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CLIMATE CHANGE ANALYSIS: A COMPREHENSIVE STUDY ABOUT PORTUGAL'S SHIFTS IN TEMPERATURES AND PRECIPITATION WITH INSIGHTS ON THEIR CAUSES AND MITIGATION STRATEGIES

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1. ABSTRACT

This research explores Earth's climate, focusing on analyzing greenhouse gas emissions, climate change, and economic repercussions. It examines Portugal's climate dynamics using historical trends and IPMA data, considering CO2 emissions to understand climate change causes. Additionally, it explores Portugal's diversities and compares them globally. The study emphasizes the intricate effects of climate change on international trade, growth, and production, advocating for impactful policies like carbon pricing. It underscores the multifaceted economic impact and calls for a comprehensive approach, integrating financial interventions and coordinated strategies to address global climate change challenges, though addressing for uncertainty.

Keywords: climate change, GHGs emissions, global warming, Portugal, temperature, precipitation, macroeconomics, mitigation policies.

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2. INTRODUCTION

Generally, this paper aims to comprehensively explore Earth's climate complexities, focusing on GHG emissions, climate change focusing on Portugal, and addressing macroeconomic impacts and mitigation policies. In the first part, the goal is to understand the complexities of Earth's climate system and the evolving patterns of greenhouse gas (GHG) emissions in order to comprehend the ongoing phenomenon of climate change. Specifically, the natural processes shaping Earth's climate, the impact of GHGs on global temperature, and the economic implications of climate-related shifts are examined. Additionally, the analysis considers variations in the climate not only in Portugal but also worldwide, studying changes in temperature and precipitation and comparing these two dimensions, as well as providing insight about GHGs emission in the country. This analysis sets the stage for a comprehensive exploration of climate change, emphasizing the importance of addressing this multifaceted issue. Secondly, Portugal's climate is evaluated using IPMA data, focusing on key factors: minimum temperature, maximum temperature, and precipitation, calculated both at national and regional levels. In particular, this assessment displays crucial indexes, including annual average, interannual variability index, standardized precipitation index and climatic anomalies. Thus, these metrics offer insights into Portugal's climate dynamics, providing a comprehensive overview of deviations from historical averages. However, this model faces constraints, that are presented, discussed and justified at the end of the chapter. Finally, the last part explores the impact of climate change on macroeconomic variables and policies to mitigate these effects. For instance, climate change affects international trade, growth, and production, with complex direct and indirect impacts. Moreover, impactful policies, such as carbon pricing and tradable emission allowances, effectively limit emissions. Additionally, financial system interventions and central bank contributions play a role, even though balancing sustainability with monetary policy objectives as well as addressing uncertainty might represent a challenge.

3. LITERATURE REVIEW

The topics of climate change and its impacts on temperature and precipitation are widely studied and discussed worldwide. Specifically, Leonel J. R. Nunes, Catarina I. R. Meireles, Carlos J. Pinto Gomes and Nuno M. C. Almeida Ribeiro present and discuss the evolution of climate changes in Portugal. Moreover, in this paper the main source of data and historical trends comes from the Instituto Português do Mar e da Atmosfera (IPMA) website, which provides a wide range of insights, though not providing explanations about climate changes in Portugal. Even though this analysis considers data coming the IPMA, the already mentioned sources consider other data coming from other universities and institutes, which depict the same trend. In order to assess the impact of GHGs emissions in the country considered, papers provided by the European Parliament are considered, specifically one on these emissions published in 2019 and about Portugal. Furthermore, the European Environment Agency on its website provides a deep analysis on the latest trend about the temperature in Europe. Its data were crucial to compare Portugal's climate with the rest of the countries in the continent. Then, the Urban Groundwater Processes and Anthropogenic Interactions (Porto Region, NW Portugal) article published on Water in 2020 by Maria José Afonso, Liliana Freitas, José Manuel Marques, Paula M. Carreira, Alcides J.S.C. Pereira, Fernando Rocha and Helder I. Chaminé represents an interesting starting point to better understand geographical aspects of Portugal. Additionally, Bernardino Adão, António Antunes, Miguel Gouveia, Nuno Lourenço and João Valle e Azevedo, after explaining how GHGs emissions affect the temperature and precipitation both globally and regionally, hugely present how these might affect economy and how policymakers can implement policies to reduce these emissions. Furthermore, the Climate Change and Decision-Making Under Uncertainty article written by Rasoul Yousefpour Marc Hanewinkel provides valuable discussion about uncertainty in models. Finally, the European Route of Industrial Heritage website provides valuable information about industrialization and industrial history in Portugal.

4. GEOPYSHICAL ASPECTS OF CLIMATE CHANGE

4.1 The natural climate system and the GHG

Earth's climate is dependent on a variety of natural processes that include the Earth's atmosphere and crust, but also the oceans, cryosphere, biosphere, Earth's interior, Sun and Moon. Due to this complexity, scientists are only able to model and quantify these processes and estimate errors and limits. The total volume of the Earth's atmosphere is around 26 billion km^3, while the annual CO2 emissions from fossil fuels in 2018 were about 20 thousand km^3, and part of them were absorbed by the oceans and other systems. However, GHG emissions are cumulative over time, becoming problematic when there are insufficient removal mechanisms. In fact, the current CO2 level is 414 ppm (parts per million), much higher than 280 ppm in the 1800s. To understand how this tiny change can affect the climate, it is crucial to explore three concepts: the thermodynamics of bodies, the energy balance of the Earth-space system, and the GHG impact on energy transfers between the Earth, its atmosphere, and the space.

Firstly, warmer bodies emit energy, either in heat or electromagnetic radiation form, and cooler bodies absorb and reflect some of this energy. The type of radiation is affected by the temperature, shape, and material of the body. Then, to explain the second phenomenon, it is crucial to understand that the Sun heats the Earth and its atmosphere by electromagnetic waves (in form of visible light, ultraviolet radiation, and infrared radiation), some of which are reflected, while others are absorbed. The ratio of reflected energy to total energy is known as albedo, and it changes with the frequency of these waves. Thus, the Earth and its atmosphere radiate longer waves to balance the incoming energy and keep the temperature stable, since the planet would become uninhabitable if the solar energy is not compensated in the right way. Finally, in order to explain the interaction between the Earth, its atmosphere and the outer space, one has to know that this energy can be modelled as a blackbody, an abstraction used in thermodynamics that absorbs and emits all the energy, which depends on the temperature.

Hence, the greenhouse effect can be defined as the trapped energy in the atmosphere given by the difference between the one reaching space and the one given from the Sun. Consequently, this difference in temperatures is due to the atmospheric gases, especially the GHG. Thus, any change in the GHG concentration can affect the energy balance. In conclusion, the Earth's temperature depends on the balance between solar radiation and long-wave radiation. If the surface temperature is too high, the Earth will adjust itself by increasing its albedo and decreasing its transmittivity, which are affected by greenhouse gases and feedback mechanisms. As effects are complex and uncertain, they require more advanced models to estimate.

It is now possible to understand why the GHGs are considered as the main cause of climate change. The global emission of greenhouse gases, particularly CO2, affects the entire atmosphere, causing economic externalities. Despite their small atmospheric presence, GHGs cause a greenhouse effect by impeding energy release to space. Moreover, these gases absorb energy in specific wavelengths, influencing the planet's balance. CO2 concentration has rapidly increased as mentioned before, mainly from human activities. This accelerated process contrasts with the slow natural carbon cycle, leaving about half of emissions induced by human activities since 1850 in the atmosphere. To sum up, resolving this issue might be challenging because of the prolonged carbon dissolution and elimination processes.

