENCHEURS DE L'ACTIVITÉ ÉOLIENNE AU COURS DU DERNIER MILLÉNAIRE EN SUD-OEST DE L'EUROPE. UNE ÉTUDE DE CAS SUR LA CÔTE PORTUGAISE. La formation de dunes et les dérives de sable le long du littoral européen sont généralement liées à la variabilité climatique et aux fluctuations du niveau de la mer. La dernière phase de formation des dunes dans le sud-ouest de l'Europe coïncide avec la période du Petit Âge Glaciaire (LIA) caractérisée par une variabilité climatique. Les sources historiques extraites du rapport d'archives mettent en évidence des occurrences de dérive de sable le long de la côte portugaise. Le sable a envahi de nombreux champs et établissements agricoles, obligeant les habitants à se déplacer ailleurs. L'article explore les relations temporelles entre les événements de dérives de sable à cause du vent et le climat comme principal déclencheur de la migration des dunes côtières. Nous avons utilisé des sources historiques sur les événements de dérive de sable comme substituts documentaires pour déduire la variabilité climatique passée dans la côte portugaise. Trois échelles spatiales de variabilité climatique ont été considérées : i) la variabilité climatique globale induite par les événements froids brusques au cours du dernier millénaire (LIA) ; ii) la variabilité climatique régionale (méso-échelle) (indice NAO) ; et iii) la variabilité du climat local (par exemple les événements météorologiques extrêmes). L'interprétation paléoclimatique indique que les dérives de sable au Portugal sont liées aux deux modes NAO, offrant de nouvelles perspectives sur la dynamique des dunes côtières, en réponse aux facteurs naturels. Cependant, l'analyse de l'activité humaine le long du littoral a également permis de mieux comprendre la relation des populations locales avec leur environnement, soulignant que les actions anthropiques ont provoqué une perturbation supplémentaire sur la dynamique des dunes côtières.

Mots clés: Événements de dérive de sable; fluctuation du climat; LIA; variabilité de l'indice NAO; Portugal.

RESUMEN – LA VARIABILIDAD CLIMÁTICA Y LAS ACCIONES ANTRÓPICAS COMO IMPULSORES DE LA ACTIVIDAD EÓLICA DURANTE EL ÚLTIMO MILENIO EN EL SUDOESTE DE EUROPA: UN ESTUDIO DE CASO DE LA COSTA PROTUGUESA. La construcción de dunas y los movimientos de arena a lo largo de la costa europea están generalmente relacionados con la variabilidad climática y la fluctuación del nivel del mar. La última fase de formación de dunas en el suroeste de Europa coincide con el período de la Pequeña Edad de Hielo (LIA), caracterizado por una pronunciada variabilidad climática. Las fuentes históricas extraídas de archivos se refieren a eventos de movimientos de arena a lo largo de la costa portuguesa. La arena invadió muchos campos agrícolas y asentamientos, forzando a sus habitantes a trasladarse a otros lugares. Este artículo explora las relaciones temporales entre la ocurrencia de movimientos de arena por causa del viento y el clima, como principal impulsor de la migración de las dunas costeras. Se utilizaron fuentes históricas sobre eventos de deriva de arena como sustitutos documentales para inferir la variabilidad climática pasada en la Costa portuguesa. Se consideraron tres escalas espaciales de variabilidad climática: i) la variabilidad climática global inducida por eventos fríos abruptos durante el último milenio (LIA); ii) variabilidad climática regional (mesoescala – índice NAO); y, iii) variabilidad climática local (fenómenos meteorológicos extremos). La interpretación paleoclimática indica que los movimientos de arena en Portugal están relacionados con ambos modos del índice NAO, proporcionando nuevos conocimientos sobre la dinámica de las dunas costeras, en respuesta a las condiciones naturales. Sin embargo, la evaluación de la actividad humana en la costa también permitió comprender mejor la relación de las poblaciones locales con sus entornos, destacando que las acciones antropogénicas provocaron una alteración adicional en la dinámica de las dunas costeras.

Palabras clave: Eventos de deriva de arena; fluctuación climática; LIA; variabilidad del índice NAO; Portugal.

I. INTRODUCTION

Several previous studies have focused on the global climate reconstructions over the past few centuries to millennia (Jones *et al.*, 2001; Jones & Mann, 2004; Klus *et al.*, 2018; Lamb, 1965, 1995; Luterbacher *et al.*, 1999, 2001, 2006; Mann, 2002; Mann *et al.*, 1999, 2009; Maslin *et al.*, 2001; Santos *et al.*, 2015). Evidence of anomalous weather and climate conditions (heavy rainfalls and droughts) appears in many ecclesiastic sources, often recorded as rogation ceremonies, used as documentary proxies to identify wet and dry extremes in many parts of the world (Alcoforado *et al.* 2000; Bravo-Paredes *et al.*, 2020; Domínguez-Castro *et al.*, 2008, 2011, 2012, 2018; Fragoso *et al.*, 2015). The past climate reconstruction, based on both documentary sources and natural proxies' indicators, such as tree rings, ice cores, ocean, and coastal sediments, speleothems, corals, and borehole data (Clarke & Rendell, 2006; Jones & Mann, 2004; Luterbacher *et al.*, 2006; Taborda *et al.*, 2004), indicates several abrupt cold events in Europe, characterized by substantial surface cooling, freshening, and severe ice shift advance. During colds periods, the increase of the availability of sediments on the coast contributed to coastal dunes formation, and also by releasing alluvial sediments to coastal drift and exposing larges beach plains to aeolian activity (Wilson *et al.*, 2001). However, there are distinct differences in the spatial resolution among the various paleo-environmental records with a high degree of geographical variability due to local specificities (Garnier *et al.*, 2006). Several authors postulated that the formation of the most recent dune fields in Europe was built during the cooling of the Little Age Period (LIA; circa. CE 1400-1850) which particularly impacted Europe during the 16th to mid-19th centuries (Mann, 2002).

Portugal possesses abundant historical sources, including a detailed description of past weather. Strong climatic variability was felt in Portugal during the 17th century, which was characterized by very long rainy periods and flood sequences and pronounced temperature variability (Alcoforado *et al.*, 2000; Daveau, 1997) and coincided with very cold conditions at the European scale (Luterbacher *et al.*, 2004). Over the last decades, the result of a past weather reconstruction pointed atmospheric circulation patterns over the Atlantic region as the principal driver of these variations (Hurrell, 1995). The NAO teleconnection patterns produce large changes in wind direction and speed over the Atlantic, in heat and moisture transport, and the intensity and frequencies of storms (Hurrell, 1997). These natural drivers promoted directly and indirectly many coastal processes, namely the increase of the aeolian activity and repeated sand drifts episodes over the adjacent lands, silting the rivers and estuaries, and destroying coastal settlements. Sand dunes deflation affected mainly the low-elevation coasts, but also the sandy embayment's on the rocky coastlines (Clarke & Rendell, 2011).

