The Climate of Portugal

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Abstract

Portugal shows a Mediterranean climate with, predominantly, a wet cool season and a dry summer. Despite the concentration of the precipitation in winter, there is a high inter-annual variability, resulting from the latitudinal position in the south-western façade of Europe. The prevailing weather conditions are anticyclonic, with Portugal's seasonality being marked by the influence of either the subtropical anticyclonic belt or the zonal circulation. Despite the relatively small area of the country, its geographical position in the interplay between the Atlantic and Mediterranean influences, as well as its relief differences, with mountainous north and central regions and a flatter south, generates a diverse mosaic of regional climates. In this chapter, we show the main climate characteristics of Portugal, followed by a brief presentation of the main climatic scenarios for the end of the twenty-first century. The chapter closes with a synthesis of the palaeoenvironmental evolution of Portugal since the last glacial stage.

Keywords

Climate • Climate evolution • Climate change • Mediterranean

2.1 Introduction—Global Context

The Iberian Peninsula is located at the southern margin of the northern hemisphere temperate zone and at the northern margin of the subtropical high-pressure zone. This geographical setting is influenced by the seasonal latitudinal shift of the jet stream that directly impacts on the trajectory of the polar front, affecting the Portuguese territory from the Azores to the mainland. This seasonal rhythm is associated with shifts in pressure zones, with direct meteorological consequences in Portugal (Ramos 1986; Trigo and da Câmara 2000; Ferreira 2005).

The zonal atmospheric circulation is linked to strong westerly winds in the upper troposphere (the jet stream), which relate with polar lows. When the jet stream moves southwards, Portugal becomes influenced by the polar front, a situation that occurs mainly in winter. When the jet stream is weaker, it becomes wavy and the flow becomes meridional with the formation of planetary troughs and valleys (Fig. 2.1). The position of the axis of the circulation waves in relation to Iberia will influence the conditions at the surface. Valleys transport cold air from Greenland, Iceland or Western Europe, while aerological shelter conditions develop under ridges, with the arrival of Subtropical air masses (Trigo and Da Câmara 2000; Santos and Fragoso 2013). The variability of temperature and precipitation in winter depends strongly on these conditions in the upper troposphere (Ramos 1986; Trigo and Da Câmara 2000; Santos and Fragoso 2013). During summer, with the northward movement of the polar front, Portugal becomes under the influence of the stable atmospheric conditions that characterize subtropical highs (the Azores anticyclone). Spring and autumn are transitional seasons, affected by the progressive shift of the zonal atmospheric belts to the north or to the south, respectively. Hence, atmospheric instability increases with the progression of autumn, and stability increases as spring advances (Ramos 1986; Ferreira 2005).

The Portuguese territory includes the Azores and Madeira archipelagos. The former are nine islands located close to the middle of the Atlantic Ocean, 1450 km west from the Iberian Peninsula, with an area of 2330 km^2. The Madeira archipelago, which also includes the islands of Porto Santo, Selvagens and Desertas, is located further south at 900 km from the Cape of Saint Vincent, with a land area of 801 km^2.

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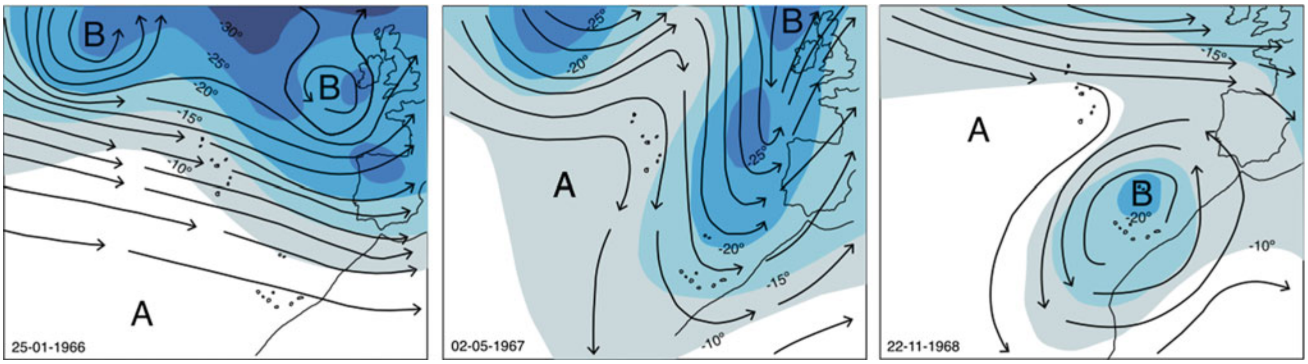

Fig. 2.1 Types of westerly circulation: **a** rapid zonal circulation (25 January 1966), **b** Meridian circulation, with a cold valley over the eastern Atlantic (May 2, 1967), **c** cut-off low over the archipelago of Madeira (November 22, 1968) (adapted from Ferreira 2005)

Both archipelagos suffer from the same influence under the shift of the pressure belts of the North Atlantic, although with a marked latitudinal gradient. The Madeira archipelago, located in the subtropics and close to Africa, shows a high influence of African air masses, being warmer and drier than the Azores (Cropper 2013).

Madeira and Azores are much more exposed to the tropical cyclones generated east of the Cape Verde islands than mainland Portugal (Ferreira 2005; Cropper 2013). These storms follow the Gulf Stream warm waters during autumn, as occurred with the cyclone Nadine in 2012 and with Hélene in 2018. Exceptionally, the case of the cyclone Hercules occurred in January 2014, affecting the Azores, in a situation of anomalously warm North Atlantic Ocean waters.

2.2 Regional Climatic Differences in Portugal

2.2.1 Main Climate Regions

According to the Köppen-Geiger classification, mainland Portugal shows a Mediterranean climate, with fresh summer in the north and hot summer in the south (respectively, Csb and Csa types, Fig. 2.2). The origin of air masses affecting mainland Portugal and their frequency largely controls the regional climate, which is influenced by flows from the Atlantic, Mediterranean, Northern Europe, the Arctic and also from North Africa (Ferreira 2005). The annual rhythm of climate is explained by the regional setting in south-western Europe, but at higher detail, the climate is mainly controlled by the gross landforms and their spatial distribution.

The regional climate organization in Portugal follows a general north–south gradient linked to the latitude control and the way it affects the exposure to the polar front influence, modulated by a west–east pattern reflecting the effects of the relief organization and the increased continentality of the interior of Iberia, which behaves climatically as a miniature continent. Daveau (1985) synthesized these patterns perfectly in Fig. 2.3, which shows that the latitudinal contrasts are emphasized by topography and especially, by the effect of elevation. The northern part of Portugal is mountainous while southern Portugal is dominated by plains and hills, with only a few isolated mountains (Fig. 2.4). Furthermore, several mountains are parallel to the coast, which exerts a major control on the inland movement of moist westerly air masses, generating a marked decrease in precipitation and increased thermal contrasts in the interior. For example, the mountains of Gerês and Peneda located in north-west Portugal and reaching altitudes of 1545 m are the wettest region of mainland Portugal, with annual precipitation surpassing 3000 mm and inducing an extreme contrast with the northeast. In only about 100 km, the annual precipitation becomes a mere 600 mm in Trás-os-Montes and 400 mm in the Côa Valley (Fig. 2.5).

