Deliverable D3.2 – 5 CRA Pilot reports: Lessons learnt and success stories

WP3 – Regional CRA prototypes and operationalization

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Document Information

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Brief Description	This deliverable describes the testing and adaptation of the CLIMAAX CRA Framework and toolbox by the 5 CLIMAAX pilot regions. This is realised as a collection of individual CRA reports by the 5 pilot regions followed by a Lessons Learnt section.
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Abbreviations and acronyms

Partner Institutes

Abbreviation / acronym	Description
ACA	Catalan Water Agency, Catalonia, Spain
CIMA	International Centre for Environmental Monitoring, Italy
DGPC	Civil Protection Directorate, Catalonia, Spain
ESAF	Emergency Services Academy Finland (Pelastusopisto), Finland
FMI	Finnish Meteorological Institute, Finland
GADSEA	Setúbal City Council's Sustainable Development and Environmental Emergency Support Office, Portugal
IGOT	Institute of Geography and Spatial Planning of the University of Lisbon, Portugal
INOVIA	INOVIA, Slovakia
ISGlobal	Barcelona Institute for Global Health, Catalonia, Spain
INTC	Interior Department of the Regional Government of Catalonia, Spain
KAJO	KAJO Services, Slovakia
LEGMC	Latvian Environment, Geology, and Meteorology Centre, Latvia
MoIFI	Ministry of the Interior, Finland
UPC-CRAHI	Center of Applied Research in Hydrometeorology, Polytechnic University of Catalonia, Spain

1.1 Data portals

Abbreviation / acronym	Description
C3S	Copernicus Climate Change Service
CDS	Climate Data Store
EFFIS	European Forest Fire Information System
EURO-CORDEX	Coordinated Downscaling Experiment - European Domain
OSM	Open Street Map

1.2 Other

Abbreviation / acronym	Description
APA	Portuguese Environment Agency
BGE	Building Georeferencing Base
BGRI	Base Reference Geographic Information
CCAP	Latvia's Climate Change and Adaptation Plan for 2030
CoP	Community of Practice
CRA	Climate Risk Assessment
EEA	European Environment Agency
FWI	Fire Weather Index
KriSu	Leadership of Major Accidents and Crisis Situations
LAI	Leaf Area Index
LST	Land Surface Temperature
ML	Machine Learning
NCPP	National Civil Protection Plan
NDDI	Normalized Difference Drought Index
NDVI	Normalized Difference Vegetation Index
NMDI	Normalized Multi-Band Drought Index
PGRI	Flood Risk Management Plan
RDI	Research, Development and Innovation

Executive summary

This deliverable D3.2 "5 CRA pilot reports: Lessons learnt and success stories" describes how the CLIMAAX Climate Risk Assessment (CRA) Framework and Toolbox have been adapted by the 5 CLIMAAX pilot regions to perform their customised, regional CRAs. The deliverable is realised as a collection of five individual reports on the regional CRAs performed by the respective pilots, each structured in the same way and broadly following the CLIMAAX CRA Framework[1]. These pilot CRA reports are followed by a Lessons Learnt section, which reflects on the progress of the pilots within the CLIMAAX project, what worked and what could be improved, and how the lessons learnt helped to improve the CRA Framework and Toolbox, to make them as useful as possible for the next stage of the CLIMAAX project. This is an updated version of the preliminary deliverable submitted June 2024.

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[1] https://files.cmcc.it/climaax/Deliverables/CLIMAAX_D1.4_Climate%20Risk%20Assessment%20Framework_revised.pdf

1 Introduction

2.1 Purpose of the document

To support climate adaptation at a regional scale across all of the EU, the European Commission introduced the EU Mission on Adaptation to Climate Change. As part of this effort, the CLIMAAX project received funding to promote and support the execution of regional Climate Risk Assessment (CRA) in European regions of NUTS3 level or smaller. Along with other, similar or supporting, projects, CLIMAAX thereby supports European regions with their disaster risk management and climate adaptation strategies. This work also contributes to overall knowledge and understanding of climate and climate change issues and promotes informed decision making throughout the EU.

The CLIMAAX project can roughly be divided into two main stages: In the first stage, the Climate Risk Assessment (CRA) Framework was developed. The framework provides European regions with the methodology to perform a comprehensive CRA at a regional level. This methodology includes all major steps of the CRA starting from the scoping and ending with the monitoring and evaluation of the CRA. The CRA Framework is accompanied by the CRA Toolbox, which is made up of so-called workflows, each of which include codes and documentation for assessing the risks occurring due to one or several climate hazards. The CRA Framework and Toolbox are accessible together in the CLIMAAX Handbook[2] and were developed together with the CLIMAAX pilot sites. In the second stage, the CRA Framework and Toolbox will be applied by more than 60 European regions which were awarded cascading funds through the CLIMAAX project to perform CRAs in their respective regions.

The five CLIMAAX pilots are all part of the first stage of the project. Their purpose was to test and evaluate the usefulness of the CLIMAAX CRA Framework and Toolbox. Both were then adjusted based on the feedback received from the pilots within a co-design process. This considerably improved both the Framework and the Toolbox to be better prepared for the 60+ European regions. Of course, the pilots each also aimed at obtaining CRA results from the project applied for their own specific aims and needs. The start of the CRA framework and toolbox development coincided with the start of the CRA applications at pilot level. As such, the methodology and tools were not available for the pilots from the start: each pilot was asked to pre-assess the hazards and risks which are of most interest to them, and then select a subset of these risks to be assessed during the pilot phase. This pre-selection of hazards and risks had direct implications on the development of the CRA Toolbox, as development of its workflows focused on the hazards most common and/or pressing to the pilots. Due to some timing issues which emerged during the first stage of the CLIMAAX project the start of the actual pilot phase was delayed by several months and thus the pilot phase (and with it the duration of WP3) were extended by an additional 6 months to 31.12.2024. Hence, a preliminary version of this deliverable D3.2 was submitted in June 2024.

The pilot regions are the Setúbal municipality in Portugal, the region of Catalonia in Spain, the Žilina municipality in Slovakia, Latvia, and Finland (Table 1-1). These were chosen to be as representative of Europe as possible, spanning its extent both in the east-west and north-south directions. This selection allows for a broad treatment of different climate, climate risk, and governance contexts to test and develop the CRA workflows. Table 1-1 shows an overview over the five pilots: The regions

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[2] CLIMAAX Handbook, 2024, https://handbook.climaax.eu/CRA_steps/framework.html

span climates ranging from dry (A) to continental (C), combined with both dry and humid conditions and a wide variety in summer and winter conditions. Furthermore, the pilots vary greatly in size, spanning from NUTS2 regions to municipalities. The Köppen-Geiger classifications are explained in Table 1-2, which was adapted from Beck et al, 2018 and Kotteck et al., 2006.

The workflows themselves are explained in Deliverable D2.4[3], and in this deliverable, we focus on the adaptation of these workflows to the context of the pilot regions. This demonstrates the CLIMAAX objective of developing a standardised, yet flexible CRA which can be tailored by different users, for example to include the use of own, local datasets, as well as an analysis and visualisation of the results, customised to the needs of the pilots.

Table 1-1: Climate categories and NUTS codes of regions analysed in the pilots. The table also lists which workflows have been used in the pilots.

region	**country**	**NUTS**	**Köppen class**			**Workflows**					
						wildfire ML	wildfire FWI	heavy precipitation	coastal flood	river flood	heatwave
North Karelia	Finland	FI1DC	D	f	b		x				
South-West Finland		FI1C1	D	f	c		x				
Helsinki		FI1B1	D	f	c			x			
Latvia	Latvia	LV0	D	f	b				x	x	
Žilina	Slovakia	SK031	D	f	b						x
Catalonia	Spain	ES51	C	s	a	x	x	x			x
			B	S							
Setúbal	Portugal	PT1B0	C	s	a		x	x			x

Table 1-2: Key to the Köppen-Geiger classification scheme. Note that keys might change slightly between publications For instance, Beck et al., 2018 do not distinguish between Savannas with dry winters or summers, and just use w for 'Savanna' instead.

1st	**2nd**	**3rd**
A (Tropical)	f (Rainforest)	
	m (Monsoon)	
	w (Savanna, dry winter)	
	s (Savanna, dry summer)	
B (Arid)	W (Desert)	h (Hot)

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[3] https://files.cmcc.it/climaax/CLIMAAX_D2.4.pdf

	S (Steppe)	k (Cold)
C (Temperate)	w (Dry winter)	a (Hot summer)
	f (No dry season)	b (Warm summer)
	s (Dry summer)	c (Cold summer)
D (Cold)	w (Dry winter)	a (Hot summer)
	f (No dry season)	b (Warm summer)
	s (Dry summer)	c (Cold summer)
		d (Very cold winter)
E (Polar)	T (Tundra)	
	F (Frost)	

2.2 Relation to other project work

The work of the pilots in WP3 was an instrumental part of the development of both the CRA Framework (WP1) and Toolbox (WP2), as well as the Handbook[4] of the CLIMAAX project. Each pilot either directly applied the CRA Framework in their risk analysis or reviewed the Framework, comparing it to their own CRA procedures. Through the feedback received from the pilots, WP1 refined the Framework to be more practical, understandable, and comprehensive. Similarly, the workflows of the CRA Toolbox developed from mere code implementations to well-documented and explained notebooks with presentable visualisations of the results. The notebooks are easy to modify, and it is fairly straight forward to extend the analysis and/or use own, local data.

2.3 Structure of the document

This deliverable has only one main section, Section 2 (Pilot CRA reports), which details the work done on the regional CRA by each pilot. Section 2 is divided into 5 subsections, one for each pilot. Each of these subsections is structured in the same manner to make the deliverable as easy to read as possible: the structure broadly follows the steps of the CRA as defined by the CRA Framework. Each of the pilot CRA reports was written by the pilot partners themselves who all have different backgrounds, interests, and entrance levels in conducting CRAs. Section 3, Lessons Learnt, delves shortly into what worked and what did not work during the pilot phase.

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[4] https://handbook.climaax.eu/intro.html

2 Pilot CRA reports

In the following, the pilots will each describe their CRA as performed within the CLIMAAX project.

2.1 Procedural remarks

During the first phase of CLIMAAX, the CLIMAAX Handbook, Framework, and Toolbox were shaped simultaneously in close collaboration with the pilots. During this phase, the risk workflows of the CLIMAAX Toolbox were also adapted to the local of the pilots. This was essential for making the workflows as useful as possible for later users (especially the 60+ regions of second phase of the project). However, several limitations remained and are currently being addressed by the project partners:

1. The resources of regional actors to perform a data driven risk analysis are limited. This includes computational power as well as data storage space. Therefore, the number of models which is feasible to use in an analysis is limited as well.
2. The climate models used in the different workflows may or may not reproduce the climates of the different regions very well. Therefore, tools and/or methods to select the 'best' models for the region in question are needed. This is especially true in light of point 1 above.
3. As of the writing of this document, different workflows still used different (pre-defined) models for their analysis, as well as different numbers of models and model years. This led to discrepancies between the results of different workflows (e.g., different trends obtained for drought and wildfire results).
4. Some workflows use pre-calculated indicators, which are available only for a subset of all Euro-Cordex models, which makes a screening for regionally feasible models even more difficult.

All the above points have been recognised by the CLIMAAX consortium and are currently being addressed. Some of the pilots have decided to re-perform their assessments once the resulting tools and guidelines become available. The results presented here should be viewed with the above constraints in mind: All the tools used have been shown to work well and the way the results are presented are helpful for the further work of the pilots. However, the results themselves are necessarily trusted by the pilots and don't always align with earlier works in the regions.

2.2 Setúbal

2.2.1 Background

Setúbal is the fifth largest Portuguese city, and capital of a district with 13 municipalities and over 800000 inhabitants. It is located in the estuary of the river Sado, in the Atlantic Coast and is part of the Lisbon Metropolitan Area. It has a territory characterized by a large urban area (City of Setúbal) and a more dispersed occupation to the east and west. About 50% of the Municipality's territory is classified as a protected natural area. Regarding climate change, rural and forest fires are the greatest risk to the territory of the Municipality of Setúbal. The risk of fire is higher in the parishes of the municipality located in Serra da Arrábida. The low water retention capacity of soils contributes to flash floods triggered by intense rainfall episodes concentrated in few hours, generating high risk to people and economic, environmental and property damages. The issues regarding Climate Change Mitigation and Adaptation in the Municipality of Setúbal begun to get addressed with the adherence to the Global Covenant of Mayors for Climate and Energy in 2015.

2.2.1.1 Earlier work on CRA

In terms of climate risk analysis, on a local scale and in the interests of the Municipality of Setúbal, two key projects should be highlighted: the Metropolitan Plan for Adaptation to Climate Change in the Lisbon Metropolitan Area (PMAAC-AML) in 2019[5], and the PLAAC - Arrábida Project in 2022[6].

The territorial approach adopted in the PMAAC-AML was assumed as a reference framework and replicated in the PLAAC project, which produced Local Climate Change Adaptation Plans for the three Arrábida municipalities (Sesimbra, Setúbal, and Palmela). Through PLAAC, the territory of Setúbal now has the climate scenarios, increasing its knowledge of the main risks and vulnerabilities to the challenges of climate change.

Setúbal is currently in the final stages of producing its Municipal Climate Action Plan, which is initially the result of a legal obligation under the Portuguese National Climate Law (2021)[7]. In methodological terms, the two projects mentioned above were fundamental to the preparation of the Setúbal Climate Action Plan. This plan is an essential strategic planning tool for the municipality, as it merges all the work it has been doing over the last decade by defining a municipal climate action strategy that combines adaptation and mitigation and is cemented in the climate risk analysis developed by the PLAAC project.

2.2.1.2 Short description of participants

During the visit to the Setúbal Pilot in January 2024, a number of relevant stakeholders from the local community took part in the working meetings with the project partners, sharing important knowledge and information, such as: Francisco Metelo from the Lisbon Metropolitan Area, João Dinis from Cascais Municipality, Helena Simões from the Setúbal Polytechnic Institute and João Diegues from the Arrábida Public Health Unit.

The main participants of the pilot were (see Figure 3.1 for full organisation names):

- DMAGPE: responsible to support the municipal executive in the design, implementation, and control of the policies and strategies pursued by the Municipality.
- SMPCB: responsible for coordinating assistance actions in situations of serious accidents, disasters, or public calamities.
- GAPAI: responsible for coordinating and monitoring special projects of great interest to the Municipality, participating in, formalising, and overseeing applications for co-financed projects.
- GADSEA: responsible for proposing and monitoring the municipal strategy for sustainable development, climate action and reducing risks arising from climate change.
- IGOT: The Centre for Geographical Studies (CEG) is a research and development unit integrated into IGOT. Its mission is to advance research in Geography and to promote and disseminate geographical knowledge.

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[5] https://www.aml.pt/en/iniciativas/plano-adaptacao-alteracoes-climaticas/

[6] http://www.plaac.ena.com.pt

[7] https://cdn.climatepolicyradar.org/navigator/PRT/2021/framework-climate-law-no-98-2021_6a10f038a28f31006b1a44110bde2a32.pdf

The pilot organisation is illustrated in Figure 3.1.

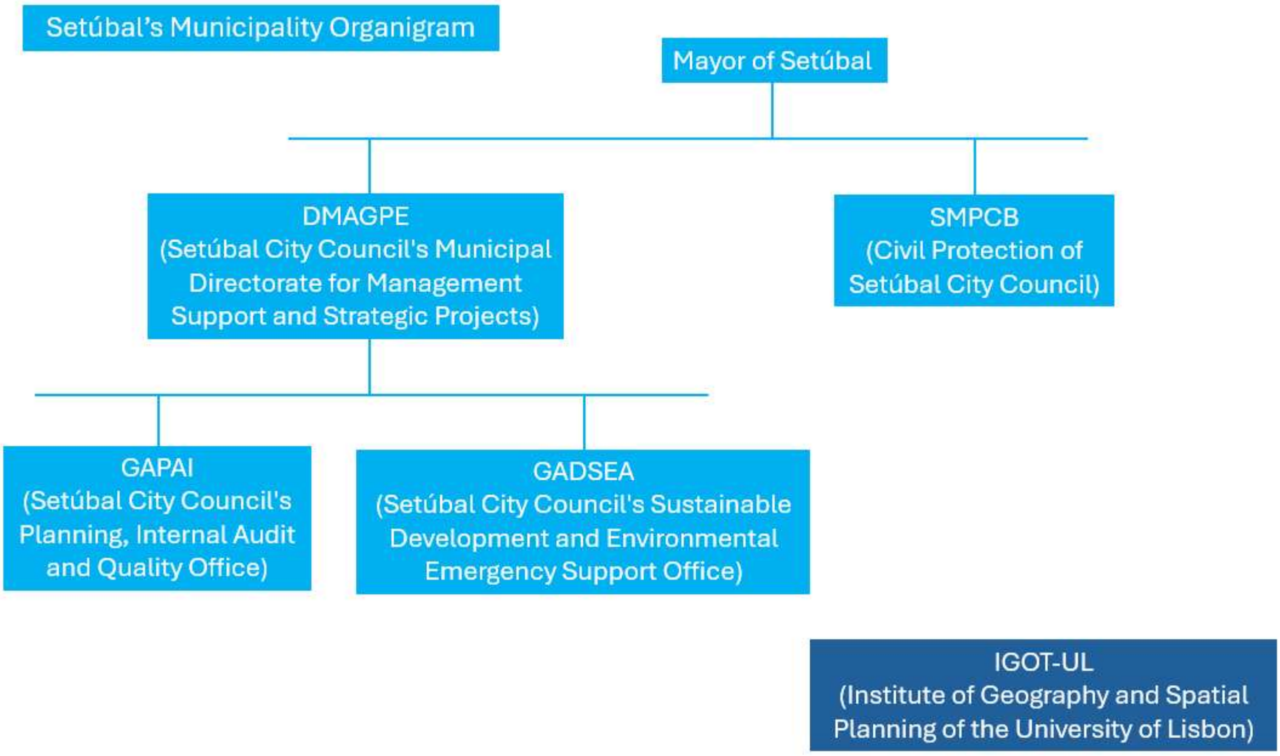


Figure 2.1: Organigram for the Setúbal pilot

2.2.1.3 Focus and goals of the CRA

Setúbal's main goals are:

- To provide the municipality with a robust scientific framework to support technical and, above all, political decision-making.
- To improve the emergency response framework for extreme weather events (in terms of civil protection emergency response).
- To support Climate Risk Management in the implementation of concrete adaptation measures.

2.2.2 Scoping and main hazard selection

2.2.2.1 Short overview over local climate

According to the Köppen-Geiger climate classification, which is the most widely used in climate studies, Setúbal has a temperate climate with hot, dry summers (Csa). The winters are mild and rainy, with high humidity. The projection for the future is that these patterns will become more pronounced.

2.2.2.2 Main hazard selection

At the start of WP3, the CRA Framework was not yet available. Instead, the pilots selected the main climate hazards, and the related risks based on local knowledge and experience. The hazards and risks were then analysed to the extent possible. The most relevant climate-related hazards in Setúbal are extreme precipitation, heat waves, and forest fires. These hazards were selected for analysis within the scope of CLIMAAX.

2.2.3 Risk identification

The risks connected to the selected hazards, which are relevant to the municipal stakeholders responsible for the Civil Protection and the Spatial Planning, are the loss of life, injuries, adverse health impacts, damage to properties, disruption of livelihoods and essential services, economic and social disruptions, and environmental damage.

The possible harmful consequences are not only dependent of the climate hazard and should be assessed based on the contribution of different drivers, including non-climatic ones (e.g., vulnerability and exposure), to quantify each specific climate risk.

2.2.3.1 Extreme precipitation

The municipality of Setúbal has historically faced flash flood events within the Livramento river watershed, largely triggered by extreme precipitation. This watershed spans 8 km along a drainage basin of 13.9 km². The Livramento river flows through the city of Setúbal from north to south, with its final stretch channelled beneath the urban landscape, ultimately discharging into the Sado estuary. The basin's concentration time is estimated to be 164 minutes, with a computed peak flood discharge of 60 m³/s for a 100-year return period.

Extreme precipitation events play a crucial role in initiating these flash floods, underscoring the importance of accurately estimating such precipitation for risk assessment. Significant events, such as those in 1983 and 2008, caused widespread disruption in downtown Setúbal. While no casualties were reported, the impacts were severe, including the flooding of major roads, inundation of residential and commercial areas, evacuation of affected populations, and interruptions to economic activities and critical infrastructure.

2.2.3.2 Heatwaves

Heatwaves has adverse effects for agriculture (e.g., reduced vineyards crop yields due to heat stress) and other economic consequences resulting from the increasing demand for electricity for cooling, leading to higher energy costs and potential strain on power grids.

However, the worst consequences of heatwaves are the increasing mortality and morbidity for the population. Typically, heatwaves are associated with higher rates of heat-related deaths, particularly among vulnerable populations such as the elderly, children, and those with chronic illnesses. In addition, the heat-related illnesses include increased incidence of heatstroke, heat exhaustion, dehydration, and exacerbation of pre-existing health conditions.

Taking this into consideration, the risk of heatwaves, besides the spatial and temporal distribution of heatwave hazard (including the identification of Urban Heat Islands) should be quantified based on the exposure of the most vulnerable population, together with the characteristics of the building environment and its ability to mitigate the excessive hot weather.

The social vulnerability of the population exposed to heatwaves should be based on variables covering the following topics: demography, health, family structure, social support, education, economy, employment, housing and building environment.

2.2.3.3 Wildfires

The consequences of wildfires in Setúbal municipality are varied. The destruction of forests and shrubs in the Arrábida Natural Park endangers several unique and well-preserved ecosystems. Furthermore, agricultural activities, particularly vineyards, are also threatened by the wildfire hazard. The escalating wildfire threat will increase the risk along the rural-urban interface, especially at the western boundary of the Setúbal city and the northern edge of the Azeitão village.

In addition, wildfires in the Arrábida Mountains pose a direct risk to people and assets (e.g., cars) as many people hike in the mountains on sunny summer days. Moreover, there is an accumulation of visitors at the small beaches nestled in the Arrábida, such as Figueirinha, Galápagos, Galapinhos, and Portinho da Arrábida, which may be trapped during a severe wildfire event.

Finally, the destruction of vegetation cover by fire leads to increased soil erosion and slope instability, as was the case after the massive wildfire in the Arrábida Mountains in 2004.

2.2.4 Risk analysis

2.2.4.1 Extreme precipitation

Hazard assessment

The extreme precipitation workflow was applied in the Setúbal municipality to analyze the potential impact of climate change on current critical impact-based rainfall thresholds. The assessment focused on precipitation intensity and examined variations in magnitude and frequency under the RCP 4.5 and 8.5 emission scenarios.

The hazard assessment was based on EURO-CORDEX climate projections for precipitation flux at a spatial resolution of 12 km. Historical (or baseline) simulations were represented by the 30-year period from 1976 to 2005, while future projections for mid-century (2041–2070) and end-century (2071–2100) were analyzed under the RCP 4.5 and 8.5 emission scenarios. The temporal series, from the EURO-CORDEX dataset, were based on the combination of the global climate model ICHEC EC EARTH and the regional climate model RACMO22E by KNMI. These models were chosen for projections in mainland Portugal because the global climate model EC EARTH provides comprehensive large-scale climate dynamics, while the regional climate model RACMO22E refines these projections with high-resolution data tailored to Europe. Additionally, as highlighted by Soares et al. (2017) in their quality assessment of Regional Climate Model's historical simulations at 0.11° EURO-CORDEX resolution for annual precipitation (approx. 12 km in Portugal), the KNMI-ICHEC model demonstrated better spatial agreement with observed data.

The annual maximum precipitation for durations of 3 hours and 24 hours was calculated using historical data and future projections (RCP 4.5 and RCP 8.5) from the EURO-CORDEX precipitation datasets. Figure 2.2 and Figure 2.3 illustrate the frequency of the annual maximum precipitation in Setúbal (lat: 38.52, long: -8.89). The graphs represent the 3h and 24h durations for historical data and future projections (mid- and end-century) under the RCP 8.5 scenario.

Figure 2.2: Maximum yearly 3h precipitation for RCP8.5. Top: historical period, middle: mid-century, bottom: end of century. NOTE: the years shown here do not correspond to real calendar years but rather reflect the variability and mean values of the respective periods.

Figure 2.3: Maximum yearly 24h precipitation for RCP 8.5. Top: historical period, middle: mid-century, bottom: end of century. NOTE: the years shown here do not correspond to real calendar years but rather reflect the variability and mean values of the respective periods.

During the historical period (1976–2005), maximum 3h precipitation reached 23.1 mm, with a mean of 16.2 mm, while maximum 24h precipitation was 73.4 mm, with a mean of 38.83 mm. Extreme events, which we defined for this study area as precipitation above the 90th percentile thresholds (21.62 mm for 3h and 52.22 mm for 24h), occurred 4 times for both 3h and 24h durations.

During the mid-century period (2041–2070) under RCP 4.5, maximum 3h precipitation will increase to 25.2 mm (mean = 18.4 mm), and maximum 24h precipitation will increase to 90.4 mm (mean = 43.9 mm). The frequency of extreme events is expected to increase significantly, with 14 events for 3h (+250%) and 13 events for 24h (+225%) durations. Under RCP 8.5, maximum 3h precipitation may reach 31.5 mm (mean = 16.64 mm), and maximum 24h precipitation may reach 70.5 mm (mean = 40.31 mm). The frequency of extreme events is also expected to increase in comparison with the historical period, with 13 occurrences for 3h precipitation (+225%) and 17 occurrences for 24h precipitation (+325%).

By the end of the century, under RCP 4.5, maximum 3h precipitation may increase further to 26.9 mm (mean = 18.2 mm), and maximum 24h precipitation may reach 92.6 mm (mean = 44.3 mm). Extreme events are also likely to increase in frequency in comparison with the historical period, with 10 occurrences for 3h precipitation (+150%) and 13 occurrences for 24h precipitation (+225%). Under RCP 8.5, maximum 3h precipitation may reach 32.75 mm (mean = 19.47 mm), and maximum 24h precipitation may reach 84.2 mm (mean = 46.43 mm). Extreme events are likely to increase in frequency further, with 12 occurrences for 3h precipitation (+200%) and 14 occurrences for 24h precipitation (+250%).

The data analysis indicates that maximum intensities will be higher at the end of the century compared to the mid-century under both RCP 4.5 and RCP 8.5. Mean precipitation will increase by the end of the century under RCP 8.5, particularly for 24h durations. The frequency of extreme events will slightly decline under RCP 8.5 by the end of the century, especially for 24h events, but remains high. For RCP 4.5, the frequency stabilizes or decreases marginally.

The General Extreme Value (GEV) distribution was used as a probability distribution function to fit the annual maximum precipitation series. The expected precipitation for each duration (3 h and 24 h) and specified return periods (2, 5, 10, 50, and 100 years) in Setúbal (lat: 38.52, long: -8.89) was computed for the historical period as well as for RCP 4.5 and RCP 8.5 scenarios. The resulting graphs display the main fitting curve along with the upper and lower 95% confidence interval curves (Figure 2.4).