The morphodynamics of coastal dunes have been largely studied using environmental criteria (geomorphological, geological, stratigraphic, and age-estimation) to identify pulses of higher aeolian activity (Aagaard *et al.*, 2007; Clarke & Rendell, 2006; Clemmensen & Murray, 2006; Ramos-Pereira, 1987; Ramos-Pereira *et al.*, 2019). However, few studies consider historical documents and archaeological excavations to describe persistent sand drifts and their impacts on societies (Clarke & Rendell, 2009, 2015; De Keyzer, 2016; De Keyzer & Bateman, 2018; Freitas & Dias, 2017; Kelley *et al.*, 2018; Provoost *et al.*, 2011). Over the last centuries, there have been many changes in coastal land uses, like agricultural practices, deforestation, grazing, or the cutting of marram grass, which drastically affected the dune systems, increasing aeolian dynamics and dune migration inland.

Our study focuses on the Portuguese coast, where many historical documents state the existence of sand drift events with a negative impact on society. In response to these, authorities implemented adaptation strategies and management measures such as the afforestation of dunes with pine trees (Freitas, 2004). This research demonstrates that strong climate variability played an important role in both the natural and socio-economic systems. The article, therefore, aims to cross a set of documentary sources information with the paleoclimatic data reconstructed over the last millennium, to assess the relationship between climate and aeolian activity, leading to different phases of coastal dunes migration.

II. DATA SOURCES AND METHODS

From a methodological point of view, we apply an overview of the paleoclimatic information and human intervention on coastal areas based on bibliographic references and archive research.

The paleoclimatic explanation presented in this article has been mostly based on descriptive documentary data, using both non-instrumental evidence and early systematic observation of weather extremes, including devastating storms caused by violent winds, heavy rainfall, and severe droughts with strong impacts on the Portuguese coast and society. For the correlation of the sand drift events and climatic variability in the North Atlantic region, the annual North Atlantic Oscillation (NAO) index on winter was used, reconstructed values based on Trouet *et al.* (2009a). For higher temporal resolution monthly (1659-2001) and seasonal (1500-1658) NAO index reconstructions, based on Luterbacher *et al.* (2002), were also used. Variability of solar activity over the last millennium was determined using the reconstructed sunspots number, based on Usoskin *et al.* (2014b). All data can be downloaded from the *paleo* directory of National Centres for Environmental Information (NCEI) from National Oceanic and Athmospheric Administration (NOAA).

Records of sand drifts and their impacts have been retrieved from different documentary sources collected under the framework of the DUNES Project. The qualitative data is registered in the *DunesOpenArchive* database which allows for systematic queries of its records, according to their type (e.g., newspaper articles, chronicles, ecclesiastical and civil sources, legislation, technical reports, images, and cartography), date, author, and localization. Portuguese historical documents were collected from several institutions such as the ANTT – Portuguese National Archive, the Portugal National Library, the Overseas History Archive, the Economy Archive, and the Archive of the Institute for the Conservation of Nature and Forests.

In order to provide the spatial distribution of the recorded sand-drift occurrences along the Portuguese coast, a map was drawn up, using a *digital elevation model* (DEM) of Portugal, generated from *ASTER* image (30m spatial resolution). Each location has been georeferenced with *ArcGIS Pro 10.6* software, using the projected coordinate reference system ETRS89/Portugal TM06 and elevations referenced to mean sea-level (MSL): Cascais vertical datum.

III. HUMAN ACTIVITY ON THE PORTUGUESE COAST AND HISTORICAL EVIDENCE OF SAND MOBILIZATION

The coastal dunes of Portugal have a long history of human activity. For centuries, settlements took place mainly on sheltered coasts, like estuaries and protected bays. The straight open coasts of the Portuguese western littoral remained almost uninhabited until the end of the 18th century, as many dangers (e.g., strong winds, storms, coastline changes, drifting sands, piracy) and a harsh environment (e.g., lack of fresh water and agricultural soils) made them unattractive for human populations (Freitas, 2011). The coastal dunes were mostly used for housing during the fishing season, hunting, and grazing (Huddart *et al.*, 1999), and marram grass was used by the inhabitants for roofing and winter fodder (Provoost *et al.*, 2011). Between the 11th and 13th centuries, the Portuguese territory experienced a significant demographic increase (Galego & Daveau, 1986), leading to the need for more crops. As a result, the cultivated lands expanded and drastically reduced the vegetation cover. Using historical documents from monasteries, Bastos (2006) showed how the sand spit of the Aveiro lagoon (fig. 1), developed then due to the increase of the rivers sedimentary budget to this coast, was caused by settlement growth and the rendering of new territories to agriculture. During the 14th century, with the beginning of the Portuguese expansion policy, the forest crisis intensified (Devy-Vareta, 1986). The overexploitation of coastal vegetation, coupled to more intensive land use for agriculture had significant impact on dunes, allowing wind erosion and sand drifts episodes across adjacent lands.

Sand drifts events have been documented in many sites along the Portuguese coast, mainly in the Western facade, with well-developed dune systems. Their spatial distribution is unequal for two main reasons: i) most of the Portuguese coast is predominantly characterized by high cliffs; and ii) most of the settlements were concentrated at the north of Tagus River. According to historical sources, the earliest sand drift episode that we have reference occurred at the south of Mondego River (fig. 1), by the late 13th-14th centuries, threatening the village of Marinha Grande (Pinto, 1938). There is also the legend that King D. Dinis had ordered the planting of the Forest of Leiria, also known as "Pinhal do Rei" (adjacent to Marinha Grande), to avoid sand movements (Borges *et al.*, 1897), but no clear reference was found about that (Devy-Vareta, 1986; Freitas, 2004). Between the 14th-15th centuries, the village of Paredes was covered by sand, destroying many houses and the fishing port. Some documents mention that by the year 1500 it was completely buried and by 1542 no one lived there (Anonymous, 1868; Brandão, 1650; Morais, 1936). Up north, the small village of Fão was also having trouble with the sands. Between the 15th and the 16th centuries, Portuguese maritime discoveries further increased forest resource exploitation (particularly oak and pine) along the country for shipbuilding, leaving the soil unprotected and allowing aeolian activity. Other evidence of the advancing of the dunes over settlements and agricultural lands are from the 16th, 17th and 18th centuries (Mano, 2000).

