Environmental Management (2020) 66:395–406
https://doi.org/10.1007/s00267-020-01313-5

Climate-Change Adaptation Framework for Multiple Urban Areas in Northern Portugal

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Received: 19 December 2019 / Accepted: 2 June 2020 / Published online: 12 June 2020

Abstract

Climate change is increasingly exerting pressure with intensified impacts in the short-, medium-, and long-term. Cities are highly vulnerable to the impacts of climate change, and it is recognized that they play a significant role in the European Strategy on adaptation to climate change. This study intends to develop a climate adaptation framework to identify effective measures that will be evaluated using a multi-urban area located in the north of Portugal, as a case study. The climate adaptation framework was developed following the Urban Adaptation Support Tool (AST), adapted to the Portuguese reality. The Weather Research and Forecasting (WRF) model was used to provide future projections with a high level of spatial resolution over the study area, increasing the accuracy of the identification of future climatic vulnerabilities. The results show a tendency for an increase of extreme weather events associated with the increase of both temperature and annual accumulated precipitation variables. A set of both urban and rural measures to promote a sustainable development path to climate adaptability and increase cities resilience to climate change are presented and discussed.

Keywords Adaptation · Climate change · Local strategies · Numerical modeling · Urban areas

Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is referred to city regions as the main areas that must respond to climate-change risks. In fact, climate-change research on urban scales has become recently an important and urgent topic (Jiang et al. 2017). These urban areas, where half the world's population lives, within complex interdependent systems, are a major challenge for climate-change adaptation planning (Revi et al. 2014). The complexity is due to the interactions between social, economic, and environmental stressors (Radhakrishnan et al. 2017, 2018). The current frameworks on risk assessment and adaptation call for accounting of all significant natural and anthropogenic drivers in adaptation related to decision-making (IPCC 2014) with the aim to improve the long-term resilience of cities against climate change. This adaptation should take into account: (i) the complexity of adapting urban systems to climate change; (ii) the need to consider multiple drivers, especially socio-economic; and (iii) uncertainties associated with the drivers (Dittrich et al. 2016; Maier et al. 2016).

The interaction between climate change and the urban environment is widely recognized (Gill et al. 2007; Toly 2008; Dugord et al. 2014; Kim and Ryu 2015). Different patterns of settlement, spatial configuration of cities, land-use allocation, lifestyle, and consumption behaviors, all influence the combined effect of climate change. All these factors result in the climate modifications that have been observed in urban areas (Davoudi et al. 2009; Yiannakou and Salata 2017). Because of that, urban areas are considered to hold the highest potential, both for adaptation to a changing climate and for sustainable development (Bai et al. 2010; Yiannakou and Salata 2017).

The international literature has been demonstrating for a long period the importance of cities in coping with climate change (Betsill 2001; Lindseth 2004; Grimm et al. 2008). A series of issues have been raised by the rapid development

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of urbanization, such as the large volumes of greenhouse gas emissions from urban systems, the sprawling layout of urban spaces, and the disordered use of land, which demonstrate the urgency of urban systems to respond to the major challenges of climate change (Pacala and Socolow 2004).

Expertise on climate change, socio-economic drivers, and integrated assessment modeling for assessing impacts and vulnerability is becoming increasingly sophisticated (O'Neill et al. 2014). However, at the municipality level there is a lack of enabling conditions and frameworks to support the timely evaluation of emerging urban adaptation measures that operate across a range of scales, timelines, and how these are rooted in local contexts (Revi et al. 2014).

Not surprisingly, in response to these threats, there is now a considerable climate-change adaptation effort in many cities around the world, with the aim to maintain or even to improve the level of comfort (Wardekker et al. 2010; Kunapo et al. 2018). Societies, organizations, and individuals have adjusted their behavior in response to past climate change, and many are now considering adapting to altered future climatic conditions. Much of this adaptation is reactive, in the sense that it is triggered by past or current events, but it is also anticipatory in the sense that it is based on some assessment of conditions in the future (Neil Adger et al. 2005).

Adaptations may include a range of both gray and green infrastructure, such as drainage system upgrades to reduce flooding, creation of stormwater control measures (e.g., infiltration-based systems), stormwater harvesting and water recycling, landscape irrigation, or enhancement of vegetation. The factors determining an urban area's potential for sustainable development and resilience promotion coincide with the factors influencing its capacity to adapt to climate change (Bulkeley and Betsill 2003; IPCC 2007). One of the best planning tools for both adaptation to and mitigation of climate change is green infrastructure, which is based on an ecosystem approach.