The Central Cordillera, with its south-westerly mountains in Montejunto NE of Lisbon, followed by the Limestone Massif of Estremadura (Candeeiros and Aire mountains), the Lousã, Açor and the Estrela mountains, the latter closer to the Spanish border, is the geographical border between the rugged north-central Portugal and the smoother and less elevated southern part of the mainland. The mountains are also a major orographic barrier to the westerly flows, generating increased precipitation and a larger number of rainy days on the western and north-western slopes, in comparison with the south and south-eastern façades. The former show a climate with a more oceanic character, while the latter show a more continental influence and are drier, with increased thermal contrasts and higher temperatures, thus a more marked Mediterranean type climate.

The interior south of Portugal (Alentejo region) also shows a marked continental influence with hot summers and cool winters, while the south-west Atlantic coastal region shows an attenuated temperature range, with very frequent fog advection events, especially during summer mornings, driven by the cool ocean waters.

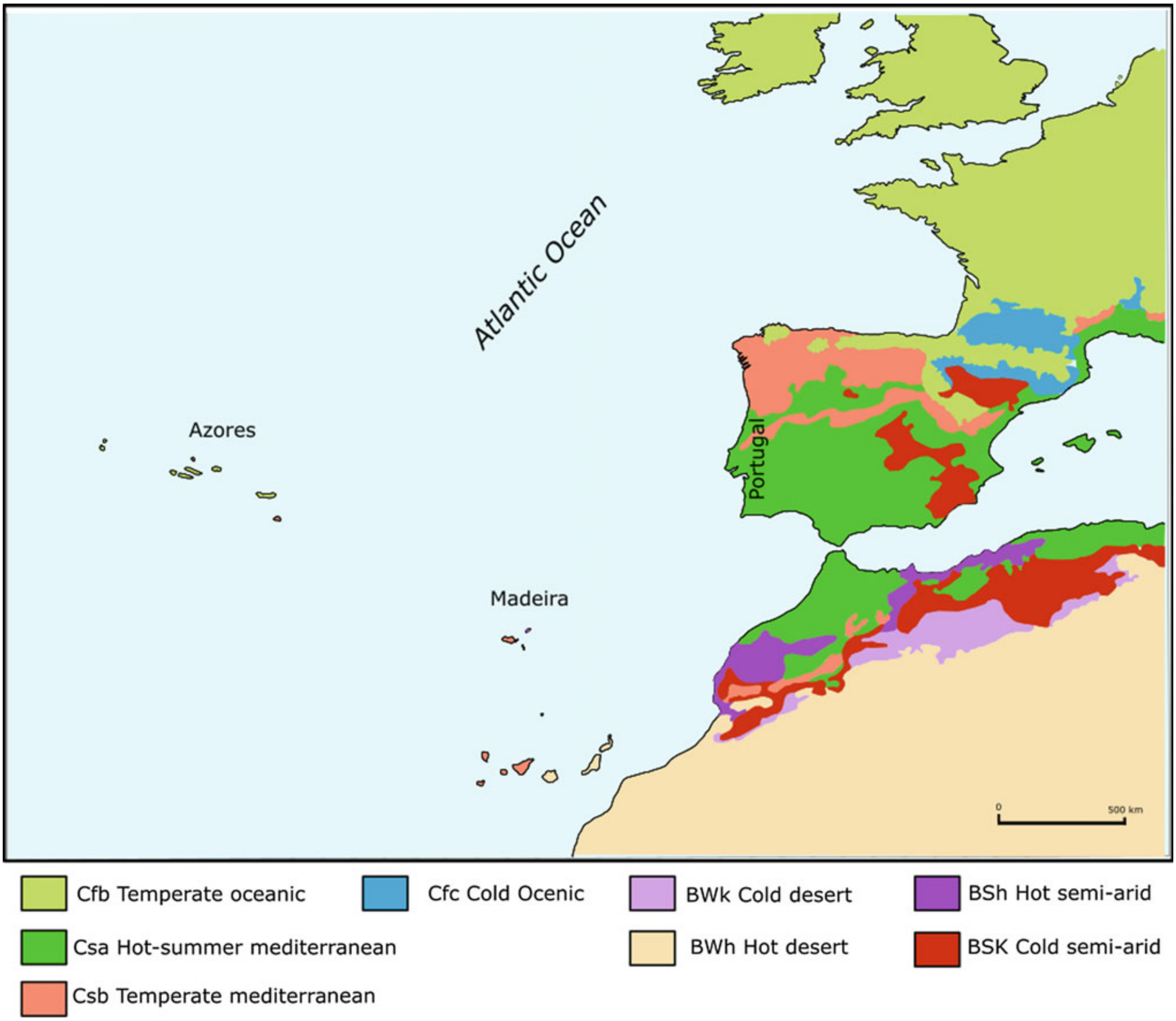

Fig. 2.2 Köppen-Geiger climate types of Western Europe and North Africa (adapted from Kottek et al. 2006)

The climate in the Azores is temperate oceanic with a weak annual and diurnal temperature range and a decrease in summer precipitation, although without the dry season that marks the mainland. The precipitation is higher on the islands of the western group, with the Flores Island showing 1512 mm and with Santa Maria Island in the eastern group showing 749 mm. Elevation, which is very significant in some islands, with the Pico Island reaching 2351 m, induces important precipitation increase, with climate becoming hyper-humid.

The climate of Madeira Island is temperate with dry and warm summers, but with a distinct altitudinal climate zonation. The island is elongated west–east and very rugged, rising to 1861 m at the Pico Ruivo and with a central zone of high elevation. The northern and southern slopes show significant climate contrasts, with the former being wetter, cloudier and windier, and the latter benefiting from orographic sheltered conditions. At about 380 m asl on the southern slope, the annual precipitation is 900 mm, while at a similar altitude on the northern slope, the respective value rises to 1400 mm (Ferreira 2005). The Island of Porto Santo is flatter and lowest, with a maximum altitude of 402 m and shows a much drier hot steppe type climate with an annual precipitation of 376 mm (Cropper 2013).