In Minho region (NW of mainland Portugal), several parishes were covered by sands, in the 16th century. In 1693, a church at Apúlia had to be repaired as it was full of sand. Later, in 1734, the same occurred with the church of Fão (fig. 1). Many properties were lost in that region during the 17th century (Lopes, 2019). A shifting sand drama was described in Costa de Lavos and the surrounding area, at the South of Mondego River mouth, where "the floods of sand that come out from the sea" were responsible for the disappearance of the entire village (Guerra, 1950). The sand flow forced the inhabitants to move twice the local church of Lavos (in 1628 and 1743). In 1758, the people of Aveiro, Esmoriz, and Mira complained about the problems in the nearby coastal lagoons that were being silted and having their access to the ocean closed by the sands (Capela & Matos, 2011). Many more examples should exist in the Portuguese historical documents, as we know that similar situations happened in other places in Europe, like the cases of the Tvorup (1680-1750), in Denmark (Knudsen & Greer, 2008), Culbin Estate (1694), in Scotland (Bain, 1900) and Soulac (1744), in France (Buffault, 1897). The use of vegetation and trees to trap the sand was an old strategy of the ones living near the coast, in Portugal and other countries (Capela & Matos, 2011; Ledru-Rollin, 1845-54), but not much is known about this, and more research is needed to understand these local empirical strategies took place for centuries in the European shores.

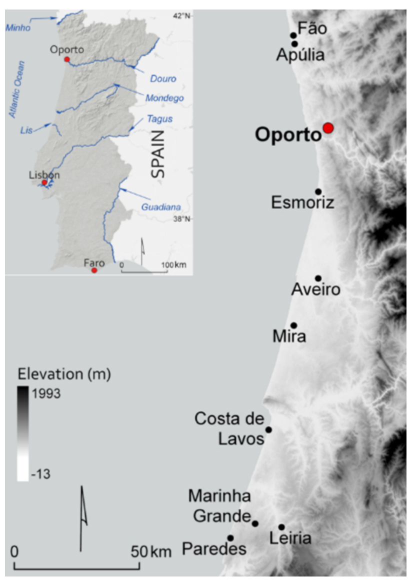

Fig. 1 – Location of the sand drift events recorded along the Portuguese coastline based on historical evidence. Colour figure available online.

Fig. 1 – Localização dos eventos de deriva de areia registados ao longo da costa portuguesa com base em evidências históricas. Figura a cores disponível online.

The 19th century was marked by major political and administrative changes. The sands movements putting at risk economic activities in coastal areas required technicians and politicians to act. Fixing the sands through afforestation was considered an urgent need across Europe. In Portugal, the first attempts were made in Costa de Lavos, by Bonifácio de Andrade e Silva, Head Chief of Mines and Forests. The works were carried out from January 1805 to March 1806, being abandoned, due to lack of money and Napoleon's troop's invasions (Silva, 1815). Only, from the mid-19th century onwards, multiple campaigns of coastal dunes afforestation were put into practice, with the support of different political regimes, until the second half of the 20th century (Freitas, 2004). For more than a hundred years, these works were carried on with one purpose, to fix the sands, converting the unpopulated dunes, considered dangerous and sterile lands, into green forests, making them productive and more attractive.

IV. CLIMATE ANOMALIES OVER THE LAST MILLENNIUM

Coastal areas are very complex systems highly sensitive to climatic variability. Hurrell *et al*. (2003a) argue that climatic variability is usually characterized in terms of anomalies. Detailed information about past climate conditions shows several thermal and rainfall anomalies. Many studies compiling global data have identified two major phases covering the past Millennium: i) the Medieval climate anomaly (MCA; ca. CE 1000-1300; Lamb, 1965), which corresponds to a warmer period in many parts of the world, also known as the Medieval Climatic Optimum, the Little Climatic Optimum, or the Medieval Warm Period/Epoch (e.g., Lamb, 1965; Mann, 2002), and ii) the Little Ice Age (LIA; ca. CE 1400-1850), which was considered as the coldest epoch since the Last Glacial Maximum (LGM; 18 000 BP). Although there is no agreement amongst the scientific community about the beginning of the LIA, further investigation showed that LIA was not installed as a continuous cold period, but rather had repeated cold events interleaved by warm periods (Easterbrook, 2016).

Possible explanations for these climatic fluctuations include external forces to the climatic system (e.g., changes in solar activity and volcanic eruptions), but also internal forces, involving shifting in ocean-atmospheric circulation (Scourse *et al*., 2010; Vaquero & Trigo, 2012). The exact timing of the LIA onset is quite controversial (Easterbrook, 2016), and several authors hypothesized that the first phase of cooling started roughly around CE 1290 to 1320 (known as the Wolf Minimum period) and has been linked to low solar activity. Easterbrook (2016) interpreted CE 1300, as the year that marked the end of the Medieval Warm Period (or MCA) and the beginning of the LIA. After the relatively warmer conditions of the second half of the 14th century, a second cold phase occurred from 1410 to 1540 (the Sporer Minimum). Mann (2002), however, suggests that more moderate weather conditions were felt during the 14th and the 15th centuries, which were associated with the transition interval between MCA and LIA. From the mid-16th century until 1850, a persistent period of cooling was installed in Europe, reaching its culminating stages between CE 1550-1700 (Lamb, 1965). Within LIA, two exceptional cold abrupt pulses at multi-decadal scale have been detected: i) the Maunder Minimum period (MM. CE 1645-1715), known as the coldest and dryer phase of LIA (Pfister *et al*., 1998); and ii) the Dalton Minimum (CE 1790-1820), the most recent intense cold event, with large negative effects in Europe. The global climate cooling, often related to the decreasing of solar activity, *i.e.,* timescale sunspots cycles, as well as volcanic eruptions (Carrasco *et al*., 2019; Carrasco & Vaquero, 2015; Klus *et al*., 2018; Santos *et al*., 2015; Vaquero & Trigo, 2012) coincides with advances of glaciers, changes in lake levels, and sudden changes of climatic conditions (Beer *et al*., 2000).

There are clearly uncertainties about the real solar activity and many debates are still ongoing. Nevertheless, the correlation of global temperatures and solar activity suggests a sunspot decline during MM periods and a substantial increase of sunspots after CE 1715, which is associated with global climate warming (Easterbrook, 2016). After this warmer period, the 2nd phase of intense cooling occurred within LIA (Dalton Minimum: CE 1790-1820), although less severe than the Maunder period. In addition to solar forcing, stronger volcanic activity was considered as a possible trigger of such climatic fluctuations (Mann *et al*., 2009). Volcanic dust can reduce solar insolation, leading to global cooling, shaping the climate on Earth. It is already known that the year 1816 was called "the year without Summer" in Europe (Trigo *et al*., 2009), as a consequence of the volcanic eruption in 1815 of the Tambora (Sumbawa Island, in modern-day Indonesia). The eruption was responsible for a subsequent cooling episode with global temperatures decreasing about 0.4 to 0.7°C (Wirakusumah & Rachmat, 2017). According to these authors, more than 200 000 people, in the world, died directly and indirectly because of the cold weather conditions and food shortages. Soon and Yaskell (2003) suggest that the ash clouds and sulphur aerosols drastically affected the climate of the Northern Hemisphere. They argued that the air pressure at sea level dropped significantly across the mid-latitudes of the North Atlantic region, pushing mid latitude cyclone tracks southward, bringing exceptionally wetter weather over Western Europe.