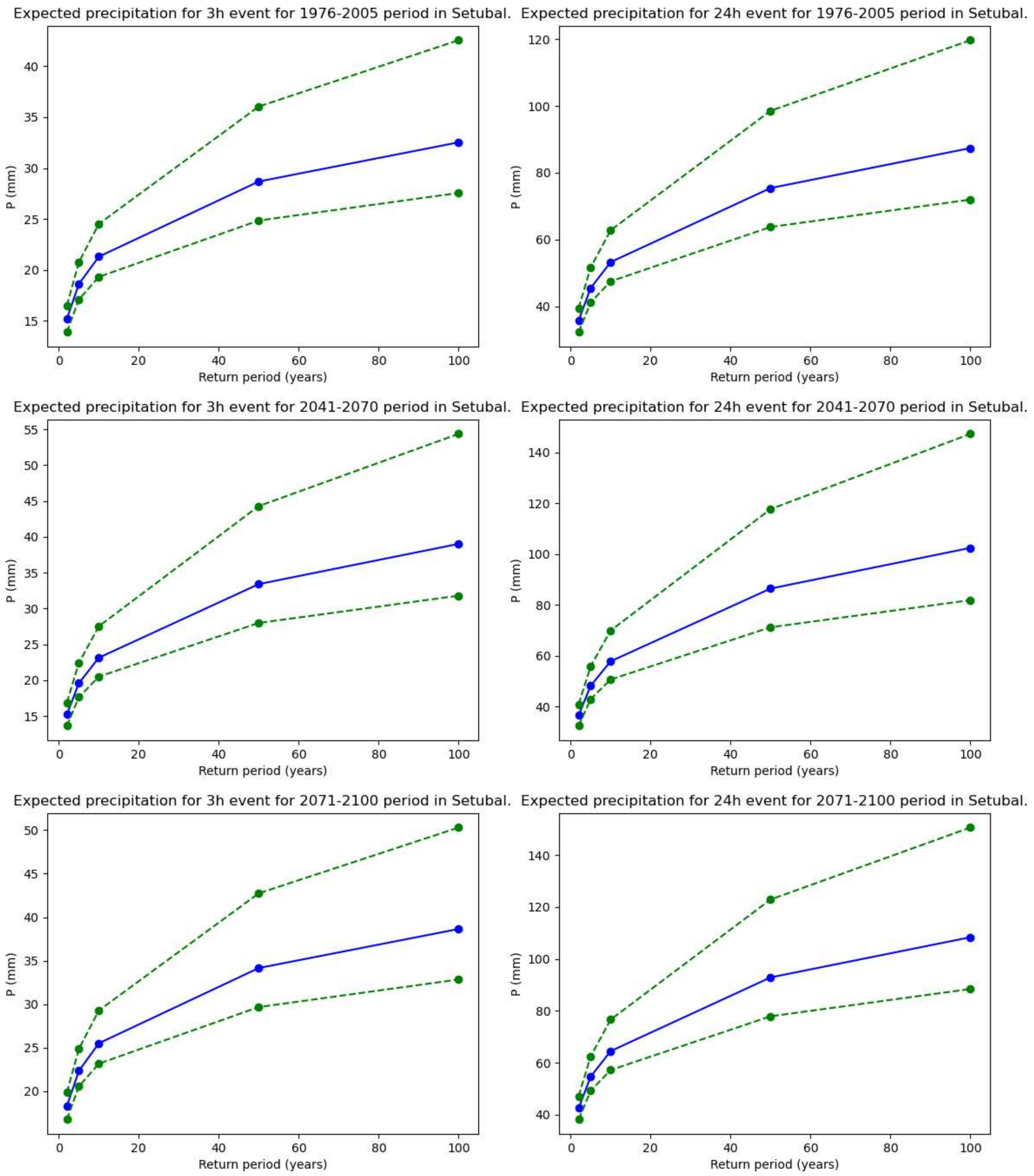


Figure 2.4: maximum precipitation for different return periods and time periods: left column 3h return period, right column 24 h return period. Top row: historical reference period, middle row: mid-century, bottom row: end of century

Figure 2.4 shows the expected precipitation for 3h and 24h events up to 100-year return period during the historical (1976–2005), mid-century (2041–2070), and end-century (2071–2100) periods, under the RCP 8.5 scenario. Regarding the 3h precipitation, there is an increase in rainfall intensity from the historical period (1971-2005) to the mid-century (2041-2070). For a 10-year return period, precipitation rises from 21.3 mm to 24.1 mm (+13.1%), while for a 100-year return period, it rises from 32.5 mm to 44.3 mm (+36.3%). However, this upward trend slows slightly by the late-century (2071-2100), with precipitation decreasing to 22.9 mm for 10 years (-5%) and 41.1 mm for 100 years (-7.2%). This indicates that short-duration rainfall events are expected to intensify by mid-century but may stabilize or slightly decline afterward. Concerning the 24h precipitation, the pattern is similar but with larger absolute values. From 1971-2005 to 2041-2070, the 10-year return period shows an increase from 53.2 mm to 58.5 mm (+10%), while the 100-year return period rises from 87.4 mm to 109.7 mm (+25.5%). By the late-century, precipitation slightly decreases to 53.6 mm (-8.4%) for 10 years and 99.6 mm (-9.2%) for 100 years. These changes suggest that while longer rainfall events are also intensifying, they follow a similar stabilization trend toward the end of the century.

The expected precipitation for 3h and 24h durations, considering 10-year (not shown) and 100-year return periods, was estimated at a regional scale (Portugal). This analysis covers the historical period, mid-century, and end-century, based on RCP 4.5 (not shown) and RCP 8.5 scenarios. Furthermore, the precipitation changes (%) relative to a defined period (historical vs future projections) was also mapped (see Figure 2.5 for an example).

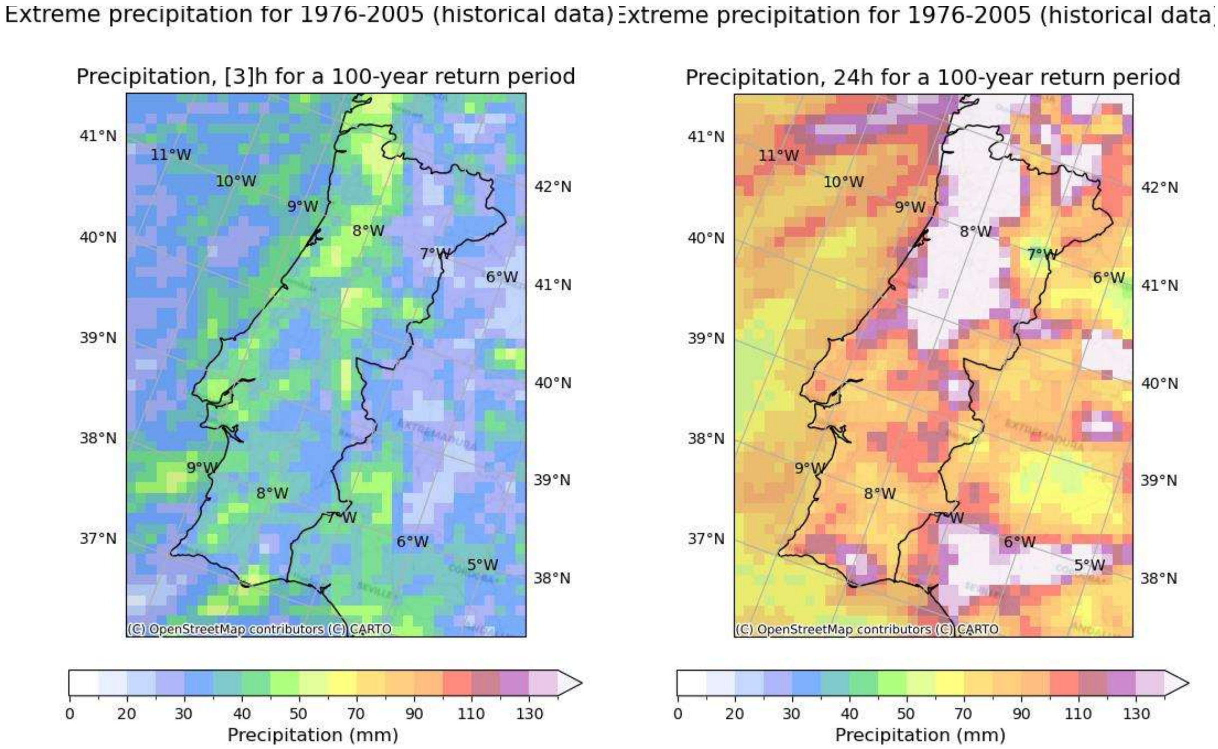


Figure 2.5: Extreme precipitation during the historical period (1976-2005) for 3h and 24h durations and a 100-year return period.

These results were analysed for the Setúbal municipality, which is represented by three grid cells (pixels). Historically, the mean 3h precipitation was 42.79 mm, ranging from 40.74 mm to 44.64 mm, while the mean 24h precipitation was 94.28 mm, with a range of 89.30 mm to 99.28 mm. These values serve as the baseline for future comparisons. By the mid-century period (2041–2070), 3h precipitation showed a decline, with the mean dropping to 38.68 mm, representing a relative change of -9.6% compared to the historical period. In contrast, 24h precipitation increased, with the mean rising to 99.73 mm, reflecting a relative change of +5.8%. In the end-century period (2071–2100), the 3h precipitation mean declined further to 38.21 mm, accounting for a relative change of -10.7% compared to historical values. On the other hand, the 24h precipitation continued its upward trend, reaching a mean of 104.85 mm, which corresponds to a relative change of +11.2%.

Risk analysis

Risk analysis for extreme precipitation was not conducted due to the low resolution of the rainfall data. The Setúbal municipality is represented by only three grid cells (pixels) for each rainfall dataset, making it impossible to differentiate hazard incidence across the municipality's territory.

Changes in the workflow for the local pilot application

Initially, the workflow was designed to display data in graphical formats, which limited accessibility for detailed statistical exploration. To address this, we modified the workflow to export the data into Excel files. These files provide tabular representations of the data, enabling convenient access to both raw and processed datasets, facilitating comprehensive exploratory statistical analyses using Excel or other statistical tools, and enhancing flexibility for stakeholders who prefer working with spreadsheets for data exploration. Moreover, the original dataset from EURO-CORDEX was provided in a coordinate reference system (CRS) that was incompatible with the Portuguese official system. To ensure accurate spatial representation and compatibility with local data and GIS tools, we enhanced the workflow to include the option to reproject the dataset to the ETRS89 / Portugal TM06 (EPSG:3763) CRS. This adjustment was essential because the official Portuguese CRS aligns with national spatial standards and ensures precise spatial alignment when integrating this data with other geospatial datasets in GIS applications. Additionally, we extended the workflow to support exporting the spatial data to GeoTIFF format, a widely supported raster file format commonly used in GIS applications.

2.2.4.2 Heatwaves

Hazard assessment

Heatwaves are prolonged periods of excessively high temperatures, often accompanied by dry conditions, that can significantly impact human health, agriculture, and ecosystems. In the Setubal municipality, the heatwave hazard assessment workflow was conducted using the Xclim methodology, as no data based on the national heatwave definition under the EuroHEAT methodology was available for this location. The Xclim methodology is based on EURO-CORDEX climate projections (12 km resolution), with data available for 1971–2100. The temporal series from the EURO-CORDEX dataset were derived from a combination of the global climate model MPI-ESM-LR and the regional climate model CLMcom-CCLM4-8-17. While other models could also be suitable, this combination was chosen for projections in Portugal due to its ability to capture large-scale drivers, such as the North Atlantic Oscillation, while also providing the high-resolution detail needed to analyse localized heatwave patterns, making it well-suited for both past and future assessments. For the Setubal municipality (lat: 38.52, long: -8.89), the frequency of heatwave occurrence was estimated for the historical period (1976–2005), while future projections for the mid-century (2041–2070) and end-century (2071–2100) were analysed under the RCP 4.5 and RCP 8.5 emission scenarios. The absolute temperature thresholds for the maximum and minimum daily temperatures (i.e. day and night temperatures) were defined as 35°C and 20°C, respectively, and a minimum time duration of 3 days. With these criteria, the heatwave workflow provides three different indicators to assess the heatwave hazard: The heatwave frequency (i.e., the number of heatwaves per year), the average heatwave length (i.e., number of days per heatwave), and the total amount of yearly heatwave days. These indicators are shown in Figure 2.6, Figure 2.7, and Figure 2.8, respectively.

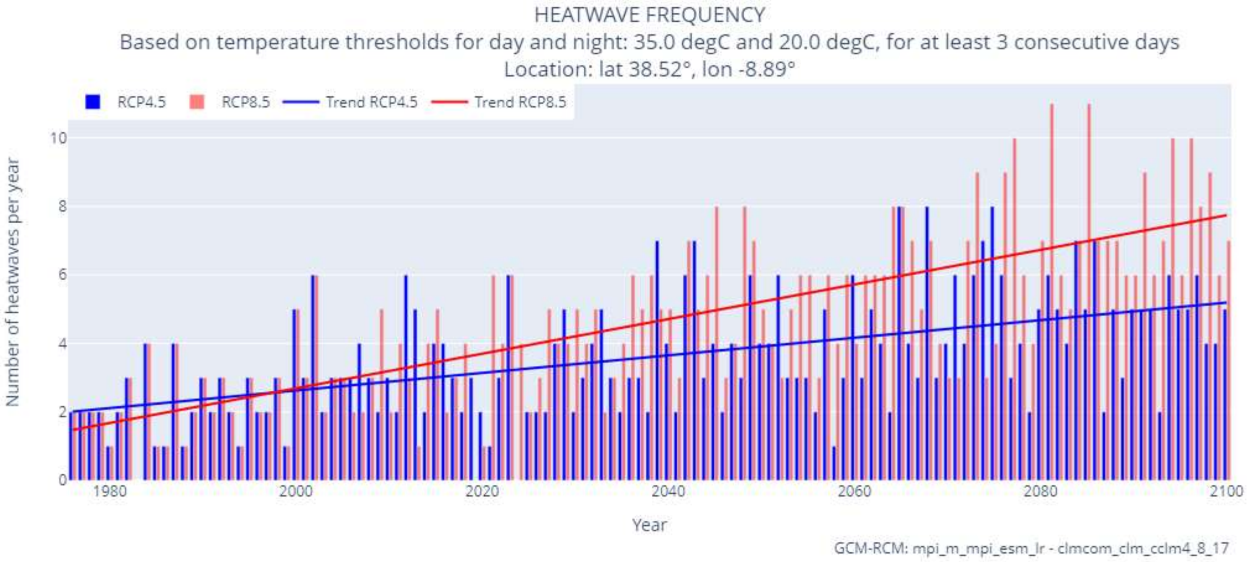


Figure 2.6: Heatwave frequency in Setúbal for RCP4.5 and RCP8.5

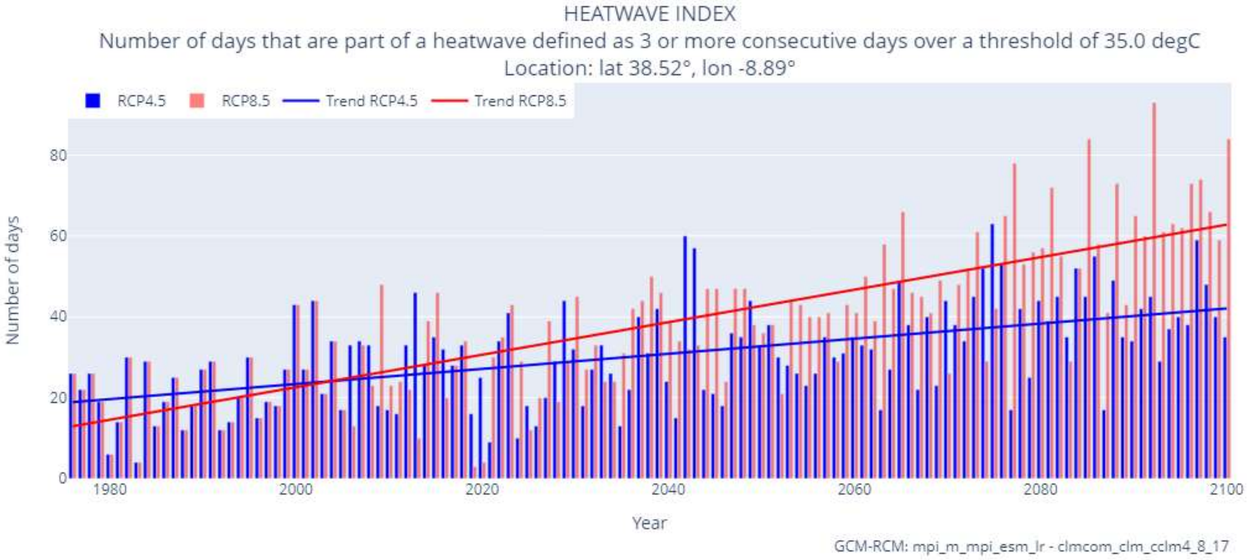


Figure 2.7: Average heatwave length in Setúbal for RCP4.5 and RCP8.5

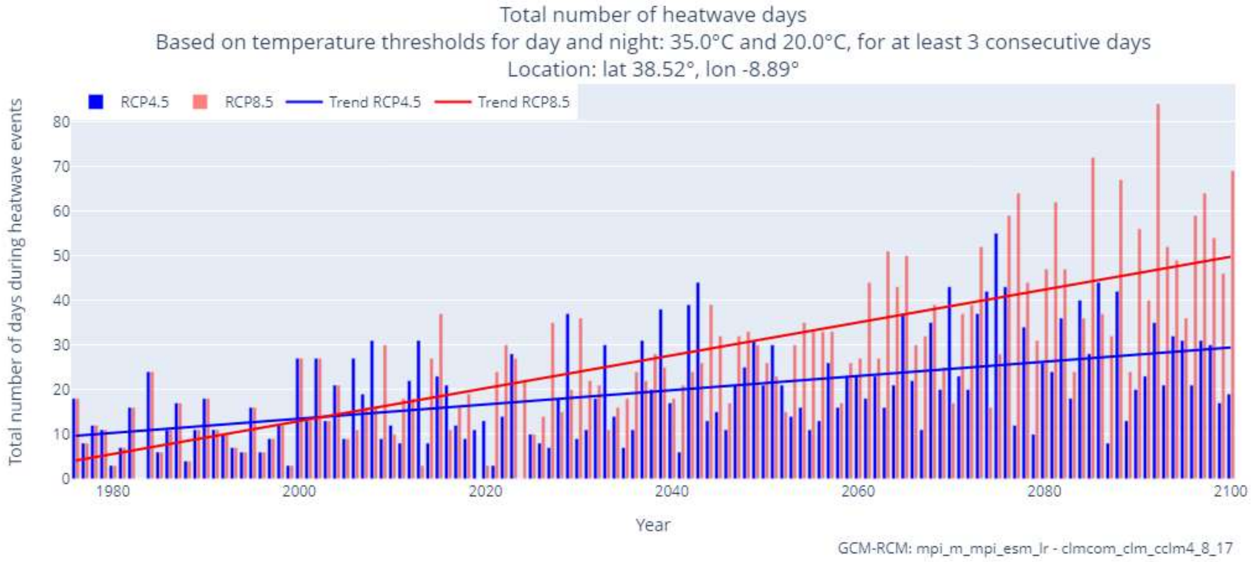


Figure 2.8: Total number of yearly heatwave days in Setúbal for RCP4.5 and RCP8.5

Between 1976 and 2005 (historical period), heatwaves frequency—defined as three or more consecutive days with daytime temperatures exceeding 35°C and nighttime temperatures above 20°C—occurred at an average rate of 2.45 heatwaves/year. Most years experienced 1–3 heatwaves, though outliers, such as 2002, recorded as many as six heatwaves. By mid-century (2041–2070), the frequency of heatwaves is projected to rise significantly. Under RCP 4.5, the average increases to 4.03 heatwaves/year (+64.5% from historical), with extreme years seeing up to 8 heatwaves/year. The least severe years still match the historical minimum (1 heatwave/year). Under RCP 8.5, heatwave frequency increases 121.6% compared to the historical period, averaging 5.43 heatwaves/year. No year has fewer than 3 heatwaves, and extreme years reach 8 events.

By the late century (2071–2100), the frequency of heatwaves continues to rise, particularly under RCP 8.5, where the average heatwave frequency ascends to 7.1 heatwaves/year (+189.8% regarding historical levels). Extreme years will experience up to 11 heatwaves, while no year falls below 3.

During the historical period, heatwaves index—defined as three or more consecutive days with temperatures exceeding 35°C—averaged 22 days/year. Extreme years, such as 2000 and 2002, experienced 43 and 44 days/year, respectively, while milder years, like 1983, recorded as few as 4 days/year. Although occasional peaks occurred, such as 34 days in 2004, most years experienced fewer than 30 days of heatwave conditions, highlighting their relative infrequency during this period. By mid-century, the number of heatwave days is projected to increase significantly. Under RCP 4.5, heatwaves are expected to average 32.3 days/year (a 46.8% increase from historical levels), with extreme years reaching up to 60 days. Under RCP 8.5, heatwaves will average 41.1 days/year (an 86.8% increase from historical levels), with peaks of up to 66 days.

By late-century, projections show further divergence between scenarios. Under RCP 4.5, heatwave days stabilize slightly, with an average of 41.1 days/year, and peaks of 63 days. However, under RCP 8.5, the average number of heatwave days rises to 60.3 days/year (+174.1% regarding the historical average). Extreme years will reach up to 93 heatwave days and even the mildest years in this scenario will exceed the historical maximum, with 29 heatwave days or more.

During the historical period, the total number of heatwave days—defined as three or more consecutive days with maximum and minimum daily temperatures of 35°C and 20°C, respectively—averaged 12.28 days/year, with most years experiencing fewer than 20 days of extreme heat. The most severe years, such as 2000 and 2002, recorded 27 heatwave days each, while the mildest years, like 1980 and 1999, had just 3 days.

By mid-century, the total number of heatwave days is projected to rise significantly. Under RCP 4.5, heatwaves will average 22.17 days/year (+80.5% from historical). Mild years will still experience at least 6 heatwave days, while extreme years, like 2070, could reach up to 43 days. Under RCP 8.5, the average increases to 30.33 days/year (+147% from historical). Even the mildest years will have at least 15 heatwave days, with extreme years exceeding 50 days.

By late-century, under RCP 4.5, the total number of heatwave days will increase to an average of 27.8 days/year (+126.4% the historical average). However, the rate of increase slows compared to earlier periods. Extreme years, such as 2075, will reach 55 days, though this remains below the projections for RCP 8.5. Under this latest emission scenario, heatwaves will average 47.6 days per year (+287.6% from historical). Extreme years are projected to experience 84 days of heat and even the mildest years, with 16 days, will exceed the historical maximum.

Risk assessment

The risk assessment workflow for heatwaves aims to identify the overheated areas as well as the exposed population.

The identification of overheated areas within the urban environment (commonly referred to as heat islands) was conducted using Landsat 8 land surface temperature (LST) data, which offers a spatial resolution of 30 meters and a temporal resolution of 16 days. These data, available for the period 2013–2024, were accessed via the RSLAB website. MODIS emissivity data (1 km resolution), which is well-suited for urban applications, was selected as the emissivity source. The study focused on the Setúbal Peninsula, specifically the municipality of Setúbal. For the selected time frame, we analysed data from April to October 2017 (13 raster images), a year marked by exceptionally dry and warm conditions in southwestern Europe, during which two heatwaves were recorded in Portugal. The mean values from the LST rasters, which are not significantly influenced by clouds, were calculated and classified into five categories (Figure 2.9a): Very Low: <20–25°C; Low: 25–35°C; Medium: 35–45°C; High: 45–55°C; and Very High: 55–60+°C.

The vulnerable population groups were identified using data from the WorldPop dataset. The most vulnerable were defined as males and females aged 1–5 years and those aged 65, 70, 75, and 80 years in the year 2020. The population data was summarized and reclassified into five categories (very low to very high) based on population density (Figure 2.9b).

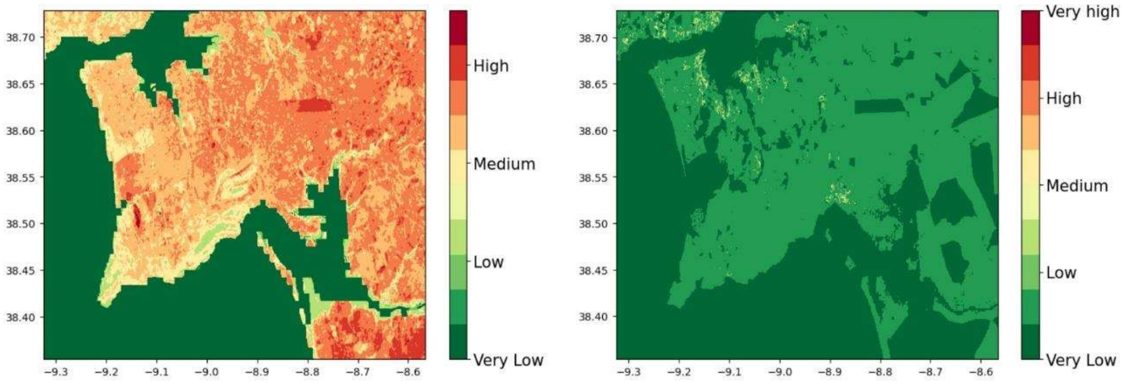
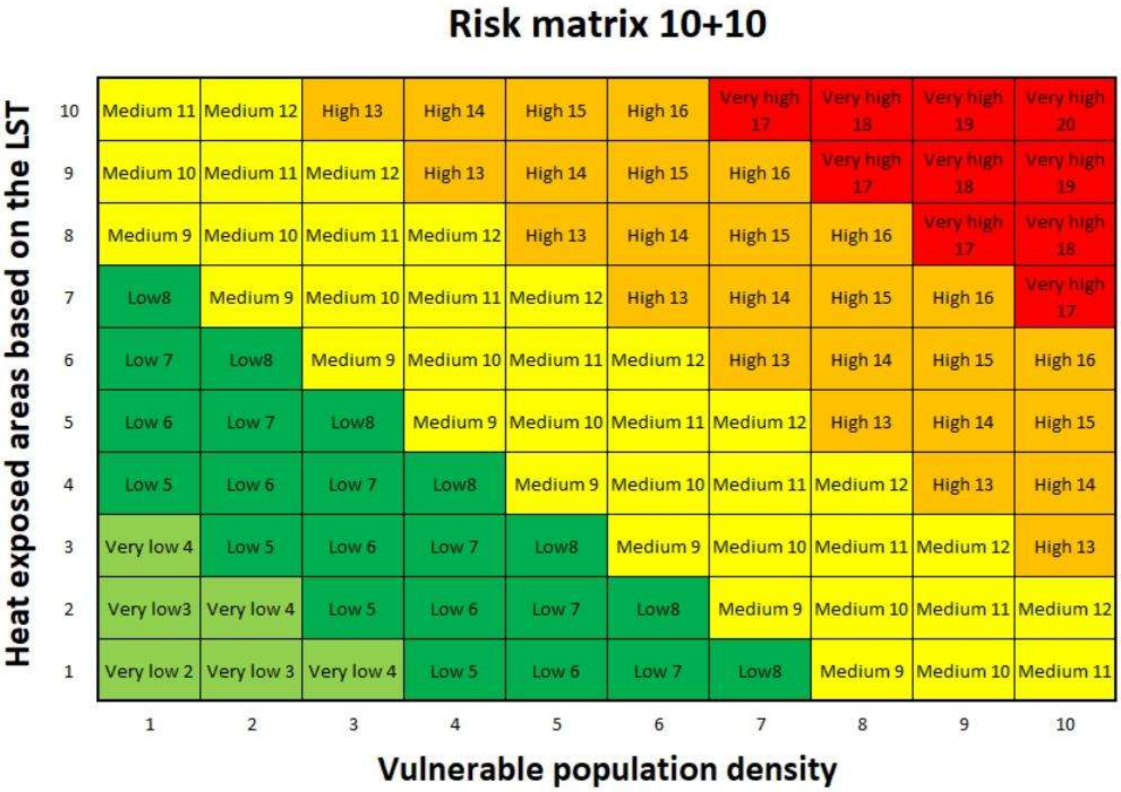


Figure 2.9: Overheated areas in 2017 (left) and the distribution of vulnerable population density in 2020 (right) across the Setúbal Peninsula.