Both Atlantic archipelagos are included in the so-called Macaronesia biogeographic region with specific vegetation

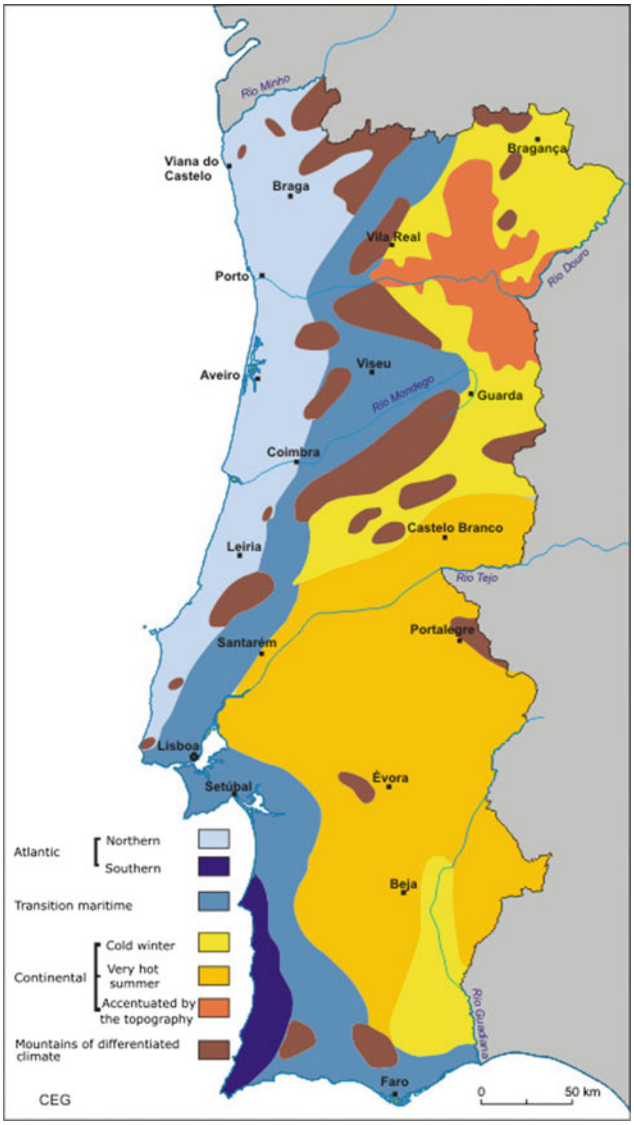

Fig. 2.3 Climate domains of mainland Portugal (Alcoforado and Dias 2002, adapted from Daveau et al. 1985)

linked to geographical position and climate conditions, unifying the islands from the Azores to Canaries and Cape Verde (Cropper 2013).

2.2.2 Temperature

Mainland Portugal is one of Europe's regions with highest incoming solar radiation, which increases from NW to SE from around 140 to 165 kcal/cm^2/year, along a gradient controlled by latitude, continentality and relief (Ferreira 2005). The number of hours of direct solar radiation is just below 2000 h in the NW region of Minho, from 2200 to 2700 h in the NE region of Trás-os-Montes, under 2600 h in the west coast at Cabo da Roca and over 3000 in the south region of Algarve (Atlas do Ambiente 7, 1988).

Mean annual temperatures across mainland Portugal vary from around 15 °C in the NW (e.g., Braga and Porto), while inland in the NE, Bragança shows 12.7 °C and Guarda in the interior centre at 1000 m altitude shows 11.2 °C. Southwards, the mean annual temperature increases, with 17.4 °C in Lisbon and 19.9 °C in Faro. Beja, in the south-central Portugal, shows 16.9 °C. In the top of the Serra da Estrela mountains at 1993 m, the estimated mean annual temperature is about 4 °C (Mora 2006). In the Azores, mean annual temperatures are 15.4 °C in Ponta Delgada, while in Madeira are 17.9 °C in Funchal. In summer, Madeira shows average monthly temperatures 3–4 °C warmer than the Azores, while in winter the difference is from 1 to 2 °C.

2.2.2.1 Summer

Daveau (1985) presented an interesting study of temperature contrasts in mainland Portugal. She showed that in summer the main controls on temperature are the distance to the ocean and altitude (Figs. 2.6 and 2.7). However, this continentality gradient is intensified by the effect of the upwelling of deep cold ocean waters along the western coast, which has an increased cooling effect (Ferreira 1984). This phenomenon is associated with the presence of the subtropical anticyclone of the Azores and of a thermal low over central Iberia, which cause a strong barometric gradient and strong northerly winds along the Portuguese west coast (the so-called Nortada). The Nortada drives surface waters off-shore, forcing the upwelling along the coast, which becomes marked by cooling, frequent advection fog and a sea breeze during the day (Mora 2014).

The effect of the Atlantic on summer temperatures is very clear when comparing the average daily maxima in July at the Roca Cape in the west coast, which is around 20 °C, with the ones measured in interior valleys of Alentejo, along the Guadiana, Douro or Tagus rivers, where the values surpass 30 °C. In the Algarve, without the influence of the Nortada and in the lee of the mountains of Monchique and Caldeirão, temperatures are higher than in the west coast, reaching monthly mean maxima between 25 and 28 °C.

2.2.2.2 Winter

The minimum temperatures decrease with the increasing distance from the coast and with increasing altitude, but with topography playing an important role (Figs. 2.6 and 2.7). The vertical lapse rates in the mountainous terrains are very dependent on the atmospheric stability conditions. Under unstable atmospheric conditions (e.g., frontal systems, subtropical lows), air temperature decreases with increasing altitude, but in the presence of a stable air mass (i.e., anticyclonic conditions), the temperature patterns are different