It is now widely accepted that a combination of these multiple factors, including astronomic and volcanic constraints, was responsible for the general cooling during LIA. During both exceptional cold events within LIA, the temperatures registered, in winter, in Europe, were about 1 to 1.5°C colder than 21th century's average (e.g., Mazzarella & Scafetta, 2018), promoting a larger than normal ice-sheet extent and glaciers advance. The end of LIA coincides with a transition to a warmer period after 1850 (Sejrup *et al*., 2010). Although it remains unclear the exact time of its beginning, the temperatures have increased in correspondence to the onset of the Current Warm Period (CWP: CE 1850-present). Deng (2016) defend that CWP warming was very similar to the Medieval Climate Anomaly (MCA) from the beginning of the last millennium. Previous results show that during the late 19th century, the global temperature slightly increased, but was still approximately 0.8°C cooler than during the early 21st century (Hartmann *et al*., 2013). However, recent investigations pointed to small climate fluctuation within CWP which culminated in a relatively cold episode between 1880-1915 (e.g., Easterbrook, 2016). This event is, indeed, consistent with another volcanic event, the Krakatoa eruption, that occurred in 1883, in an island between Java and Sumatra, with great impact over high and mid-latitudes, leading to a significant drop of temperatures, of about 0.4°C in the northern hemisphere land areas (Bradley, 1988; Gleckler *et al*., 2006). This suggests that volcanic-induced ocean surface cooling can accelerate the sink of surface waters into a deeper ocean layer (thermohaline circulation), where they can persist for decades and could be one of the reasons for the thermal variability that occurred from 1880 to the end of the 20th century. After another subsequent warmer period in the early 20th century (1915-1945), the climate cooled again for another 30 years, between 1945 and 1977 (Easterbrook, 2016). Like LIA, the onset of large-scale global warming remains uncertain, but several anomalous events marked the final phase of the last millennium, involving a combination of external forcing and inter-annual and inter-decadal climate variability. Some authors speculate that the most prominent accelerated warming period after LIA started roughly from 1900 onwards and could be related to a slight increase in solar irradiance. Scafetta *et al.* (2017) also claimed that peaks of warmer periods recorded during the 20th century seem to be produced by astronomical forces. Although they do not exclude the IPCC anthropogenic global warming theory paradigm, these authors believe that global warming emerged from the combination of the natural oscillation of climate astronomically induced with some anthropogenic contribution.

An alternative explanation of such climatic changes over the last millennium is related to internal forces driven by ocean-atmospheric interaction (Trouet *et al.*, 2009a), which has a profound impact on Earth's climate. Hence, the pronounced atmospheric-ocean variability might be linked to several internal mechanisms, including sea-ice transport (Wanner *et al.*, 2011) and sea-ice-atmosphere interactions (Li *et al.*, 2005), as major triggers of climate dynamics. Many studies suggest that the Global Conveyor Belt, also known as the Atlantic Meridional Overturning Circulation (AMOC), plays a prominent role in air-sea interactions and global climate. Mikolajewicz *et al.* (1997) defend that the ocean system can be suppressed in response to massive freshwater input, suggesting that the cooling of the Atlantic sea surface temperature may be related to the weakness of this global-scale system of currents. The internal variability of the global ocean circulation is driven by changes in deep-water transport, altering both the distribution of sea surface temperature (SST) and thermohaline circulation (THC), in response to air-ocean exchanges (Hurrell, 1995, 1997; Hurrell *et al.*, 2003a, 2003b, 2006). Therefore, it is believed that changes in ocean-atmospheric systems dictate global climate processes and the spatial pattern of the North Atlantic Oscillation (NAO) across the northern Atlantic region, with considerable inter-seasonal and interannual variability, although, prolonged periods (several months) of both phases are very common (Hurrell *et al.*, 2003a). This oscillation and resulting teleconnections, i.e., linkages between climate anomalies, are an integral part of the global atmospheric circulation pattern (Allan, 2012), and define the jet stream behaviour in the North Atlantic (Hurrell, 1995). It is a measure of the variability of the zonal flow (i.e., surface westerly winds) over the Atlantic basin, with essentially strong zonal flow during the positive phase, and meridional Rossby wave blocking, with north-south patterns, during the negative mode (Woolings & Hoskins, 2008). Typically, positive NAO phase (NAO+) reflects below-normal high pressure over the high latitudes and central North Atlantic, the eastern United States and Western Europe, and above-normal high pressure over South-western Europe and North Africa (fig. 2). This means that stronger-than-average westerlies flow over North Atlantic and middle latitudes, with wet and relatively warmer maritime air over North and Western Europe and Eastern US, while cold and dry mass air go through northern Canada and Greenland. These atmospheric conditions have been associated to a north-eastward displacement of storm activity and frequency (Roger, 1990). However, on the east coast of the USA, alternating phases of NAO alter circulation patterns on a synoptic scale. This situation can cause changes in the seasonal temperatures and, consequently, in the type of precipitation (Hurrell, 1995), including the occurrence of snowfall during the positive phase (Hurrell & Dickson, 2004). Contrariwise, in the South-western Europe and the Mediterranean basin, NAO+ shows high-pressure conditions and rainfall scarcity. Inversely, during the negative phase (NAO-), opposite patterns are observed with a weakness of both subtropical high and Icelandic low, bringing moist air into the Mediterranean basin and Western Iberia and cold air to northern Europe. The USA east coast experiences then more cold air intrusion and possible snowy weather conditions. This means that in Portugal, the occurrence of storminess and the increasing of precipitation usually correspond to NAO- phase.