Datasets and models which assess the vulnerability to climate change, have been developed for a number of cities around the world, particularly in relation to flooding and water resources (Sanchez-Rodriguez 2009). International governments have been recognizing climate change as a key environmental problem that crosses local to global scale and, as result, has actively promoted the development of city action plans for climate-change adaptation and mitigation. At European level, the European Strategy on adaptation to climate change has recognized that cities and towns play a significant role in adaptation to climate change in Europe. As a result, the Urban Adaptation Support Tool (Urban AST) was developed as a practical step-by-step guidance tool to assist signatories of the Mayors Adapt initiative in planning and taking adaptation action (Climate-ADAPT 2016a; Coelho et al. 2018). The Urban AST highlights the main issues to be considered when planning and implementing adaptation measures and, for this reason, it is an important tool to assist local authorities in this relatively new area of activity. The several steps of the tool help to prepare the ground for adaptation, assess climate-change risks and vulnerabilities to current and future climate hazards, identify and assess adaptation options, develop and implement a climate-change adaptation strategy, and monitor the results of adaptation action (Climate-ADAPT 2016a).

In the light of the above, the main aim of this paper is the development of a climate adaptation framework, identifying potential effective measures, for a specific multi-urban area located in the north of Portugal. The climate adaptation framework was developed following the Urban AST, adapted to the Portuguese reality, which brings together the scientific community with the key actors (city council, firefighters, civil protection, and environmental agency). The climate adaptation framework created by this study, if used appropriately by the local key actors, has the potential to increase the local adaptative capacity and lessen the sensitivity of society, reducing its vulnerability to climate-change effects.

Case Study Characterization

The development of an adaptation plan to climate-change effects requires a detailed characterization of each area.

The case study is a multi-urban area located in the Northeast region of Portugal, integrated in the administrative unit called Terras de Trás-os-Montes (TTM), covering a total area of ~5544 km^2 (Fig. 1). Due to its orography with deep valleys and highlands, this subregion is divided into two distinct territories with distinct microclimates: Terra Quente Transmontana (TQT) (which includes four municipalities, covering an area of 1946 km^2) and Terra Fria Transmontana (TFT) (which includes five municipalities, covering an area of 3598 km^2).

Regarding its demography, the TTM region accounts for 117,527 inhabitants (PORDATA 2011) (around 1% of the national population), corresponding to a population density of 19.9 inhabitants/km^2 (considerably lower than the national level [114.5 inhabitants/km^2]). The urban fabric is restricted to the Bragança municipality (TFT) with 35,341 inhabitants. The TTM is one of the regions with a higher index of elderly people (260.4 per 100 young people); this age population group is highly vulnerable to changes in meteorological conditions, and so, to the impacts of climate change.

According to the Portuguese Institute for Sea and Atmosphere (IPMA 2013), TTM is under a general westerly influence, which is characterized by the frequent unstable

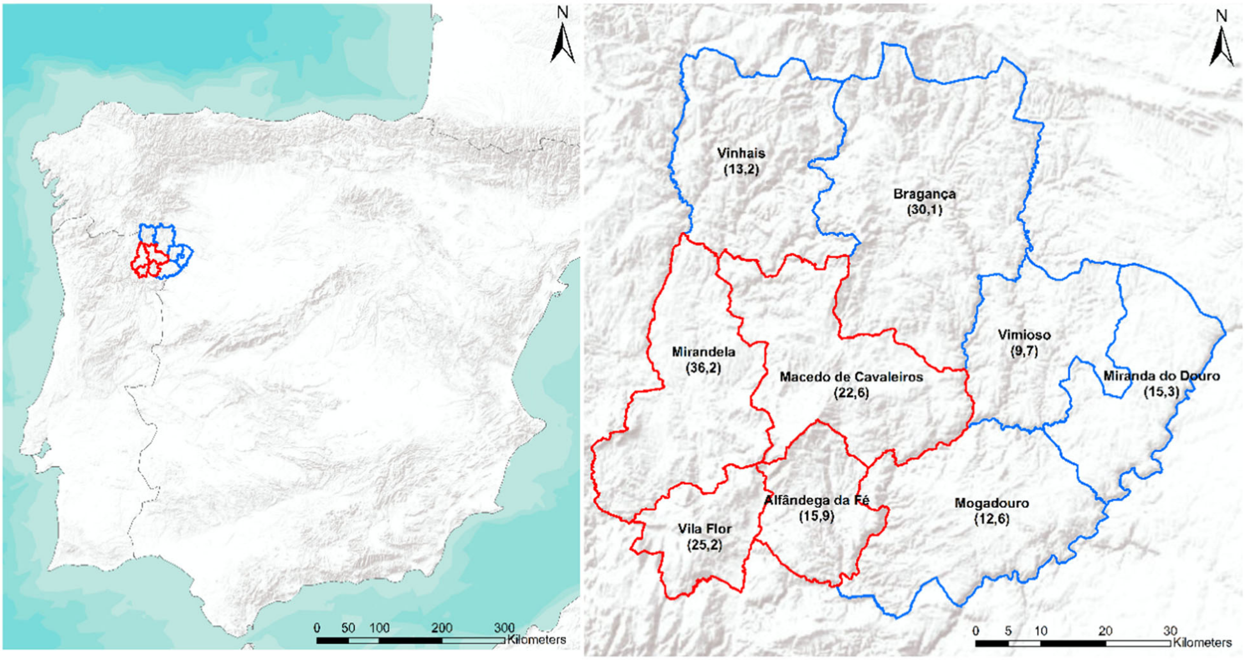


Fig. 1 Geographic location of TQT (red) and TFT (blue) and name and population density, in inhabitants/km^2, of each municipality