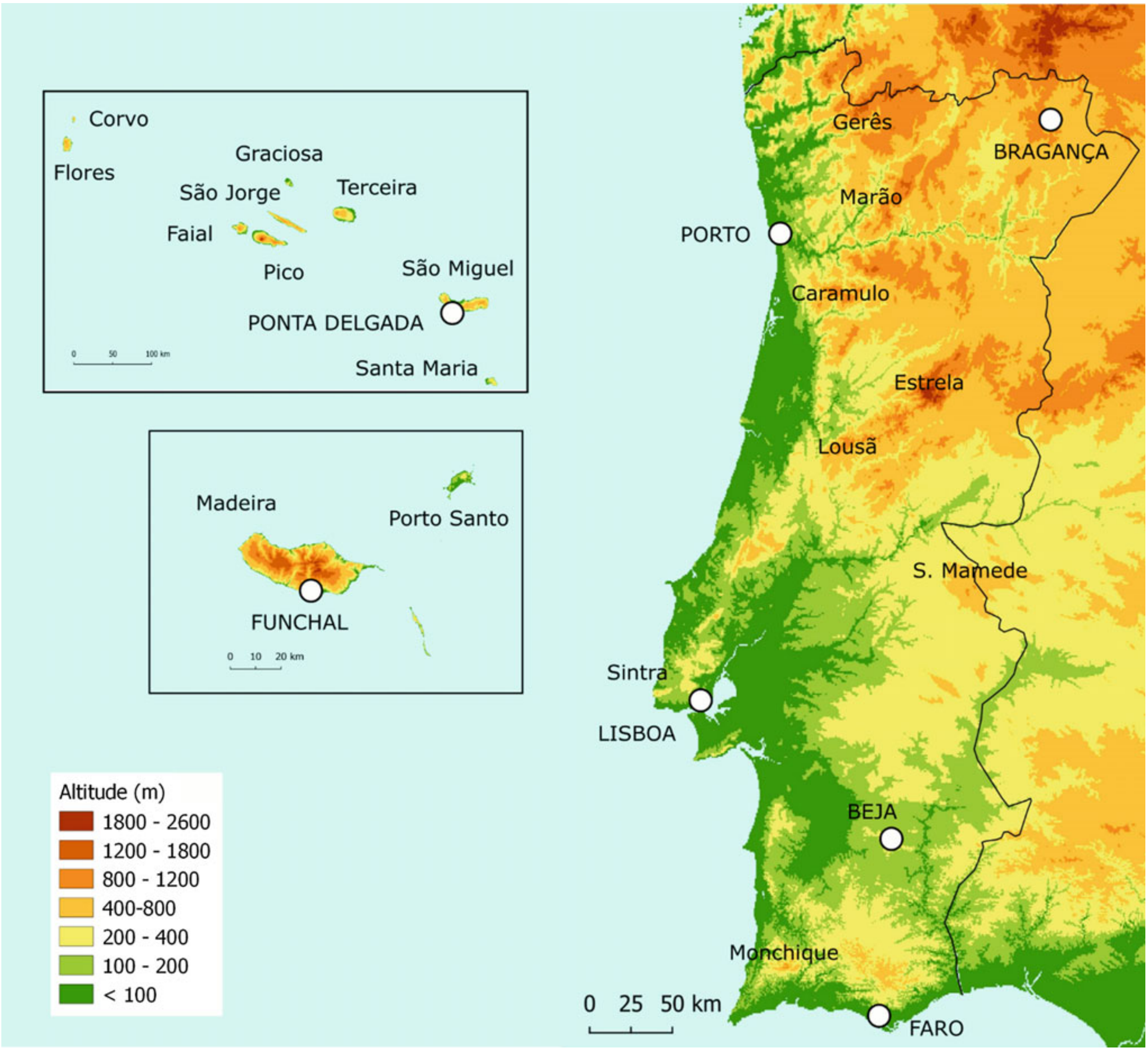

Fig. 2.4 Topography of Portugal, with main mountain ranges and towns used for the climatic characterization (topography from NASA SRTM V2). Madeira and Azores archipelagos shown at different scales

during night and day. In the former, valley floors frequently show the lowest temperatures, with a thermal belt forming in mid-slope positions, a phenomenon associated with high irradiation losses on the upper slopes and summits and cold air drainage, with the formation of cold-air pools. In the Serra da Estrela, temperatures at the summit (1993 m) may be higher than those at the floor of the Zêzere valley, some 1000 m below. Minima of −17 °C have been measured in the floor of the glacial cirque of the Covão Cimeiro (1600 m asl), while the crest of Cântaro Gordo (1875 m asl) showed −9 °C (Mora 2006).

2.2.3 Precipitation and Its Consequences

Mediterranean climates are characterized by summer dryness and by the concentration of precipitation in the cold season, but annual precipitation totals can be similar to other oceanic regions (Fig. 2.7). The wet season lasts from October to March, while April to September is generally drier, with almost no precipitation in July and August. Despite this general behaviour, the distribution of precipitation is variable across Portugal, reflecting factors of latitude, continentality and relief.

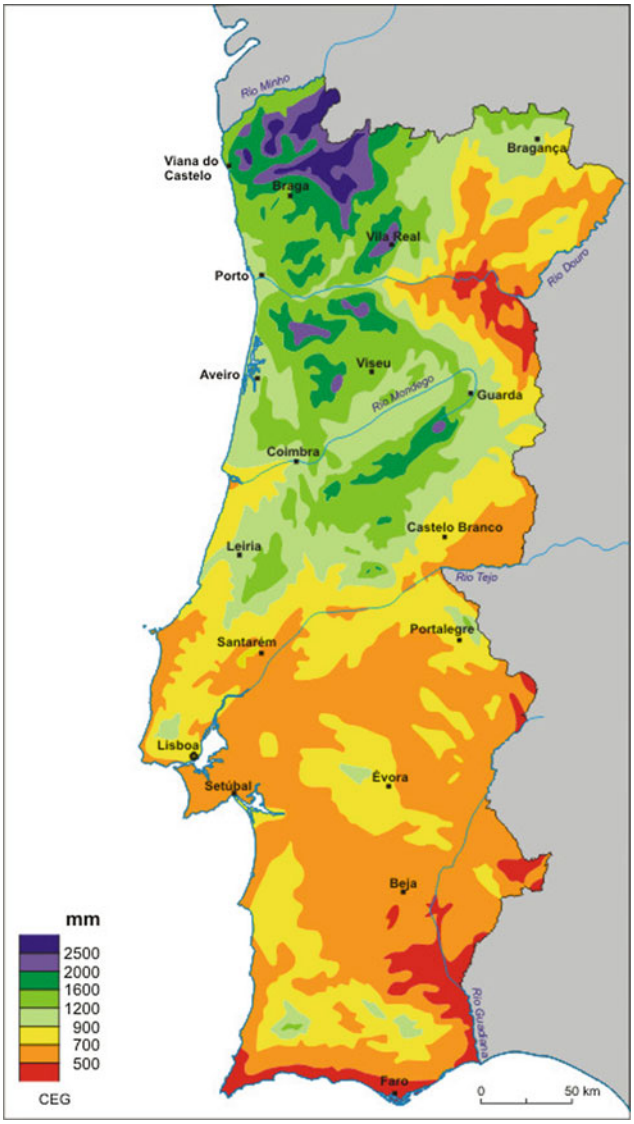

Fig. 2.5 Annual precipitation in Portugal (Alcoforado and Dias 2002, adapted from Daveau et al. 1985)

Another important characteristic of the Mediterranean climate is the high inter-annual irregularity of precipitation. When mainland Portugal is under a persisting aerological shelter atmospheric circulation with a ridge in the North Atlantic, the cold season is dry. But if the region is under a zonal flow allowing for the successive passage of polar fronts, then precipitation amounts are higher. During summer, atmospheric circulation is normally under the influence of the subtropical anticyclone of the Azores, which moves northwards and generates prevailing NW winds, frequently strengthened by the thermal low that forms over Iberia. The North Atlantic Oscillation Index (NAO), which consists on the standardized difference between the pressure in the Azores and Iceland, has been widely used to characterize climate variability in Europe. Trigo et al. (2004, 2005) have shown that a low NAO index links to above average precipitation, while a high NAO index is associated with lower precipitation.

The regional differences in annual precipitation are shown in Fig. 2.7, with clear contrasts from north to south and from the coast to the interior, which are remarkable accounting for the small size of the Portuguese mainland, with about 550 km from north to south and about 150 km from west to east. Precipitation is highest in the mountains of the north-west (Peneda and Gerês) with values above 3000 mm, which are high even when comparing with other wet areas in Europe (Figs. 2.5 and 2.7). The next wettest area is the Central Cordillera from Lousã to Estrela, with values reaching 2000–2800 mm. Southwards, the Alentejo with average altitudes of 200 m and the absence of significant mountains show 500–900 mm.

The effect of the distance from the ocean is clearer in northern Portugal, with some valleys in the Trás-os-Montes region receiving a mere 400–600 mm, in contrast with the wet north-west mountains of Minho. In the south, the Alentejo coast shows 700 mm with values below 400 mm in sectors of the Guadiana valley close to the Spanish border. On the other hand, the highest mountains of the interior Alentejo, such as São Mamede, show 1200 mm.