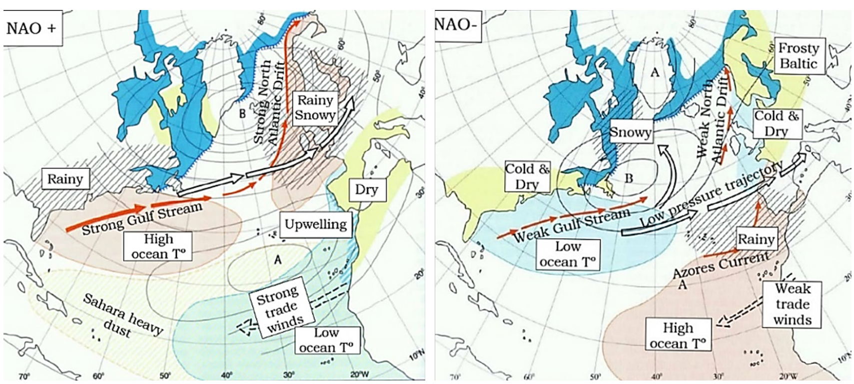

Fig. 2 – Impact of positive NAO mode (NAO+) and negative NAO mode (NAO-) on the North Atlantic climate system. Colour figure available online.

Fig. 2 – Impacto do modo NAO positivo (NAO+) e modo NAO negativo (NAO-) no sistema climático do Atlântico Norte. Figura a cores disponível online.

Source: Adapted from Brum Ferreira (2005)

These results demonstrate the atmospheric response to internal and external climate mechanisms consistent with abrupt changes in temperatures over the last millennium. A considerable number of studies reported that MCA and LIA events seem to be related to pervasive phases of the NAOi (NAO index; Trouet *et al.*, 2019b, 2012), defending the hypothesis of a stronger AMOC and a pervasive positive NAO mode during the MCA period and a shift to negative NAO conditions induced by the weakening of AMOC, consistent to the strong cooling over the Atlantic region and the adjacent areas during LIA.

The temporal sequence of the main climatic events reported above shows clear synchronization with the reconstructed solar activity and the large volcanic eruptions within the last millennium, and a very good correlation to sand drifts episodes recorded along the Portuguese coastline (fig. 3). The global climate changes over the last millennium including repeated periods of cooling related to the referred internal and external forces will be discussed below to explore the temporal relationships between climate and sand drifts occurrences.

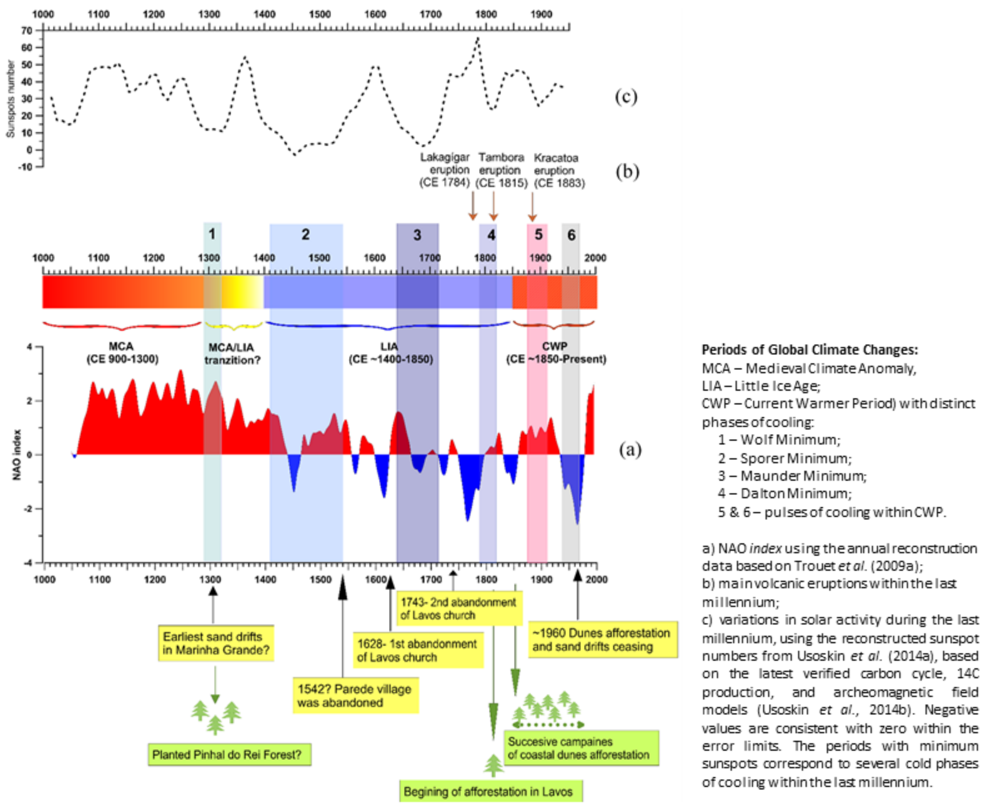

Fig. 3 – Correlation of sand drift events and climate variability, induced by internal and external forces to the climate system. Colour figure available online.

Fig. 3 – Correlação entre os eventos de deriva de areia e a variabilidade climática, induzida por forças internas e externas ao sistema climático. Figura a cores disponível online.

V. AEOLIAN SAND HISTORICAL RECORDS AND PALEOCLIMATE INTERPRETATION FROM GLOBAL TO REGIONAL SCALE

The climatic extremes, both cold and hot, influence vegetation cover and can have devastating effects on natural and socioeconomic systems. The use of historical data on the sand drift occurrences allowed us to reconstruct the regional paleoclimate and understand coastal dune dynamics as a function of both natural and anthropogenic drivers.

Given the previous evaluation of climate conditions, significant changes in global temperature have been recorded over the last millennium, with warmer conditions during the MCA period and a shift to the persistent cold period of LIA, afterward. During periods of cooling, the environmental conditions inland caused vegetation degradation and subsequent soil exposure. When these coincide with periods of NAO- mode, abundant rainfall during storms further promoted soil erosion in the exposed slopes, rivers carried out the sediments, and heavy discharges were made at their mouth. These sands could be moved inland during storms, as they are capable to mobilize the dunes, even in humid weather conditions (Roskin *et al.*, 2011). Under dryer conditions and abundant supply of sands coupled with strong onshore winds promoted dunes accretion and sand drifts episodes.