conditions caused either by the polar front oscillation or by subtropical anticyclones (the Azores anticyclone). The region's latitudinal location favors the influence of the polar front oscillations, typically in the cold season, when most of the yearly precipitation occurs (around 60% of the annual total). In the summer, the polar front retreats to the higher latitudes, leaving this region under the influence of subtropical anticyclones, resulting in very scarce precipitation in this season. According to the Koppen classification, the climate of this region is temperate with warm, dry summers and mild, rainy winters. The criteria devised to differentiate between the two climatic types, TFT and TQT, are the mean annual temperature thresholds. TFT is characterized by a climate of extremes: a very cold winter—usually with air temperatures between 11 and −1 °C and a hot and dry summer, in average between 29.1 and 14 °C. TFT presents an average value of annual precipitation of 800 mm, with an altitude ranging between 400 and 1000 m. The TQT is characterized by an average annual temperature of 15 °C and an annual precipitation between 400 and 600 mm, with an altitude ranging between 350 and 400 m. The frost-free period in this region is longer than the observed at TFT, which starts at the beginning of April until the middle of November.

Despite the different Koppen classification, both TQT and TFT are exposed to the same extreme climate events. In recent years, the most frequent extreme climate events recorded in TQT and TFT were the following: (i) extreme precipitation; (ii) heat wave; (iii) drought; (iv) snowfall; (v) cold wave; (vi) frost; (vii) fog; and (viii) thunderstorm.

The identification of these events was based on the analysis of the monthly climatological bulletins of the Portuguese Institute for Sea and Atmosphere, from January 2007 to December 2016. These bulletins present the summary of the air temperature and precipitation recorded in the Portuguese territory, as well as description, where relevant, of extreme climate events, such as heat waves, thunderstorms, and strong winds among others.

For each extreme climate event recorded in TQT and TFT, different types of impacts/consequences were registered. The main impacts related to these events, with observed impacts/consequences in the study regions are presented in Table 1.

These impacts were identified based on evidence and robust information collected through national databases, such as the District Command for Relief Operations (ProCiv 2019), the Institute for Nature Conservation and Forestry (ICNF 2017), and the Regional Directorate for Agriculture (DRAPN 2019). In addition, interviews, workshops, and round tables were conducted with several key actors, such as city council, firefighters, civil protection, and environmental agency, with the aim of discussing climate-change issues, with emphasis on the identification of current vulnerabilities of the territory.

Evaluation of Future Climate

The development of a robust climate adaptation strategy at local level is highly dependent on the evaluation of how the

Table 1 Main impacts related to extreme climate events, with consequences observed in TQT and TFT

Climate event	Observed impact
Extreme precipitation	• Damage to agricultural production chains • Material damages (e.g., buildings and vehicles) • Road closure • Floods
Heat wave	• Damage to agriculture and livestock production chains • Ecosystems change • Wildfires • Lifestyles changes
Drought	• Restrictions and/or interruptions in water supply • Damage to agriculture and livestock production chains • Wildfires • Ecosystems change
Snowfall	• Road closure • Services closure • Increased road accidents • Damage to human health • Lifestyles change • Materials damage
Cold wave	• Lifestyles change
Frost	• Damage to agricultural production chains
Fog	• Changes in the operation of infrastructure (e.g., total or partial airfield closure)
Thunderstorm	• Damage to agriculture and livestock production chains

climate is expected to change in a particularly urban area or region (and its related impacts) and, consequently, on the identification of the risks that those changes will pose. In this section, the methodology followed to assess the future changes in climate of TFT and TQT is presented (“Model Setup for Climate Change Projections”), as well as its results (“Climate Analysis”).

Model Setup for Climate Change Projections

To evaluate the climate-change impacts on the study area, the Weather Research and Forecasting (WRF) (Skamarock et al. 2008) model, forced by the Max Planck Institute Earth System Model (MPI-ESM-LR) (Giorgetta et al. 2013), with the horizontal resolution of 1.9°, was applied. The global climate model chosen was the MPI-ESM-LR since it is considered one of the best models to simulate the climate of Europe (Brands et al. 2013).

Four online-nested domains with increasing resolution at a downscaling ratio of three were used, with the coarser domain of 27 km horizontal resolution covering part of Europe and part of the North Atlantic Ocean, and the innermost domain of 1 km horizontal resolution focusing on a confined area, which comprises the North Portugal (Fig. 2).