Most rainfall is generated either by lows associated with the polar front, with a flow from the west, or by convective lows with flows from the south-west. In southern Portugal, conditions such as cut-off lows may persist for several days and generate heavy rainfall episodes.

Flooding may be generated by both types of the above-mentioned atmospheric conditions, but the longer lasting floods that affect the large hydrographic basins of the Tagus and Douro are generally associated with the persistence of polar frontal systems over Portugal, that cause several days of continuous precipitation. Such conditions occurred in winters of 1978/79, 1982/83 and 2008. As an example, the flood of February 1979 showed 36 times the average river flow (405 m^3/s in Santarém) and 273 times the value of the characteristic flow during drought (Ramos and Reis 2001).

On the other hand, flash floods, the deadliest natural disasters in Portugal during the twentieth century (Ramos and Reis 2001), occur mostly in small catchments and are associated mainly with convective lows. The most damaging events in mainland Portugal occurred in the Lisbon region in November 1967 with over 500 fatalities and more than 1800 displaced people (Liberato et al. 2013). In February 2008 precipitation in Lisbon showed 118.4 mm in a single day, which is the highest value in the record (since 1864). The synoptic conditions showed an atmospheric block with high pressures in northern Europe and low pressures in the Azores during a week. The advection of warm moist air from the south provided the energy needed for convection to

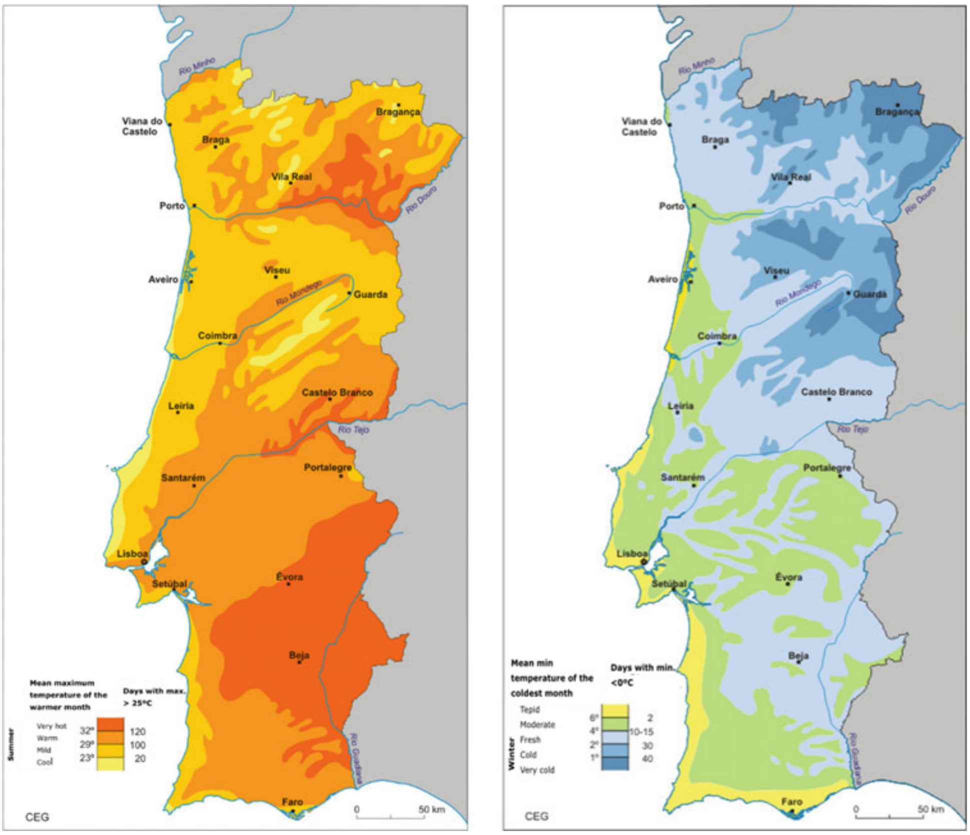

Fig. 2.6 Mean monthly maximum (left) and minimum (right) temperatures in mainland Portugal (Alcoforado and Dias 2002, adapted from Daveau et al. 1985)

occur, generating an event with an estimated 220 years return-period (Fragoso et al. 2010). The region suffered from numerous urban inundations, flash flooding and landslide occurrences.

According to Zêzere et al. (2014) that have studied a 146-year period from 1865 to 2010, flooding occurred more frequently from November to February, while landslides occurred later in the hydrological year, between December and March, with rainfall being the main triggering factor. Floods caused 1012 deaths, 418 injuries, 133,772 displacements and 40,283 homeless cases in Portugal. The same authors studied weather types associated with damaging floods in northern Portugal for the period of 1871–2011 and found the main causes to be low-pressure systems from south-west.

Most precipitation in Portugal falls as rain and snow occurs only in rare events below 1500 m, its presence on the ground being confined to the highest mountains of northern and central Portugal. The Serra da Estrela is the mountain region where snow cover lasts for longer, but data and studies allowing for its quantification are scarce. Andrade et al. (1992) studied the snow cover based on data for 1957–1985 from three meteorological stations: Lagoa Comprida (1604 m), Penhas da Saúde (1510 m) and Penhas Douradas (1380 m). They showed that snowfall events are more frequent from December to March, but only in February the number of days with snowfall is largest than the number of days with rain. Snow cover is characterized by a large inter-annual and even inter-monthly irregularity, and its presence on the ground is more frequent in the Estrela plateau above 1800 m, lasting for several weeks in winter. However, even at that elevation, warm rainy episodes may generate extensive snowmelt, interrupting the persistence of winter snow cover.

2.3 Recent Climatic History and Future Scenarios

2.3.1 Recent Climate Evolution

The longest air temperature series in Portugal is from the station Lisboa–Geofísico, which shows a warming trend since 1856 (Fig. 2.8). In Portugal, there were two main periods of warming: 1910–1945 and 1976–2000 divided by a cooling one from 1946 to 1976 (Carvalho et al. 2014). Ramos et al. (2011) focused on the period 1945–2006 and found a decrease of 0.17 °C/decade in the daily maxima and of 0.19 °C/decade in the minima for 1941–1975. For 1976–2006 the warming rate was more than twice as high, with 0.49 °C/decade in the maxima and 0.54 °C/decade in the minima. In the same period, the mean annual temperature increased by 0.52 °C/decade (Carvalho et al. 2014).