Systematic historical research on sand invasions before the 16th century has never been done (table I). Given the sparse knowledge we have on this issue, the sand drift episode at the beginning of the 14th century, near the town of Marinha Grande is uncertain as it has never been assessed in depth. Also, climatic reconstructions before the 16th century are quite scant, even though some works explored how the past record of climate can be reconstructed (e.g., Lamb, 1965, 1995). Besides documentary descriptions about sand drifts events used in this research which include mostly qualitative data, the paleoclimatic interpretation carefully needs attention. The temporal concordance between climate and this sporadic aeolian pulse may suggest climate control, with sand mobilisation linked to possibly storms increasing during the short cold period of Wolf Minimum event (ranging between CE 1290-1320). Later, during the 14th relative warmer weather conditions have been hypothesized, being synchronous to tidal marshes developments in Western Portugal, because of major sediment supply provided by the enhancing of river runoff (Moreno *et al.*, 2019). This may suggest an alluvial response to rainfall increasing and explain the accelerated input of sediments in the coast feeding the littoral drift (Abrantes *et al.*, 2005). Under mild conditions, we would expect slow dune dynamics since higher temperatures and moist should allow the development of halophyte vegetation. However, Sousa (1993) states that at the beginning of the 14th century, the Portuguese vegetation cover was diminishing due to the overexploitation of the scrubs and forest resources, agricultural land expansion, and grazing. These deforestation actions and agriculture spread obviously influenced the sediment budget of dunes. The protection and afforestation measures taken then were not enough to compensate for the increasing needs of a growing population, which used firewood and timber in almost all its activities (building, travelling, producing, cooking, heating). This population growth, however, leads to crisis of famines and plagues. Also, the warm conditions during the 14th century could have contributed to the spread of diseases by promoting the diffusion of bacteria that cause dysentery and other epidemics (Post, 1984). It was estimated that the Black Plague killed more than 30% of the European population in just over 1000 days from 1347 to 1351 (Kelly, 2005). Therefore, many lands were completely abandoned and before being recovered by scrubs, the soil was exposed to erosion, providing more sediments to the coast.

Table I – Main historical records considering the temporal sequence and the scales.

Quadro I – Principais registos históricos considerando a sequência temporal e as escalas.

Century	Date	Geomorphological/ Hidrometerological Event	Climate conditions/Atmospheric circulation pattern	Framework
13th		Sand drifts near Marinha Grande (?)	Cold conditions – Wolf Minimum (1290-1320)	North Atlantic/Portugal
14th		Tidal marshes development	Warmer conditions: MCA/LIA Transition	Portugal
15th	1430	Extreme cold weather conditions	The onset of LIA: Sporer Minimum (1410-1540)	North Atlantic
		Increase of sediment supply	Idem	Portugal
16th	–	Severe droughts	Idem	North Atlantic
	1540	"Megadrought"	End of Sporer Minimum	Western & Central Europe, Mediterranean Basin, and Iberia
	1542	Sand drifts buried Paredes village	Climatic variability (LIA)	Portugal/North Atlantic
17th	1600s	Exceptional storms	Atmospheric instability (LIA)	Portugal
	1628	Sand-drifts in Lavos	Climatic variability (LIA)	Portugal
	1693	Snowfall in Lisbon	Maunder Minimum (MM: 1645-1715)	Portugal
	1694, 1695	Strong storm tracks	NAO- values in winter- MM	North Atlantic
18th	1729, 1732, 1736	Rainy years	Climatic variability (LIA)	Portugal
	1734, 1737, 1738	Severe droughts	Idem	Portugal
	1739	Barbara storm	Strong atmospheric instability: NAO-mode	Portugal
	1743	Sand invasion in Lavos	Anticyclone conditions: NAO+ mode	North Atlantic/Portugal
	1779/82	Severe droughts	Blocking Anticyclone conditions	North Atlantic/Portugal
	1782	Snowfall in Lisbon	Climate cooling (LIA)	Portugal
	1783/89	Rainy years	Strong climatic instability (LIA)	Portugal
	1783, 1784	Persistent frost in Europe	Injections of volcanic aerosols in the climatic pattern	Northern Hemisphere
	1788/89	Particularly cold winter in Portugal	The onset of Dalton Minimum: DM: CE 1790-1820	North Atlantic/Portugal
19th	1800s	Repeated sand drifts events	Climatic variability/Atmospheric instability (DM)	North Atlantic/Portugal
	1850-1900s	Dune's stability	Current Warmer Period (CE 1850-Present)	North Atlantic/Portugal
20th		Heat-wave frequencies, forest fires, coastal overwashes, coastal erosion, dunes reactivation	Current global warming	Northern Hemisphere/ Global

In the beginning of the 15th century, climate reconstructions indicate another cold period, consistent with the early Sporer Minimum event, with the year 1430 particularly cold causing remarkable impacts on society and economy (Camenisch *et al*., 2016). The cold weather has also an influence on grain production and prices. Sousa (1993) mentions the existence of plagues, famines, and political and economic conflicts, in Portugal, all along the 15th century. By the 1500s, the population starts recovering and new marginal lands were converted into agricultural fields. As a consequence of the cultivated lands expanding, deforestation also increased. Substantial use of wood products (shipbuilding due to the Portuguese discoveries surely contributed to it, using particularly oak and pine wood), significantly enlarged the bare soil area and consequently more soil erosion. Therefore, the intensive land cultivation led to accelerated sediment infilling of many coastal lagoons which progressively impacted on coastal sediment budget (Dias *et al*., 2000). The increase of sediment supply silted the mouths of the rivers, creating serious problems for navigation (Magalhães, 1993). This suggests that sand-drift pulses recorded between the 14th and 16th centuries could have been triggered by natural drivers, but certainly amplified by human disturbances, allowing aeolian dynamic and drifting events.

By the 16th century, past climate reconstruction points to significant changes in temperature and moist. Substantial droughts were reported in Eastern US with wind-blown deposits probably transported by dry westerlies covering the fertile lands of the Great Plains (Lamb, 1965). This suggests, that in North and Western Europe, similar trends would be expected, consistent to NAO- mode (fig. 2). In the Portuguese case, many studies have shown the influence of the NAO on precipitation regime, with rainy periods and storms compatible with NAO- phase, while dryness reflects prolonged NAO+ mode (Fragoso *et al*., 2015; Luterbacher *et al*., 2006). According to annual NAOi reconstruction in winter based on Trouet *et al.* (2009a), the beginning of the 16th century is consistent with NAO- mode, which shifts to a prolonged NAO+ phase until the 1550s (fig. 3). It is also important to stress that this period corresponds to the Sporer Minimum phase of LIA, spanning between CE 1410-1540. This means that until the mid-16th century, Europe experienced both rainy and dryer cold conditions in winter, with heavy rainfalls and strong onshore winds causing sediment supply on the coast, followed by persistent dryer conditions that would have impacted for many years and definitively promoting the increase of aeolian activity and dune migration inland. Pfister *et al*. (2015) analysed distinct sources of weather evidence (chronicles recorded by more than 300 documents from all parts of Europe and other records of local authorities and diaries) to reconstruct the 1540 “Megadrought” (term used because of its large duration and spatial extent). They provide a picture of the large-scale weather conditions across Europe and confirmed the existence of extreme heat and drought in 1540, with high impact in Western and Central Europe, from France to Hungary, but also in the large Mediterranean land area and Iberia. This severe dryness had large negative consequences on society, including an extremely low level of the water bodies, fountains and soil drying, depletion of ground water resources, and forest fires (Pfister *et al*., 2015). In these circumstances of a reduced level of rivers and moist, a large amount of sediments from the river basins remained under sub-aerial environment, further promoting aeolian processes. According to annual and seasonal NAO index reconstruction (fig. 3), based on Trouet *et al.* (2009a) and Luterbacher *et al.* (2002), respectively, this extreme hot across Europe, is indeed, consistent to NAO+ values during winter and spring, suggesting anticyclone conditions over Iberia and the Mediterranean basin. However, extreme droughts in Europe are often associated with persistent blocking anticyclones (Alcoforado *et al.*, 2012), which can explain the large extend of the drought over Western and Central Europe. This means that during the late Sporer Minimum, many parts of Europe experienced rather cold and dryness conditions and higher water deficit, which would have affected the vegetation cover on coastal environments.