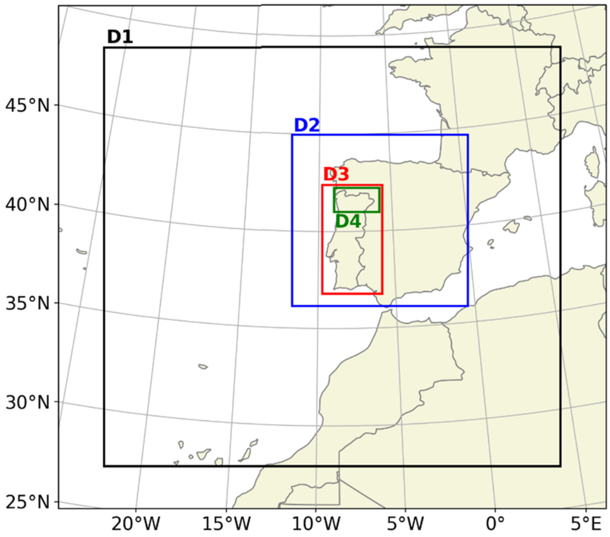


Fig. 2 Model domains implementation using two-way nesting mode with 27 [D1], 9 [D2], 3 [D3], and 1 [D4] km resolutions

To improve WRF-BEM performance, detailed topography and land-use/cover data was taken from the Coordination of Information on the Environment Land Cover (EEA 2007). This has been recategorized to be compatible with the model processes into the 24 classes of the United States Geological Survey dataset.

The WRF lateral boundary conditions were provided to the model at 6-h intervals. The model physical configuration was selected based on previous sensibility tests (by comparing the model outputs against observations) conducted for the Iberian Peninsula and for mainland Portugal (Ferreira 2007; Rafael et al. 2017). The following set of parameterizations were used in the analysis: WRF Single-Moment 5-Class Microphysical Scheme (Hong et al. 2004); Dudhia Shortwave Radiation scheme (Dudhia 1989); Rapid Radiative Transfer Model Longwave Radiation model (Mlawer et al. 1997); MM5 Similarity Surface Layer scheme (Zhang and Anthes 1982); Unified Noah Land Surface Model (Tewari et al. 2004); Yonsei University Planetary Boundary Layer scheme (Hong et al. 2006) and Grell 3D Ensemble Scheme for cumulus parametrization (Grell and Dévényi 2002).

Two time periods were considered, which are statistically representative of each period of 20 years, one representative of the medium-term future climate scenario (2041–2070) and another representative of the recent past climate (1976–2005), used as a reference scenario. This means that the simulated years represent the historical and future climate change in daily temperature and precipitation extremes, detected through a set of indices proposed by the Expert Team on Climate Change Detection and Indices

(Rafael et al. 2017). A more detailed description of these indices can be found in Bartolomeu et al. (2016) and Fonseca et al. (2016).

For the future simulations, the Representative Concentration Pathway Scenario RCP8.5 has been adopted (Riahi et al. 2007). RCP8.5 was developed using the IIASA Integrated Assessment Modeling Framework, that encompasses detailed representations of the main emitting sectors of greenhouse gases (energy, industry, agriculture, and forestry), and the MESSAGE model (Riahi et al. 2011). The greenhouse gas emissions and concentrations in this scenario increase considerably over time, leading to a radiative forcing of 8.5 W m^{-2} at the end of the century (IPCC 2013). This scenario is considered by the scientific community to reflect the worst set of expectations with the most onerous impacts (Rafael et al. 2017).

For the climate-change assessment, the following variables were considered: maximum (Tx), average (Ta), and minimum (Tn) daily temperature and daily accumulated precipitation (Pr). For these variables, some extreme index were estimated, according to the World Meteorological Organization (Klein Tank et al. 2009), namely:

- Number of tropical nights ($Tn \geq 20$ °C) per year;
- Number of summer days ($Tx \geq 25$ °C) per year;
- Number of frost days ($Tn \leq 0$ °C) per year;
- Number of rainy days ($Pr \geq 1$ mm) per year;
- Number of very-intense rainy days ($Pr \geq 20$ mm) per year.

Climate change was assessed by comparing the results obtained for the medium-term future climate with the results for the reference climate. The comparison was made for each season: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February).

Climate Analysis

Annual and seasonal results for the temperature and precipitation variables, as well as the associated extreme indices defined above, are presented in this section.

Temperature

The differences between the medium-term future climate and the reference climate (anomalies) for the annual averages of Tx, Ta, and Tn, show an increase in temperatures between 1.5 and 2 °C, relative to the reference, with a uniform spatial distribution throughout the study region. These anomalies, when analyzed seasonally, present different variations, with the highest anomalies of Tx, Ta, and Tn projected for the autumn, where the Tx can increase by 4.5 °C. However, in winter no significant anomalies are projected. Moreover, no negative anomalies of Tx, Ta, and Tn are projected for any of the seasons.

The extreme events, for the summer, associated to the increase in Tx (summer days) and Tn (tropical nights), are presented in Fig. 3. The anomaly of summer days varies between 15 and 40 days per year and are projected for the higher and lower altitude areas, respectively. These anomalies are expected mainly in summer and autumn. For the number of tropical nights, an increase of up to 30 days per year is expected.