4.2 Greenhouse gases emissions in Portugal and their effects on its climate

The EU's climate and energy legislation for 2030 mandates Member States, including Portugal, to adopt national energy and climate plans (NECPs) from 2021 to 2030, according to papers published by the European Parliament for each country. Portugal contributes 1.8% of the EU's greenhouse gas (GHG) emissions, with carbon intensity exceeding the EU average by 22% in 2019. Particularly, the transport sector, responsible for 26% of emissions, reduced by 10.3% between 2005 and 2019, even though its share increased by 3.3 percentage points. However, the NECP aims to reduce transport emissions by 40% by 2030. Considering emissions from one of the other more important sectors in Portugal, the energy one, they represent 19% of total in 2019, decreased by 50% from 2005 to 2019. Furthermore, it is important to mention that total GHG emissions in Portugal were 69 million tons of CO2 in 2019, decreasing by 22% from 2005 to 2019 and that the land use sector acted as a carbon sink, except in 2017 due to forest fires. Under EU effort-sharing legislation, Portugal can increase non-ETS GHG emissions by 1%, but it never exceeded allocated emissions. Portugal's 2019 share of renewable energy was 30.6%, targeting 47% by 2030, with an 80% target for renewable energy in electricity. Nevertheless, Portugal is on track to overachieve the Effort-sharing Regulation target of a 17% reduction in emissions by 2030, based on NECP measures, and the country aims to reduce emissions in various sectors, including services, residential, and transport, by 70%, 35%, and 40%, respectively. It also important to assess that Portugal increased its renewable energy share by 11.1 pp from 2005 to 2019. The NECP includes sectoral targets for the electricity, transport, and heating sectors. Portugal's hydrogen strategy, approved in 2020, focuses on decarbonization and increased hydrogen production by 2030. The Wind Float Atlantic project, the first of its kind in Europe, generates electricity off the Portuguese coast. Finally, the gradual elimination of tax exemptions associated with coal use for electricity aims to fund decarbonization projects and reduce the tariff deficit for the electricity sector. Overall, even if this paper provides a deep understanding and description of GHGs emissions in Portugal, to assert whether GHG emissions in Portugal are one of the main causes of climate change within the country, a more detailed and explicit examination of the factors contributing to climate change in the Portuguese context would be necessary. However, data about other variables across Portugal are presented and considered in the following paragraphs, providing different points of view also on more geophysical and regional aspects.

4.3 Portugal’s industrial history and its effects on CO2 emissions

Portugal's historical isolation, both geographically and through a policy of limited interaction with confining nations, led to a reliance on colonies, particularly in the 15th century when a global trading network was established. By the 17th century, pressure from competing nations forced Portugal to focus on its rich colony, Brazil. Therefore, the economic consequences became dire when the flow of resources from South America diminished. Then, in the 18th century, the Marquis de Pombal attempted to counteract this decline by founding commercial colleges, limiting the influence of nobility, and establishing manufacturing enterprises. Despite efforts, agricultural modernization was hindered by conservative landowners in the south and subsistence farming in the north, leading to low productivity and a lack of investment capital. Moreover, the lucrative sugar production in Brazil, along with the slave trade, brought substantial income. Even after Brazil's independence in 1822, Portugal continued supplying slaves until 1869. However, the impact of these profits on Portugal's industrialization is unclear due to the scarcity of mineral resources. Consequently, industrialization in Portugal was slow until the late 19th century, with textile production, tungsten mining, and other industries emerging. The lack of job opportunities in rural areas led to significant emigration. Agriculture remained the economic backbone until the 20th century, with improved cultivation methods and mechanization supporting exports of wine, fruit, and cork. Hence, the dominance of British trade and the lack of qualified workers and capital further hindered industrialization. The Salazar regime's isolationist policies from 1932 to 1968 prioritized colonial exploitation, delaying progress. However, in the 1960s, industrialization began with expansions in steel, shipbuilding, paper, petrochemicals, and electrical equipment manufacturing. Despite remaining elite-dominated, this marked a significant structural change in the economy.

Having this historical overview, it is possible to conclude that Portugal’s economic development has been slower compared to other countries in Europe, for example the United Kingdom. As a result, CO2 emissions are lower in Portugal rather than in other countries, causing an overall smaller rising of temperatures. Additionally, this will be further discussed in the following paragraph and considering moving averages in temperature in the next chapter.

4.4 The evolution of precipitation and temperature globally and in Portugal

Firstly, it is crucial to analyze precipitation and temperature changes from a worldwide point of view. On one hand, considering the period 1900-2017, the Earth's surface temperature exhibited a roughly 1°C anomaly increase concentrated in the latter half of the 20th century, resulting in a 0.017°C per year warming rate from 1950 to 2017. The Intergovernmental Panel on Climate Change (IPCC) in 2021 attributed this warming to greenhouse gas emissions associated with human activities, expected to reach 0.8–1.3°C by the late 2010s. This observation is coherent with what explained and presented in the previous paragraph, as most of Portugal's GHGs emissions comes from the transport and the energy sectors. On the other hand, global precipitation exhibited less uniform behavior, as there was an impressive drop during the late 1970s and early 1980s, followed by a rise since 1985 at an average rate of 0.87 mm per year, reaching values comparable to the early 20th century. Specifically, Africa, Southeast Asia, southern Europe, and the Middle East witnessed a decline in rainfall, while increased precipitation was observed in the temperate zones of Europe, North and South America, and extensive areas north of the Indian subcontinent.

Moving on to analyzing the two key climate variables for Portugal (average annual temperature and total annual precipitation), it is possible to witness a 0.6°C temperature increase from 1900 to 2017, with an annual warming rate of 0.0077°C from 1950 onward, using University of Delaware data for Portuguese mainland. As discussed in the following paragraphs, this pattern presented by the University of Delaware is coherent with the conclusion one can draw from the IPMA dataset. Furthermore, Portugal's temperature displays higher volatility compared to the global surface due to its smaller size and ocean proximity. On the contrary, precipitation data indicates no significant trend from 1900 to 2017, with high annual variability. Specifically, the northern interior experienced remarkable precipitation reduction (1950–2020), while coastal and southern regions resisted such declines. As a result, disparate impacts on climate change might emerge. Hence, climate change goes beyond just changes in average temperature or total precipitation, as it also includes shifts the rainfall distribution and the prevailing temperature conditions, all of which impact economic outcomes.

This heterogeneity in the general climate conditions significantly influences building energy consumption, particularly heating and cooling, resulting in regional disparities. In fact, the north experiences energy savings due to decreased heating, while the interior sees rising cooling demands, leading to increased energy expenditure. These evolutions highlight the dynamic impact of climate change on energy use, with potential economic consequences. Overall, recognizing these past trends to have an historical perspective is crucial in order to implement models for creating future projections.

4. DESCRPTION OF THE ANALSYSIS CONDUCED AND COMMENT OF OBTAINED RESULTS

In this chapter the analysis completed, and results obtained about Portugal's climate will be briefly analyzed, both at a national and regional level. All data examined are gathered from the IPMA website, and these are comprehensively about the minimum temperature, maximum temperature and precipitation. Hence, the evaluation is based on the computation of the following key indexes, whose formulas used can be found in the appendix: annual average, interannual variability index, standard deviation, climatic anomalies and exclusively for the precipitation the standardized precipitation index. Then, only for national data, a moving average for a period of ten years are calculated. Additionally, given the massive dimension of data in terms of years considered for each region as well as monthly information available, the calculation for the climatic anomalies is carried out on an annual basis rather than on a monthly basis, as it is showed on the IPMA website instead. These anomalies are calculated by taking as reference a 30-years average for the whole period and computing the differences between the annual average for every year and that average. Moreover, the standardized precipitation index is a tool used in climatology to measure how much rain is below or above the usual amount for a specific place and timeframe. Hence, this index says if an area is experiencing less or more rain than it typically gets based on historical weather data.