The temporal correspondence between the abandonment of Paredes village at the beginning of the 16th century (some sources mention the year 1542) and climate could be interpreted as a response to these extremes from the late Sporer Minimum period. The validity of this interpretation depends on the accuracy of historical documents about the exact timing of the abandonment of this village and whether the extreme dryness episodes occurred during all the hydrological year. In particular, in Portugal, the climate is characterized by great temporal (annual and seasonal) variability (Fragoso *et al.*, 2018), with vegetation development depending on the winter conditions since lack of precipitation is common in summer. Such explanation accounts for the fact that vegetation decline in the Portuguese coastal dunes is usually linked to drier conditions and water deficit during winter, which could imply the increase of aeolian activity and dunes migration inland. After the 1550s, climate display a remarkable variability over the western Iberia, with a prolonged period of NAO- mode, suggesting an intensification of storm activity, although interposed by anticyclone conditions compatible with NAO+ phase (fig. 3). Taborda (2006) also reported several peaks of storm frequencies in the beginning of the 17th century, in Portugal, with some exceptional events in the 1600s with violent winds, suggesting strong atmospheric instability. The significant variation of storminess from 1600s onwards coincide with some episodes of sand drifts occurrences along the Portuguese coastline, causing damages to local populations. Evidence of aeolian sand mobilisation during first half of the 17th century are provided by historical documents, reporting a notable sand-drift episode that led to the transfer of the local church of Lavos to a higher place in 1628. This event seems to be compatible with NAO- mode and possibly storm-induced and could be resulted from the reworking of existing dunes and deflation on the beach by strong onshore winds. By the late 17th century and the beginning of the 18th one, a period of particularly severe winters must be mentioned. Alcoforado *et al.* (2000) produced a compilation of historical records for the past climate reconstruction and describes rather cold conditions after AD 1693, with snowfall events in Lisbon (unusual nowadays) and pronounced variability of rainfalls. Based on the NAO reconstruction data (Luterbacher *et al.*, 2002), we found very strong NAO- values in winter, in 1694 (-2.02 in January) and 1695 (-3.71 and -3.23 in January and February, respectively), suggesting severe storm tracks over Iberia. These cold outbreaks could suggest large-scale climate control in coastal dunes dynamics. The beginning of the 18th century exhibits strong climate variability with two first decades particularly cold

(Fragoso *et al*., 2015), followed by three rainy years between 1706-1709, and severe droughts in winter of 1711/12 and between the spring of 1714 and autumn of 1715 (Luterbacher *et al*., 2006). The temporal correspondence of the 1715 drought event and climate seem to be consistent with the end of the MM period and the transition to the subsequent global climate warming (Easterbrook, 2016).

In addition to these extremes, sand movements also provide clear evidence of past weather and possible scenarios of the atmospheric circulation pattern. Hence, the sand drifts occurrences from the beginning of the 18th century can be correlated with the precipitation pattern induced by the pronounced interdecadal or even interannual variability of the NAO index. In fact, based on Luterbacher *et al.* (2002) NAO reconstruction, NAO- values have been registered in these first two decades, with possibly storm tracks in winter and spring, increasing the sediment supply on the coast and subsequent sand-drift initiation (Clarke & Rendell, 2006). Nevertheless, from the final of the 1720s onward, the pronounced precipitation variability was very similar to present days, with rainy years (1729, 1732, and 1736) alternated to a set of very dry periods during the 1730s (1734, 1737, and 1738), registered in the pro-pluvia and pro-serenitate ceremonies (Fragoso *et al*., 2015; Taborda *et al*., 2004). Starting to 1730, opposite pattern with persistent NAO+ values was observed, which would have amplified coastal upwelling and subsequent cooler and dryer conditions on the coast (Abrantes *et al*., 2005). These dryer conditions clearly suggest the presence of an anticyclone system over western Iberia, providing aeolian processes across the dunes, transporting large amounts of sand inland, burying coastal settlements. This supports the idea that the transfer of the local church of Lavos for the second time, in 1743 could be tentatively related to the NAO+ phase, as a consequence of strong Northwesterlies winds. Similar results have been found by Costas *et al.* (2012) who identified transgressive dune fields at 18km south of Costa de Caparica (South of Lisbon), which have been related to N-S windblown sand migration (Rebêlo *et al*., 2009). Whilst several authors found a significant correlation between aeolian activity along Portuguese coastline and the prolonged periods of NAO- during winter (Clarke & Rendell, 2006, 2009, 2011), here we hypothesized that strong positive NAO+ could also provide dry sand movement inland. Given the above discussion, we consider that the transgressive phases of the Portuguese coastal dunes might be linked to both NAO modes. Under NAO- mode conditions in winter, storm events could have moved inland great sand volumes by overwashing. However, during the NAO-, the abundance of rain does not provide better conditions to aeolization as the water creates a film that aggregates the sand grains (Ramos-Pereira, 1987). In such periods and subtropical latitudes as in Portugal, the aeolization may occur mostly during summer. Nevertheless, even during the cold LIA, with the interspersed episodes of NAO+ and the Northwesterlies winds, the aeolization would be much more efficient. This interpretation is in accordance with Aagaard *et al*. (2007) who also suggests that in the current conditions there is a land migration of sand bars during high water levels associated with storms surges, joining to the subaerial beach, where they later constitute a source of dry sediment available for deflation and dune accretion.