Figure 4 shows the anomalies of frost days, for autumn, winter, and spring seasons. A decrease in the number of frost days of up to 12 days per year is expected for autumn and spring in the higher altitude areas, due to the increase in

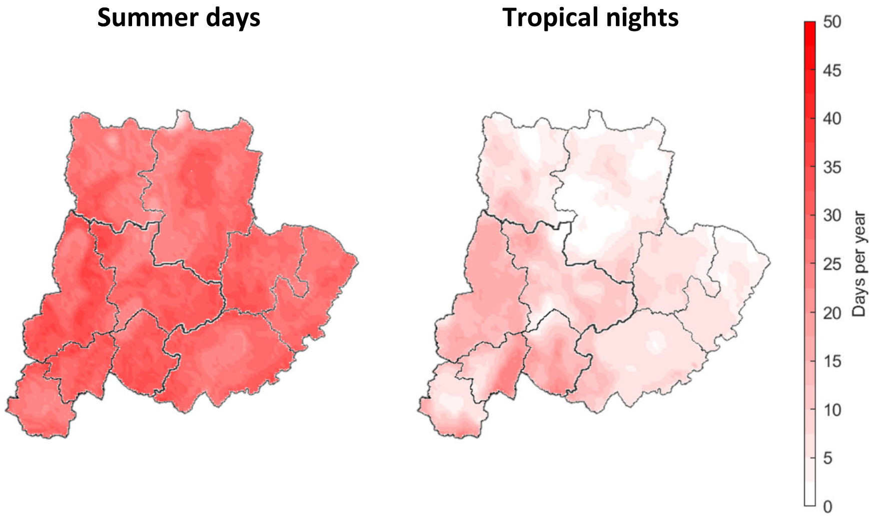


Fig. 3 Anomalies, in number of days per year, of summer days and tropical nights, for summer season

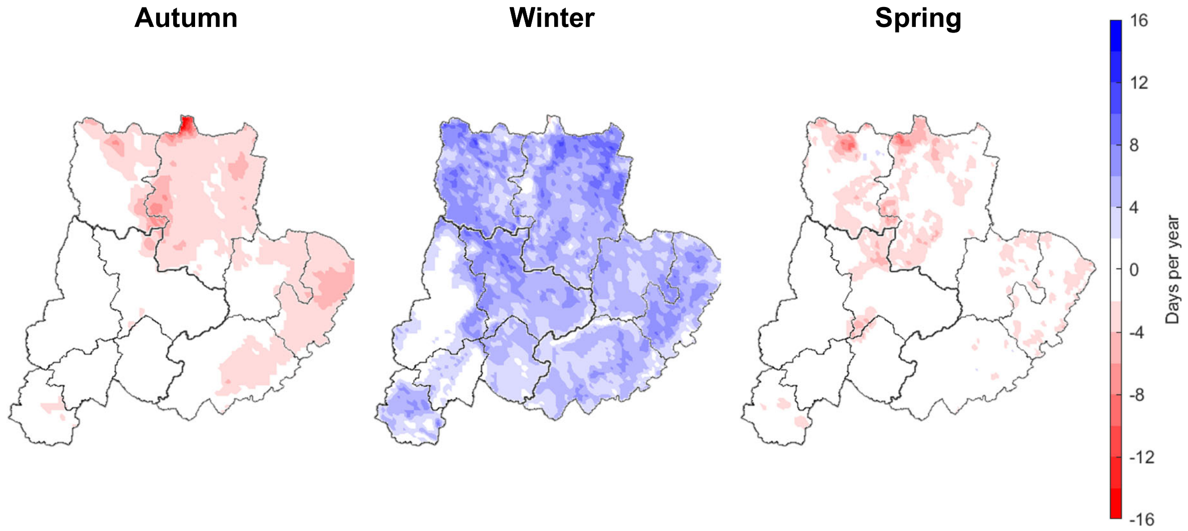
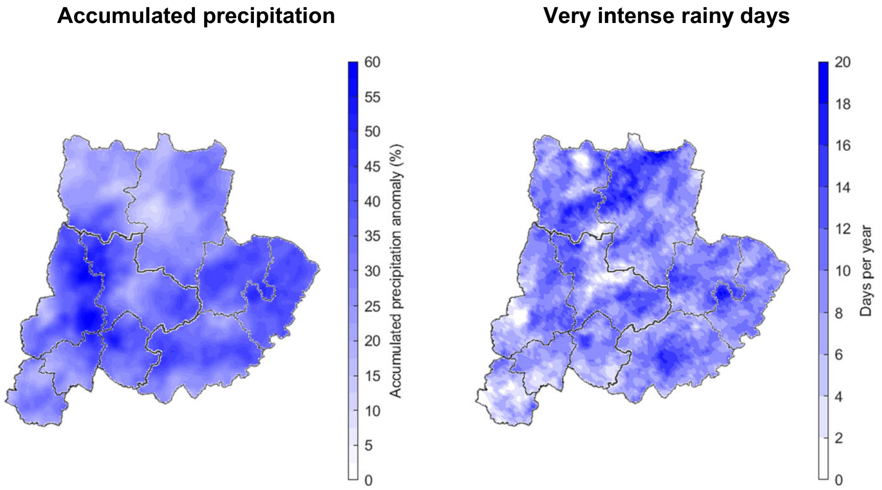


Fig. 4 Anomalies, in number of days per year, of frost days, for autumn, winter, and spring

Fig. 5 Annual accumulated precipitation anomalies (%) and number of very-intense rainy days



Tn. In winter, the number of days of frost tends to increase, up to 12 days a year, in almost all the study region.