It is also worth mentioning that even if Portugal includes the Azores Islands and Madeira Island, in this analysis these two regions are not considered, as they might be altering the results being located in a completely different geophysical and economic environment. Moreover, in the National Data the average temperature is also computed and analyzed as described above, since it is a key measure to have a complete overview on Portugal's temperature and to compare this country with the rest of the world. Additionally, it is important to mention that in the tables presented for each region, the climatic anomalies are counted, and the years considered for this measure change slightly for each region, as available data from the IPMA website change from one part to another of the country. Therefore, they are counted setting as anomaly ±1 for the minimum temperature, ±1.5 for maximum temperature and ±15 for precipitation.

5.1 National Data – Overview

The data series related to the continental territory of Portugal were obtained using approximately 50 stations, whose material collected underwent processes of treatment, validation, as well as homogenization, as reported on the IPMA website, and they depict the period of almost a hundred of years from 1931 to 2020. Firstly, considering the temperature information, it is possible to notice that both the minimum and maximum temperature have widely changed over the period considered. More specifically, while the minimum temperature annual average has slightly increased, the interannual variability index shows a high volatility in this measure, supported by a very various annual standard deviation (Graph 1, 2 and 3). However, the maximum temperature follows a more linear trend, as the annual average starts just below 20° and finishes at above 20°, and the interannual variability index clearly rise almost constantly over the years (Graphs 4, 5 and 6). Overall, considering the medium temperature, it is possible to conclude that this variable has slightly increased over the years, as it starts at around 14° in 1931 and in ends at around 16° (Graph 7). This is supported as well by the interannual variability index, which depicts a very strong rising, hence witnessing a change of almost 0.5°, coherently to the conclusion given by the University of Delaware (Graph 8). However, the path is not very linear, as the annual standard deviation demonstrates (Graph 9).

Moving on to considering the moving averages for 10 years, for the minimum temperature it is worthy noticing that from 1931 for almost 20 years it is growing. Then, until the 1970s, it drops to grow again until the end of the century. After this, from 2000 to 2020, it declines again (Graph 10). Contrarily, moving averages for maximum temperatures show a more linear trend, demonstrating that this measure is constantly increasing over the years considered, though descending from the 1940s to the 1970s and then again in the few last years (Graph 11). Overall, by considering medium temperature's moving averages, it is possible to observe that it follows the same path as the minimum temperature for the first years, hence growing in 1930-1950, then dropping until 1970. However, from that moment on it rises until the 1990s to remain steady until the end, when it declines again as the maximum temperature (Graph 12).

Moving on to considering the precipitation, it is worthy to observe that, despite the widely changes in the annual variance, all the other measures delineate a slightly declining tendency, especially considering the annual average (Graphs 13, 14, 15, 16). Conversely to what happens to moving averages for temperature, the ones for precipitations display a clear downward trend, even though this measure increases from 1945 to 1960. Then, as mentioned, it constantly falls over the period (Graph 17).

In conclusion, by considering the annual average temperature and annual total precipitation, it is worth saying that Portugal is getting warmer and drier. This, as already mentioned, is not only supported by the data presented and studied in this paper, but also from other analyses carried on by external sources. While some reasons behind this have already been discussed in previous chapters (GHGs emissions and human-related activities emissions), geographical aspects of this country are considered in the following paragraphs, specifically considering the natural environmental in each region. Additionally, it is also possible to conclude that there are some cyclical patterns, are temperatures seem to rise from 1930 to 1950, then decline and then increase again starting from the 1980s. These trends will also be further discussed and compared to the rest of Europe in the next paragraph. Finally, if one takes into account temperature anomalies compared respectively both to the 1971-1990 and the 1981-2000 averages, as depicted as well as on the IPMA website, the movement is clearly ascending (Graphs 18 and 19). Detailly, most of negative climatic anomalies happen in the first part of the XX century and again during the 1980s. Then, starting from the last decades of 1900, climatic anomalies become higher than the average for the period, pointing out how the last years are anomally warmer. Conversely, for the same two periods, precipitation anomalies illustrate a descending trend (Graphs 20 and 21). This means that in the early years of the periods considered precipitation anomalies mostly positive and higher (hence, it rained more than the average), while in the latter years these same anomalies became mostly negative and lower, concluding that it rained less than the average for the period.

5.2 Portugal’s national data trends compared with the Europe and worldwide patterns

The global mean near-surface temperature from 2013 to 2022 was 1.13 to 1.17°C warmer than the pre-industrial level, marking the warmest decade on record, while European land temperatures increased by 2.04 to 2.10°C during the same period. Despite commitments in the Paris Agreement to limit global temperature increases, projections indicate that the 2°C limit may be surpassed before 2050 without significant reductions in greenhouse gas emissions. Global temperatures have risen steadily since the late 19th century, accelerating since the 1970s at approximately 0.2°C per decade. The past eight years (2015–2022) are the warmest on record. As mentioned in the first part of this paper, anthropogenic activities, particularly greenhouse gas emissions, are the primary cause of this warming. To prevent severe impacts of climate change, the Paris Agreement aims to limit global temperature increases to well below 2°C above pre-industrial levels by 2050, with efforts to limit it to 1.5°C. However, observed warming has already exceeded half of the 2°C increase allowed by the agreement. Moreover, climate models project a temperature increase of 2.1-3.5°C and 3.3-5.7°C by the end of the 21st century. The only scenarios meeting Paris Agreement limits are 1.0–1.8°C and 1.3–2.4°C with drastic emission reductions. Europe is warming faster than the global average, with the last decade's mean annual temperature 2.04 to 2.10°C warmer than the pre-industrial period. Projections suggest continued warming, with temperatures in Europe increasing by 1.2 to 3.4°C and 4.1 to 8.5°C by 2071-2100. The highest warming is expected in north-eastern Europe, northern Scandinavia, and Mediterranean inland areas, while western Europe is projected to experience lower warming. Considering that this is a general overview of the European situation about global warming and bearing in mind Portugal’s changes explained in the previous paragraph, it is now possible to draw a conclusion making a comparison. Even though all European countries are geographically, economically, and socially different among them, hence affecting climate in various ways, they all seem to follow the same pattern as described above. In fact, the rising in temperature in Portugal and in the rest of Europe is very close and similar, meaning that this country’s trends are coherent to what is happening to other parts of the continent.

Moreover, moving on considering cyclical patterns in the rising of temperature at a global level, it is important to acknowledge that, as already discussed, the Earth's climate has been undergoing a warming trend since the Industrial Revolution, primarily attributed to human activities, particularly the release of greenhouse gases. According to NASA's Goddard Institute for Space Studies (GISS), the global average temperature has increased by at least 1.1°C since 1880, with the majority of this warming occurring since 1975 at a rate of approximately 0.15 to 0.20°C per decade. Data analyzed by GISS reflect variations in temperature compared to a base period of 1951-1980, indicating a gradual rise in temperatures, with a notable cooling period from 1880 to 1939, followed by a leveling off in the mid-20th century, attributed to natural variability and aerosol-induced cooling. However, it is also crucial to understand that global warming does not manifest uniformly, with some regions experiencing higher temperature increases than others, as land areas generally warm more than oceans due to thermal inertia, and variations exist within specific land masses and ocean basins. Moreover, while local temperatures fluctuate daily, global temperature changes are crucial as they depend on the balance between incoming solar energy and outgoing heat radiation. Hence, even a one-degree global change signifies a substantial heat increase across oceans, atmosphere, and land masses. Global temperature records dating from 1880 show peaks and valleys, with a consistent warming trend in recent decades. NASA's GISS team selected the baseline period of 1951-1980 for its analysis, aligning with the U.S. National Weather Service's definition of "normal" temperature. The analysis incorporates data from over 20,000 weather stations, sea surface observations, and Antarctic research stations. Overall, understanding global temperature trends is essential in comprehending the impact of climate change. Human activities, notably the release of greenhouse gases, have contributed significantly to the observed warming.