The final risk map was computed using a 10+10 risk matrix (Figure 2.10). This matrix combines areas representing the highest risk of exposure to elevated temperatures with those of high vulnerable population density.


Risk matrix 10+10

Heat exposed areas based on the LST	1	2	3	4	5	6	7	8	9	10
10	Medium 11	Medium 12	High 13	High 14	High 15	High 16	Very high 17	Very high 18	Very high 19	Very high 20
9	Medium 10	Medium 11	Medium 12	High 13	High 14	High 15	High 16	Very high 17	Very high 18	Very high 19
8	Medium 9	Medium 10	Medium 11	Medium 12	High 13	High 14	High 15	High 16	Very high 17	Very high 18
7	Low8	Medium 9	Medium 10	Medium 11	Medium 12	High 13	High 14	High 15	High 16	Very high 17
6	Low 7	Low8	Medium 9	Medium 10	Medium 11	Medium 12	High 13	High 14	High 15	High 16
5	Low 6	Low 7	Low8	Medium 9	Medium 10	Medium 11	Medium 12	High 13	High 14	High 15
4	Low 5	Low 6	Low 7	Low8	Medium 9	Medium 10	Medium 11	Medium 12	High 13	High 14
3	Very low 4	Low 5	Low 6	Low 7	Low8	Medium 9	Medium 10	Medium 11	Medium 12	High 13
2	Very low3	Very low 4	Low 5	Low 6	Low 7	Low8	Medium 9	Medium 10	Medium 11	Medium 12
1	Very low 2	Very low 3	Very low 4	Low 5	Low 6	Low 7	Low8	Medium 9	Medium 10	Medium 11

Vulnerable population density

Figure 2.10: Risk matrix combining overheated areas and vulnerable population density.

Consequently, the risk matrix is used to estimate the severity of risk. Figure 2.11 presents the overlay of critical infrastructures, such as hospitals, schools, and emergency services, with potential heat risk levels for vulnerable populations in Setúbal municipality. The analysis highlights areas where the intersection of high vulnerability and essential services necessitates targeted mitigation measures to enhance resilience to extreme heat events. Of the 312 critical infrastructures identified, 36 are located in very low-risk areas, 191 are in low-risk areas, and 85 are in medium-risk areas. As of the writing of this report, no critical infrastructure is located in high-risk areas.

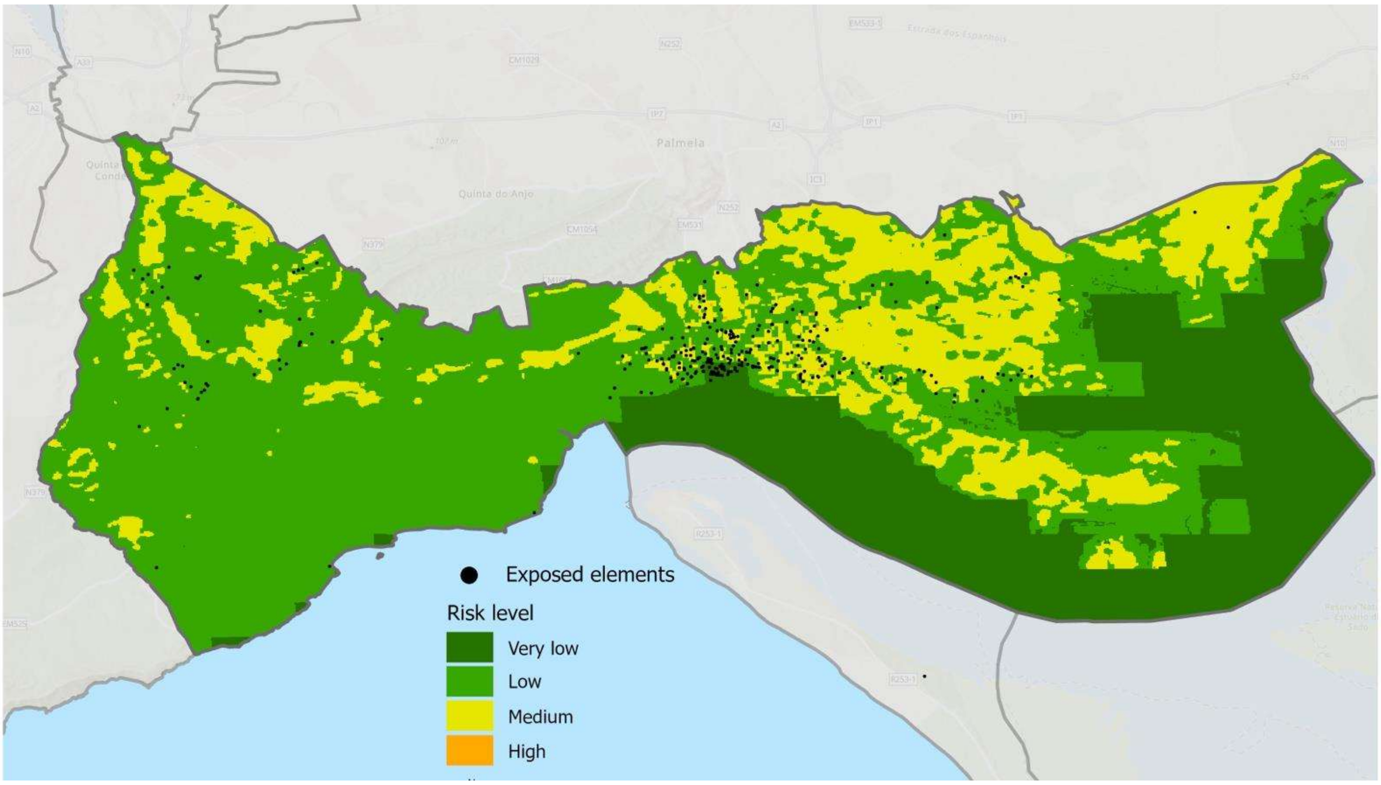


Figure 2.11: Potential heat risk level for vulnerable population and critical infrastructures in Setubal municipality.

2.2.4.3 Wildfire

Hazard assessment

The wildfire hazard assessment workflow for Portugal used data from the Fire Weather Index (FWI), sourced through the Copernicus Climate Data Store. The FWI is a climatic indicator that integrates daily observations of surface air temperature, rainfall, wind speed, and relative humidity, reflecting the influence of weather conditions and fuel moisture on fire behaviour. The index assigns a score ranging from 0 to 100, representing the suitability of climatic conditions for wildfire occurrence. This workflow enables the analysis of spatial and temporal patterns in FWI intensity, offering insights into changes in the duration and onset of the fire weather season. Seasonal variations in FWI intensity reveal how evolving climate conditions are impacting the likelihood and potential severity of wildfire events. The seasonal FWI estimated for Portugal (not shown) represents the mean Fire Weather Index value during the European fire season (June-September). It is calculated by summing the daily FWI values throughout the fire season and dividing the total by the number of days within this period. The FWI for Portugal can be interpret according to Table 2-1.

Table 2-1: Fire danger categorisation from the European Forest Fire Information System

FWI value	**Fire Danger Class**
< 11.2	Low
11.2 - 21.3	Moderate
21.3 - 38.0	High
38.0 - 50.0	Very high

50.0 - 70.0	Extreme
> 70	Very extreme

To estimate the fire season length for Portugal, two time periods were analysed: mid-century (2041–2070) and end-century (2071–2098), using projections based on the RCP 4.5 (not shown) and RCP 8.5 emission scenarios. The temporal series were obtained from the EURO-CORDEX dataset, with the global climate model MPI-ESM-LR. This model was chosen for projections in Portugal due to its ability to capture large-scale drivers, as described when assessing the heatwaves hazard assessment. FWI data from the historical period (1976–2005), derived from all available global climate models, was used as the baseline for calculating future changes.

The length of the fire weather season was calculated for each selected year as the total number of fire weather days, defined as days when the FWI exceeds a designated threshold. For Portugal, a threshold of 38 was used (see Table 2-1) to account for days classified as having very high, extreme, and very extreme fire danger levels. The length of the fire weather season is calculated in the historical and in the future periods to quantify the projected future changes. For the historical period, mid-century (2041–2070), and end-century (2071–2098), the "best," "worst," and "mean" case conditions are presented (Figure 2.12). The worst-case and best-case scenarios were calculated by respectively adding and subtracting the inter-model and inter-annual standard deviation of the fire weather season from the mean. This approach provides an estimate of the range of possible conditions, covering 95% of the potential distribution.

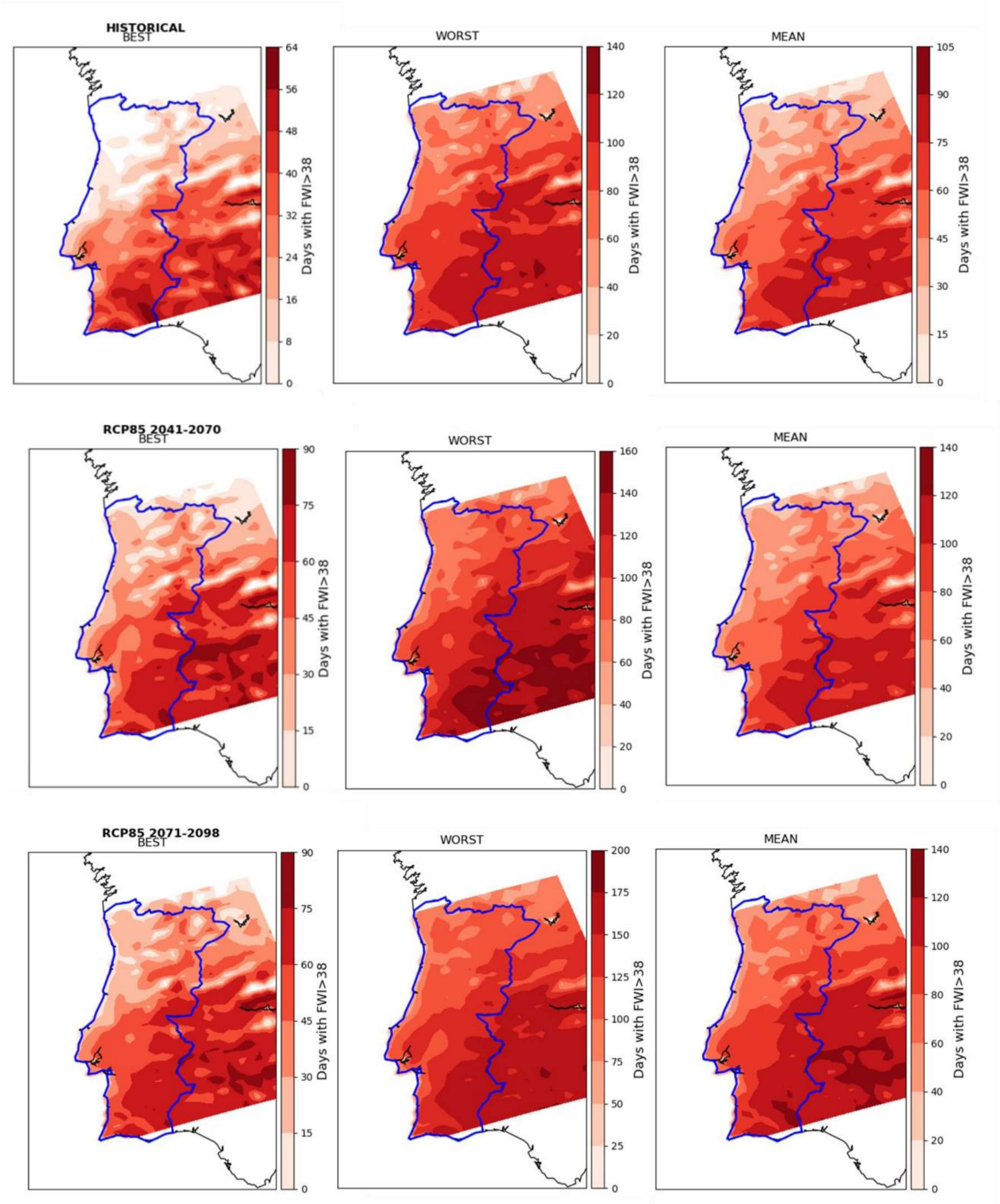


Figure 2.12: Number of days with FWI>38 in Portugal for RCP8.5. Top: historical reference period, Middle: mid-century, Bottom: end of century. The columns show the best case (left), worst case (center) and mean (right) values.

According to Figure 2.12, during the historical period, the Setúbal region experienced 16-32 days/year exceeding FWI > 38 in the best-case scenario. However, under the worst-case scenario, this number significantly increases to 60-100 days/year, indicating a substantial rise in fire risk. In the mean scenario, the number of days with FWI > 38 is projected to range between 30-45 days/year.

In the mid-century, under the RCP 8.5 emission scenario (Figure 2.12), the Setúbal region will experience 15-45 days/year exceeding FWI > 38 in the best-case scenario. Considering the worst-case scenario, this number increases to 80-120 days/year and in the mean scenario, the number of days with FWI > 38 is projected to range between 40-80 days/year.

In the late century, under RCP8.5 emission scenarios (Figure 2.12), the Setúbal region will experience 30-60 days/year exceeding FWI > 38 in the best-case scenario and 75-125 days/year in the worst-case scenario. In the mean scenario, the number of days with FWI > 38 is projected to range between 40-80 days/year.

Risk analysis

Risk analysis for wildfire was not conducted due to the low resolution of the FWI data. The Setúbal municipality is represented by only three grid cells (pixels) for each FWI dataset, making it impossible to differentiate hazard incidence across the municipality's territory. However, the analysis of Fire Weather Index (FWI) projections for the Setúbal region underlines a concerning increase in fire-prone conditions. During the historical period, the number of days per year with FWI exceeding 38 ranged from 16–32 days in the mean scenario. By mid-century, projections under the RCP 8.5 scenario suggest this will increase to 40–80 days/year, with a similar range persisting into the late century. This gradual yet significant rise in high-fire-hazard days underscores the urgent need for adaptive measures, including improved land management, early warning systems, and climate-resilient infrastructure to mitigate the escalating fire hazard.

2.2.5 Future plans

For the extreme precipitation workflow, we aim to analyse climate projections from a diverse set of models. Since no single model can fully encompass the range of potential future conditions, relying on multiple models allows us to address the inherent uncertainties in climate projections. By incorporating a variety of models that reflect this uncertainty, we ensure that the projections capture a broad spectrum of possible scenarios. This approach enables the exploration of a range of potential outcomes, from moderate conditions to more severe, worst-case scenarios.

For the heatwaves hazard assessment workflow, we aim to expand our analysis by incorporating climate projections from a broader set of models also suitable for estimating both past and future heatwave events in the Mediterranean environment, addressing the current limitation of relying on a single combination of global and regional climate models. In the heatwaves risk assessment workflow, we plan to test the use of NDVI-based emissivity, which provides a higher spatial resolution (30 m) and is also suitable for urban areas. For the vulnerable population analysis, we intend to use official census data to enhance the accuracy and reliability of our analysis.

For wildfire risk assessment, we aim to enhance our analysis by incorporating the machine learning approach with support from the CIMA team.

2.2.6 Conclusion

2.2.6.1 Usability of the results

The performed analysis has provided valuable insights into climate risk management, focusing on key hazards such as extreme precipitation, heatwaves, and wildfires. However, the Setúbal pilot faced significant challenges, particularly the spatial resolution of climate data from Copernicus, which limited the precision of the analyses at the municipal level. This constraint highlights the importance of acquiring higher-resolution datasets for more detailed and localized climate assessments at the municipal level.

While the results are not groundbreaking, they offer a foundation for improving workflows and methodologies in climate risk adaptation planning. The tools and approaches developed have helped clarify the types of data and processes needed for more accurate risk assessments and effective municipal planning.

2.2.6.2 Lessons learned for the project

The project provided important insights that can inform future work:

High-resolution data is essential: The resolution of the Copernicus climate data restricted the level of detail achievable in the analyses. Future work should prioritize integrating finer-scale datasets to enhance the accuracy of hazard and risk assessments.

Engagement with local expertise: Collaborating with municipal and academic stakeholders enriched the process, ensuring that the methodologies and final deliverables aligned with local needs and priorities.

Although the findings are constrained by the limitations of the input data, they have underscored the need for enhanced methodologies and data quality in future climate risk adaptation initiatives. These lessons will serve as a steppingstone for refining approaches to better meet the challenges posed by climate change in the Municipality of Setúbal.

2.3 Žilina

2.3.1 Background

Žilina is the fourth largest city of Slovakia, and capital town of a region and a district of the same name, home to 80000 inhabitants (city). Located in the north central part of the country, at the confluence of Váh, Kysuca and Rajčianka rivers. The Žilina city and district is a part of the Trans-European Transport Network (TEN-T) (Baltic Adriatic Corridor). The Žilina valley is characterised by continental climate and is exposed to a host of climate-related risks, including pluvial and fluvial floodings (and natural hazard-induced technological risks), protracted droughts (and subsequent forest dieback), forest fire, landslides and extreme heat.

2.3.1.1 Earlier work on CRA

The city of Žilina recognizes the need to address the current and projected impacts of climate change on the urban environment. To this end, they have commissioned the preparation of the document "Strategy and Action Plan for Adaptation to the Adverse Effects of Climate Change in the City of Žilina." The document identifies risks and proposes specific adaptation and mitigation measures.

Utilizing data from the Copernicus Climate Change Service, the EURO-CORDEX (Coordinated Downscaling Experiment - European Domain) suite of future climate projection models was used to analyse climate change hazards, and to estimate their impacts on the city. A model ensemble (average of 7 projections) was used to calculate the values of climate indicators for the future period under the RCP 8.5 emissions scenario and to assess climate change related risks in Žilina and its surroundings.

The analytical part of the document is based on data reflecting the current state of the climate. The generated information includes the current (2019-2021) extent of vegetation and its quantity, as well as built-up and mixed areas. Using these data, vegetation indices such as Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), Soil and Vegetation Moisture Index (NMDI), and Drought Monitoring Index (NDDI) were calculated. The municipality has also performed a citizen survey leading to creating an emotional city map of climate change and environment quality.

The adaptation strategy was prepared by a contractor who provided the Žilina municipality office with a ready report. The report provided all the information including pictures and graphs. Žilina was provided with explanations of how the results can be interpreted. Actions proposed to mitigate the individual risks identified in the strategy have been prioritised in the light of the results of the assessment.

The city of Žilina has data from mapping of feelings: Climate Feelings Map Žilina 2019, which is available in Slovak language[8]. They were obtained by collecting feelings and opinions of 501 city's inhabitants on the quality of the environment and the impacts of climate change. The mapping covered the current situation and proposals for adaptation measures to the negative impacts of climate change.

The first part mapped feelings on the listed threats of climate change: heat and extreme temperatures, locations with comfortable temperatures, excessive drought, heavy rainfall, flooding

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[8] https://www.pocitovamapa.sk/klima-zilina-2019/nahlad

on rivers and streams, air quality and lack of green space. In the second part, the public was involved in an exploration of the proposal in which spaces measures should be implemented to improve the negative effects of climate change and what these measures should be.

2.3.1.2 Short description of participants

Since the topic of climate change risk assessment and adaptation is relatively new to Žilina, a group of stakeholders has been gradually formed through activities such as CLIMAAX. We are still identifying who can contribute to this topic and how to best utilize the results of our cooperation. As a result, the team representing the city of Žilina in this project is quite diverse, involving several institutions through the part-time participation of their members.

The Žilina pilot has had participants in the CLIMAAX project from the following institutions:

- City of Žilina, Municipal Office – Principal member of the pilot city.
- Chief Architect's Office Žilina – A department within the municipal structure responsible for the development of the city's public spaces.
- University of Žilina, Faculty of Civil Engineering – Provides academic expertise on the project's topic within the city and supports the principal member.
- Fire and Rescue Corps in Žilina, District Headquarters – Part of the Ministry of Internal Affairs, offering experience in recovery actions after extreme weather events within the city.
- Innovation Centre INOVIA – Supports communication with stakeholders and facilitates teamwork.

All these participants are members of the CLIMAAX team contracted by the City of Žilina to carry out its project mission. By contributing directly to the project's results, they also create a connection between the CLIMAAX project and their institutions, thus forming a community of practice.

In addition, many more stakeholders have been involved in the Žilina pilot. An organigram which outlines the internal and external interactions of the pilot as well as the contributors and (potential) beneficiaries of the work are outlined in Figure 2.13.

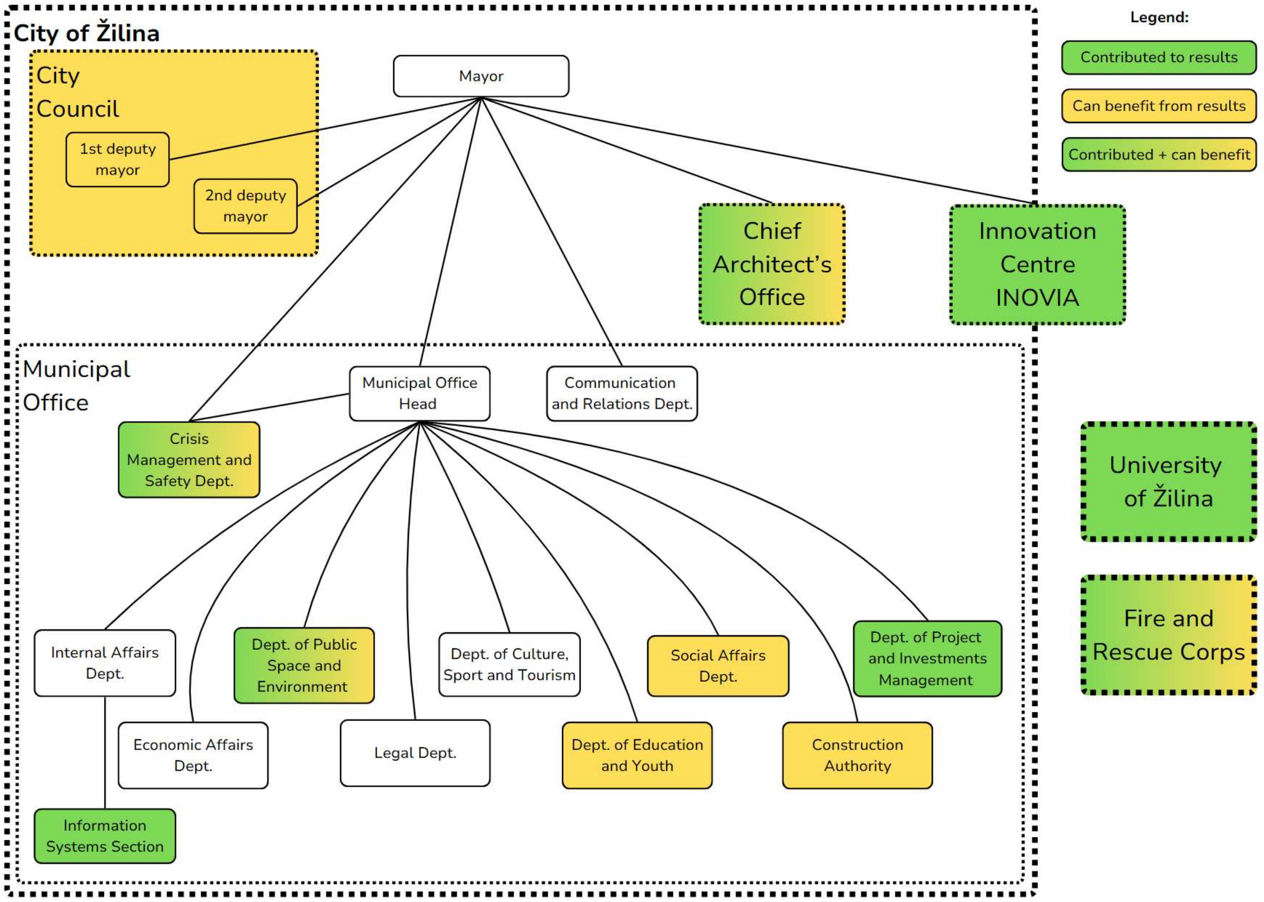

Figure 2.13: Organigram for the Žilina Pilot

2.3.1.3 Focus and goals of the CRA

We set the following goals:

- To have a system for regular assessment of climate risks on the territory of Žilina to be readily available at hand when needed, including a data collection system.
- To get scientifically supported arguments for further city planning and communication with stakeholders asking city's approval for their development plans.

2.3.2 Scoping and main hazard selection

2.3.2.1 Short overview over local climate

According to statistics, the local climate so far has been mild with the cycle of approximately evenly distributed 4 seasons with average temperatures of 17,3 °C in July and −3,1 °C in January. The average annual rainfall is 760-780 mm and there is snow cover from 66 to 75 days per year.

In the Köppen-Geiger climate classification, the Žilina territory belongs to the Dfb climate category, i.e. warm summer humid continental climate.

2.3.2.2 Main hazard selection

At the start of WP3, the CRA Framework was not yet available. Instead, the pilots selected the main climate hazards, and the related risks based on local knowledge and experience. The hazards and risks were then analysed to the extent possible. The project team has identified the following hazards actual for the pilot city: extreme heatwaves, urban flash floods, landslides, windstorms, droughts, blizzards, forest fires. The top priority has been given to extreme heatwaves and urban flash floods.

2.3.3 Risk Identification

2.3.3.1 Heatwaves

Heatwaves are prolonged periods of excessively hot weather that significantly impact health, agriculture, and infrastructure. To quantify the risks for our city, we consider the following factors:

- Temperature threshold
- Heatwave periods length
- Number of affected people

2.3.3.2 Urban Floods

Urban floods occur when heavy rainfall overwhelms drainage systems. To quantify the risks for our city, we consider the following factors:

- Frequency of rainfalls
- Intensity of rainfalls
- Land use and urban planning

2.3.4 Risk Analysis

2.3.4.1 Heatwaves

To analyse the heatwave hazard in Žilina, a workflow was developed for the CRA Toolbox, which was then adapted to the needs of Žilina municipality. To this end, the results from the CRA Toolbox workflow were integrated on satellite imagery and world population data . Landsat8 satellite imagery (the computed land surface temperature) was used for analysing the strength of the urban heat island, thereby identifying places exposed to the heat. Data about the distribution of the vulnerable population were obtained from the World pop website. To estimate the influence of heat on vegetation, we used the Sentinel2 L2A satellite imagery. From the heatwave workflow of the CRA Toolbox we obtained the probability of heatwave occurrences in the region.