Precipitation

The anomalies of the annual accumulated precipitation and the number of very-intense rainy days are presented in Fig. 5. In both cases, an increase of precipitation of up to 50% in some areas of the region is predicted. This increase may be justified by the increase in the amount of water vapor in the atmosphere associated with an increase in the evapotranspiration process as a result of the increase in temperature. The extreme index, associated with extreme precipitation events, points to an increase of up to 20 days of very-intense rain per year. However, it should be noted that for precipitation the uncertainty of the future climate is substantially higher than that for the temperature (Marta-Almeida et al. 2015; Bartolomeu et al. 2016).

Climate-Change Adaptation

Based on previous sections, a comprehensive picture of current and future climate-change risks is presented and discussed in "Climate Risk Assessment." As recognized by the Urban AST (Climate-ADAPT 2016a), adaptation cannot be planned based on climate projections alone; information on risk and vulnerabilities is also needed to determine how the climate interacts with socio-economic issues. Quantifying the risk will help to identify opportunities arising from climate change, and provide information to select the most suitable adaptation options for its specific region ("Identification of Adaptation Measures")

Climate Risk Assessment

The climatic risk assessment was developed for the climatic events presented in "Case Study Characterization" and

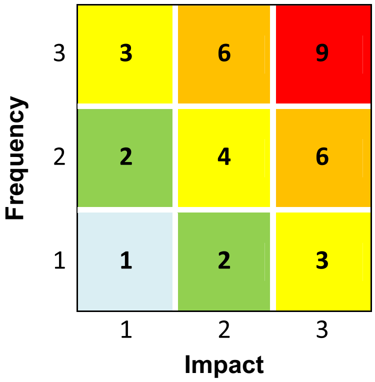


Fig. 6 Climate risk assessment matrix

Table 2 Classification of the frequency and the impacts, for each climate event, for present and medium-term future

Climate event	Present		Medium-term future	
	Frequency	Impact	Frequency	Impact
Temperature increase (T)	1	1	3	2
Heat wave (H)	1	2	2	3
Extreme precipitation (P)	1	2	3	3
Drought (D)	1	2	2	3
Cold (C)	2	2	1	2
Fog (F)	1	1	1	1

"Evaluation of Future Climate." The climatic events of snowfall, cold wave, and frost, being the ones that register less frequency of occurrence, were grouped in a single event: cold.

The level of risk is determined based on a matrix of intersection between the frequency of the climate event and the impact of the event. The frequency of the climate event is classified as:

(1) Average: may occur every 5 years;
(2) High: may occur from 2 to 5 years;
(3) Very high: likely to occur at least every 2 years.

Regarding to the classification of the impacts of climate events, there was a subdivision into three classes:

(1) Slightly severe: liable to cause damage to infrastructures; it is possible to revert quickly and at low costs to the original situation;
(2) Severe: may cause localized accidents; reparation requires investments at the municipal level;
(3) Very severe: likely to cause large-scale accidents; reparation requires the intervention of the central administration.

Climate risk is determined by multiplying the frequency and impact classifications of the climate event, and can be represented in the climate risk assessment matrix according to Fig. 6. In this matrix, in the lower-left quadrant are the events of lower risk and of low priority while in the opposite quadrant are located the events of greater risk and, consequently, high priority.

To define the frequency classification, for the present, for each one of the climate events, the databases referred in "Case Study Characterization" have been used. For the medium-term future, the classification of the frequency was elaborated based on the climate projections described in "Evaluation of Future Climate." For the classification of the impacts caused by each one of the climate events, once again, the "Case Study Characterization" database, was used, together with the knowledge of stakeholders, decision-makers, and relevant entities of the region, for present and medium-term future scenarios. Table 2 shows the classification of the frequency and the impacts, for each climate event, for present and medium-term future.

From the analysis of Table 2, it can be concluded that the climatic events that present a greater climate risk, after the priority ones, are those related to the temperature increase (T), heat waves (H), extreme precipitation (P), and drought (D). For these events, it is considered that there will be a worsening of both frequency and impacts. The climate risk associated with the fog event remains the same. Concerning the cold episodes, in the medium-term future, it is likely to decrease. The climate risk matrices, resulting from the Table 2 classifications, for the present and medium-term future, are presented in Fig. 7.

The comparison of Fig. 7 shows a worsening of the potential climatic risks with the occurrence of an event (extreme precipitation) in the maximum level of risk (red) and three events (temperature increase, heat waves, and drought) in the second highest level of risk (orange). Considering all the climatic events and consequent impacts, with a level of risk higher than 4, as a prioritization criterion, there is an increase from 2 to 4 events that deserve greater attention. This risk assessment suggests that there is a need to adapt to the events with major risks projected in the future, namely: (i) extreme precipitation; (ii) temperature increase; (iii) heat waves; and (iv) drought.