In conclusion, cyclical trends presented in the national analysis about Portugal’s temperatures seem to follow the pattern presented by this comprehensive study from GISS about rising temperature all over the world. These cyclical movements must be considered as well when addressing climate change and global warming, even though they are mostly due to human activities and their GHGs and CO2 emissions.

5.3 Northern region insights

In the northern part of Portugal, the meteorological stations of Bragança, Montalegre, and Porto/Serra Pilar provide insights into the region's Mediterranean climate with continental influences.

Located in Trás-os-Montes, Bragança's weather station, established in 1931 at an elevation of 720m, moved to 710m in 1947 and 690m in 1963. The station incorporates an automatic weather station since 1996 (ID - 575). The rugged terrain, proximity to Spain, and continental influences contribute to temperature extremes and moderate precipitation. Moreover, the Montesinho Natural Park enhances biodiversity in the region. Operating since January 1879, Montalegre's station (ID - 11) moved from Montalegre Castle to its own facilities in 1951. Transitioning to an automatic station in 1999 (ID - 611), it covers the period between 1879 and 2019. In addition, situated near the Serra do Gerês mountain range and national park, Montalegre's mountainous terrain influences local microclimates, impacting biodiversity and weather patterns. In operation since December 1859 (ID - 546), Porto's station moved to the Geophysical Institute in 1888 and became an automatic station in 1998 (ID - 546). Covering the period from 1863 to 2010 (excluding 1921), Porto experiences a maritime climate with Atlantic influences. The city's proximity to the Atlantic Ocean moderates temperatures, resulting in mild winters, cool summers, and evenly distributed rainfall. Also, the Douro River's presence influences local microclimates and contributes to the overall climate character.

In Table 1 the most important results are presented. It is possible to notice that Bragança and Montalegre have a lower minimum temperature (6.76° and 5.43° respectively) than Porto (10.29°). However, by looking at the maximum temperature, it is worth noticing that Porto and Bragança both have an average of 18°, while Montalegre presents a smaller one (almost 15°).

As a result, the average temperature 12.39° for Bragança, 10.00° for Montalegre and 14.62° for Porto. Despite these differences in the averages, the interannual variability indexes for all three stations and both for minimum and maximum temperature are very close to zero. Moving on to climatic anomalies, they are depicted and witnessed in Table 2. As Bragança has less data available in terms of years than the other two regions, the period considered for the anomalies is 1950-1980. Therefore, the period for the other two regions is chosen so that the data are comparable at least in terms of period of time, given that they are numerically different. In fact, for Montalegre the period is 1940-1969 and for Porto it is 1954-1983. Montalegre has the higher amount of anomalies over the years in terms of minimum temperature (40), followed by Porto (38) and then Bragança, which only has 5. For the maximum temperature, they are all very close in number (22, 10 and 15 respectively). Finally, Montalegre has again the biggest number of anomalies regarding precipitation (93), while Porto and Bragança has smaller amounts (77 and 30).

5.3 Centre region insights

The central region of Portugal encompasses a network of climatological stations in Castelo Branco, Coimbra, Lisbon, Penhas Douradas, Pontalegre, and Santarém, each serving as a crucial repository of valuable data contributing to a nuanced comprehension of the region's complex climate dynamics.

Commencing operations in 1915 and evolving into an automatic weather station (ID - 570) since 1996, the Castelo Branco station has traversed various locations, starting from Nuno Alvares High School, then the city's high school, the Industrial and Commercial School, and finally settling at the Coordination Center in May 1985. Hence, the city's altitude fluctuations, proximity to Spain, and urbanization collectively shape its local climate, impacting temperature, precipitation, and the urban heat island effect. Established in 1864 (ID - 549) near the Mondego River, the Coimbra station has been a consistent source of climate data.

Furthermore, the city's elevation, albeit not significant, plays a role in influencing temperature and precipitation patterns. The urban heat island effect is pronounced, and changes in land use, including urban expansion and shifts in agricultural practices, contribute to the city's evolving climate. Operational since 1854 (ID - 546), Lisbon's station has undergone shifts in altitude and position. Nestled along the Tagus River estuary on the western coast of Portugal, Lisbon's climate is characterized by maritime influences. Particularly, the city's diverse topography, encompassing hills and coastal plains, combined with urbanization, contributes significantly to its climate dynamics. Sea level rise is a noteworthy concern, and regional wind patterns play a crucial role in shaping the local climate. Functioning since 1903 and transitioning to an automatic weather station (ID - 568) in 1996, Penhas Douradas, situated in the Serra da Estrela Mountain range, experiences a climate influenced by its higher altitude. Therefore, the mountainous terrain introduces variations in temperature, precipitation, and microclimates, while vegetation types and human activities further impact the local climate. Operating since 1932 (ID - 571) and transformed into an automatic weather station in 1996, Pontalegre, located in the Alentejo region, is characterized by elevation-driven climate patterns. In addition, proximity to water bodies and the types of vegetation in the region adds complexity to its local climate dynamics, contributing to unique variations in temperature and precipitation. The Fonte Boa Weather Station in Santarém (ID - 734), operational since 1955 and transitioning to an automatic weather station in 1996, captures the diverse topography of the town, featuring both flat areas and hills. Situated along the Tagus River, Santarém's climate is shaped by factors such as humidity, temperature moderation, and air quality, with urbanization playing a significant role. Moreover, changes in land use, particularly urban development and alterations in green spaces, introduce complexities to the local climate dynamics.

Climatological data for the central region of Portugal provide a comprehensive understanding of the diverse climate dynamics in the area, presented in Table 3, which reveals significant variations and trends that are crucial for a comprehensive climatic analysis.

Examining the minimum and maximum temperatures reveals intriguing variations across the stations. Castelo Branco registers a relatively mild minimum temperature of 10.60°C, while Penhas Douradas experiences the lowest minimum temperature at 5.44°C. Moreover, the Interannual Variability Indices for both minimum and maximum temperatures consistently exhibit negative values, suggesting a trend towards decreased temperature variability over the specified period. Hence, this may indicate a certain level of climatic stability or predictability in the region. Moreover, Lisbon emerges with the highest average temperature at 16.63°C, while Penhas Douradas records the lowest average temperature at 8.79°C. Average precipitation levels demonstrate substantial variability across the region. Penhas Douradas stands out with the highest recorded precipitation at 162.95 mm. In contrast, Santarém exhibits the lowest average precipitation at 55.35 mm, reflecting a drier climate. Furthermore, the negative Interannual Variability Indices for precipitation imply a decreasing trend in precipitation variability over the specified period, indicating potential shifts in the region's precipitation patterns. The SPI values provide crucial insights into the departure of precipitation from long-term averages. Coimbra's slightly below-average SPI of -0.06 suggests a trend towards drier conditions relative to historical averages. The consistent negative trend in both temperature and precipitation variability indices points towards a certain level of climatic stability or predictability in central Portugal. The decreasing temperature variability implies a gradual homogenization of temperatures across the region, while the reduced precipitation variability suggests a potential shift in precipitation patterns. The climatic anomalies presented for the period between 1950 and 1980 in Castelo Branco, 1956-1995 in Coimbra, 1962-1991 in Lisbon, 1944-1973 in Penhas Douradas, 1950-1980 in Pontalegre, and 1955-1985 in Santarém provide valuable insights into the historical climatic variations within central Portugal. The anomalies are witnessed in Table 4. Castelo Branco experienced a notable anomaly count of 3.00 instances, while Coimbra, with 15.00 instances, exhibits a higher frequency of such anomalies, indicating a greater variability in minimum temperatures over the specified period. Moreover, Lisbon recorded 16.00 instances, while Penhas Douradas, Pontalegre, and Santarém observed 33.00, 11.00, and 8.00 instances, respectively. These anomalies underscore the diverse temperature dynamics across the region. In terms of anomalies in maximum temperatures exceeding ±1.5°C, Castelo Branco recorded 6.00 instances, indicating occasional deviations from the norm. On the contrary, Coimbra displayed a higher count at 33.00 instances, pointing to a notable variability in maximum temperatures over the observed period. Lisbon and Pontalegre had 32.00 and 7.00 instances, respectively, while Penhas Douradas and Santarém recorded 40.00 and 9.00 instances. Therefore, these anomalies highlight substantial fluctuations in maximum temperatures, particularly in Coimbra and Santarém. The anomalies related to precipitation deviations exceeding ±15 mm provide insights into irregularities in rainfall patterns. Castelo Branco, Coimbra, Lisbon, Penhas Douradas, Pontalegre, and Santarém recorded 32.00, 58.00, 54.00, 106.00, 37.00, and 24.00 instances, respectively. Additionally, the higher counts in Coimbra and Penhas Douradas suggest pronounced variability in precipitation levels, indicating a propensity for both dry and wet anomalies over the studied periods.