The coincidence of several drifts reported in the 18th century on the Western coast of Portugal may be also associated with the migration of the sediment inland during extreme marine events, such as storms. Severe extreme storms have been reported in the beginning of this century (Taborda, 2006), being the Bárbara storm (3rd to 6th December 1739), one of the most devastating hydro-meteorological extreme events in Portugal (Fragoso *et al*., 2013). A range of information about this storm collected from ecclesiastic sources, memories, and anonymous manuscripts (Daveau, 1978; Pfister *et al*., 2010; Taborda, 2006; Taborda *et al*., 2004), referred to violent winds of about 120km/h from the southwest direction, accompanied by heavy rains and very high floods on the Tagus, Mondego and Douro rivers, causing loss of human lives and material damages. The winds were recorded by the logbooks of two English vessels as "hard gales" on December 4 (what today corresponds to the Beaufort 9 and 10 wind scale) and "fresh gales" (Beaufort 7 and 8), the next day (Pfister *et al*., 2010), are clear evidence of the atmospheric instability which probably resulted from the passage of successive frontal systems (Taborda, 2006). Hence, we can speculate that all these extreme events may be responsible for the dune's accretion and inland migration of sands by overwashing. By the late 18th century, after the catastrophic destruction of Lisbon by the 1755 earthquake, the systematic observations of different weather elements encouraged by the Royal Academy of Sciences, contributed to the development of meteorology in Portugal (Alcoforado *et al*., 2012). The recorded instrumental data analysed by these authors confirm several positive and negative rainfall extremes during the last decades of the 18th century. The interval between 1779-1782 was predominantly dry, including three severe droughts, related to the persistence of a blocking anticyclone over Central Europe, followed by eight heavy and persistent rainy years, after 1783 (Alcoforado *et al*., 2012; Fragoso *et al*., 2015; Luterbacher *et al*., 2006). Remarkable cooling has been also reported during the 1782 winter, with a snowfall event documented in February in Lisbon, followed by very low temperatures and persistent frost across Europe in the next winter (1783/84 winter and spring), which froze the Thames River (Fragoso *et al*., 2015). They also pointed that this cold anomaly might have been driven by the Lakagígar volcanic eruption (from June 1783 until February 1784). The end of the 1780s has been characterized by the anomalous weakness of the Azores anticyclone ridge, located westwards of Iberia and a largely zonal flow, suggesting strong cyclone systems over western Europe and significant anomalies in precipitation associated with the passage of frontal systems (Fragoso *et al.,* 2015). The positive precipitation anomalies, from 1783 to 1789 are synchronous with the global climate variability and they seem to precede the cold episode of the Dalton Minimum event, spanning between CE 1790-1820. In fact, winter 1788/89 was particularly cold, with very low temperatures and frosts unusual in Portugal (Fragoso *et al.,* 2015), and corresponds to the onset of the cooling period of Dalton Minimum. These atmospheric conditions associated with both pressure systems, clearly suggest a good correspondence between the cold period of Dalton Minimum with the last transgressive phase of dunes in Portugal. These dynamic features indicate the pronounced climate variability in the beginning of the 19th century, with episodic sand mobilization in many sites on the Portuguese coast (Andrade, 1904), causing serious problems for the society and economy. This was the time when many countries along Europe assumed the task of preventing sand drifting and stopping its damages by fixing the dunes through afforestation. In Portugal, the Head-Chief of Forests, José de Andrade e Silva, pointed the failure of the first works for dune fixing to the lack of money and the French troops' invasion (Silva, 1815). But this can be also assisted by very cold weather conditions during the late stage of the Dalton phase, considered as an important conditioning factor for the development and growth of dunes. This idea is supported by NAO monthly reconstruction (Luterbacher *et al.*, 2002), which shows the predominance of NAO- mode between January 1805 and March 1806. Moreover, based on this data, possible strong storm tracks over the Western Iberia, generated by an exceptional NAO- phase (-3.11) in April 1806, can also be a reason for the lack of success of the works in Lavos. Only after 1850, the dune sands began to be systematically fixed by planting pine trees. The second half of the 19th century seems to be a turning point for the stabilization of the dunes (fig. 3), due to two major changes: i) the improvement of the weather conditions, culminating to the onset of the Current Warmer Period, with NAO+ values prevailing afterward, offering favourable climatic conditions for the dune vegetation development; and ii) the development of technical knowledge and the effort done by authorities to invest – through financial support, human resources and legislation – in dune afforestation. During the 1900s, an accelerated increase of the forestry area has been quite clear, and the sand drifts problems seemed to be solved. In fact, the paradigm would change, and this century would experience the lack of sand and coastal erosion as its bigger problem.

Since the late 20th century, the warming has been significant in the Northern Hemisphere, with the greatest temperature changes (0.6°-0.9°C) within any century in the past two millennia (Jones & Mann, 2004). These conditions have increased the heatwave frequencies and intensities, causing extensive forest fires. In addition, due to sea-level rise, coastal overwashes caused foredune erosion, implying sand drifts reactivation and blowouts development. Moreover, the transformation of dunes into an attraction for many economic activities had serious negative impacts on coastal dune ecosystems.

VI. FINAL REMARKS

The article allowed to emphasize the importance of the subtropical position of Portugal concerning global atmospheric circulation and sand mobility.

An overview of the climatic regime over the last Millennium indicates a strong relationship between the cold periods and sand drifts in the coasts of central Europe. In Southwest Europe, mainly in Portugal, the historical documents show a pronounced climatic variability, mainly during the cold period of the Little Ice Age, which played a key role in coastal dunes dynamic and vegetation cover. Under cold conditions and NAO- phase in winter, heavy rainfall during storms promoted sediment discharges by the rivers on the coast. Alternatively, many severe winters in Portugal also resulted from the blocking anticyclones with cold and dry air masses tracks. So, under NAO+ mode, large beaches remained under subaerial environments, favourable to sand mobilization by the Northwesterlies winds. The temporal consistency between some known sand drifts episodes and climate, suggests a correlation with both NAO modes, although pulses of aeolian activity were hypothesized to be preceded mainly the NAO+ phase. The combination of the extreme dryness with the prevailing Northwesterlies winds possibly reduced the vegetation cover on the coast causing sand-drift initiation.

This study demonstrates that the historical records on sand-drift occurrences can be used in a geographical context. These sources should be considered as important tools, which can provide insights into the past climate, including variations in the strength of the prevailing winds. The research showed that coastal dunes dynamics over the last Millennium seem to be both climatically and human-induced, being the human activity drastically modified the coastal systems, by depleting local vegetation, promoting inland transference of the sand dunes. For future work, details need to be considered, including the reconstruction of sand drift events based on instrumental data. Given the temporal variability of these episodes, stratigraphic approach (e.g., GPR data) and sedimentological proxies supported by the age estimation (e.g., OSL; C14) should be performed for more quality records, including both qualitative and quantitative data interpretation. The accuracy of the obtained data in Portugal will allow us to relate the sand drifts episodes in the European framework.

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