For these events, it is essential to evaluate current measures and to identify, if necessary, new adaptation options to be evaluated and prioritized.

Identification of Adaptation Measures

This section aims to identify and characterize options for adaptation to the climate vulnerabilities previously identified, in order to serve as a basis for a precise and objective

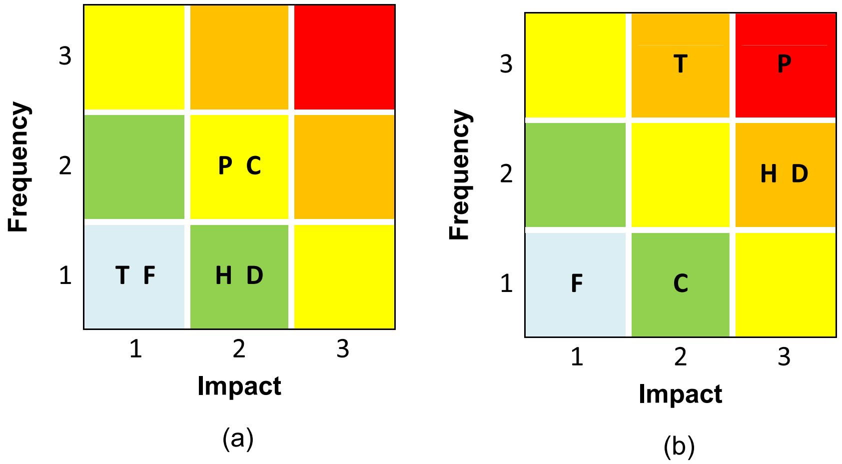


Fig. 7 Climate risk assessment matrix, for present (**a**) and medium-term future (**b**)

evaluation of the options to be included in the strategy and discussed with the key actors.

It was considered in this context that it would be essential to analyze national and international good practices for adaptation to climate change (benchmarking analysis), allowing the analysis of projects that represent success cases in this scope. The good practices analyzed were selected based on the capability of promote positive effects in different activity sectors, identified as priority according to the climate risk assessment: (i) economy, which includes the agriculture, energy and transport and communication field areas; (ii) ecosystems, which include areas such as forests and biodiversity; and (iii) society, which covers areas such as human health, urban environment, and safety of people and goods.

The options for adapting to climate change presented in order to diversify and strengthen the adaptive capacity of the territory, reducing its vulnerability to climate change, were divided into three types: gray infrastructures, green infrastructures, and non-structural (Table 3).

Adaptation measures 1, 2, 3, 9, 11, 12, 13, 15, and 16 increase the resilience of the urban environment and resident populations to climatic events whose intensity will increase according to the climatic projections. These examples include measures of good adaptation in urban areas, where the “heat island effect” is more intense due to the presence of extensive inert areas that have greater thermal absorption than green areas. Moreover, in urban areas, the effects of urbanization and impervious surfaces cause serious disturbances in hydrology, reducing the resilience of the territory to events of excessive precipitation. The ecosystems scarcity in urban areas also reduces resilience to extreme weather events, affecting the regenerative capacity of current systems to absorb disturbances and reorganize to maintain their function, structure, and identity. In urban areas, population concentration is higher and therefore measures should be adopted to promote greater security of the resident population.

The selected options also include adaptation measures in rural areas, increasing the resilience of agroforestry systems that are particularly affected by climate change. TQT and TFT have large rural areas, with agriculture representing a high form of subsistence. Thus, adaptation measures 4, 5, 6, 7, and 8 include solutions that increase the resilience of the rural environment to climatic events whose intensity will increase, according to the climate projections. In particular, adaptation measures 6, 7, and 8 include solutions for adapting to climate change in agricultural systems.

At the same time, climate change will produce imbalance and stress for the biosphere, negatively affecting the morphology and physiology of the species, and resistance to pests and diseases. In addition, the new climate trends will promote the occurrence of new biological invasions, considered the second biggest loss of biodiversity in the world, after the destruction of habitat (Nunez et al. 2019). Taking into account the serious negative impacts expected for ecosystems due to climate change, adaptation measures 1, 4, 5, 8, and 10 were selected, demonstrating solutions of great relevance for both TQT and TFT.

Climate change associated to the land-use patterns and high desertification rate will increase the risk of fire in the territory, with serious impacts on society, ecosystems, and the economy. Forest fires are an extremely serious catastrophic event in Portugal, due to their frequency, extent, and their effects (Carvalho et al. 2011). TQT and TFT have several areas of high and very-high fire hazard, and urgent fire prevention measures must be adopted. For this reason, an adaptation measure of special relevance in this field was also selected, the adaptation measure 14, which promotes the development of an integrated analysis system for the protection of forests against fire.