Hazard assessment

The heatwave workflow of the CRA Toolbox provides three different methodologies to define heatwaves:

- the EUROheat[9] project's definition of a heatwave (Hooybergh, 2019)
- the heatwave definition established in PESETA IV[10] (Naumann et al., 2020),
- the XCLIM methodology that employs the XCLIM[11] Python library (Bourgault et al., 2023)

All three methods use the EURO-CORDEX climate model projections for their analysis. Please see CLIMAAX deliverables 2.2 and 2.4 for more details on the heatwave workflow. As examples of the

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[9] https://climate-adapt.eea.europa.eu/en/metadata/tools/euroheat-online-heatwave-forecast

[10] https://joint-research-centre.ec.europa.eu/scientific-activities-z/peseta-climate-change-projects/jrc-peseta-programme-detail_en

[11] https://xclim.readthedocs.io/en/stable/

workflow outputs, Figure 2.14 shows the occurrence frequency (number of heatwaves per year) and Figure 2.15 shows the number of heatwave days per year. Both figures show the results of the heatwave analysis for the PESETA IV method. In addition, the yearly heatwave occurrence, the PESETA IV method (which is based on percentiles of daily temperature distributions) also allows to analyse monthly heatwave (or hot spell) occurrences. A result of this analysis is shown in Figure 2.16.

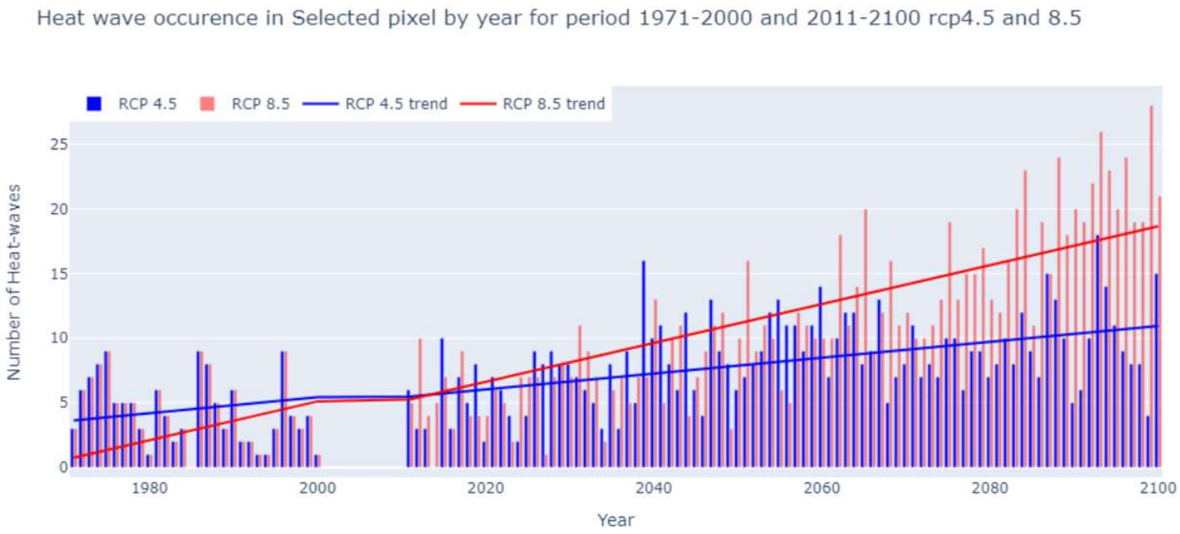

Figure 2.14: Heat wave occurrence frequency in Žilina city for both RCP4.5 and RCP8.5.

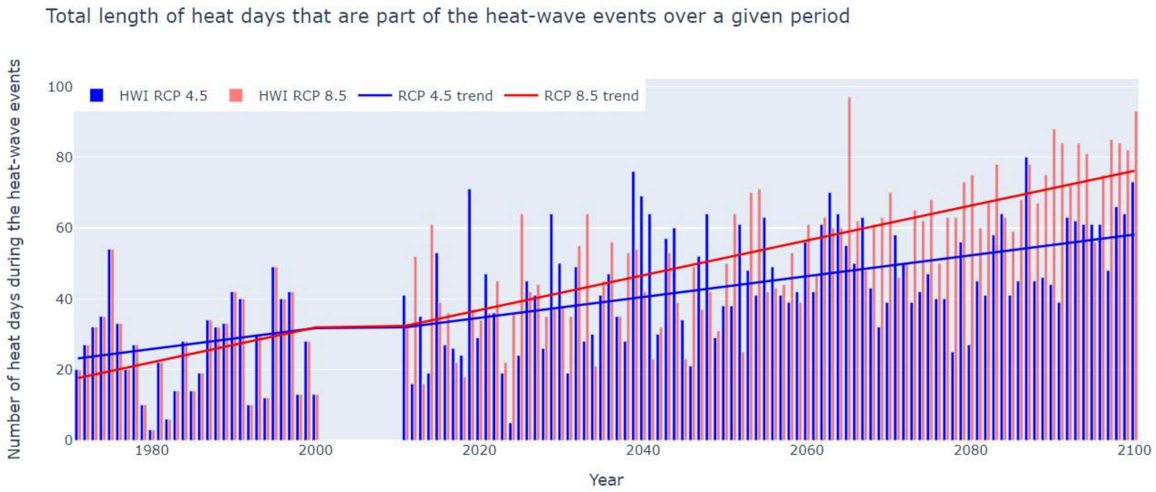

Figure 2.15: Total number of heat weaves per year in Žilina city for both RCP4.5 and RCP8.5.

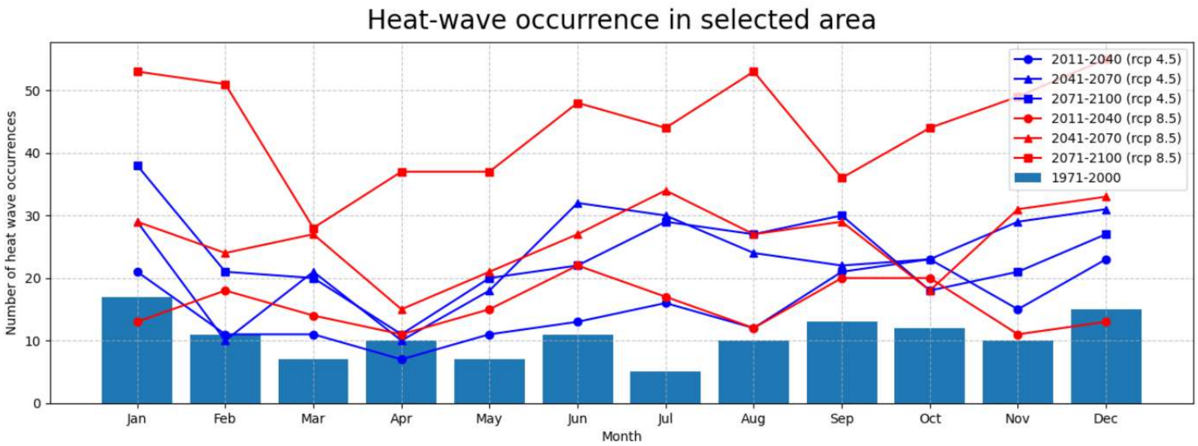

Figure 2.16: Total amount of heatwaves (or hot spells) in Žilina city during several 30-year periods, separated by month. The figure shows the historical reference period as bars, while the future projects are shown as line plots for RCP4.5 (blue) and RCP8.5 (red).

Risk analysis

To assess the risk associated with the heatwave hazard, we used a 5x5 Risk matrix, which divides both exposure and vulnerability into 5 classes (as an example, see Figure 2.10 in the Setúbal CRA report, where this has been done with a 10x10 matrix). Here, exposure was defined as overheated areas, i.e. with an average temperature above a regional reference temperature, which was then translated into 5 exposure classes (Figure 2.17, left panel). Similarly, the density of vulnerable population was translated into 5 vulnerability classes (Figure 2.17, right panel). For more details, please refer to the description of the heatwave workflow in Deliverable 2.4[12]. The two so categorised datasets were then multiplied for each grid point resulting in values between 1 and 25. These values were then combined with the different heatwave occurrence indicators (see CLIMAAX Deliverable 2.4[12] for details) to define the heatwave risk, which helped us identifying the most critical areas in the city. The result of this analysis is shown in Figure 2.18, which contains additional information about areas which are especially crowded.

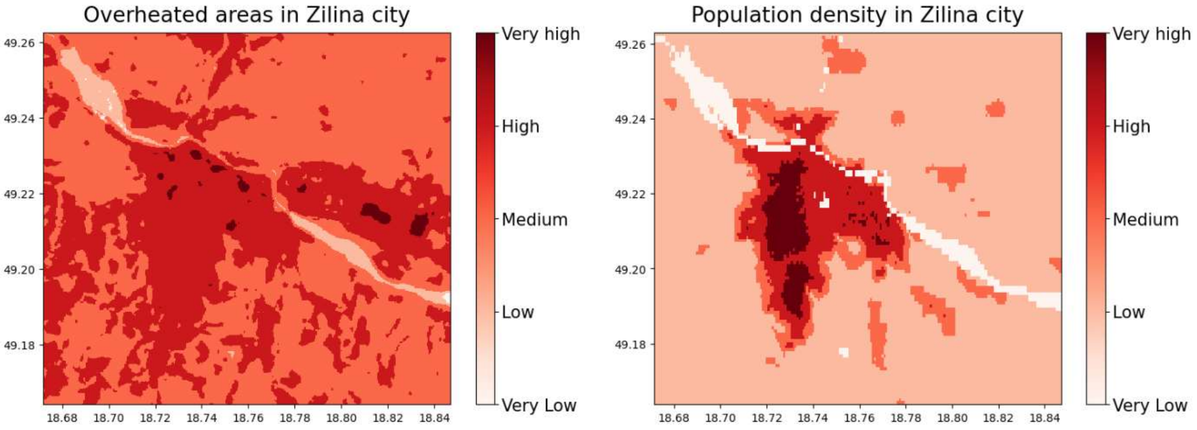

Figure 2.17: Overheated areas in 2017 (left) and distribution of the vulnerable population density in 2020 (right) in Žilina city.

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[12] https://files.cmcc.it/climaax/CLIMAAX_D2.4.pdf

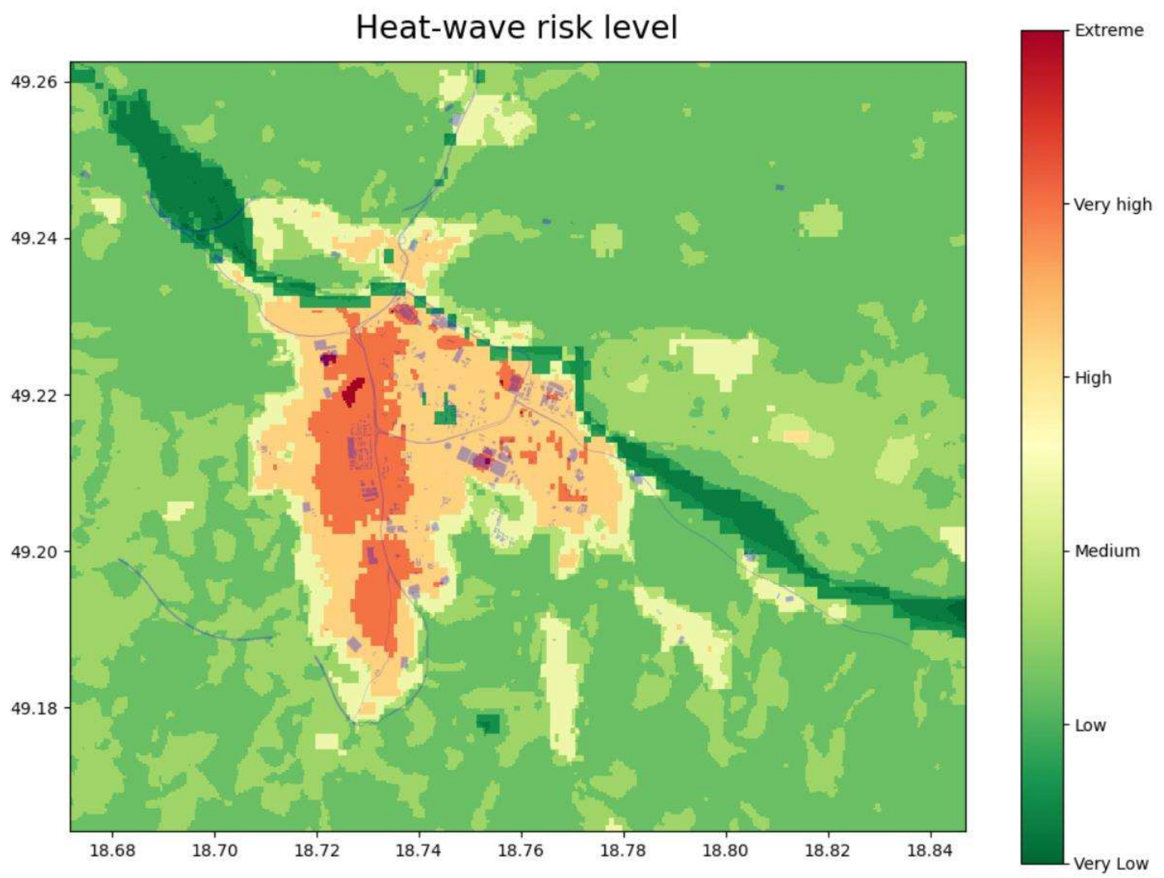

Figure 2.18: Heatwave risk to population in Žilina city (green to red colour bar), with most crowded areas overlayed in blue.

2.3.4.2 Urban Floods

The different flood workflows of the CLIMAAX Toolbox all use European datasets for flood extent and inundation depth for their risk calculation. These datasets only include the main European waterbodies and are not suitable for many local purposes, especially pluvial flooding. As CLIMAAX does not provide modelling tools, and resources of the project were not sufficient to perform detailed flood modelling at the Žilina city scale in time, Žilina ultimately decided to not include the results of this analysis into their CRA. The time constraint was here of special importance, because the results of the CLIMAAX CRA were presented to the Žilina city council at the end of 2024.

However, the pilot did collect historical data and visualised them on a map of the city (Figure 2.19). The map shows an analysis of past events (heavy rainfalls in the catchment areas of the city and the resulting urban flash floods) within the city.

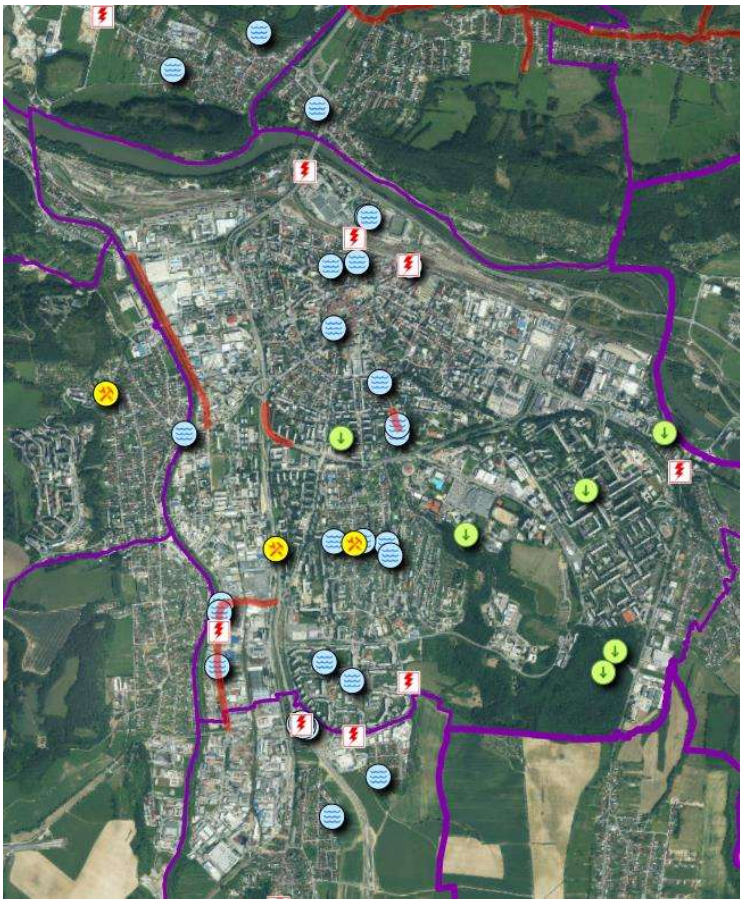

Figure 2.19: Map showing past urban flooding events in the city of Žilina.

2.3.5 CRA in Žilina with CLIMAAX results

2.3.5.1 Added value from project and key achievements

The project has yielded several significant outcomes through our pilot work:

- Analysis of Historical Data -- Conducted analysis of flooding incidents following heavy rainfall over the past 4 years
- Key results displayed via city GIS on a project-dedicated webpage: https://climaax-zilina.hub.arcgis.com/
- Key Learning:
    - Fire and Rescue Corps identified opportunities to improve their data collection methods for more detailed information
    - Mapped locations affected by urban floods within the past 5 years
    - Data Collection and Analysis
    - Gathered comprehensive data about vulnerable locations within Žilina
- Identified gaps in data collection, including:
    - Pupil population in schools
    - Number of clients in senior homes
    - Age distribution across different city districts
    - Critical infrastructure mapping in GIS
- Technical Integration
    - Technical partners supplemented local data with European sources

    - Developed specialized models for the city's needs
- Enhanced ability to identify risk spots with greater precision
- Alternative Approach to Investment Justification

While the project didn't directly quantify future incident severity, it introduced a valuable alternative approach. Through virtual reality simulation of future projections, the project enables:

- Detailed modelling of specific city districts or planned investment areas
- Integration of green-blue infrastructure solutions
- Simulation of extreme rainfall events and their impacts
- Visualization of water distribution patterns
- Assessment of potential damage and drainage timelines

This capability provides practical decision support for urban planning and infrastructure investments.

2.3.5.2 Current implementation of CRA

The city has established specific channels for implementing climate risk findings:

- The Main Architect Office integrates results into planning processes and investor communications
- Previous adaptation measures are being validated and strengthened through CLIMAAX project results, which demonstrate potential future impacts
- There is a need to expand implementation beyond technical departments to include broader stakeholder engagement

2.3.5.3 Framework impact and implementation challenges

Strengths:

- Brings new perspectives on values and principles into climate risk discussions
- Provides structured approach to process-oriented climate change adaptation
- Supports scientific argumentation for city planning decisions

Challenges:

- Municipal officials often don't prioritize addressing value and principle questions
- Limited capacity for broader citizen engagement despite recognizing its importance
- Need for better integration of existing data collection systems

Future Opportunities:

- Potential for expanded stakeholder engagement beyond current limited interactions with municipal officers
- Framework provides foundation for more systematic citizen participation
- Opportunity to develop more comprehensive participation processes when resources allow

2.3.5.4 Toolbox adaptability

For the heavy rainfall hazard, the toolbox has not fulfilled the ambition of providing detailed simulation of urban floods in local areas as mentioned above. The project partners have not found a solution to it despite of investing efforts and it remains to be a challenge for the future.

For the successful heat wave hazard, the main challenge has been to configure the solution in the local conditions. Here, the toolbox could become more robust and fault tolerant.

For the successful deployment and utilization of toolboxes, data and the level of detail in their processing are very important. The location where the toolbox is applied is also crucial—whether it's a region (in our context, a county or district), a basic administrative unit (city or municipality), or a smaller area where a significant investment or construction is planned.

Based on the desired outcomes, it is necessary to choose, adapt, and most importantly, understand the input data and correctly interpret the toolbox results. The adaptability of the toolboxes also depends on the user's experience. From our experience in Žilina, we can state that the main issue is not the adaptability of the toolboxes but rather the use of appropriate data. Obtaining suitable and more detailed data may lead to increased investment demands on municipal resources.

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2.3.6 Future plans

The Chief Architect's Office will use the results as a basis for city urban planning and as an argumentation base in discussions with investors. We are interested in making flood inundation and drainage models of planned infrastructure changes and calculate their impacts to show to the investors. We want to have clear arguments supported by clear visual information for the decision-making meetings to persuade the people in power.

In addition, we want to be able to perform the calculations on demand, always with up-to-date climate data to receive as accurate forecasts as possible. In the coming months we will explore what is possible within the CLIMAAX context and what is out of the scope and/or capabilities of the developed tools.

2.4 Catalonia

2.4.1 Background

Catalonia is a Mediterranean region in NE of Spain with a huge exposure to climate related hazards, the main hazards being flash floods and forests fires. In the past it registered one of the major floods in Europe (over 800 deaths in 1962) and several mega-fires. With a population of over 7.5 M inhabitants and an economy with a big component based in tourism and agriculture/food, it is a region with high vulnerability to climate change impacts. It has been one of the first regions in setting a Strategy for Climate Change Adaptation in 2011, that has been updated in 2021, and a specific law for fighting Climate Change (2017). In the last years the frequency and intensity of the climate-induced emergencies has increased in a noticeable way, especially in relation to wildfires, windstorms, and pluvial and flash floods.

2.4.1.1 Earlier work on CRA

The Regional Law 16/2017 on climate change aims at reducing CO2 emissions and facilitating the transition towards a carbon-neutral economy. Implementing the law, the Catalan Strategy for Adapting to Climate Change 2021-2030 (2023)[13], labelled as ESCACC30, sets the objectives and measures for the territorial, natural and socioeconomic systems to adapt to climate change and reduce its vulnerability.

ESCACC30 specifically asks Civil Protection to integrate climate change and its impacts in the planning and assessment of risks. The strategy also calls for enlarging and strengthening observation, alerting and communication systems on disaster risks; defining funding mechanisms for these types of systems; and incorporating climate risks in the spatial, urban, and sectorial planning. So far, civil protection planning rarely includes the climate change dimension.

2.4.1.2 Short description of participants

The Directorate General for Civil Protection (referred to as DGPC from now onwards) is part of the regional government of Catalonia (Spain). It manages and coordinates actions to protect people, properties, and the environment threatened by catastrophes or collective risks. The system is based on the collaboration of different services and resources, both of public and private ownership.

The DGPC regularly identifies and assesses risks and their impacts to define prevention and intervention actions, including information campaigns for the population and recovery tasks. From one side, the results of risk assessments serve to identify municipalities that are at high risk and should develop their own local plans. On the other hand, the study of risk facilitates the coordination of preparedness and response activities with operative teams at regional level (fire fighters, police, medical services, etc.). Plans and protocols are usually drafted in working groups and commissions, where different stakeholders are represented.

For the CLIMAAX project, the DGPC has built communities of practice (CoP) for the three main hazards to be tackled: wildfires, flash flooding/intense rainfall and heatwaves. The CoPs contain members from different organisations and institutions from the region that share their experience and data, which are included in Figure 2.20. Different organisations and institutions own and manage

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[13] https://canviclimatic.gencat.cat/ca/ambits/adaptacio/estrategia-catalana-dadaptacio-al-canvi-climatic-2021-2030/

data and knowledge that can be used in the CLIMAAX workflows while these and other actors can take advantage of the results from the project.

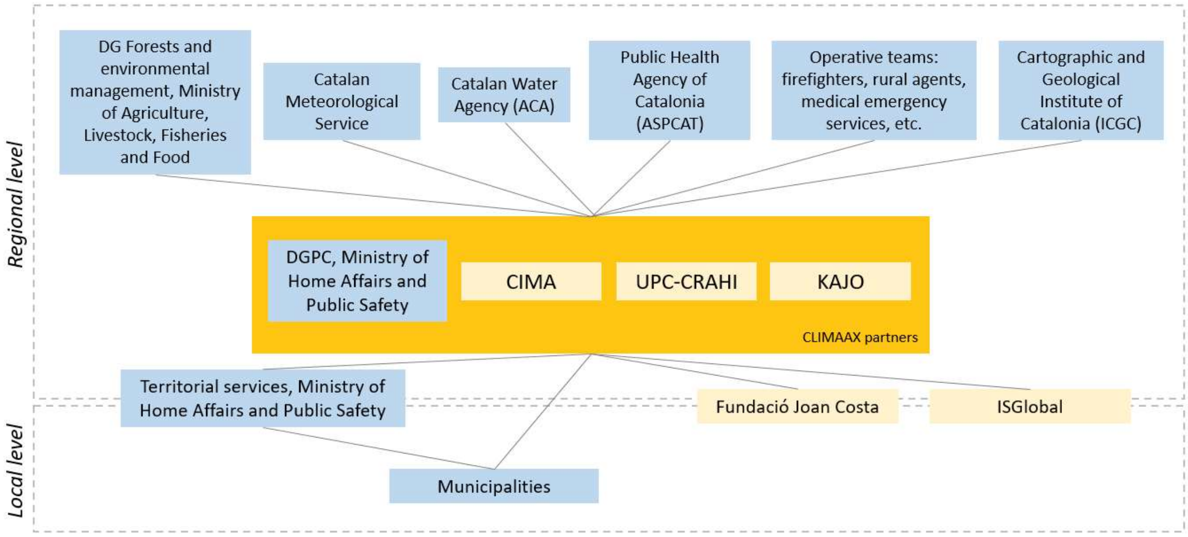

Figure 2.20: Organigram of the Catalonia pilot.

In addition to serving as the region’s point of contact for stakeholders and gathering their requirements and feedback, the DGPC also shares its expertise on the subjects and promotes the achievement of outcomes that are pertinent to all parties involved and appropriate in the local setting. The technical experience of the projects’ partners - CIMA, UPC-CRAHI, KAJO – helps to construct the workflows and desired outcomes.

2.4.1.3 Focus and goals of the CRA

Integrating climate change projections would reinforce the civil protection system in different ways, described below.

- First and foremost, CLIMAAX products will serve to detect risk hotspots, understood as areas and elements for which the risk will potentially increase. This is the case for communities that could experience higher fire danger in the future or areas that would be exposed to more frequent episodes of torrential floods and heatwaves. In the case of the municipalities of the region, which have the competence of civil protection within their territory, it can be helpful to identify for which risks they should prepare for and adapt to.
- In line with the previous, knowing how hazards and risk may change in time provides insights into how to update response and preparedness action at the regional level. In some cases, the projected severity of the hazards may suggest working on reducing the vulnerability of assets of interest (such as population and critical infrastructures). This is very much related to land-use planning and information/raising awareness campaigns.
- Actually, the DGPC would like to inform social groups and economic activities on how hazards and risks will potentially change in the short (next decade) and long-term, encouraging the protection of their own interests. Part of the efforts of the DGPC are devoted to informing citizens and organisations about how to self-protect and act to confront risk and emergencies.

- Besides citizens, messages should be clear for decision makers of the region to understand the main needs and added value of different options to prioritise funding for suitable adaptation, prevention, and preparedness actions.
- Finally, CLIMAAX could provide information to guide future efforts in disaster response, and to strengthen the coordination with operative teams. For example, understanding how the fire season could potentially become longer and the number of days of extreme temperatures serve to size efforts when preparing for and responding to these events.

2.4.2 Scoping and main hazard selection

2.4.2.1 Short overview over the local climate

The Catalan region, in the north-east of Spain, has 8 million people. Almost half of the population live around the city of Barcelona, and there is an important concentration of people living along the coast. Nonetheless, most of the municipalities are small; around 77% of municipalities have less than 5 000 inhabitants (see IDESCAT homepage[14]). The region is diverse geographically speaking. It has more than 500km of coast and different mountain ranges. The highest grounds are found in the north of the region, in the Pyrenees. There is a big river basin, the Ebro, and many medium and small basins that generally lead to the Mediterranean Sea.