5.4 Alentejo and Algarve insights

Alentejo’s region includes Beja, Setúbal and Évora meteorological stations, while Algarve includes only Faro one. Beja Station, operational since January 1, 1897, underwent two relocations in 1939 and 1956, settling at an altitude of 246m from 1956 to 2004. Equipped with an automatic weather station (ID: 562) since 1996, the dataset spans 1901-2018. Beja's relatively low altitude contributes to higher temperatures, especially in summer, and its inland location may lead to temperature extremes. Moreover, the station's distance from major water bodies, such as the Atlantic Ocean, influences its climate. Hence, as an inland area, Beja might experience greater susceptibility to temperature variations, particularly during summer months. Setúbal Weather Station, originally at Ameijoa Lighthouse, relocated to Fruticultura Station in 1952 (altitude 14m) and transitioned to an automatic station (ID: 770) in 1996. The dataset covers 1950-2018, showcasing a Mediterranean climate influenced by the Atlantic. In fact, coastal areas typically benefit from the moderating effects of the ocean, experiencing milder temperatures. Setúbal, being in close proximity to Lisbon, is susceptible to climate change impacts, including sea level rise and shifts in precipitation patterns, which could affect local wind patterns and precipitation. Évora Weather Station, operating since December 1869 at the Sertório Tower in the Alentejo region, observed changes in altitude and location but maintained observations at 9 AM and 3 PM initially, adding 9 PM in 1906, and expanding to 6 AM, 12 PM, and 6 PM from 1947 onward. The dataset spans 1871-2008, revealing a Mediterranean climate influenced by the Atlantic. Furthermore, Évora's inland location may make it more susceptible to temperature variations, especially in summer. Climate change may alter precipitation patterns, affecting water availability and impacting agriculture and ecosystems. Thus, , Évora's geophysical features play a crucial role in water management, where changes in precipitation and temperature can significantly affect water resources. Finally, Faro Station, designated Faro/D. Francisco Gomes, began regular operation in May 1884, undergoing multiple relocations and altitude changes until settling at an elevation of 7m in 1980. Equipped with an automatic weather station (ID: 554) from 1996, the dataset spans 1966-2018. Faro's southern coastal location contributes to a Mediterranean climate influenced by the Atlantic. As a result, the station's susceptibility to climate change impacts, such as sea level rise and temperature increases, is heightened due to its coastal setting. These changes could have profound implications for coastal erosion, flooding, and the overall sustainability of coastal infrastructure in the region.

Table 5 presents key climatic parameters for Beja, Setúbal, Évora, and Faro meteorological stations in Portugal. Beja has the lowest minimum temperature (10.56°C), while Faro, influenced by its southern coastal location, has the highest (13.27°C). For maximum temperatures, Beja and Faro have the highest (22.03°C and 22.07°C), reflecting regional differences. Negative indices across all stations indicate consistency, with Faro standing out with the most pronounced negative index, highlighting stability. Moreover, average temperatures are identical for Beja and Setúbal (16.29°C), with Faro having the highest (17.67°C), aligning with its coastal Mediterranean climate. In terms of precipitation, Setúbal records the highest average (60.38 mm), while Faro has the lowest (40.28 mm), indicative of its relatively arid conditions. Furthermore, Setúbal exhibits the highest negative index for precipitation consistency, and Faro has an exceptionally large negative index, indicating substantial variability. Generally low SPI values across stations suggest a tendency towards drier conditions, with Faro standing out with the most negative SPI, emphasizing its susceptibility to arid patterns.

Additionally, Table 6 details climatic anomalies in Beja, Setúbal, Évora, and Faro. Beja records 25 anomalies in minimum temperatures from 1961-1990. Setúbal and Évora register 1 and 13 anomalies, respectively, while Faro, from 1966-1996, has 23 anomalies, indicating significant deviations. For maximum temperatures, Setúbal leads with 19 anomalies (1950-1980), while Beja and Évora report 17 anomalies. Contrarily, Faro shows stability with no anomalies from 1966-1996. Évora has the highest count of precipitation anomalies, recording 37 instances (1962-2008). Setúbal follows closely with 29 anomalies (1950-1980), and Beja reports 25 anomalies (1961-1990), while Faro signals only 20 anomalies (1966-1996).

5.5 Conclusions and limits of the model

In summary, the northern region experiences notable temperature variations, with Montalegre showing higher anomalies, while the central region displays diverse climates, with Coimbra and Penhas Douradas exhibiting significant temperature fluctuations. The southern region (Alentejo/Algarve) demonstrates higher temperatures, with Faro experiencing the most pronounced arid conditions. Furthermore, anomalies in precipitation are more prevalent in the central and northern regions, with Évora and Setúbal exhibiting higher counts. Overall, while all regions exhibit temperature and precipitation anomalies, the central region, particularly Coimbra and Penhas Douradas, stands out with more significant variations. Faro in the Algarve region showcases a consistent negative SPI, indicating a trend towards drier conditions. Finally, the northern, central, and southern regions of Portugal each contribute to the country's diverse climate dynamics. However, the central region exhibits more notable temperature and precipitation variations, while the southern region, represented by Faro, faces a pronounced tendency towards drier conditions.

Moving on to considering the limits of the study presented, it is important to recognize that the described model tries to analyze from a statistical point of view the historical data sets available about all the regions in Portugal. However, it presents some constraints.

The first one worth mentioning is that even if the analysis is carried out in the attempt to be as complete as possible, for some regions there are much more data available than in others. One of reasons behind this could be that some zones are rural or isolated ones, such as Bragança, Castelo Branco, Faro, Pontalegre and Santarém, meaning both that climatological station were instituted after other more important regions and that they are physically less easy to reach out to. Moreover, they are located close to other important parts of Portugal, implying that for some time there was no need to install any station in these same zones. Additionally, this difference in time frames makes it much more complicated to aggregate data at regional and national level.

The second huge drawback for this model is that it does not account for all the different factors that could affect the fluctuations in the indexes calculated, such as pollution, diverse industrialization in the various areas over the country, the cumulative effect of GHGs emissions, changing tides and winds in the oceans, changing Moon phases, and so on. However, as explained in the first chapter of this paper, it is very complex to account for all the variables affecting climate change, even though only considering the GHGs emissions. Finally, generally in models, mistakes can affect decision making, as further discussed in the following paragraph. Specifically, in this case land weather stations change due to location shifts, technology upgrades, and adjustments in observation times. Hence, these movements introduce variations influenced by latitude, elevation, and urbanization. Similarly, equipment upgrades and replacements can alter measurements, with adjustments made for stations deviating significantly from nearby readings.