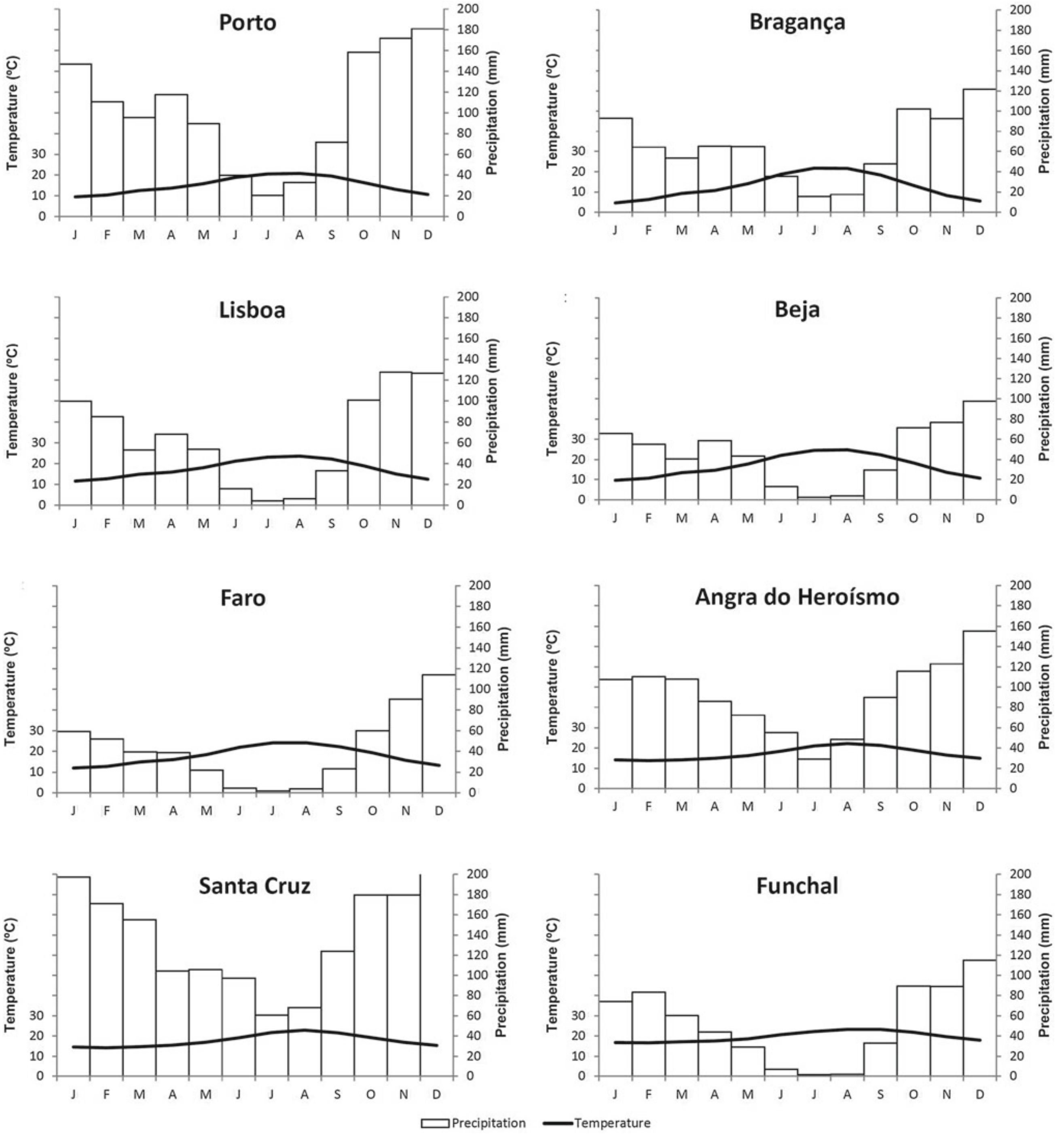

Fig. 2.7 Temperature and precipitation regimes in Portugal (data from Normais climatológicas 1981–2010, IPMA)

The frequency of heat waves, with major events in 1981, 1991, 2003, 2006, 2009 and occurring regularly every year since then, has been increasing since the early twentieth century and the opposite trend has been found regarding cold waves (Espírito Santo et al. 2014). Increasing drought has been noticed by several authors. Gallego et al. (2011) have shown a decrease in days with light rain in southern Portugal from 1903 to 2003, with Costa and Soares (2009) identifying an increase in the length of periods with drought and the frequency of droughts in general between 1955 and 1999. Data show that extreme weather and climatic events become more and more common, particularly heat waves, droughts and the annual number of very wet days (Carvalho et al. 2014). The irregularity typical of the Mediterranean climate

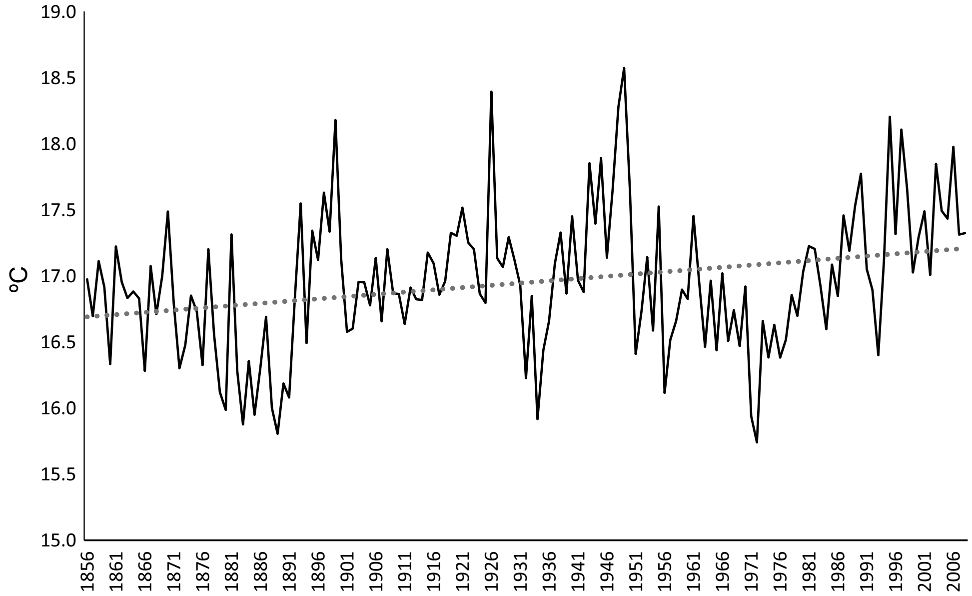

Fig. 2.8 Mean air temperature in Lisboa—Geofísico from 1856 to 2008. Trend line in dashed (data from Morozova and Valente 2012)

is thus increasing under recent climate change. For example, recent droughts occurred in 2004–2005 and 2011–2012 (Páscoa et al. 2017; Carvalho et al. 2014) and extremely wet years occurred in 2010, 2013, 2014, 2015, 2016 and 2017.

2.3.2 Climate Scenarios for the Twenty-First Century

Regarding future climate scenarios, the project ADAPT under the Portal do Clima (https://portaldoclima.pt) synthesizes model results for different meteorological variables in Portugal. Mean annual temperatures in Lisbon are estimated to increase by 1.67 °C in 2050 under the RCP 8.5 IPCC scenario and 1.02 °C under RCP 4.1. In 2100, these values may increase by between 4 and 1.9 °C, respectively. Precipitation should suffer a strong decrease, especially after 2050, with a potential decrease of 170 mm in the worst-case scenario in 2100. Porto shows similar climate deterioration scenarios, with an increase in average temperature by between 1.31 and 1.24 °C in 2050 and between 3.65 and 1.36 °C in 2100. The precipitation change scenarios are very different with values ranging from 3 to 265 mm less for 2100. The most severe changes should occur in the interior, with warming in RCP 8.5 of up to 4.9 °C in Bragança and 4.5 °C in Beja by year 2100, with concurrent significant reduction in precipitation, which can be up to 202 mm in the former and 199 mm in the latter.