Overall, the Catalan region has a Mediterranean climate, with mild temperatures during the winter and dry and warm summers. The rainfall pattern in the region is very irregular, with possible torrential episodes close to the coast in autumn. Following the Köppen-Geiger climate classification, the coast is generally classified as Csa (hot-summer Mediterranean climate) although the western part of the region is even classified as a cold semi-arid climate (BSk). Moving from the coast inland, the annual precipitation decreases, and the thermal amplitude increases. Most of the inland part of the region is classified as temperate. The mountain areas of the region generally experience lower temperatures and higher amounts of rainfall. Certain areas in the Pyrenees can experience a more continental climate (Dfc and Dfb). The Spanish National Meteorological Agency states that in the last decades the arid climates have expanded in the Iberian Peninsula, while the temperate (C) and cold (D) climates have seen their areas reduced (Bernabé et al., 2023).

The climate scenarios prepared by the Regional Meteorological Service state that a warmer and drier region is expected in the future (Altava-Ortiz and Barrera-Escoda, 2020), in line with the latest IPCC report (2021) conclusions. The annual average temperature will increase: both the maximum and minimum temperatures are expected to increase, leading to more tropical and torrid days and nights. The change in the annual precipitation is more uncertain, although a reduction in this variable is observed. At the same time, intense rainfall events can increase in frequency, while the number of consecutive days with no rain will potentially increase, leading to more intense dry periods.

2.4.2.2 Main hazard selection

At the start of WP3, the CRA Framework was not yet available. Instead, the pilots selected the main climate hazards, and the related risks based on local knowledge and experience. The hazards and risks were then analysed to the extent possible. The territory of Catalonia, which suffers from recurrent wildfires yearly, is vastly occupied by forests and shrubs (see IDESCAT homepage[15]).

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[14] https://www.idescat.cat/indicadors/?id=aec&n=15225

[15] https://www.idescat.cat/indicadors/?id=basics&n=10547

Considering the future increase in temperature, decrease in rainfall and more consecutive dry days, as Civil Protection we are interested in knowing if new areas would be potentially at higher risk of wildfires, how long the season could become, or if fire would change in behaviour in these extreme conditions.

The largest damages and losses registered in Catalonia are related to floods. Most of the casualties are reported in secondary basins, in small watercourses and canyons. Due to its fast behaviour, as Civil Protection we would like to focus on flash floods. High rainfall intensities in short periods of time can lead to flash flooding. Considering that the frequency and intensity of such events are likely to evolve under the influence of climate change, it would be useful to understand how these variations will materialise in the territory to anticipate action.

Our third priority in CLIMAAX is on heatwave events, due to its large impact on population and economic activities. In the face of climate change, we need to reinforce our knowledge of these events and work closely with other stakeholders to better plan, prepare and respond to heatwaves. Besides the three hazards mentioned, the DGPC is interested in getting insights on other events, such as river and coastal flooding.

2.4.3 Risk Identification

The civil protection system manages and coordinates action to protect people, properties and the environment. When designing action (preparedness and response), it is key to contemplate:

- The time available for reaction (based on the information given by studies/forecasts and its related uncertainties),
- the characteristics of the hazard,
- and the context.

Similarly, to prepare the population and the authorities for different types of activities (communication campaigns, drills and exercises, procure and organise material and human resources, etc.), DGPC is interested in having information on the dimensions of risk separately: hazard, exposure and vulnerability.

CLIMAAX represents an opportunity to understand how hazards will materialise in different climate change scenarios, while we provide our own data on exposure and vulnerability of population, properties and services/infrastructures of interest. In particular, it is helpful to obtain information on the future exposure and vulnerability of key infrastructures, such as road and railways, and activities which are particularly dangerous or vulnerable.

2.4.4 Risk analysis

The DGPC needs more information on how climate change will affect the different hazards of natural origin, and how these are already materialising into more frequent and impactful consequences. In order to capture the uncertainty of possible future emissions, and considering that civil protection aims at mitigating and preparing to major disasters, the risk analysis phase provided results for RCP 4.5 and 8.5 and different time windows up to the end of the century. DGPC worked with CIMA Foundation, UPC-CRAHI and KAJO to shape and obtain relevant results for wildfires, intense rainfall, and heatwaves, respectively.

2.4.4.1 Wildfires

The ML wildfire workflow (see Deliverable 2.4[16] for more details) has only been fully implemented for Catalonia during the pilot phase of the CLIMAAX project. It provides an understanding of the new areas of potential risk in the territory, assuming that the geo-environmental conditions do not change much in the future. Three features have been mapped for Catalonia under RCP 4.5 and 8.5 scenarios and for four periods of time: 2021 –2040, 2041 – 2060, 2061 – 2080 and 2081 – 2100.

- The **susceptibility of the territory** to experience wildfires in the future. The susceptibility maps produced represent the propensity of an area to experience fire in a given time window where climate conditions and land cover do not change drastically. The maps are generated by a trained machine-learning (ML) model, which crosses past fire history and geophysical-climate indicators. The algorithm utilises topographic data (provided my MERIT DEM – YAXA), land cover information (in this case, CORINE land cover), historical climate data (ECLIPS2.0 Cordex based dataset is adopted), and past fire polygons (provided by the Regional Government of Catalonia, ranging from 1986 to 2022). The CORINE land use types that entered in the calculation are aligned to the definition of wildfire events used in the region. Five climatic models were combined to obtain results. The standard deviation of these was calculated for each of the maps (Figure 2.21) showing that results are generally in agreement with the average shown in the susceptibility map that combines all models.
- The **fire hazard**, which combines susceptibility maps with fuel maps generated by aggregating CORINE Land Cover data. This process requires using a hazard contingency matrix to assign intensity levels to different susceptibility levels based on four main fuel types (grassland, shrubland, coniferous and broadleaves). High hazard values are assigned to pixels where high-intensity wildfires are likely to happen. The wildfire hazard is categorised in six classes, from very low to extremely high for each RCP and every time window analysed.
- The **wildfire risk** suffered by certain assets in the territory: population, socio-economic activities, infrastructure and protected areas. These maps are obtained crossing hazard maps for a given RCP (and time window) to vulnerability layers and exposed assets. The Catalonia pilot studied the exposure of different assets of interest, such as transport infrastructure, industries that have to follow SEVESO–III Directive, and vulnerable activities, such as campsites. An example of the results obtained for the road network of an area of Catalonia is shown in Figure 2.22.

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[16] https://files.cmcc.it/climaax/CLIMAAX_D2.4.pdf

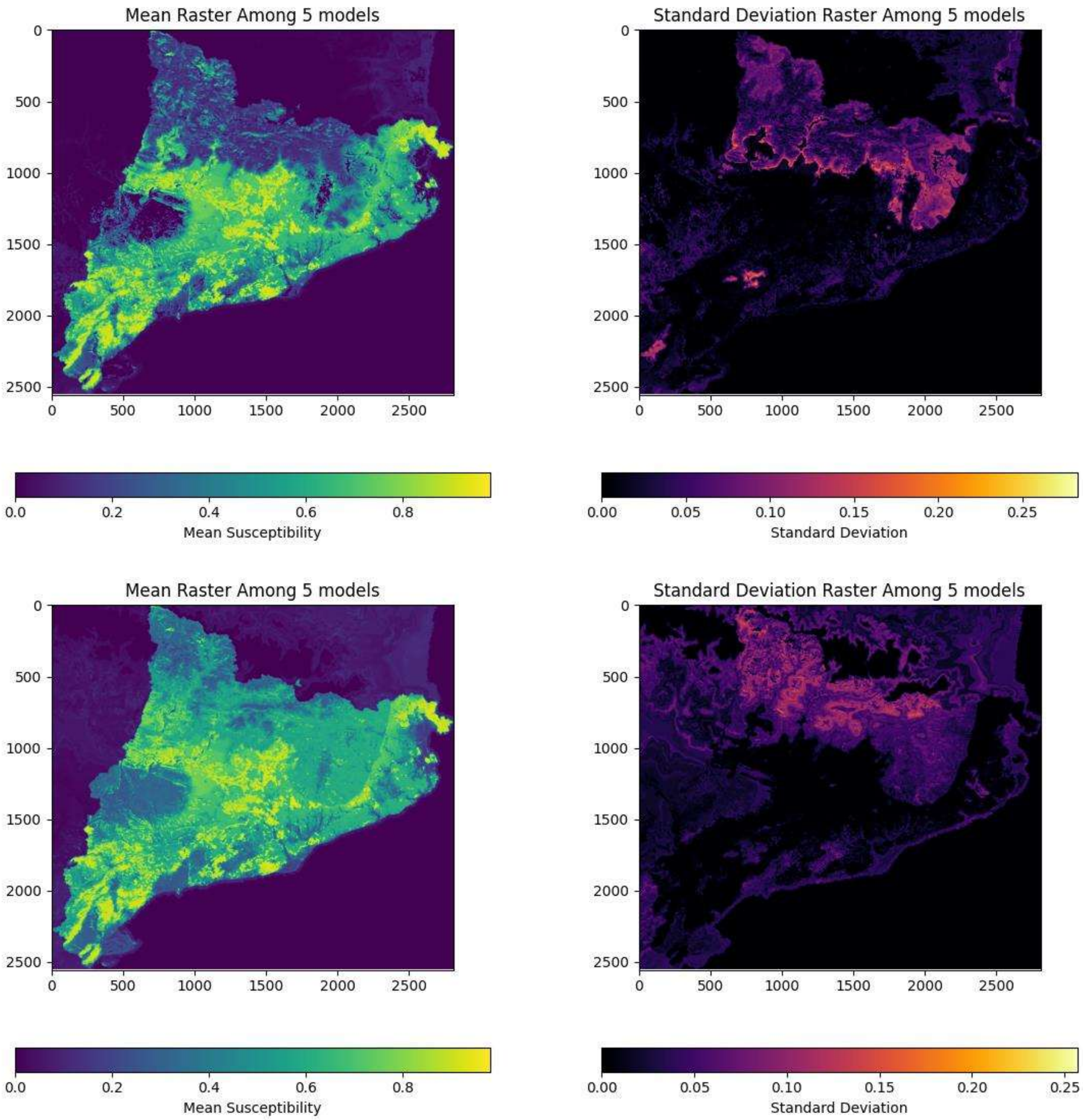

Figure 2.21: Susceptibility maps(left) for RCP8.5 based on the average values of the different models used, accompanied with the standard deviation (right), for the time windows 2021-2040 (top) and 2081-2100 (bottom).

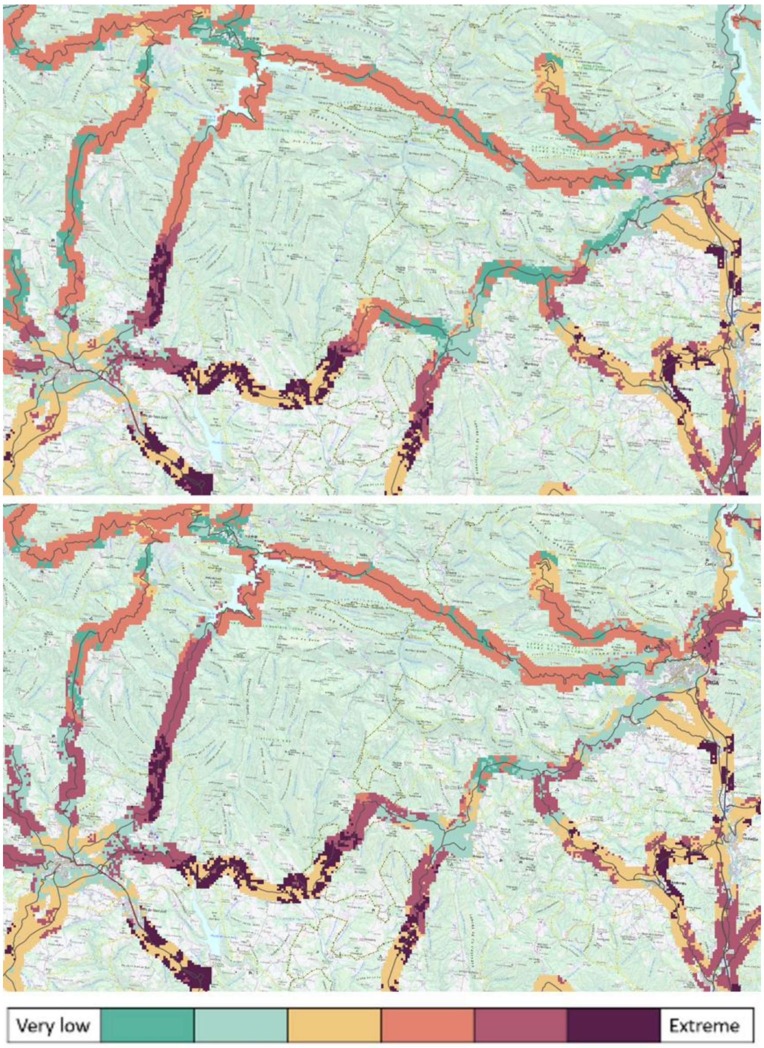

Figure 2.22: Visualisation of the exposure of roads to wildfire hazard classes in present conditions (top) and its projection in 2061-2080 for RCP 4.5 (bottom) using the CLIMAAX Toolbox.

In order to focus the attention of users to the new areas threatened, the Toolbox allows to estimate the difference between future hazard and present one. The preliminary results indicate that the Pyrenees will see an evident increase of danger as well as big forest masses in the south of the region in the long term for both under RCP 4.5 and 8.5 scenarios.

The CLIMAAX Toolbox proposes an additional approach to study wildfire hazard using the Fire Weather Index (FWI), developed by CMCC and FMI. CIMA applied it to provide insights on how the fire season length could potentially evolve based on the occurrence of extreme hazard days (FWI>50) in the present and in the future under RCP 4.5 and 8.5 using five climate models. The workflow predicts the best, mean and worst-case scenario. On average and under RCP 8.5, the occurrence of days of extreme FWI values could almost double in many parts of the territory towards the end of the century (Figure 2.23). In a worst-case scenario and for RCP 8.5, the days of extreme wildfire hazard will be experienced everywhere in the region and most of the territory could face this level of danger for at least 60 days per year.

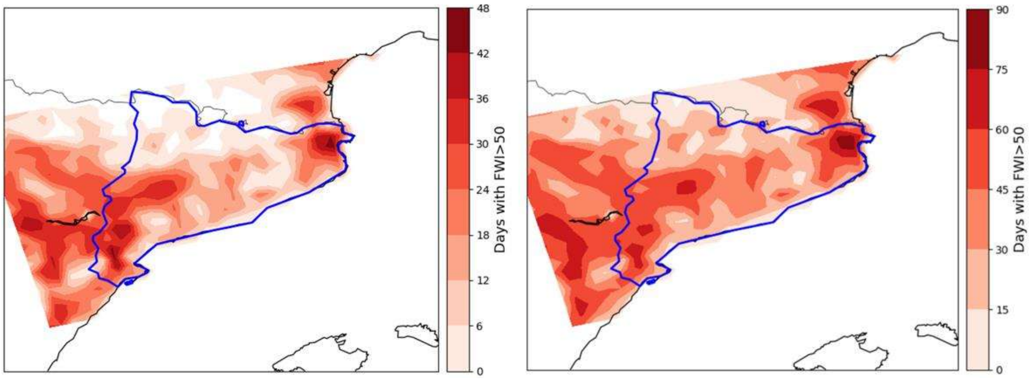

Figure 2.23: Number of days of extreme wildfire danger in the territory of Catalonia historically (left) and its projection for the period 2078-2097 in an RCP 8.5 scenario (right).

2.4.4.2 Heavy rain

Taking into account that torrential and urban floods are usually triggered after episodes of intense rainfall, the UPC has developed a workflow comparing the EURO-CORDEX climate projections for precipitation with critical rainfall thresholds for the area of study. The workflow allows the pilot to study how the frequency and intensity of their rainfall episodes will evolve in the RCP 4.5 and 8.5 climate scenarios.

The current regional emergency plan for flooding (INUNCAT) contains various indicators to guide the issuance of alerts and support decision-making. In terms of forecasted amounts, there are two indicators: one for low risk, based on forecasted events of more than 100mm of rain in 24h, and one for high risk, represented by events expected to be of at least 200mm in 24h.

For this analysis, a multi-model ensemble mean approach was employed to account for the uncertainties in predicting future climate conditions. Three different Global/Regional combinations were selected based on their availability in both bias and non-bias corrected EURO-CORDEX datasets simulations. These are ichec-ec-earth/RACMO22E (Ireland/Netherlands), mohc-hagdem2-es/RACMO22E (UK/Netherlands) and mpi-m-mpi-esm-lr/SMHI-RCA4 (Germany/Sweden). In the reference period (1976-2005), events of 100mm/24h are very frequent in the south and the northeast of the region, both in the coast and in the Pyrenees. Under RCP 4.5 and 8.5 scenarios, the workflow shows that these types of rainfall events will become more frequent in other parts of the Pyrenees and on the coast (Figure 2.24). Similar results were obtained for events of 200mm/24h.

The workflow allows to visualise the shift of the return period and intensities when comparing future and present values. Results indicate that the mentioned events will become much more frequent in the central-western part of the region. In terms of intensity, it is expected a general increase of intensity in the region, particularly in the long-term.

The same analysis was done for rainfall events of 60mm/3h and 80mm/3h, as potential indicators for short episodes. For rain episodes of 60mm/3h, the expected changes in terms of frequency and intensity are in line with the findings for longer episodes.

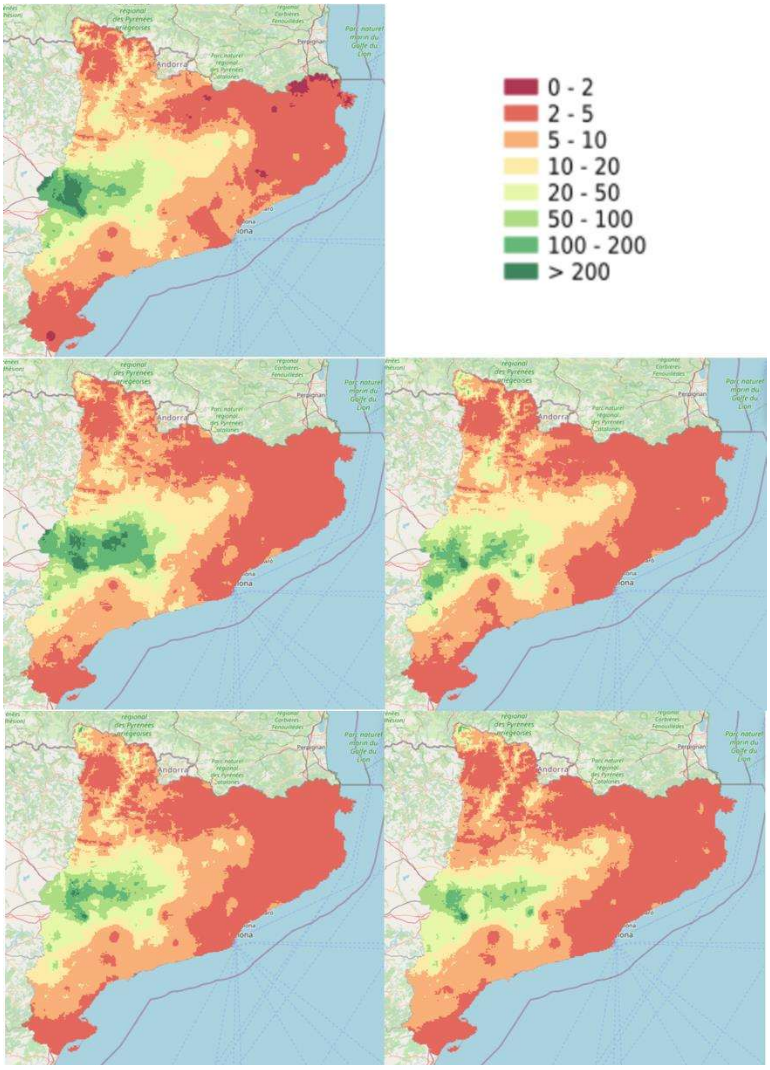

Figure 2.24: (top row) Return period (years) for rainfall episodes of 100mm/24h in the current climate. (middle row) mid-century projection of the same values for RCP 4.5 (left) RCP8.5 (right). (bottom row) end of century projection for RCP4.5 (left) and RCP8.5 (right). Results were obtained using data from three climate models (see text).

2.4.4.3 Heatwaves

The Catalonia pilot used the PESETA IV method to define heat days as days when the maximum temperature exceeds the 98th percentile of the reference period (2014-2023). A heatwave was then defined as a sequence of at least 3 consecutive heat days. This analysis was performed for the summer months only. Figure 2.25 shows the evolution of the number of heatwaves defined in this way over the timeline of the 21st century. An increasing trend towards the end of the century is clearly visible, especially for the RCP8.5 scenario.

Using the same definition for heat days and heatwaves as above, but for a different reference period (1971-2000), the occurrence of heatwaves was further analysed on a per-month basis. The results are shown in Figure 2.26: the increase of the heatwave occurrence frequency towards the end of the century is evident for both RCP4.5 and RCP8.5 scenarios. Furthermore, one can also clearly see that the typical heatwave season extends from mainly August in the reference period to include also July and September. This is especially evident for the end of the century in the RCP8.5 scenario.

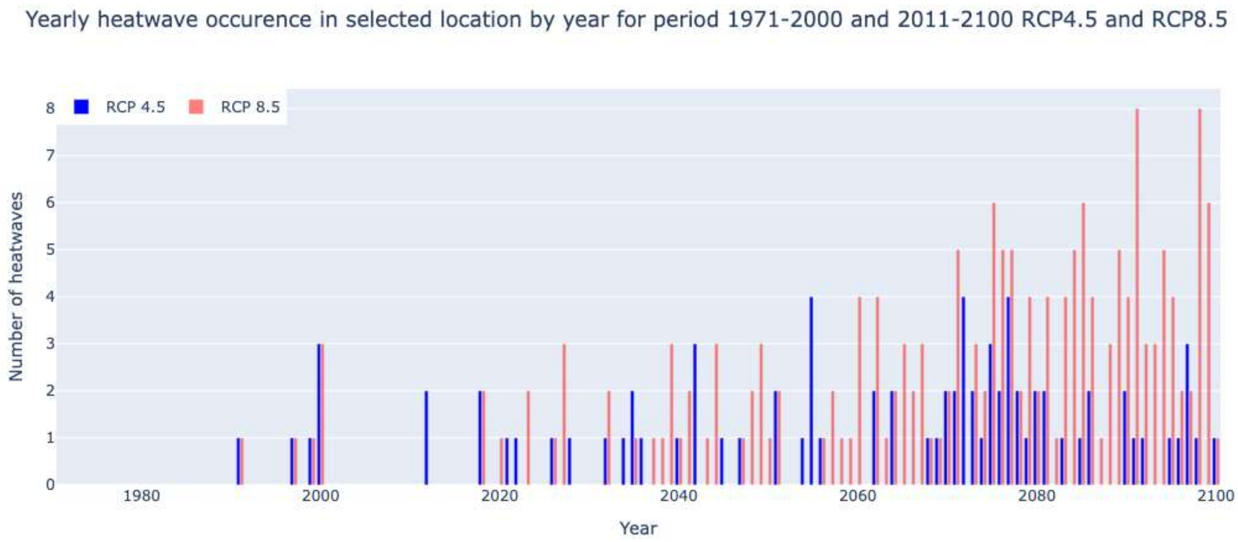

Figure 2.25: Number of heatwaves in Barcelona per year from 1970 to 2100 in RCP 4.5 (blue) and RCP 8.5 (red).

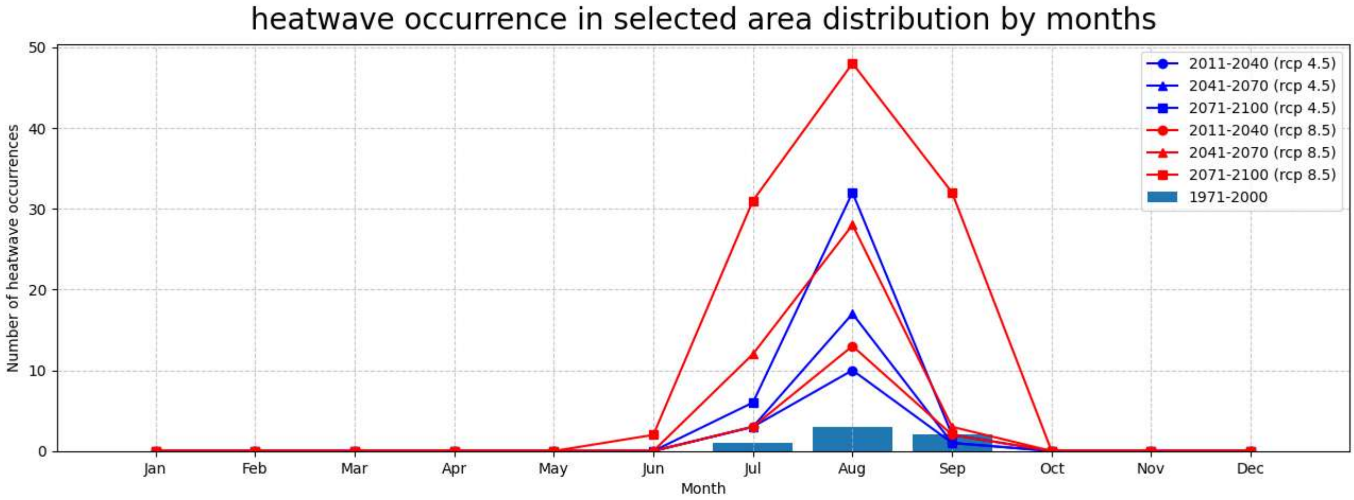

Figure 2.26: Total number of heatwaves during a 30-year period in Barcelona in the reference period (1971-2000) shown as bars, and the projected number of heatwaves for the periods 2011-2040, 2041-2070 and 2071-2100 in RCP 4.5 and 8.5.

2.4.5 Findings

The first results obtained applying the CLIMAAX Toolbox in Catalonia show that there will be a potential increase of hazard and risk in the territory due to wildfires, heavy rainfall and heatwaves.

As shown above, the susceptibility to wildfires and wildfire hazard will increase in Catalonia in the future, particularly in areas of the north of the region where wildfire events have been rare so far. In terms of precipitation, the frequency of the events will change. The centre-west of the region will experience more frequent and intense episodes in the future both for RCP 4.5 and 8.5 scenarios. Finally, and in alignment to IPCC 2021, the number of heatwave episodes will significantly rise in Catalonia, becoming more recurrent under the RCP 8.5 scenario. In order to ensure that we pass relevant and complete messages, it is necessary to consider the trends, the projection of variables and the potential change of these when compared to present situation of different variables.

The time variable is key for civil protection to prepare and act in case of emergencies. It may be critical to update the existing detection and early warning systems and the actions triggered by the thresholds agreed. Nonetheless, the current workflows on wildfires do not allow to study the intensity of these events and its capacity to spread, which are topics of concern in the region in view of the more extreme wildfires seen in the last years.