6. AN ECONOMIC POINT OF VIEW ON THE CLIMATE CHANGE

6.1 Climate Change and Macroeconomics: Impacts, Policies, and Decision Challenges

The international impacts of climate change extend to various economic sectors, including international trade, economic growth, and production allocation. Hence, policymakers in macroeconomics need to delve into the implications, but quantifying the impacts is challenging due to uncertainty, regional variations, and discretionary policy evaluation horizons. These effects, categorized as direct and indirect, encompass disruptions in the natural climate system and efforts to adapt and mitigate by transitioning to a low-carbon economy. While some sectors may see short-term gains, the long-term outlook predicts negative impacts outweighing the positive. Developing countries, particularly in warmer regions, face severe consequences. Additionally, stress test scenarios indicate higher impacts than calculated, underlining potential harm to the economy. Thus, the interconnectedness of sectors poses challenges in assessment, emphasizing the need to consider indirect effects and transmission channels.

When considering possible actions to be undertaken by policy makers, one has to consider that addressing climate change often involves strategies like imposing a price on carbon emissions. This approach encourages economic agents to reduce emissions or shift to low-carbon processes. However, there are other options, which include corrective taxes and tradable emission allowances. The choice between these mechanisms depends on factors such as environmental costs, emission reduction costs, transaction costs, and administrative costs. Moreover, implementing a carbon price, covering a larger proportion of emissions, is crucial for effective public policies. Complementary financial system-related actions, such as improved information disclosure and fiscal interventions, can enhance the overall policy mix. While debates on the superiority of one mechanism persist, the implementation details of both are crucial. In conclusion, a hybrid system, as seen in Europe's Emissions Trading System (ETS) and carbon taxes, can be effective.

Finally, future climate trends are entwined with socio-economic factors, introducing uncertainty and errors in decision-making. Decision-makers grapple with the dynamic nature of decision-making and face challenges in dealing with uncertainties. Therefore, portfolio management, diversifying adaptation strategies, and robust decision-making (RDM) are strategies to mitigate uncertainties. RDM aims to make decisions resilient to climate change uncertainty, even if it comes at the cost of optimality. Moreover, the Paris Agreement reduces some uncertainties, but challenges persist due to multiple pathways. Adapting to climate change requires dynamic strategies, considering adaptive and robust decision-making. Hence, ongoing collaboration and technological progress offer promise, emphasizing the importance of learning from monitoring efforts. In summary, model challenges highlight the need for continuous advancements in understanding and adapting to the complex interplay of climate and its causes.

7. CONCLUSION

Overall, Earth's climate, shaped by natural processes and influenced by human induced GHGs, challenges the planet's energy balance. As presented in the first part, it is possible to say now that global temperature anomalies (1900-2017) indicate a 1°C rise, while Portugal experienced a 0.6°C increase with region-specific precipitation changes. These variations impact regional energy consumption, creating economic disparities. Thus, comprehending historical climate trends is crucial for anticipating future impacts, emphasizing the dynamic link between climate change, energy use, and economic outcomes.

Then, considering Portugal's climate evolution using IPMA data, it is crucial to conclude that the data, spanning nearly a century from 1931 to 2020, depict a notable increase in both minimum and maximum temperatures, with high volatility in the former and a more linear trend in the latter. Despite variations in precipitation variance, there is a general decline. Temperature anomalies, compared to 1971-1990 and 1981-2000 averages, show an upward trend, while precipitation anomalies exhibit a downward trend. Generally, Portugal is undergoing a shift towards increased warmth and reduced precipitation.

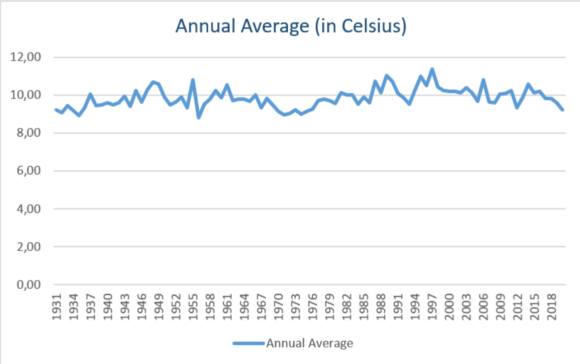
Furthermore, as already discussed in the last chapter, climate change significantly impacts various economic aspects, including trade, growth, and production. Estimating these effects is complex due to uncertainties and nonlinear effects. Hence, understanding interconnected sectors beyond GDP is crucial, considering factors like price volatility, trade flows, infrastructure, asset obsolescence, and migration effects.

Finally, mitigation strategies involve carbon pricing and financial system interventions, aiming for a comprehensive and coordinated approach. Moreover, this multifaceted strategy recognizes the financial system's role, addresses market failures, and seeks to improve information disclosure for effective climate change action.