These adaptation measures, based on benchmarking analysis, present diverse solutions, integrated and easily adapted to both TQT and TFT in its various aspects. However, some challenges of implementing adaptation measures can be found.

Table 3 Adaptation measures considered in the benchmarking analysis

Types of measures	Measure	Reference
Green	(1) Combating the heat island effect and poor air quality with green ventilation corridors in Stuttgart, Germany	(Climate-ADAPT 2014e)
	(2) Consolidation and expansion strategy of The Urban Green Infrastructure of Vitoria-Gasteiz	(Climate-ADAPT 2018)
	(3) Development of sustainable drainage measures in Portland	(Environmental Services of City of Portland 2005)
	(4) Landscape planning adapted to floods and heat waves in the Emscher Valley	(Climate-ADAPT 2015a)
	(5) Ecological restoration of the Regge River in the Netherlands	(Climate-ADAPT 2014d)
	(6) Autonomous adaptation to droughts in an agro-silvo-pastoral system in Alentejo, Portugal	(Climate-ADAPT 2016a)
	(7) Adaptation measures to drought in an agroforestry system in Montpellier	(Climate-ADAPT 2014a)
	(8) Water retention landscape to restore the water cycle and reduce vulnerability to droughts in Alentejo, Portugal	(Climate-ADAPT 2015b)
	(9) "Garden/Garden" initiative in Santa Monica, California	(City of Santa Monica—Office of Sustainability and the Environment 2016)
	(10) Climate-adapted management of the Körös-Maros National Park, Hungary	(Climate-ADAPT 2014c)
Gray	(11) Bioclimatic design of the building of the Madrid Institute for Advanced Studies	(Climate-ADAPT 2015c)
	(12) Flood protection measures for the city of Prague	(Climate-ADAPT 2016b)
	(13) Reuse of rainwater and wastewater in Sidwell Friends School, Washington, D.C.	(Landscape Performance Series—Landscape Architecture Foundation 2012)
	(14) An integrated analysis system for the effective fire conservancy of forests (CALCHAS)	(Climate-ADAPT 2014b)
Non-structural	(15) Heat hotline parasol in Kassel, Germany	(Climate-ADAPT 2017)
	(16) Promotion of water saving measures in Zaragoza, Spain	(Climate-ADAPT 2014f)

Worldwide, financial and resource constraints are the most frequently discussed (IPCC 2014). Similar barriers were found in TQT and TFT. According to round tables conducted with various key actors in TQT and TFT, local authorities are usually the ones to take the lead in preparing adaptation plans and are then required to find external funds to implement the adaptation measures, although climate change being a global problem. For them, the involvement of public and private actors, both at the local and national levels, can also be a problem, leading to institutional and governance conflicts, capable of reducing decision-making capacity and the desired level of adaptation. Finally, local authorities identified the staff capacity as a great challenge to the implementation of climate-change plans. This issue is mostly related to the lack of staff with the technical and scientific capacity to monitor the implementation of the adaptation measures, needing to invest on scientific training or delegating to specialized entities.

Conclusions

This study developed a climate adaptation framework and identified potential development measures, for a specific multi-urban area located in the northeast of Portugal. For the region under study, the simulations carried out indicated a tendency for an increase in maximum, minimum, and average temperature, as well as an increase in extreme events associated with this temperature increase. Increases in extreme precipitation events are also projected and consequently an increase in annual accumulated precipitation for the medium-term future climate. The model approach used, with its high spatial resolution, is an added value in the assessment of climate change, allowing to include, in greater detail, the effects of the topography. A set of measures to promote a sustainable development path to climate adaptability was identified and discussed. Adaptation measures focused on urban areas were selected to reduce the "heat island effect": e.g., green corridors, bioclimatic design of buildings, green roofs, etc. Measures in rural areas were also considered, adapting landscape planning to floods and heat waves and promoting the autonomous adaptation to droughts. Some of these adaptation measures will prevent the occurrence of new biological invasions and, also very urgent, fire prevention.

These types of studies are crucial to accomplish the 2030 Agenda for Sustainable Development Goals, where, by

2030, climate-change measures must be integrated into national policies, strategies, and planning. The work also highlighted the role of scientific knowledge for policy makers and key actors in the development of local adaptation strategies.

Acknowledgements This work was partially supported by "Associação de Municípios da Terra Fria do Nordeste Transmontano" and "Associação de Municípios da Terra Quente Transmontana" through projects "Plano Intermunicipal De Adaptação Às Alterações Climáticas Da Terra Fria Do Nordeste Transmontano" and "Plano Intermunicipal De Adaptação Às Alterações Climáticas Da Terra Quente Transmontana," respectively. The authors would like to thank "Sociedade Portuguesa de Inovação—SPI" for the access of the information used in this work. Thanks is also due, for the financial support to CESAM (UIDB/50017/2020+UIDP/50017/2020) and the PhD grant of S.C. (SFRH/BD/137999/2018), to FCT/MEC through national funds, and the co-funding by the FEDER, within the PT2020 Partnership Agreement and Compete 2020.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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