As heatwave episodes are increasing in number, we will need to see if these will become longer in their duration to prepare efficiently. Besides that, the region issues alerts for individual intense warm days and warm nights. It may be interesting to study the distribution of these type of days in order to capture episodes that can have also fatal consequences.

The heavy rainfall workflow in the Toolbox could serve to signal the spatial distribution of urban floods in the territory although other factors at basin level (such as terrain gradient, soil type and vegetation cover) should be integrated to study how precipitation could turn into flash flooding downstream. Areas that may not necessarily see big intensities of rainfall could be impacted, challenging the capacity to protect citizens and key assets.

2.4.6 Future plans

The participation of the DGPC in CLIMAAX project has been an opportunity to advance in understanding how climate change will affect civil protection capacities and interests. The results of CLIMAAX will be disseminated within the institution and partners and they may be used for different purposes.

- First of all, we would like to present the most relevant outputs obtained in the Civil Protection map (Generalitat de Catalunya[17]), which contains information of current risks for citizens and organisations. Furthermore, the main conclusions should be integrated in raising awareness and educational campaigns.
- Divulgate the project, its results and its products to municipalities of the region as they have the competence to plan for and act towards the risk that could affect people and properties within their municipal boundaries.
- Integrate the results in the discussions and updates of hazard plans at regional level, to strengthen prevention and preparedness action.

To ensure that the main outputs of CLIMAAX are correctly understood by non-expert audiences, it is necessary to adapt the outputs of the workflows to concise and relevant findings. This step is key to ensure its applicability in the region. Moreover, the outputs of CLIMAAX can show a partial picture of the future projections on the different dimensions of risk so the limitations and the variables not covered by the CLIMAAX outputs must be displayed to the audience, complementing the main conclusions with other studies and reports on the topic. The remaining gaps in knowledge and the limitations in the various risk analysis carried out should be highlighted to be addressed by future research.

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[17] https://pcivil.icgc.cat/

2.5 Latvia

2.5.1 Background

In Latvia, there is no national agency in charge of climate risk and vulnerability assessments. Instead, the 43 municipal cooperation territories (NUTS3) are responsible for developing civil protection plans, which include all aspects of climate change adaptation. The identified related challenges include a lack in administrative capacity, coordination of action, data collection processes, involvement of the private sector, and lack in available funding for risk assessment and adaptation strategy development.

2.5.1.1 Earlier work on CRA

In Latvia, the risk assessment process is governed by the Civil Protection and Disaster Management Law (2016) (Law No. 100, 5672/2016)[18], which aligns with ISO 31000 standards and defines three primary stages: risk identification, risk analysis, and risk evaluation. The national risk assessment is incorporated into the National Civil Protection Plan (NCPP) (2020)[19], which was adopted in 2020 and drafted by the State Fire and Rescue Service.

Climate-related risks and their potential impacts are comprehensively addressed in Latvia's Climate Change Adaptation Plan for 2030 (CCAP) (2019)[20]. The CCAP focuses on the effects of climate change across various sectors of the Latvian economy, proposing over 80 specific measures aimed at enhancing adaptation for both the population and the economy.

Both the NCPP and the CCAP are underpinned by six sectoral risk and vulnerability assessments, conducted by expert groups as part of the project titled "Development of a proposal for the National Climate Change Adaptation Strategy, identifying scientific data and measures for ensuring adaptation to climate change, as well as carrying out impact and cost assessment," funded by the European Environment Agency (EEA) and Norway Grants (2009–2014). This project, known as the "EEA project" (2020)[21], provided the scientific foundation for these strategic documents.

According to the Cabinet Regulation No. 675 (2022) on "Procedures for Establishing and Maintaining the System for Greenhouse Gas Inventories, the Projection System, and the System for Reporting on the Adaptation to Climate Change," adopted in 2023, the Latvian Environment, Geology, and Meteorology Centre (LEGMC), in collaboration with the Ministry of Climate and Energy, is tasked with climate change monitoring. LEGMC is responsible for collecting data from the six sectors (landscape planning and tourism, biodiversity and ecosystem services, civil protection and emergency assistance, construction and infrastructure planning, health and well-being, agriculture and forestry), calculating the relationships between climate data and sectoral information, and providing future climate projections, along with analysing historical climate trends in Latvia.

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[18] https://likumi.lv/ta/en/en/id/282333-civil-protection-and-disaster-management-law

[19] https://likumi.lv/ta/id/317006-par-valsts-civilas-aizsardzibas-planu

[20] https://likumi.lv/ta/id/308330-par-latvijas-pielagosanas-klimata-parmainam-planu-laika-posmam-lidz-2030-gadam

[21] https://www.varam.gov.lv/lv/projekta-ietvaros-veikto-petijumu-nodevumi

2.5.1.2 Short description of participants

Before the initiation of the CLIMAAX project, Latvia had established documentation and conceptual frameworks addressing climate risk assessment. However, from the perspective of the project partners at the Latvian Environment, Geology, and Meteorology Centre (LEGMC), this initiative represents their first direct involvement in the development and implementation of a comprehensive climate risk assessment. Although the LEGMC team possesses extensive expertise in analysing climate change data and conducting climate-related research, their routine responsibilities primarily centre on data analysis, climate monitoring, and projections, rather than conducting in-depth assessments of climate risks at national or regional scales. LEGMC's core responsibilities in climate-related tasks include climate monitoring and data collection, analysing past climate changes, producing climate change projections, managing greenhouse gas inventories, operating early warning systems, and raising public awareness.

The Climate and Energy Ministry serves as the central authority overseeing climate change-related tasks in Latvia, functioning as the primary institution that coordinates national efforts in this domain. Annually, the ministry assigns specific objectives and tasks to LEGMC, ensuring alignment with national strategies and compliance with international climate policies. While the ministry is pivotal in addressing broader climate-related challenges and implementing cohesive strategies at both regional and national levels, it is not the sole institution engaged in these efforts. Other key players include the Ministry of Environmental Protection and Regional Development, Latvian municipalities and planning regions, universities, and various research institutions. (Figure 2.27) These organizations contribute significantly to advancing climate action and promoting sustainable development in Latvia.

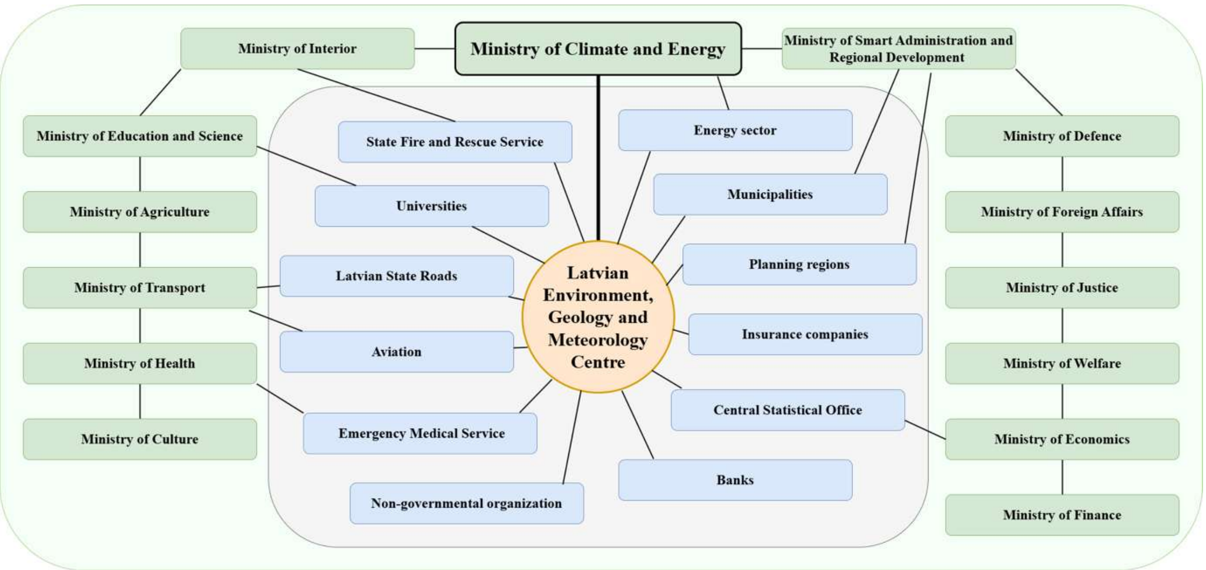

Figure 2.27: Organigram of key institutions and sectors involved in CRA in Latvia.

This collaboration highlights the significance of the CLIMAAX project, which represents a substantial advancement in creating a robust climate risk assessment framework for Latvia. Such a framework is indispensable not only for LEGMC but also for enabling diverse regions, each with unique socio-economic and environmental conditions, to systematically approach climate risk assessment. By equipping these regions to identify vulnerabilities, comprehend the potential impacts of climate change, and derive actionable insights, the project fosters the development of informed adaptation strategies. Consequently, the CLIMAAX project plays a critical role in enhancing Latvia's capacity to evaluate and respond to climate change challenges, ensuring that the nation is well-prepared to address both present and future risks.

2.5.1.3 Focus and goals of the CRA

From the perspective of the CLIMAAX pilot, Latvia's primary goal is to understand the methodology for conducting climate risk assessments (CRA) and to outline the necessary steps for obtaining both qualitative and quantitative results. Given the technical expertise of the personnel at the LEGMC, the pilot project focuses primarily on developing the climate risk assessment framework, rather than delving into the technical details, which are already well-understood by the team. Another key focus of the pilot is improving inter-institutional communication. Effective climate risk assessment requires strong collaboration among various institutions, and the pilot aims to foster this communication to ensure a more coordinated and comprehensive approach to addressing climate risks.

Throughout the project, extensive discussions have taken place between LEGMC climatologists and experts from a variety of sectors, with a shared focus on enhancing climate risk analysis. These discussions have centred on identifying the types of data currently available, evaluating their utility, and determining what additional data should be monitored to achieve more accurate and meaningful results when assessing climate risks for specific economic sectors.

A critical aspect of these conversations has been understanding the data gaps that exist in certain sectors and exploring how targeted data collection could support more robust climate risk assessments. By engaging with stakeholders from diverse fields, the project has aimed to ensure that the data collected is not only scientifically valuable but also practical and actionable for the end users in these sectors. This collaborative approach emphasizes the importance of tailoring data monitoring practices to meet the unique needs of each economic sector, thereby enabling a more nuanced and effective response to the challenges posed by climate change.

2.5.2 Scoping and hazard selection

2.5.2.1 Short overview over local climate

Latvia is located in the Baltic region of Northern Europe, bordered by Estonia to the north, Russia to the east, Belarus to the southeast, Lithuania to the south, and the Baltic Sea to the west, where it shares a maritime border with Sweden. Latvia's coastline along the Baltic Sea spans nearly 500 km. The country is predominantly flat, with the highest point being Gaiziņkalns at 311 meters. Over 40% of Latvia's land area is covered by forests, and in 2015, the total forested area reached 32,983.6 km². Latvia is also home to more than 3,000 lakes and 12,000 rivers.

According to the Köppen-Geiger climate classification system, Latvia falls under the D climate category, specifically the Dfb sub-climate type. This classification indicates a warm-summer humid continental climate, with the coldest month averaging below 0° C. In Latvia, February is typically the coldest month, with an average temperature of -3.1°C. For the Dfb sub-climate, average air temperatures remain below 22°C, and at least four months (May, June, July, August, and September) must have an average temperature above 10°C. Additionally, there are no significant seasonal differences in precipitation. Summer is the wettest season, with an average of 222.3 mm of precipitation, while spring is the driest, receiving an average of 123.4 mm.

The average air temperature in Latvia during the climate normal period (1991–2020) was +6.8°C[22], compared to +5.6°C in the reference period (1961–1990). This indicates a rise in average temperature of 1.2°C over the past several decades. The most rapid temperature increase has occurred during the winter months, posing challenges for various sectors. Warmer winters have led to more frequent winter floods caused by ice jams, which have resulted in significant damage in recent years. Rising temperatures have also made summers hotter, with more frequent heatwaves and longer growing seasons. In contrast, winters are seeing fewer snow days.

In terms of precipitation, Latvia has experienced an increase from 656.0 mm in the reference period to 684.6 mm today. However, a major concern is the increasing intensive precipitation days especially if they appear after prolonged droughts. These local heavy rainfall events have caused substantial damage, often accompanied by thunderstorms, strong winds, and hail, further intensifying the impact.

Latvia's extensive coastline, stretching over 500 kilometres, makes the country particularly vulnerable to the impacts of rising sea levels and wind surges. These phenomena have already posed significant challenges to Latvia's coastal regions, as evidenced by events such as the wind surge Ervin (Gudrun) in January 2005, the storm in January 2007, and another in November 2001.

Long-term sea level time series from LEGMC meteorological stations, measured using the LAS-2000,5 reference system[23], indicate that mean sea level has increased from 19 cm a.s.l. in the LAS-2000,5 reference system during the reference period (1961–1990) to 20.5 cm a.s.l. in the current climate normal (1991–2020). While this rise may appear modest, climate change scenarios based on Shared Socioeconomic Pathways (SSPs) project that by the end of the 21st century, sea levels will rise to between 53 and 71 cm, representing an increase of 34 to 52 cm[24] compared to the reference period, which will significantly increase coastal risks in Latvia. Higher water levels will lead to more frequent and stronger wave action, accelerating land loss. At the same time, areas that once accumulated sediment may no longer accumulate enough to keep pace with rising seas. This combination of accelerated erosion and reduced accumulation reduces the ability of natural coastal barriers to protect against incoming water. As a result, coastal flooding becomes more frequent and severe, with higher tides and storm surges overwhelming weakened coastlines.

2.5.2.2 Main hazard selection

In the first phase of the project, Latvia focused its analysis on flooding risks, considering the country's extensive geographical features, its 500 km long Baltic Sea coastline and over 12,000 rivers. Given these characteristics, both riverine and coastal flooding are significant concerns for Latvia. The analysis aimed to assess the potential impacts of these flood types across various regions of the country. As a result, it was found that nearly all municipalities in Latvia are affected by flooding to some extent, whether from river floods, coastal surges, or a combination of both. This widespread vulnerability highlights the importance of understanding and addressing the risks associated with flooding in both river and coastal areas across the country.

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[22] https://klimats.meteo.lv/klimats_latvija/latvijas_klimatiskais_raksturojums/

[23] https://likumi.lv/doc.php?id=239759

[24] https://klimats.meteo.lv/data/climate_change_data_viewer/report_downloads/LVGMC-klimata-parmainas-2024.pdf

2.5.3 Risk identification

Flooding has long been recognized as a significant risk in Latvia, both historically and in recent years, as the country has faced numerous events that have caused considerable damage to communities, infrastructure, and the economy. Among the most notable incidents is the river flooding near Jēkabpils in 2023, where large portions of the city were submerged, causing severe disruption to daily life and substantial damage to property. Similarly, the wind surges brought by Storm Ervīns in 2005 led to devastating impacts on coastal towns and several suburbs of Riga, Latvia's capital. These events resulted in widespread destruction and multi-million-euro losses, underscoring the country's vulnerability to both riverine and coastal flooding.

Current climate change projections paint a concerning picture for Latvia's future, as they suggest that the amount and intensity of precipitation will likely increase over time. This trend is expected to contribute to more frequent and severe flooding events, posing an even greater threat to the infrastructure, economy, and population. Such projections emphasize the urgency of understanding and addressing flooding risks as part of Latvia's broader climate adaptation strategy.

Latvia’s critical infrastructure, much of which is located near large rivers and along its extensive coastline, faces heightened vulnerability to future flooding. Ports, transportation networks, industrial facilities, and residential areas in these regions are at particular risk, making it essential to conduct precise and thorough assessments of flooding risks. These assessments should not only consider current hazards but also account for future scenarios driven by climate change, ensuring that mitigation and adaptation measures are effectively targeted.

2.5.4 Risk analysis

During the risk analysis phase of the CLIMAAX project, Latvia examined all the relevant workflows but focused its efforts on flood risk for river and coastal flooding. The CLIMAAX pilots were tasked with comparing flood risk analysis results derived from global datasets with those based on local data and knowledge. As expected, the use of local data led to improved accuracy in the Latvia pilot; however, the improvement was relatively modest, and global datasets proved sufficient to meet the needs of the pilot.

Latvia’s flood risk assessment focused on several critical indicators, including local flood maps created by LEGMC, which consider return levels of water measured at sea and river gauges across Latvia and integrate projections of future flooding depths[25] based on the RCP4.5 climate change scenario. The second component of flood analysis involved using global climate change scenarios, generated with the CRA Toolbox. This approach enabled the calculation of return periods for various flood depths, which were combined with land cover data to assess the risks of flood-related damage.

2.5.4.1 Coastal flooding

The coastal flood workflow was applied to conduct a qualitative analysis of sea level rise, adjusted for Latvian conditions using the latest SSP climate change scenarios (Figure 2.28)[26]. A comparison of results from both global and local datasets revealed that, for areas like Riga, the coastal flooding workflow (Figure 2.29) —as represented in the CRA Toolbox—produced results closely aligned with

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[25] https://videscentrs.lvgmc.lv/iebuvets/pludu-riska-un-pludu-draudu-kartes

[26] https://klimats.meteo.lv/data/climate_change_data_viewer/report_downloads/LVGMC-klimata-parmainas-2024.pdf

results based on the local flood maps (Figure 2.30)[27]. While some discrepancies were observed, with global datasets yielding either higher or lower values compared to local data in certain areas, the workflow provided an excellent and concise initial overview. This demonstrates that, for areas like Riga, the CRA Toolbox is capable of delivering reasonably accurate projections of future flood damage.

While local data can be integrated into the flooding toolbox by a technical expert to improve accuracy, the current outputs of the CRA Toolbox already provide policymakers with adequate information for decision-making. Enhanced flood and land cover maps could further refine future risk calculations, supporting more precise adaptation measures.

Projections of sea level also highlight an increased risk of flooding in the future, which aligns with the global trends identified in the CLIMAAX toolbox.

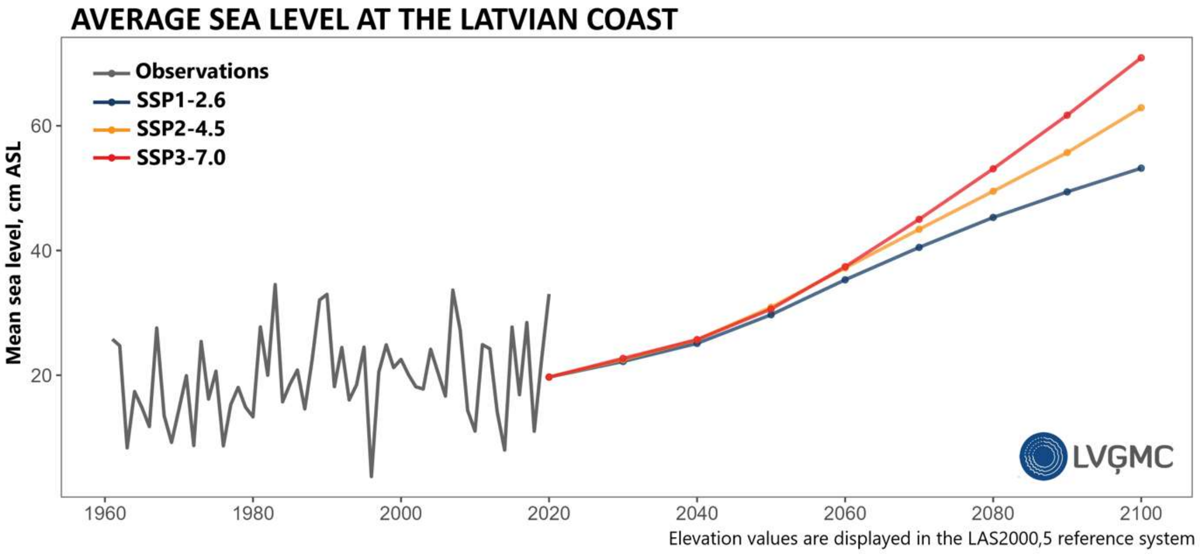

Figure 2.28: Average sea level at the Latvian coast based on the LEGMC station observations and CMIP6 data (average value for 30 year periods), cm a.s.l.

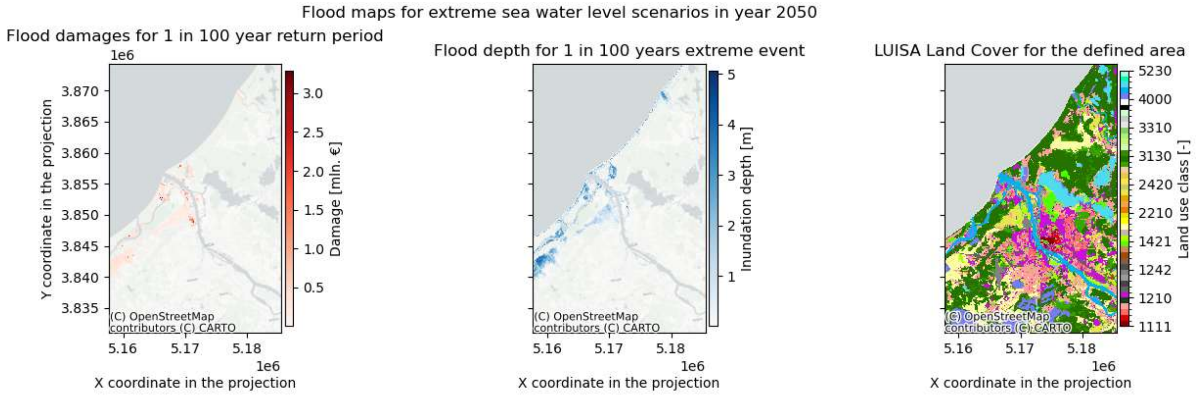

Figure 2.29: Results of the coastal flood workflow for Riga area using the provided global dataset from the CLIMAAX Toolbox.

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[27] https://videscentrs.lvgmc.lv/iebuvets/pludu-riska-un-pludu-draudu-kartes

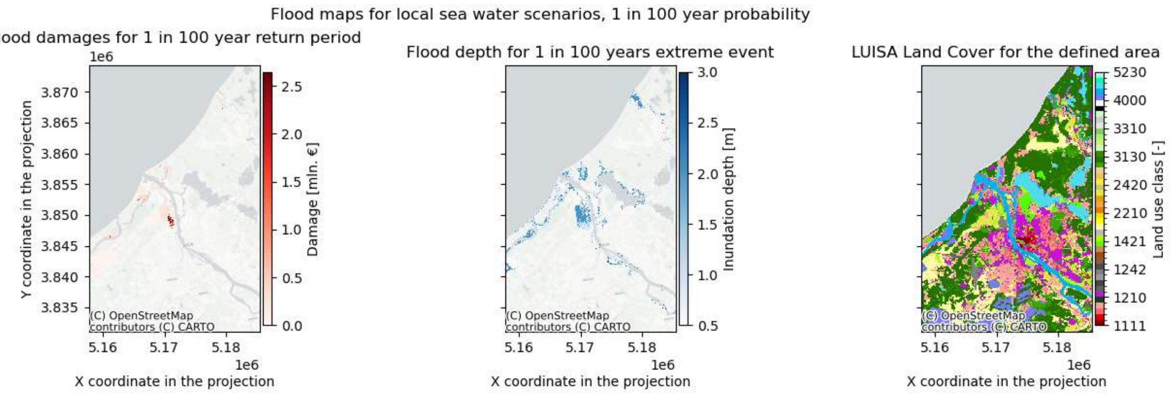

Figure 2.30: Results of the coastal flood workflow for Riga area using the local water level dataset.

2.5.4.2 River flooding

The river flood workflow of the CLIMAAX toolbox (see Deliverable 2.4[28]) was utilized to analyse river flooding in Latvia, incorporating recent observations of seasonal variability influenced by climate change. Traditionally, river floods in Latvia have occurred during spring due to ice-jam events; however, in recent years, such floods have been observed in winter as well. For instance, in January 2023, significant flooding occurred along the Daugava River in Jēkabpils, resulting in damages exceeding one million euros[29]. Precipitation-induced floods are also becoming increasingly common, underscoring the need for comprehensive flood analysis.

While Latvian hydrologists have historically focused on spring floods (Figure 2.31) and ice-jam events (there are publicly available flood maps[30]), precipitation-based floods remain less studied, but, due to climate change, there are increasing frequency of intense precipitation, such as floods in Latgale region in the 2017[31], and it will persist also in the future. The CLIMAAX toolbox addresses this gap by providing workflows for river floods driven by precipitation, enabling a more integrated analysis of flood hazards.

Combining data from ice-jam floods and precipitation-driven floods (Figure 2.32), which were obtained from earlier studies, enhances the utility of these tools. From the perspective of society, the distinction between different types of river floods is less significant than understanding the overall risk and impact. Integrating these analyses allows for more comprehensive flood risk management, aligning with the needs of both policymakers and local communities.

Projections from the CLIMAAX toolbox highlight the increasing complexity of flood risks due to climate change, emphasizing the importance of unified approaches to hazard assessment and mitigation planning.

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[28] https://files.cmcc.it/climaax/CLIMAAX_D2.4.pdf

[29] https://www.lsm.lv/raksts/zinas/latvija/20.06.2023-jekabpils-novada-pasvaldibai-pieskir-898-613-eiro-janvara-pludu-radito-izdevumu-segsanai.a513632/

[30] https://videscentrs.lvgmc.lv/iebuvets/pludu-riska-un-pludu-draudu-kartes

[31] https://www.lsm.lv/raksts/laika-zinas/laika-zinas/latgales-upes-udens-limenis-kapis-par-vairak-neka-2-metriem-mazajas-upes-kapums-beidzas.a247862/

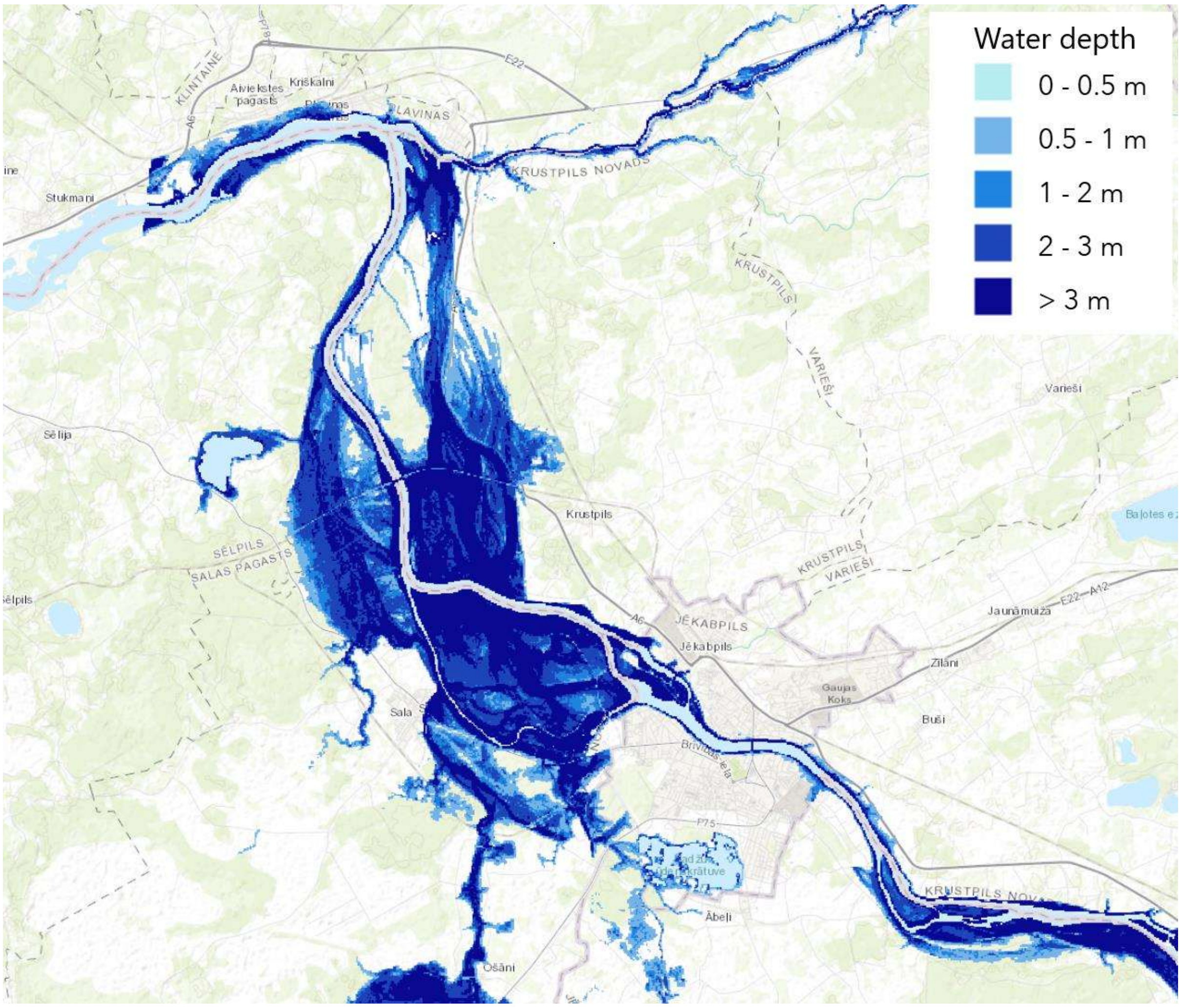

Figure 2.31: Latvian hydrologists' results, based on historical local hydrology data, for the 1-in-100-year extreme event in the Jekabpils area.