Overall, the models estimate an increase between 1 and 4 °C (RCP 8.5 and RCP 4.1) in the mean annual air temperature in mainland Portugal for year 2100, especially in the interior. Summer extremes will experience a more significant increase. Andrade et al. (2014) indicate a warming of 2–4 °C for 2041–70, especially in the summer and autumn maxima. Winter warming will be weaker than in other seasons (Andrade et al. 2014).

Precipitation and the duration of the rainy season are shown to decrease, which will result in increased droughts and an even more extreme Mediterranean climate with an increased risk for the onset of arid conditions in the south of mainland Portugal. Trigo et al. (2002) and Pinto et al. (2007) indicate strengthening and northward displacement of the Azores high, especially in winter, with more frequent positive phases of the NAO, which will lead to drier atmospheric conditions in the future. The strengthening of the dry season will occur mainly in autumn and spring, associated with greater persistence of anticyclonic ridges (Costa et al. 2012). Soares et al. (2017) focused on rainfall projections for the end of the twenty-first century and estimated a decrease of 10–50% in precipitation in Portugal in spring, summer and autumn, following the RCP8.5 emission scenario (business-as-usual). Southern Portugal is the region that will show more profound changes. The RCP4.5 scenario shows the same overall signal and features, although with smaller magnitudes.

2.4 Climate Evolution Since the Last Glacial Cycle

2.4.1 The Last Glacial

2.4.1.1 Timing of Maximum Glaciation

The last glacial cycle that lasted from about 120–11.6 ka BP showed an alternation of rapid climate changes with periods of about 1450 years, with fast warming, followed by slow cooling, the so-called Dansgaard–Oeschger cycles (Wolff et al. 2010; Moreno et al. 2012a, b). The Last Glacial Maximum (LGM—23–19 ka) in Portugal is still poorly constrained in the geomorphological record. Glaciers were present in the Serra da Estrela mountains in Central Portugal, and also in the Gerês and Peneda mountains in the north-west, although absolute chronology results are preliminary. Vieira (2004) indicates the maximum glacial extent in the Serra da Estrela within the last glacial period occurred at about 30 ka BP, with the LGM showing already smaller glacier extent. These observations are consistent with palaeoglacier reconstructions elsewhere in Iberia, which place the Iberian Last Glacial Maximum close to the transition between MIS 5 and MIS 4 (García-Ruíz et al. 2010; Oliva et al. 2018). At the maximum extent of the Estrela glaciation, when a plateau ice field with radiating valley glaciers occupied a total area of 66 km^2, the equilibrium line altitude was at 1650 m asl (Vieira 2008). It decreased in elevation north-westwards, reaching 1100–1200 m in the Gerês and 900 m in Galicia (Coudé Gaussen 1981; Vidal Romaní et al. 1990; Ferreira et al. 2000; Pérez-Alberti et al. 2004, 2011; Oliva et al. 2018). With the sea-level some 120 m below the present-day one (Peltier and Fairbanks 2006), the coast was located several kilometres west of the current one (Dias et al. 1997), especially in northern Portugal, where the continental shelf is wider and in some areas the 120 m isobath is over 30 km west from the coast.

2.4.1.2 Ocean Sediment Core Data from the Iberian Margin

Sea surface temperature (SST) reconstruction for the LGM off the Portuguese coast at 40° N show values only 1–2 °C colder than present-day ones, which conflicts with earlier data from CLIMAP (1981) and Ruddiman and McIntyre (1981) by about +5 °C (Abreu et al. 2003). Salgueiro et al. (2014) confirm the relatively warm SST in the LGM in the Iberian Margin, with an average of 15.5 ºC. The largest SST differences between LGM and the Holocene have been found off-shore, with 3–6 °C. At 42° N cold water conditions occurred, with values close to 11.5 °C.

During the Late Pleistocene, there are six known cold phases with iceberg discharge in the North Atlantic that occurred between 70 and 14 ka BP, the Heinrich Stadials (HS) (Plaza-Morlote et al. 2017). From these, HS1 to HS3 are the best-studied, revealing SST from 5 to 11 °C in the coast off Portugal, with HS1 being the coldest, followed by HS3 and HS2 (Salgueiro et al. 2014). HS is particularly significant for climate, since they resulted in a migration of the polar front to the Iberian Margin with significant impacts in climate.

The Younger Dryas showed cold conditions in the ocean along the western Iberian Margin, with the coldest conditions inferred from cores obtained at 39° N, with SST ranging from 8.6 to 12.5 °C. Close to the coast, waters were warmer with 14.1–19.1 °C, which is just 1–4 °C colder than the Holocene before 8 ka (Salgueiro et al. 2014).

2.4.1.3 Lacustrine Sediments

Moreno et al. (2012a, b) presented multi-proxy data analysis from several lakes in Spain and obtained important insight into the environmental conditions during the last glacial cycle. Iberia experienced a relatively wet and cold period during the transition from MIS 5 to MIS 4, corresponding also to the maximum glacier extent in the Pyrenees and Cantabrian mountains. The MIS 4 showed increased aridity and the MIS 3 was characterized by rapid climate changes, with very arid episodes, which may have been responsible for rapid deglaciation. The aridity pulses in the continental record correlate with the Heinrich events of the marine record and hence should have also affected the Portuguese mainland. The global LGM was neither the coldest nor the driest phase of the last glacial in Iberia, with such extreme conditions having been recorded later, in the so-called Mystery Interval (MI) at 17.5–14.5 cal ka BP (which includes the HS1) (Moreno et al. 2012a, b; Denton et al. 2006). The authors indicate that the Lateglacial started synchronously with warming in Greenland at 14.6 cal ka BP, but not so abruptly, and with the highest humidity occurring in the Allerød. The Younger Dryas (YD) shows up in the lake records, but with variable signals in the pollen spectra, depending probably on regional and local conditions. The Holocene climatic optimum is recorded only after 10.5 to 9.5 cal ka BP (Moreno et al. 2012a, b).

Cores from the Charco da Candieira lake at 1409 m asl in the Serra da Estrela (Central Portugal) were studied by Van den Brink and Janssen (1985) and Van der Knaap and Van Leeuwen (1994, 1997), who obtained a very good sedimentary sequence starting at about 14.8 ka BP. The results for the period from 14.8 to 9.5 ka BP that represent the transition from the Lateglacial to the Holocene have shown the presence of glaciers at the start of the sequence (Bølling) in the higher parts of the catchment and periglacial conditions. Climate conditions showed several oscillations until the YD, with the ecosystem dominated by grassland formations on the plateaus and open scrublands in the valleys. The YD was cold and dry, with open grasslands prevailing in the headwater valleys and plateaus. After the YD and at the onset of the Holocene, there was an expansion of open woodlands in the mountains, with *Quercus* forests occupying the lower parts of the valleys.