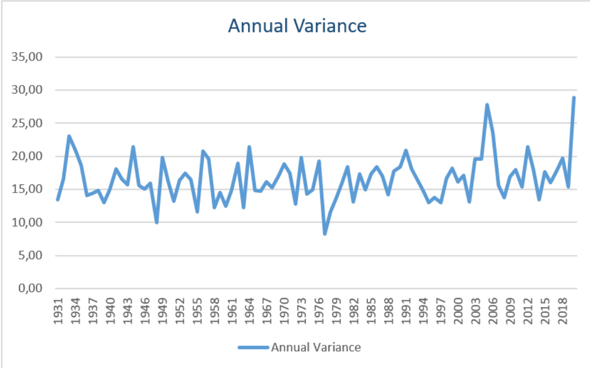
8. APPENDIX

NATIONAL DATA

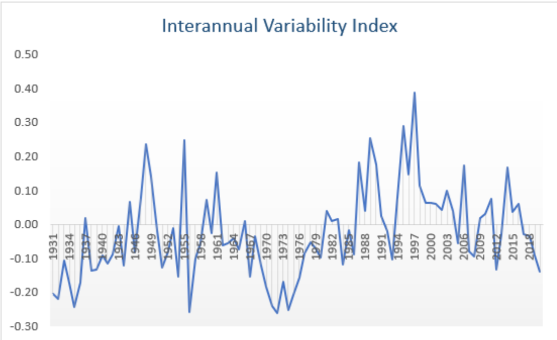
Graph 1



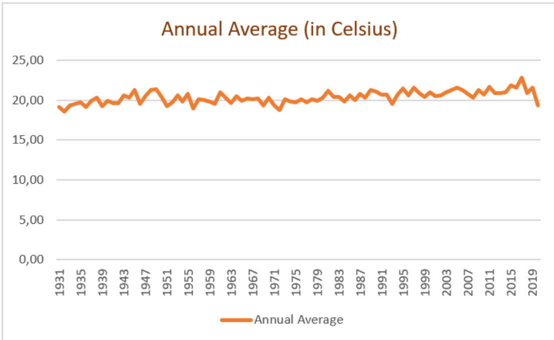
Graph 2



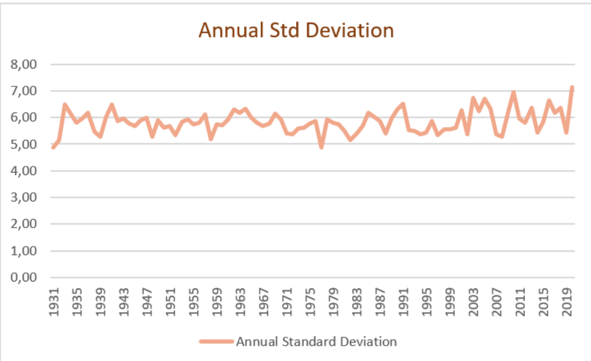
Graph 3



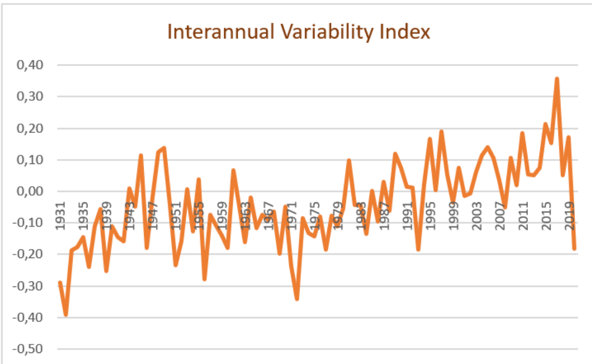
Graph 4



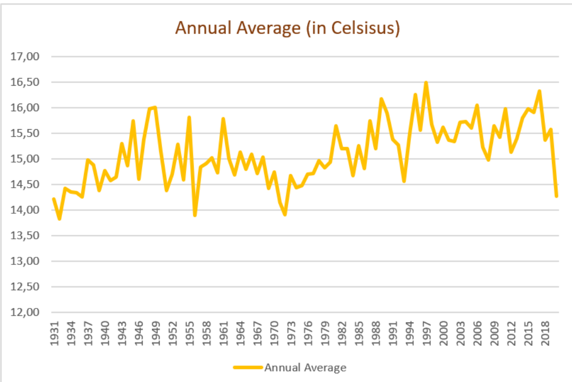
Graph 5



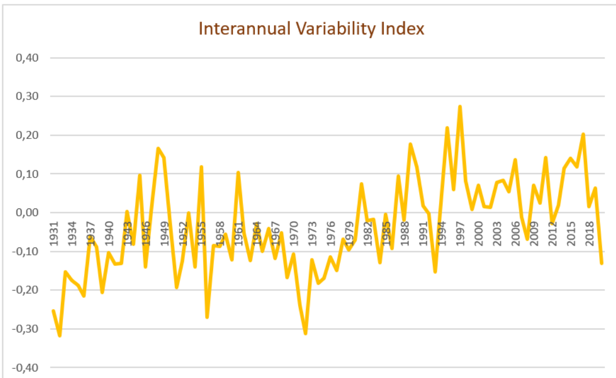
Graph 6



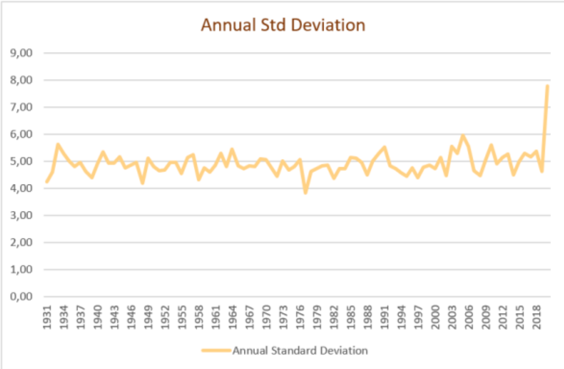
Graph 7



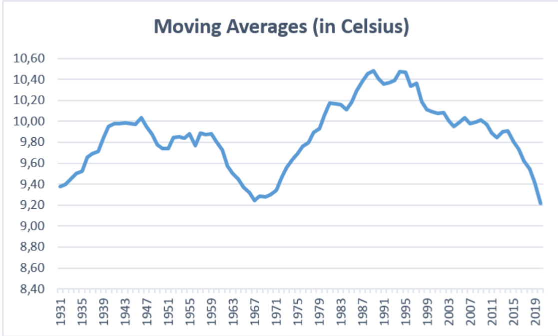
Graph 8



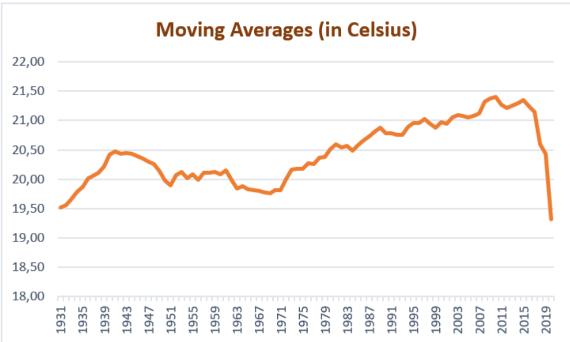
Graph 9



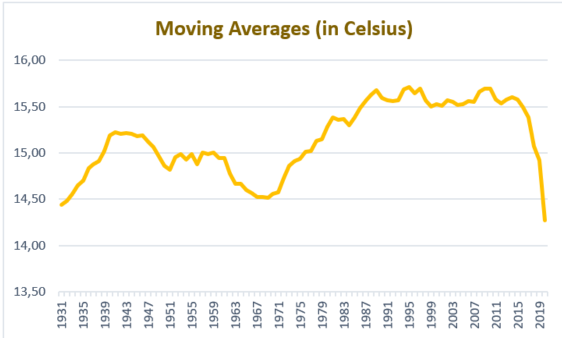
Graph 10



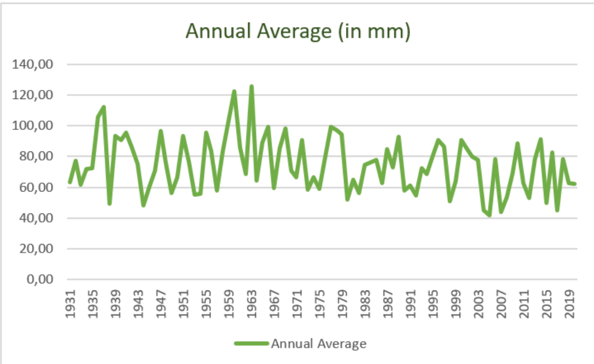
Graph 11



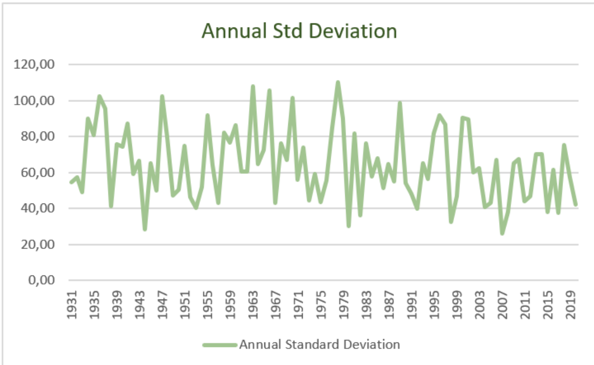
Graph 12



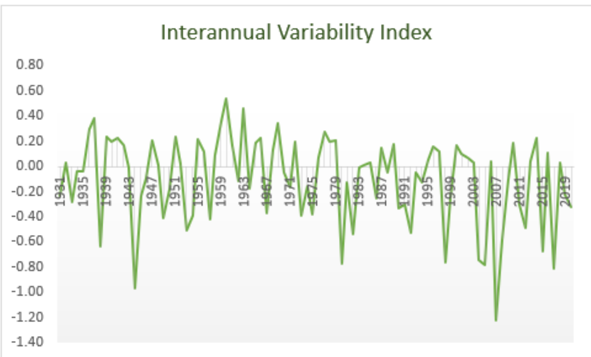
Graph 13



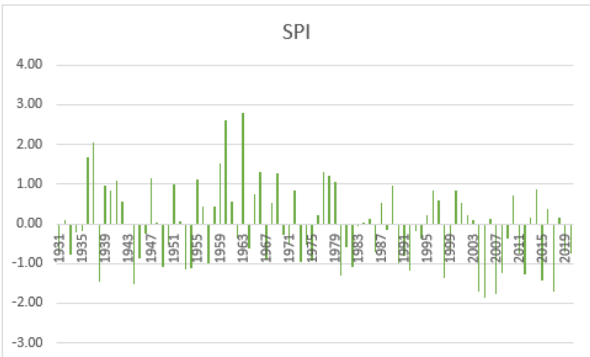
Graph 14



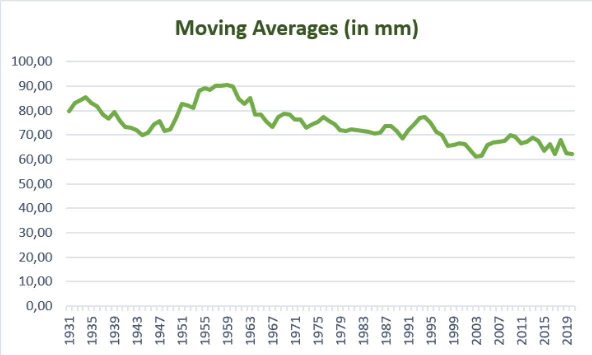
Graph 15



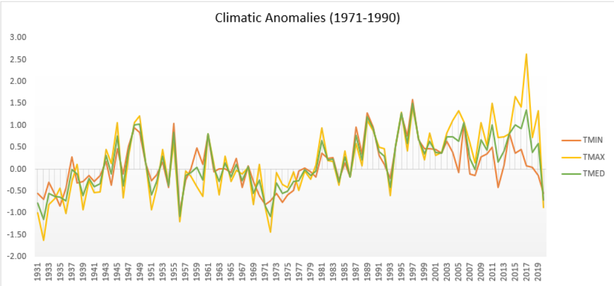
Graph 16



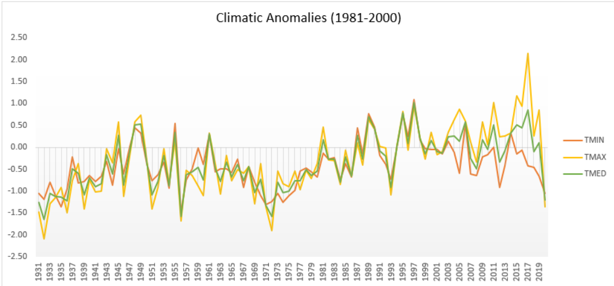
Graph 17



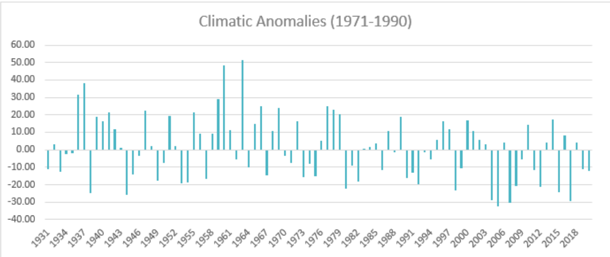
Graph 18



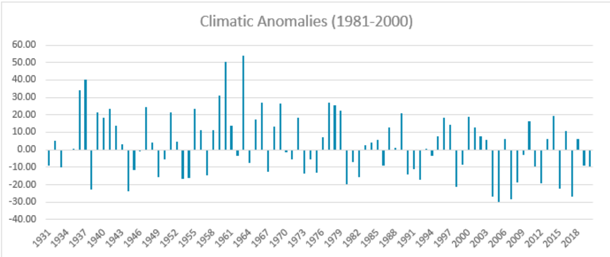
Graph 19



Graph 20



Graph 21



REGIONAL INSIGHTS

Table 1

INDEX - averages	BRAGANÇA	MONTALEGRE	PORTO
Minimum temperature	6.76	5.42	10.29
Interannual Variability Index - min. tempterature	-0.02	-0.01	0.00
Maximum temperature	18.01	14.58	18.95
Interannual Variability Index - max. tempterature	-0.04	-0.02	0.00
Average temperature	12.39	10.00	14.62
Average precipitation	62.94	106.39	103.25
Interannual Variability Index - precipitation	-0.11	-0.14	-0.09
SPI	0.01	-0.02	-0.03

Table 2

CLIMATIC ANOMALIES	BRAGANÇA (1950-1980)	MONTALEGRE (1940-1969)	PORTO (1954-1953)
Minimum temperature (>± 1)	5.00	40.00	38.00
Maximum temperature (>± 1.5)	15.00	22.00	10.00
Precipitation (>± 15)	30.00	93.00	77.00

Table 3

INDEX - averages	CASTELO BRANCO	COIMBRA	LISBOA	PENHAS DOURADAS	PONTALEGRE	SANTARÉM
Minimum temperature	10.60	10.50	12.84	5.44	10.95	10.94
Interannual Variability Index - min. tempterature	-0.03	-0.02	-0.02	-0.01	-0.04	-0.04
Maximum temperature	21.09	20.55	20.41	12.14	20.03	22.32
Interannual Variability Index - max. tempterature	-0.04	-0.03	-0.03	-0.02	-0.05	-0.07