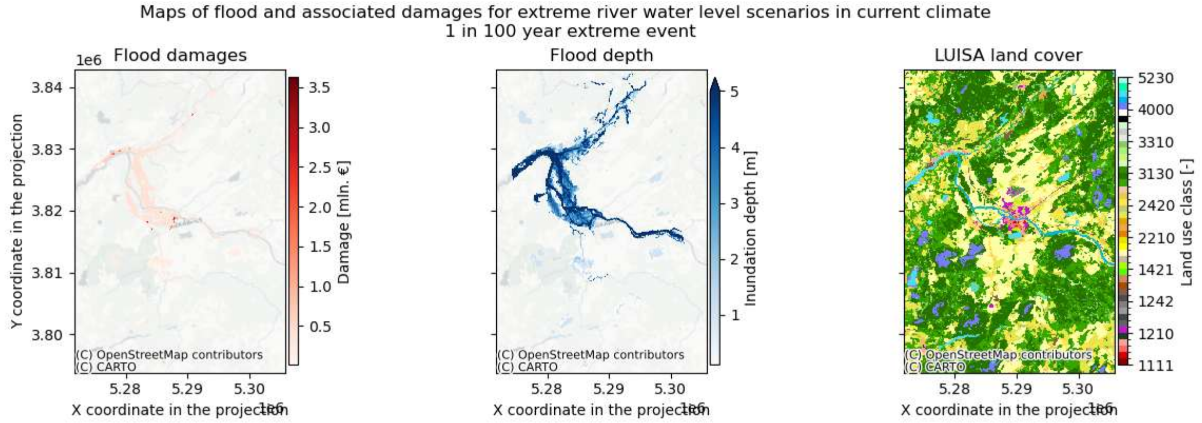

Figure 2.32: Results of the river flood workflow for Jekabpils area using the global dataset.

2.5.4.3 Climate change scenarios

RCP4.5 (Representative Concentration Pathway 4.5) is a moderate greenhouse gas emissions scenario that assumes significant mitigation efforts to stabilize radiative forcing at 4.5 W/m² by 2100. It represents a balanced approach between continued emissions growth and aggressive reductions, projecting gradual declines in emissions starting mid-century. The LEGMC has analysed the impacts of RCP4.5 on Latvia's climate[32], focusing on potential changes in temperature, precipitation patterns, snow cover, wind speed. This analysis provides valuable insights into regional climate trends and helps inform adaptation and mitigation strategies tailored to Latvia's environmental and socioeconomic conditions.

The LEGMC has conducted an in-depth analysis of future climate projections for Latvia using the Shared Socioeconomic Pathways (SSP) scenarios, as detailed in their 2024 report[33]. These scenarios, developed by the Intergovernmental Panel on Climate Change, encompass various pathways based on differing levels of greenhouse gas emissions and socioeconomic developments. LEGMC's analysis focuses on SSP1-2.6, SSP2-4.5, and SSP3-7.0, which represent low, intermediate, and high emission trajectories, respectively. These scenarios were chosen based on discussions between climatologists and data analysts from LEGMC and policymakers from the Ministry of Climate and Energy. The report examines potential impacts on Latvia's climate, including changes in temperature, precipitation patterns, snow cover thickness, wind speed, and sea level rise, providing critical insights for developing effective adaptation and mitigation strategies tailored to the region's specific conditions.

2.5.5 Future plans

Latvia’s future climate risk assessment efforts will center on two key areas to address the country’s growing vulnerabilities. The first focus lies in improving the precision of flooding risk analyses through the integration of local, high-resolution data. This enhancement involves refining the workflows within the Climate Risk Assessment (CRA) Toolbox to better accommodate detailed local datasets. By tailoring analyses to reflect Latvia’s specific environmental and geographic conditions, these improvements aim to provide a more accurate and context-specific understanding of flooding risks, which are crucial for effective planning and decision-making.

Beyond flooding, Latvia’s approach to climate risk assessment is set to broaden its scope. The methodology and CRA Toolbox, initially developed for flood risk analysis, will be expanded to encompass other climate hazards, such as heatwaves, storms, and droughts. As expertise with the framework and tools grows, applying them to additional climate challenges is expected to become more seamless. This expansion will enable the assessment of a wider array of environmental risks, contributing to a more robust and comprehensive national strategy for climate adaptation.

While the current findings have yet to directly inform policy decisions, their potential influence is significant. Ongoing collaboration with the Ministry for Climate and Energy, alongside key stakeholders and relevant authorities, underscores the importance of these efforts in shaping Latvia’s future climate strategies. These initiatives are expected to provide critical insights that will support informed decision-making and drive the development of effective adaptation measures, ensuring that Latvia is better prepared for the challenges posed by a changing climate.

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[32] https://www4.meteo.lv/klimatariks_vecais/files/summary.pdf

[33] https://klimats.meteo.lv/data/climate_change_data_viewer/report_downloads/LVGMC-klimata-parmainas-2024.pdf

2.6 Finland

2.6.1 Background

CRA in Finland is generally of good standard, but further development is needed, especially considering the climate change induced changes to extreme weather events, like windstorms, snow conditions, heat waves, and forest fires. FMI and MoIFI have collaborated in piloting projects concerned with near-future climate risk and vulnerability assessment (e.g. ANYWHERE project[34]). Despite the progress in Finland, there are still many components that need further improvement.

2.6.1.1 Earlier work on CRA

Under the Finnish Climate Act[35], the objectives and measures concerning climate change adaptation must be based on scientific evidence so that the progress of climate change, its probable positive and negative impacts, the risks and hazards associated with it, and the capabilities to prevent disasters and limit their adverse effects are taken into account. The most recent weather and climate change risk and vulnerability assessment for Finland[36] was compiled in 2021-2022 to support the development of the current National Climate Change Adaptation Plan 2030[37]. It contains a description of the observed and future evolution of various climatological variables and hazards, and a sectorial and cross-sectorial impact and risk assessment. Compared globally, Finland is well prepared for the additional challenges brought by climate change, meaning the climate impacts in the next decade are not expected to be as severe as the global average. However, climate change is also associated with significant risks in Finland. In addition to the changing climate, they are affected by developments in current and future social and economic conditions. The risks vary greatly in different parts of the country, and they depend on the characteristics of the areas, such as location and the structure of the economy and population. Regional livelihoods, nature and the rest of society have adapted to the current climate, but climate change as a result, is increasing the risks all over Finland, as it does in the Arctic and Baltic Sea regions.

At the national level, sectorial weather and climate change risk and vulnerability assessments have a long history in Finland. A general assessment of vulnerability across sectors was the basis for the original National Adaptation Strategy in 2005. For the first National Adaptation Plan published in 2014, a study of the impact of climate change and the vulnerability of sectors was conducted in 2013. In 2018, a comprehensive national weather and climate risk assessment collated new and recent knowledge of risks and vulnerabilities generated in sectorial assessments[38].

In Finland, the Ministry of Interior (MoIFI) is in charge of executing the National Risk Assessment every three years. The assessment report, (latest version Finnish National Risk Assessment, 2023[39]) is publicly available and is also submitted to the European Commission as part of the EU Civil Protection Mechanism and is prepared in a wide cross-administrative cooperation process. The focus of the assessment is on immediate and short-term (next years) threats, and the report concentrates mostly on larger risks with national significance. The report is at the national level, but

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[34] http://anywhere-h2020.eu
[35] https://www.finlex.fi/fi/laki/ajantasa/2022/20220423
[36] http://urn.fi/URN:ISBN:978-952-383-566-5
[37] http://urn.fi/URN:ISBN:978-952-383-814-7
[38] http://urn.fi/URN:ISBN:978-952-287-601-0
[39] http://urn.fi/URN:ISBN:978-952-324-602-7

Finland's regions also perform their individual assessments, which are publicly available in Finnish. The national assessment includes a section on climate change and mentions that the management of weather and climate risks is especially linked to regional risk assessments, although what this means in practice remains unclear.

The regional risk assessments focus on those regionally significant risks which require extraordinary actions and, if realized, would result in significant regional effects. For example, in Southwest Finland, a logistics disruption (production and distribution) is viewed as highly likely (once every 10-100 years), and it would have significant impact on people and environment and very significant financial impact (livelihoods and energy). It would also have significant societal impacts (to internal security, infrastructure, population's functional capacity etc). The format of the regional assessment follows a set of methodological guidelines by MoIFI (Ministry of the Interior, 2022[40]) and they have been prepared cross-administratively. The purpose is that the regional risk assessment is used as a starting point for preparing regional operators, along with the national risk assessment.

As climate risks are mainly assessed at the national level, for the next round of the national risk assessment, CLIMAAX could provide the missing assessment methods and tools along with examples of their usage, which would help to (1) also bring the climate risk assessment to the regional level in a more comprehensive and meaningful way and (2) streamline climate risk assessment not only across Finland but across the entire EU.

2.6.1.2 Short description of participants

The Ministry of Interior Finland (MoIFI), among its other responsibilties, guides and directs rescue services and maintains oversight of their coverage and quality, is in charge of the organisation of rescue services at the national level and coordinates the activities of various ministries and sectors in the field of rescue services and their development. The Ministry also decides on providing international assistance in this field. Additionally, it drafts legislation on rescue services and emergency response centre operations. The Department for Rescue Services is responsible for carrying out central government tasks that fall within the scope of the Ministry of Interior and for ensuring joint regional government preparedness for emergency conditions and incidents under normal conditions. The Department is responsible for the guidance of the wellbeing services counties together with other ministries responsible for the guidance. As member of the CLIMAAX pilot, MoIFI coordinated the CRA.

Emergency Services Academy Finland (ESAF) strengthens the safety and security of society by providing vocational education, further training, and continuing professional education for rescue service and emergency response centre professionals. The Academy also provides preparedness training. The Emergency Services Academy is responsible for the training system of contract fire brigade personnel as well as for the training, recruitment, and deployment of personnel to international civil protection operations. The Academy coordinates research, development, and innovation activities (RDI) in rescue services and maintains the rescue services' central library. As member of the CLIMAAX pilot, ESAF provided data and expert knowledge, and took a central role in

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[40] http://urn.fi/URN:ISBN:978-952-324-609-6

facilitating the wildfire response coordination training and its evaluation during the KriSu (Leadership of Major Accidents and Crisis Situations) exercise.

The Finnish Meteorological Institute (FMI) makes observations and research on the atmosphere, the near space and the seas. It also provides services on weather, sea, air quality, climate, and near space for the needs of public safety, business life and citizens. The Finnish Meteorological Institute is an administrative branch of the Finnish Ministry of Transport and Communications but also answers assignments by other ministries and governmental bodies. For instance, FMI provides expert knowledge on climate and extreme weather events to the Finnish National Risk Assessment (Finnish National Risk Assessment, 2023). As partner of the CLIMAAX pilot, FMI performed the data analysis for the CRA, helped design the FWI-based wildfire workflow and provided the wildfire scenarios for the KriSu exercise.

In addition to the partners (Figure 2.33), representatives from regional rescue departments, Finnish Forest Centre, National Emergency Supply Agency, Finnish Environmental Institute, Finnish Institute for Health and Welfare and Natural Resources Institute Finland were involved in the pilot as participants in the onsite visit and/or providing information for the execution of the pilot.

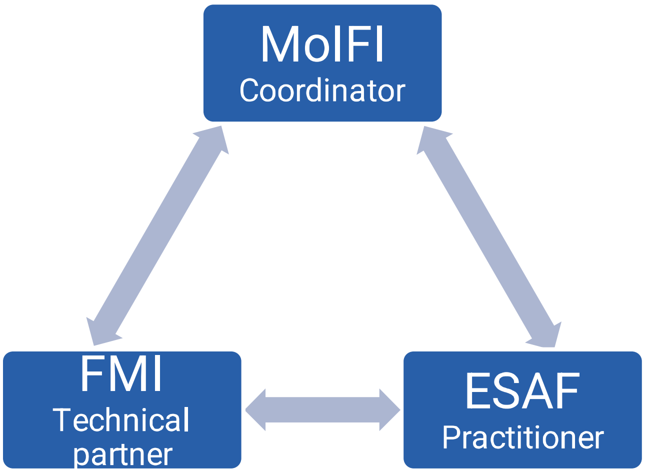

Figure 2.33: Organigram of the Finnish pilot.

2.6.1.3 Focus and goals of the CRA

The focus of the Finnish CRA performed during the CLIMAAX pilot period was on disaster management (emergency response) and disaster prevention. Especially the former also included some work on early warnings of climate-related hazards. Our key focus was to find out if we can identify the effects climate change has on selected hazards and how this changes the overall risk.

2.6.2 Scoping and main hazard selection

2.6.2.1 Short overview over local climate

According to the Köppen-Geiger climate classification, Finland belongs to the Df group (continental subarctic or boreal climates). The Finnish climate has characteristics of both maritime and continental climate, and because of its latitudinal extent, many meteorological features, like season lengths and average temperatures vary a lot within the country. For instance, average temperatures in Helsinki (60.2° N) are 16.2°C in the summer and -3.5°C in the winter, while in Sodankylä (67.4° N) they are 13.1°C and -11.4°C, respectively. Yearly precipitation amounts on average to about 600 mm/yr[41].

Finland is part of the Arctic region, so the projected warming of the climate is larger than average (Rantanen et al., 2022). Finland's annual average temperature has already risen by about 2°C compared to pre-industrial times, and there are visible effects already: for example, shorter winters have led to a decrease in snow cover in the south and an increase in the number of heat waves and their intensity has been observed[42]. In the future, average temperatures are expected to increase most during the winter, while during the summer months the temperature increase is projected to be moderate. However, climate models also project longer and more intense heat waves during the summers. In terms of precipitation, climate models project fairly constant trends in Finland until the end of the century, with a slight increase in precipitation during the winter. Due to the strong warming, the fraction of rain and sleet during the winter will increase. Additionally, precipitation during the summer is projected to contain more intense rainfall events and the amount and length of dry spells is projected to increase[43].

2.6.2.2 Main hazard selection

During the interview phase of the CLIMAAX project, the Finnish pilot identified windstorms, extreme precipitation, heatwaves, drought, river floods (e.g., due to ice jams, snowmelt), flash floods, and wildfires as the most concerning climate hazards. While some of these hazards do not currently pose a significant risk, there are big concerns that this may change in the future due to climate change. Wildfires, for instance, are in the current situation still relatively easy to manage with the existing resources, but there are concerns that already small changes in local climate could change the situation drastically. Combined with the fact that about 70% of all land area of Finland is covered with forest, a small change in climate may lead to a big change in the associated risks.

During the scoping session, it became clear very quickly that wildfires were indeed of most interest to the Finnish pilot. This is partly due to the large uncertainty in the wildfire-related risks and partly due to the interests of the partners of the Finnish pilot. In the National Climate Change Adaptation Plan42[42] it is mentioned that increasing periods of drought and heat increase the risk of extensive forest fires. Drought and wildfire preparedness have positive effects from the point of view of asset protection, freedom of business, and health protection. In addition, the measures have reinforcing effects on the fundamental environmental rights, incl. regarding the implementation of cultural heritage and environmental law.

Another hazard of high interest for the pilot partners was heavy precipitation. In cities, the intensification of heavy rain together with the expected denser urban structure leads to a growing risk of stormwater flooding, especially in already built-up areas. Heavy rain floods cause economic losses and often acute high-power pumping tasks for rescue operations. Extensive stormwater floods can at worst cause significant disruptive situations, and, for instance, complicate first aid tasks.

At the time of proposal writing, the Finnish pilot had not decided on a specific region for wildfire risk assessment. During the scoping phase, we decided to assess two regions, which are very different

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[41] https://www.ilmatieteenlaitos.fi/ilmastollinen-vertailukausi

[42] http://urn.fi/URN:ISBN:978-952-383-814-7

[43] https://www.climateguide.fi/articles/projected-climate-change-in-finland

in many aspects, including average temperature and precipitation, population density, and forest cover and type. These regions are Southwest Finland and North Karelia.

In Southwest Finland, climate risk development has not been monitored on a yearly basis[44]. This is a challenge for the coming years together with risk management and developing indicators for adaptation. However, according to Southwest Finland's climate strategy 2020[45], the effects of climate change were already visible in the province in the early 2010s. In addition to forest fires, floods are another big risk in Southwest Finland (Gregow et al., 2021). Climate change is not estimated to change the probability of high sea levels in the Archipelago significantly by 2050, but they are estimated to increase towards the end of the century (although the estimates are subject to significant uncertainty). The risk of pluvial floods will increase – these are caused by the increase in heavy rains.

The province of North Karelia consists of 13 municipalities. 164,000 inhabitants live in North Karelia, of which 77,000 live in the county centre Joensuu (Gregow et al., 2021). The majority of the population are elderly. Even though the province has a low population density, it contains the popular national park Koli which is Finland's fourth most popular national park with 249,800 visitors annually[46]. In addition, there are a lot of other popular parks and hiking trails nearby, such as Herajärven kierros Trail, Patvinsuo National Park, Petkeljärvi National Park, Kolvananuuro Nature Reserve, Reposuo Area and Ruunaa Hiking Area. 70% of North Karelia is forest. National parks and hiking trails pose a possible issue for forest fire prevention and management. In Finland, human activity is the main cause of forest fires. In addition, evacuation and warning becomes more difficult with unknown hiker locations and multiple language needs.

Flood management has long been a central focus in Finland. In recent years, however, urban flooding caused by heavy rainfall has emerged as a growing concern. This issue has gained particular attention due to predictions that climate change will lead to more frequent heavy rains and associated pluvial floods (Aaltonen et al., 2008, Dyrrdal et al., 2023). Most of Finland's annual precipitation occurs in the summer months, as heavy rain or thunderstorms. Based on FMI statistics (https://www.ilmatieteenlaitos.fi/sade-ennatyksia), precipitation events accumulating over 100 mm/day have occurred between June and August.

Statistics on daily rainfall in Finland can be obtained from long observation records, but the weaknesses of rain gauge observations include sparse network of stations and small amount of statistical data available for short but intense rainfall events lasting between 10 minutes and 6 hours (Aaltonen et al., 2008). The highest recorded daily rainfall in Finland is 198 mm (21.7.1944 in Espoo Lahnus[47]). For example, in Pori in August 2007, more than 100 mm of rain fell in just three hours over a zone less than 5 km wide. As a result, more than a thousand properties suffered water damage, and underpasses were flooded. Heavy rains caused extensive and widespread damage in Pori, and the damages caused by stormwater was estimated at around 20 million euros (Aaltonen et al., 2008).

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[44] https://www.turku.fi/sites/default/files/atoms/files/turun_ilmastoraportti_2022_saavutettava.pdf

[45] https://ymparistonyt.fi/wp-content/uploads/2023/05/Varsinais-Suomen_Ilmastotiekartta_FINAL_1705023.pdf

[46] https://www.metsa.fi/wp-content/uploads/2025/01/visitationnumbers_2024.pdf

[47] https://www.ilmatieteenlaitos.fi/sade-ennatyksia

The Finnish Meteorological Institute (FMI) starts issuing rain warnings when short-term rainfall exceeds 20 millimetres in an hour or long-term rainfall 50 millimetres in a day[48]. The risk of flooding is heavily influenced by the location of the rainfall. Urban and paved areas are significantly more prone to flooding than undeveloped or rural regions due to reduced surface permeability. Water often accumulates in low-lying areas, increasing the likelihood of flooding.

Rainfall associated with weather fronts can generally be predicted 12 to 48 hours in advance. However, intense, localized showers and thunderstorms are much harder to forecast, with predictions limited to rough estimates of intensity and location up to 12 hours in advance. Heavy rain and thunderstorms typically last anywhere from under an hour to a few hours in one location, affecting relatively small areas. Conversely, rainfall linked to weather fronts can cover much larger regions and may lead to prolonged flooding. Such flooding can persist for hours or even days in low-lying areas or near rivers, even after the rain has stopped. Preparing for flash floods is challenging because heavy rainfall can occur anywhere.

For the heavy precipitation analysis, we decided to focus on the Helsinki capital region (formed by the cities of Espoo, Helsinki, Kauniainen and Vantaa), which is the biggest population centre of Finland, and therefore of particular interest concerning urban pluvial flood risk.

2.6.3 Risk identification

2.6.3.1 Wildfires

For wildfires, the main risks to be considered are loss of human life and damage to buildings and infrastructure.

- In Finland, many private homes are made of wood and often settlements border directly with wooded areas.
- Population density in Finland is low and settlements are spread out. On the one hand this means that the number of people in danger is usually low, but on the other hand it also means that e.g. evacuation action can quickly become complicated.
- There are other risks, for instance traffic impairment, damage to electricity lines (which are mostly installed above ground in Finland), etc.

The factors which affect these risks the most are:

- The hazard itself: We use the Canadian Fire Weather Index (FWI) as indicator for high wildfire danger periods and combine it with other factors to compute hazard probability, including forest type (fuel content, flammability), topography, and slope.
- Critical infrastructure: We are particularly interested in schools, hospitals, factories, power plants
- Demographic information: population density, age distribution, tourism
- Accessibility: topography, road density, water availability
- Preparedness: enhancing the preparedness of rescue services e.g. through equipment planning, increasing personnel strength during wildfire risk periods, training, and exercises.

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[48] https://www.ilmatieteenlaitos.fi/sadevaroitukset

2.6.3.2 Pluvial flooding

For pluvial flooding the main risks to be considered are damage to buildings and infrastructure, as well as accidents and disruptions to traffic.

The factors which affect these risks the most are:

- The hazard itself: the flooded areas for different return periods connected to the climatic conditions which affect these floods.
- Affected infrastructure and buildings, damage curves, etc.

2.6.4 Risk Analysis

2.6.4.1 Wildfire

For our risk analysis, we adapted the FWI workflow from the CLIMAAX Toolbox, which utilises the Canadian Fire Weather Index (FWI), and was developed by FMI and CMCC. The FWI is available from the climate data store (CDS) as pre-calculated datasets for reanalysis data and for a several climate projection simulations. Here we used FWI data which was derived from five EURO-CORDEX regional climate models for the RCP4.5 scenario.

Hazard

The FWI is mostly used to help authorities to set up early warning systems, which supports both informing the general public the increase wildfire danger and to set preparedness levels of emergency response services. However, the FWI can also be used to assess parameters like the length and severity of the wildfire season, and how these change in a changing climate. It should be noted that FMI officially uses the Finnish wildfire index (Vajda et al., 2014). While the Canadian FWI has an open-ended scale, the scale of the Finnish wildfire index ranges from 1 to 6, with 6 being the highest danger class. In this analysis we decided to use the Canadian FWI, because (1) pre-calculated data were available for several climate models and (2) it is more widely used, also in Europe, and therefore results are more readily comparable to other European regions. In our analysis we used the mapping of Table 2-2 between Finnish and Canadian wildfire indices.

Table 2-2: Mapping between wildfire danger classes for Finnish and Canadian wildfire index.

Finnish wildfire index	Canadian FWI equivalent	danger level
4	> 10	high
5	> 17.5	very high
6	> 25	extreme

The FWI data available from CDS provides daily averages, for altogether 6 Euro-CORDEX models, for a historical period (1971-2005) and future projection of three RCP emission scenarios (RCP2.6, RCP4.5, and RCP8.5) for the years 2006 through 2098. However, not all six models provide data for all scenarios. In Finland we were most interested in the RCP4.5 scenario, for which results were available for the models CHEC-EC-EARTH/RCA4, MPI-M-MPI-ESM-LR/RCA4, MOHC-HadGEM2-ES/RCA4, CNRM-CERFACS-CNRM-CM5/RCA4, and IPSL-IPSL-CM5A-MR/RCA4. For our analysis we compared the historical reference period (1975-2005) to the mid-century (2039-2068) and the end-of-century (2069-2098) periods. As short-term preparedness of the Finnish rescue service was one of the most important goals of this analysis, we focused most on the mid-century results. A model average of the FWI and its projected change in Southwest Finland and North Karelia is shown in Figure 2.34 and Figure 2.35, respectively.

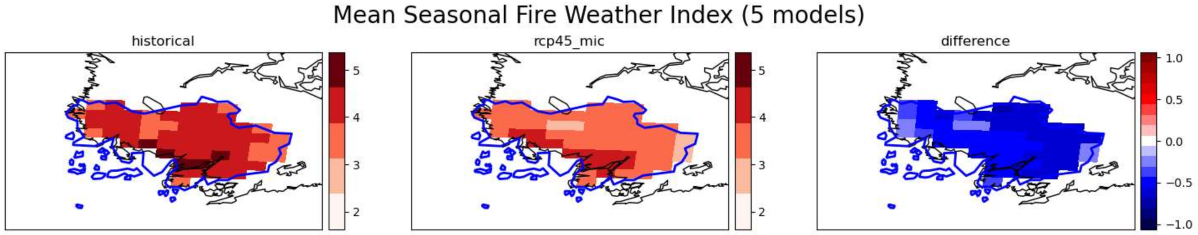

Figure 2.34: Mean Seasonal FWI in Southwest Finland. Means are over 5 models. Left: historical period, centre: mid-century, and right: projected change.