2.4.1.4 Climate Modelling

Ludwig et al. (2018) used climate modelling with the Weather Research and Forecast model (WRF) to understand climate differences between the LGM and HE 1 that could have led to the decrease in human settlements in Southern Iberia in the latter period that has been found in archaeological studies. They have found that HE 1 was marked by extreme aridity in southern Iberia, with an enlargement of the total area of Iberia classified as ultrahyperarid in summer from 2% in the LGM to 22% in HE 1. This was confirmed by the modelling of vegetation types that showed an increase in open shrubland and grassland and a decrease of arboreal types.

2.4.2 The Holocene

In the Serra da Estrela, the pollen data from the Charco da Candieira (Van der Knaap and Van Leeuwen, 1994) show the progressive expansion of *Quercus* woodlands following the warming. At around 7.6 ka (non-calibrated) *Cerealia* pollens show an increase, with the forest becoming less dense. Human activity became especially significant and the main driving force on forest dynamics from 5.6 ka. The first large-scale deforestation took place at 3.6 ka BP, initially at 1400 m asl and climbing to 1750 m asl around 2.8 ka BP. This important record shows the significance of human activity on landscape dynamics in Portugal during the Holocene, with impacts even in the highest mountains, which surely have also resulted in increased soil erosion, still characterizing the Portuguese mountains.

Morellón et al. (2018) reconstructed the humidity patterns in the Iberian Peninsula in the Early Holocene (ca. 11.7–8 cal ka BP) from multi-proxy data and found significant regional differences between the north-western part of Iberia, under Atlantic influence, and the continental and Mediterranean sites. The former showed a gradual increase in humidity from the YD to the Middle Holocene, while the latter showed prolonged arid conditions, until an abrupt increase in moisture at 10–9 cal ka BP.

Queiroz (1999) has studied the coastal lakes from the lowlands of NW Alentejo and found four different stages in the regional evolution of the vegetation: (i) from 14 to 10 ka BP, with the formations showing affinity to the current oromediterranean bioclimatic stage (*Pinus sylvestris* in the sandy interfluves, *Pinus pinaster* in the sheltered slopes, deciduous *Quercus* woodlands with *Betula*, and heathlands), (ii) from 10 to 8 ka BP, with mixed formations between the meso- and supramediterranean stages (*Pinus sylvestris* disappears and *Pinus pinaster* occupies the interfluves, semi-evergreen *Quercus* woodlands prevail in the valleys and deciduous *Quercus* woodlands and *Betula* occur only in relict settings), (iii) from 8 to 4 ka BP in the Middle Holocene, with mesomediterranean formations (*Pinus pinaster* prevails in the interfluves but is gradually replaced by sclerophyll species and heathlands) and (iv) since the end of the Middle Holocene to the present day, a phase of thermomediterranean character (*Pinus pinaster* disappearing and expansion of *Pinus pinea* and *Quercus suber*, as well as sclerophyll woodlands).

The North Atlantic experienced an increase in temperatures with hydrological anomalies during the so-called Medieval Climate Anomaly (MCA: 900–1300 AD) (Goose et al. 2011; Graham et al. 2011). These were explained as a response of the climate system to weak changes in radiative forcing associated with a positive phase in the Arctic Oscillation and with a northward shift in the Gulf Stream (Goose et al. 2011). Moreno et al. (2012b) studied the MCA in the Iberian Peninsula from marine and lake records and showed that the period was dry in the Mediterranean Iberia, but it showed increased humidity in the Atlantic region. This reveals a different regional pattern in the MCA when compared to the previous Dark Ages (ca 500–900 AD) and the subsequent Little Ice Age, which were colder periods. The data support a persistent North Atlantic Oscillation positive mode during the MCA. The pattern found in Iberia shows how the region interfaces between the typical Southern European and North-west European conditions, with Diaz et al. (2011) indicating that in the MCA the former showed major hydrological anomalies with dry conditions, while the latter showed more humidity.

Oliva et al. (2018) present a review on the LIA in the mountains of the Iberian Peninsula using multi-proxy data and also observations from extra-mountainous sites. They interpret the cooling as a consequence of external forcing such as volcanic activity and reduced solar irradiance, affecting internal climate variability dominated by negative phases of the NAO. They have identified eight different phases in the LIA in Iberia, relating them to extreme weather events, with the coldest conditions coinciding with the Maunder Minimum in the period of 1620 to 1715 AD and severe cold and prolonged droughts between 1680 and 1700. The temperatures were on average 1 °C lower than in 1850 and 2 °C lower than present day.

An extreme case during the LIA was 1816, the famous ‘year without summer’, that followed the Tambora eruption of 1815 that took place in the Island of Sumbawa in Indonesia (Trigo et al. 2009). In July and August 1816, the temperatures were 2 to 3 °C below the average, with significant impacts on agriculture in Portugal and famine in several regions in Europe. In Portugal, Franzini’s systematic records from 1815 to 1826 and from 1836 to 1859, as well as historical reports, allowed to identify 184 windstorms from south and south-west that occurred mainly during winter (Marques et al. 2014).

In the Iberian Peninsula mountains, the environmental consequences of the LIA included glacier expansion, downslope expansion of the periglacial belt, low lake productivity, increased sediment runoff and periods of increased flooding (Oliva et al. 2018). In many mountain areas, an increase in natural hazards has also been reported. The post-LIA represents a period of resettlement of populations in mountain areas and occupation of previously abandoned agriculture areas.

Correia and Safanda (1999) studied deep borehole data from southern Portugal and through inversion techniques were able to reconstruct the ground surface temperature evolution since the second half of the eighteenth century. They showed an increase of 0.5–0.6 °C until the 1940s, followed by a 0.2 °C cooling until the 1980s.

2.5 Conclusions

Portugal shows a Mediterranean climate, being dry in the summer and having precipitations concentrated in the coldest semester, but its latitudinal position in relation to the atmospheric pressure systems is responsible for high inter-annual variability. The NAO reflects this irregularity, with positive values resulting in drier periods and negative values in wettest periods. Together with latitude, the topography and distance to the Atlantic are the major controls over the climate of Portugal. Precipitation is highest in the mountains of the north-west and decreases into the interior valleys and towards southern Portugal. The relief is also an important control for the intensity of rainfall events, but these are very much controlled by the general patterns of atmospheric airflow too. Temperature patterns reflect the same controls and show the maritime attenuating effect close to the coast and a more continental regime in the valleys of the interior, especially when sheltered in the lee of mountain ranges.

Climate in Portugal, as in other parts of the World, played an important role in the morphogenesis, with the present-day geomorphological landscapes of Portugal being the result of the complex interplay of post-Miocene tectonics, rock control and climate evolution. Today, the prevailing Mediterranean character of the climate induces significant stresses to the vegetation due to high summer dryness, promoting forest fires, but also extensive soil exposure. Intense autumnal rainfall events can thus become especially effective for soil erosion, resulting in very high rates of soil loss and mass movement events. The scenarios for this century show that climate will become marked by even more extreme events and irregularity, with increasing temperatures and decreasing precipitation. In some regions, such as southern Portugal, or the interior valleys of the Douro Basin, which are already quite dry, this will result in increased aridification, with important consequences for the ecosystems and geomorphological dynamics.

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