Average temperature	15.85	15.53	16.63	8.79	15.49	16.63
Average precipitation	65.33	79.68	62.09	162.95	73.03	55.35
Interannual Variability Index - precipitation	-0.11	-0.08	-0.09	-0.15	-0.09	-0.11
SPI	0.00	-0.06	-0.03	-0.02	-0.06	-0.06

Table 4

CLIMATIC ANOMALIES	CASTELO BRANCO (1950-1980)	COIMBRA (1956-1995)	LISBOA (1962-1991)	PENHAS DOURADAS (1944-1973)	PONTALEGRE (1950-1980)	SANTARÉM (1955-1985)
Minimum temperature (>± 1)	3.00	15.00	16.00	33.00	11.00	8.00
Maximum temperature (>± 1.5)	6.00	33.00	32.00	40.00	7.00	9.00
Precipitation (>± 15)	32.00	58.00	54.00	106.00	37.00	24.00

Table 5

INDEX - averages	BEJA	SETÚBAL	ÉVORA	FARO
Minimum temperature	10.56	10.73	10.80	13.27
Interannual Variability Index - min. tempterature	-0.02	-0.03	-0.01	-0.20
Maximum temperature	22.03	21.84	20.32	22.07
Interannual Variability Index - max. tempterature	-0.03	-0.07	-0.02	-0.21
Average temperature	16.29	16.29	15.56	17.67
Average precipitation	46.84	60.38	52.02	40.28
Interannual Variability Index - precipitation	-0.07	-0.12	-0.01	-20.56
SPI	-0.03	-0.05	-0.03	-0.05

Table 6

CLIMATIC ANOMALIES	BEJA (1961-1990)	SETÚBAL (1950-1980)	ÉVORA (1962-2008)	FARO (1966-1996)
Minimum temperature (>± 1)	25.00	1.00	13.00	23.00
Maximum temperature (>± 1.5)	17.00	19.00	17.00	0.00
Precipitation (>± 15)	25.00	29.00	37.00	20.00

FORMULAS

$$Average = \frac{\sum(average\ for\ the\ years\ considered)}{number\ of\ years\ considered}$$

$$Interannual\ Variability\ Index = \frac{annual\ average - total\ long\ term\ average}{annual\ standard\ deviation}$$

$$Annual\ Std\ Deviation = \sqrt[2]{variance}$$

$$Variance = \frac{\sum(x_i - \bar{x})^2}{n-1}$$

where:

x_i: value of a single observation

$\bar{x}$: mean value of all observations

n: number of observations

$$Standardized\ Precipitation\ Index = \frac{annual\ cumulative\ precipitation - annual\ average}{cumulative\ standard\ deviation}$$

$$Simple\ Moving\ Average = \frac{Sum\ of\ values\ over\ a\ specified\ period\ of\ time}{number\ of\ data\ points\ in\ that\ period}$$

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