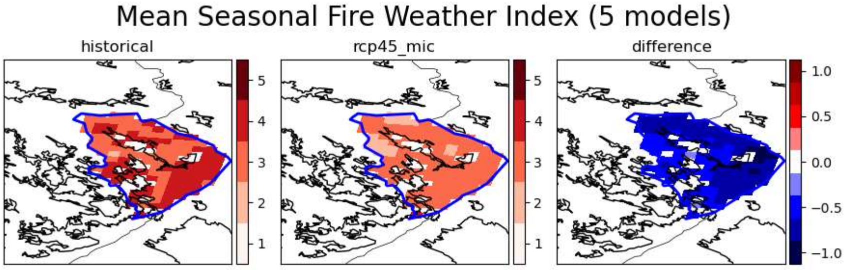

Figure 2.35: Mean Seasonal FWI in North Karelia. Means are over 5 models. Left: historical period, centre: mid-century, and right: projected change.

As can be seen in the figures, the projected change in FWI is fairly small in general, with a slight negative trend. However, when looking at the results of the five models used separately, a big spread in model results is apparent. In particular, one model, CNRM-CERFACS-CNRM-CM5/RCA4, deviates from all other models quite a lot, especially for the historical period, and has a big influence on the mid-century trend (see Figure 2.36 for a visualisation). The CLIMAAX project is currently working on methods and practices to evaluate regional model performance and better guidelines to select models for regional risk assessment (see also Section **Error! Reference source not found.**). We decided to use all five models and repeat the analysis once the CLIMAAX tools are ready.

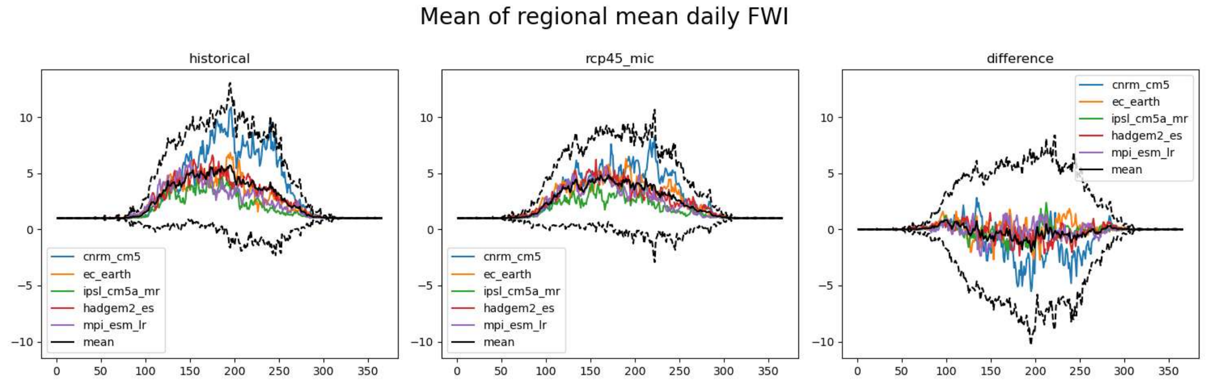

Figure 2.36: FWI as a function of day-of-year. Each coloured line is the average over 30 model years, while the black solid line is the average over all 150 model years. Black dashed lines show one standard deviation to the model mean. Left: historical period, centre: mid-century, right: change.

One indication of a change in Finland is a persistent increase of the FWI in the springtime (see Figure 2.36, right panel around day 100 for an example). We decided to analyse this behaviour further in our analysis. To this end, we developed a special indicator, which we call the Regional Fire Weather Day (RFWD): in each pixel presenting the region, exceedances of a given FWI threshold are calculated for each day of the analysis period. If this exceedance is detected in a pre-defined fraction of the region on the same day, the day is declared an RFWD. The reason for using an area fraction is the way that fire danger alerts are given in Finland, which is based on daily maps released by FMI showing the Finnish fire weather index and its prediction for the coming few days. The regional rescue departments then decide on further action based on these maps.

For the RFWD definition we used four different FWI thresholds: The three thresholds listed in Table 2-2 are the most practical for use by the rescue services, as the limits are well known and understood, but because of the high model discrepancies we also used the model-specific definition by El Garroussi et al., (2024). The latter calculated the 95th percentile of all FWI values in the region over the historical reference period and uses half of this value as a model specific threshold. Table 2-3 shows the model specific threshold values computed by the workflow. The percentile method to define an FWI threshold for fire weather days is a helpful method to overcome problems with model biases but unfortunately makes it hard for users to read the results, as the specific thresholds vary between models and are often quite far from the actual values used in practice. Figure 2.37 shows an example of the distribution of the fire weather day for high (FWI > 10) fire danger -- it is quite apparent from the graphs, that the variation within the region is not very large.

Table 2-3: Model-specific thresholds based on the percentile method by El Garoussi, et al., 2024.

model	**Southwest Finland**	**North Karelia**
CNRM-CERFACS-CNRM-CM5/RCA4	7.4	6.3
ICHEC-EC-EARTH/RCA4	4.7	4.3
IPSL-IPSL-CM5A-MR/RCA4	3.5	3.9
MOHC-HadGEM2-ES/RCA4	4.9	3.8
MPI-M-MPI-ESM-LR/RCA4	4.3	3.5

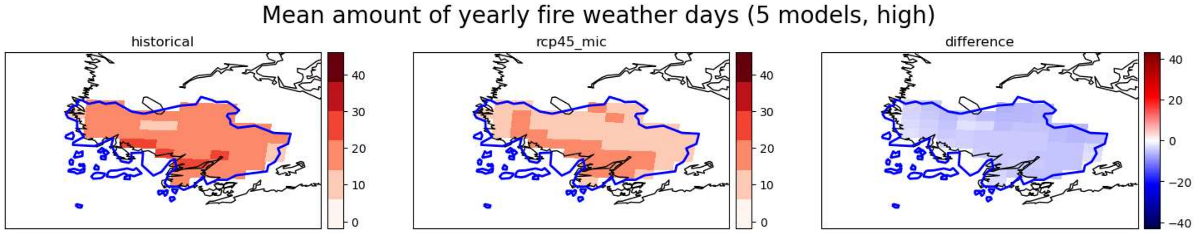

Figure 2.37: Mean amount of fire weather days in Southwest Finland for high fire danger (FWI > 10).

To test the sensitivity of the index to the choice of threshold and regional cover fraction, a sensitivity analysis was performed to both FWI threshold and regional cover fraction. As can be seen, the RFWD is quite robust with respect to the regional cover fraction, and results for the different FWI thresholds are similar, but become less pronounced as the FWI threshold increases. Especially for the percentile-based threshold (El Garroussi et al., 2024) the result is very clear: During the springtime the number of regional fire weather days increases (to a lesser extent the same can be seen in the autumn), while during the summer months the number decreases. As an example, Figure 2.38 shows the result of this sensitivity analysis for the case of Southwest Finland. The results for North Karelia (not shown) are qualitatively similar. Note here, that the same trend (more fire weather days during the spring) can be observed by all models used in this analysis individually (not shown). Taking into account that the number of regional fire weather days is much larger during the summer months than in the springtime (in the historical period), we interpret this as a lengthening of the fire danger season in Finland already mid-century. This is a very important result for the Finnish authorities, as this means that preparedness measures will have to be extended to the springtime (and possibly also to the autumn).

Apart from the amount of fire weather days, the length of an RFWD episode is important in Finland. Depending on forest type and moisture content of the forest floor, it may take 2 to 5 days for the forest to dry out. Hence, even with relatively small FWI thresholds, a lengthening of a typical RFWD episode may be of additional concern in Finland. We performed an analysis using the same definition for RFWD with the same thresholds and regional cover fractions as before. While the distributions for the length of the fire danger episodes within the region look as expected, the change in that distribution between historical period and mid-century depends very strongly on the choice of threshold and regional cover fraction (can result in both positive and negative changes). Therefore, we could only conclude that a change in the typical length of a fire danger episode, based on the model results used here, is unlikely.

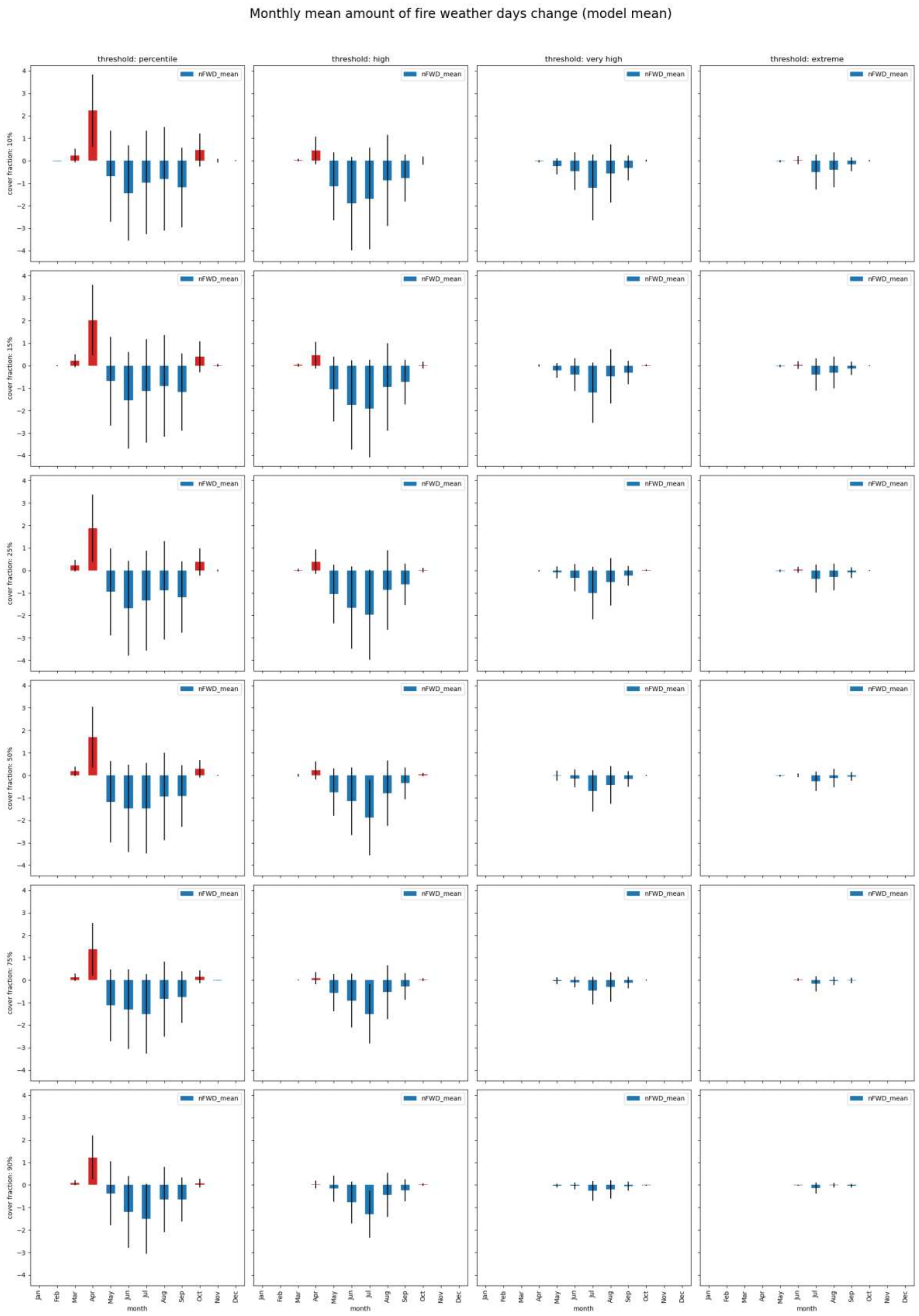

Figure 2.38: Change in the amount of RFWD from historical to mid-century periods for Southwest Finland as a function of month using different thresholds and regional cover fractions. Error bars denote confidence intervals.

Risk

The risk part of the FWI workflow combines data from the FWI hazard part with data describing other factors contributing to wildfire risk, including, e.g., burnable vegetation fraction[49], population density, irreplaceability index, and restoration cost index. These additional data are loaded from the EFFIS data portal[50]. As the wildfire analysis for Finland focuses on emergency response, we decided to exclude certain data from the analysis, which are by default included in the workflow. The final data we included were

- The FWI-data from the five climate models listed above, averaged over these five models and the fire season of the historical period 1976-2005.
- The burnable vegetation fraction per pixel derived from ESA landcover data[49]
- The population density
- The amount of people living in the woodland-urban interface (WUI)

The average FWI and burnable area were first combined into a fire danger index by normalising both data sets between 0 and 1 and then multiplying them. An example of this is shown in Figure 2.40 and Figure 2.40 for Southwest Finland and North Karelia, respectively.

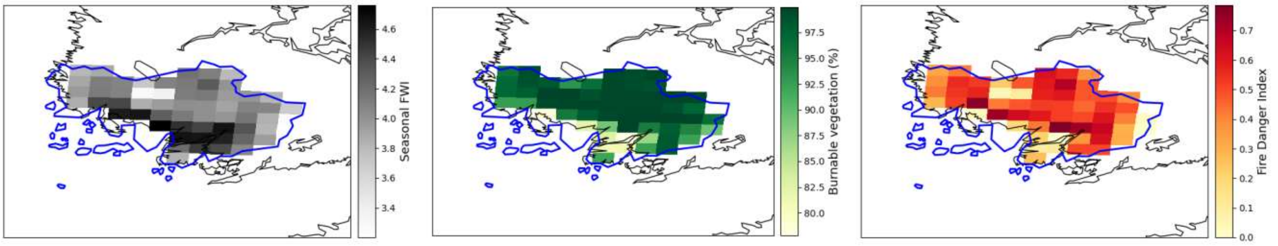

Figure 2.39: Computation of fire danger index in Southwest Finland: The seasonal FWI (left; averaged over 5 models and 30 model years each) and the burnable vegetation fraction (centre) are both normalised and then combined into the fire danger index (right).

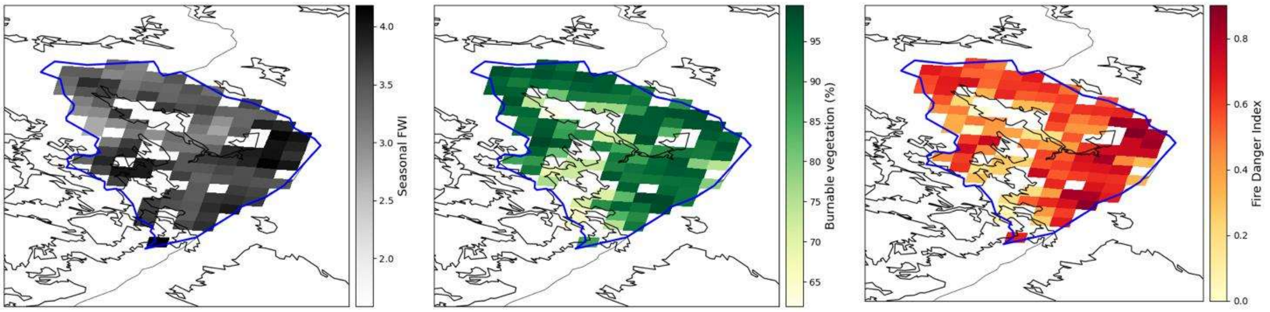

Figure 2.40: Computation of fire danger index in North Karelia: The seasonal FWI (left; averaged over 5 models and 30 model years each) and the burnable vegetation fraction (centre) are both normalised and then combined into the fire danger index (right)

As can be seen from the figures, the average seasonal FWI in Southwest Finland is in general higher than in North Karelia. This is expected and well in line with what is observed. In Southwest Finland, the data show a slight decrease (note the small range in the colour scale) in FWI from the coast inwards, but in the fire danger index this is offset by the burnable vegetation fraction, which is larger

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[49] from https://cds.climate.copernicus.eu/datasets/satellite-land-cover?tab=overview

[50] https://forest-fire.emergency.copernicus.eu/apps/fire.risk.viewer/

further inland. In North Karelia no such trend is visible and the local variations in FWI appear to be mostly random and may well disappear if more climate model data were to be used.

The fire danger index together with the other data sets (here population density and WUI) were then combined using Pareto analysis to identify the areas of highest risk in the region. Note that the original workflow also computes areas of minimal risk, but, as pixels with sea or lake coverage are excluded from the analysis (all values equal to zero), the result of that analysis is not meaningful and thus was excluded from our analysis. The results of the Pareto analysis are shown in Figure 2.41 and Figure 2.42 for Southwest Finland and North Karelia, respectively.

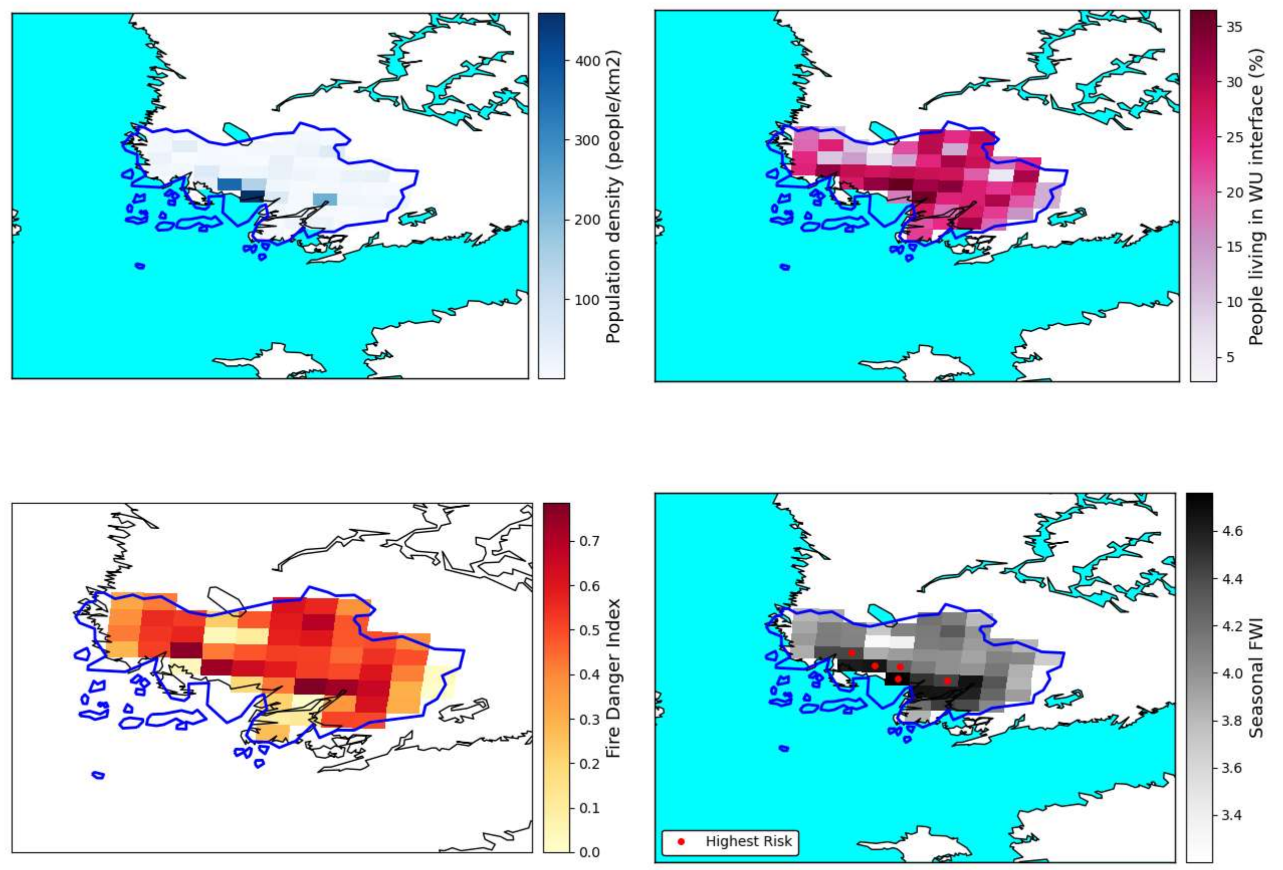

Figure 2.41: Fire Risk in Southwest Finland. The factors included in the analysis are population density (upper left), people living in WUI (upper right), and fire danger index (lower left). The lower right panel shows the average seasonal FWI (gray shading) and the areas of highest risk as red dots.

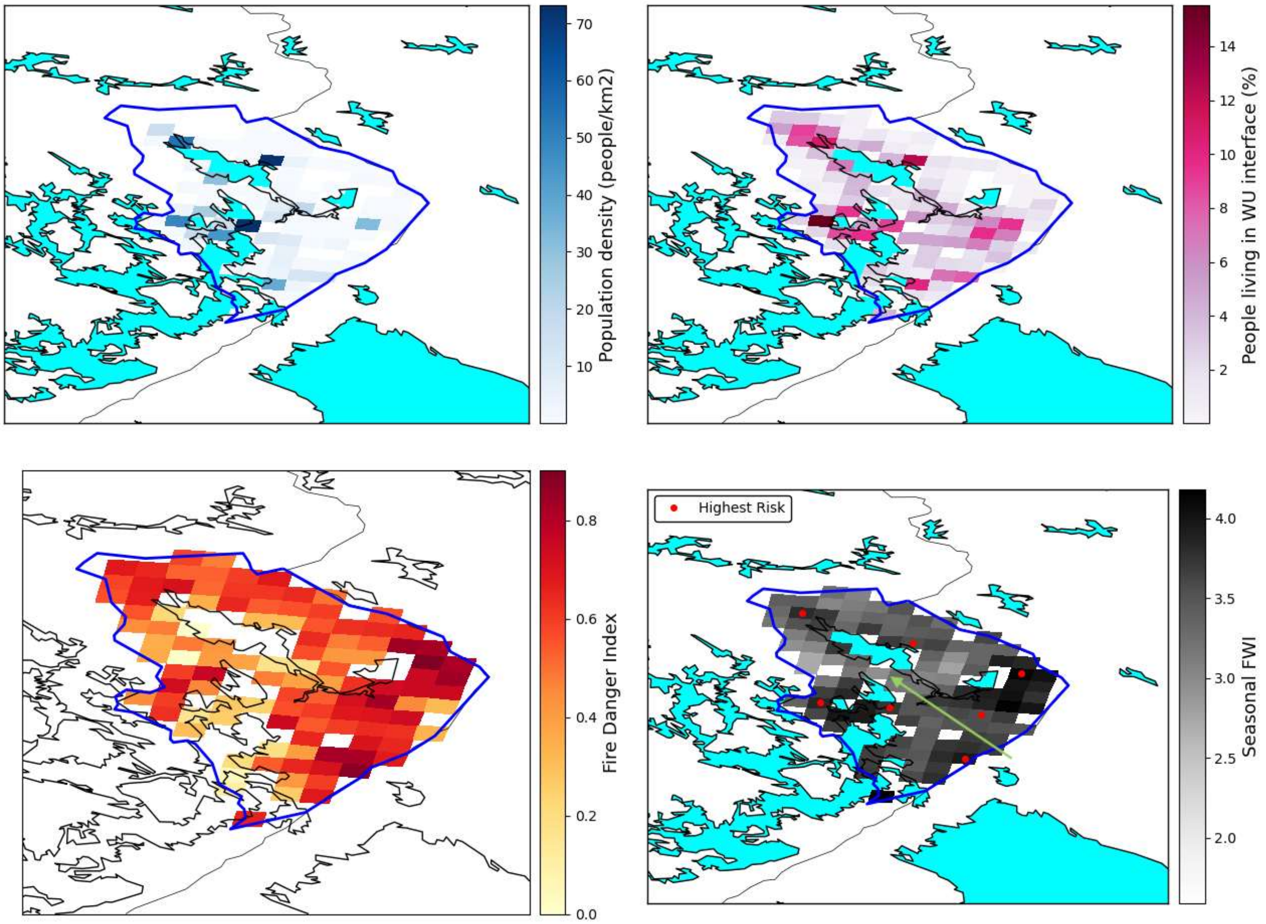

Figure 2.42: Fire Risk in North Karelia. The factors included in the analysis are population density (upper left), people living in WUI (upper right), and fire danger index (lower left). The lower right panel shows the average seasonal FWI (gray shading) and the areas of highest risk as red dots.

As in Southwest Finland both fire danger index and population in WUI do not vary much throughout the region, the results of the risk analysis are dominated by the population density data: The region of highest risk in Southwest Finland is located around the city of Turku, which is the third most populous urban area in Finland after the Helsinki metropolitan area and the city of Tampere.

In North Karelia the regions of largest risk are not as clear cut. Larger settlements, like the city of Joensuu, Lieksa, and Nurmes are marked either because of the population density or WUI data. However, some pixels are also marked because of the slightly higher fire danger values, which, based on the small variation in FWI values, is probably superficial. To analyse the risk due to wildfires in Finnish national parks, additional data sets are needed. For instance, the Koli national park (rough location marked in Figure 2.42), does not show up in the results, because neither population density nor people living in WUI are high there. However, the number of yearly visitors (e.g., hikers) is significant there, as is the level of complexity of possible rescue operations. Even though the pilot phase of the CLIMAAX project is officially ending, this will be analysed further in the future.

Analysing forest fire risk for the two Finnish regions has shown that the process is neither easy nor straightforward. There are still large uncertainties, which means that relying only on the results obtained during the project is not feasible or meaningful. The tools of the CLIMAAX Toolbox are still a work in progress, and this should be considered when interpreting the results.

Nevertheless, we can use the results to gather valuable information for the key stakeholders identified in the beginning of the pilot (forest owners and rescue services). As mentioned in the hazard analysis, one indication of a change in Finland is a persistent increase of the FWI in the springtime already in the mid-century. This information as a single piece of data doesn't tell us that much other than rescue services might need to be alert earlier in the coming years. However, once we combine the data with other, existing data, we get more tangible results. For example, we know that winter storms in Finland will be more destructive due to loss in ground frost[51]. This would imply that after the winter there is more flammable debris in the forest. As the forest fire season is beginning early, this could be a potential threat to especially those high-risk areas identified in the analysis. This information would be useful to both forest owners and rescue services; the former can be informed to clear out their forests before spring and the latter can allocate resources to those areas where there is debris and can be seen as a high-risk area. For areas with higher population density and number of people living in WUI area (Southwest Finland), it would make sense to allocate FRS resources to those high-risk areas identified in the analysis, but also to consider awareness-raising activities and communication campaigns with the residents. For areas with less population (North Karelia), similar activities would still be needed, due to the high number of visitors with different skill levels and awareness on possible risks. In this case, the activities would also need to consider different languages and age groups. For rescue services, different kind of options should be considered, as having full units on standby might not feasible due to resource strains and lack of personnel. These options could include e.g. drone operations for quicker detection and better situational awareness, scouting visitors' capabilities in advance (to be able to help in case of need) and providing small sets of fire extinguishing gear in campsites.

2.6.4.2 Heavy precipitation

Due to the small scale and random spatial occurrence of short-term heavy rain events we did not want to assess the extreme precipitation changes and return period estimates in map form. Instead, histograms showing the precipitation distribution in the selected area were found more suitable to study the precipitation events and possible changes in the study region. In addition, to obtain better statistical significance of the results, we extended the heavy precipitation analysis to include all of the region of Uusimaa (see Figure 2.43), of which the Helsinki capital region is part. This extension is possible, as precipitation characteristics do not change significantly within Uusimaa and, therefore, any subregion of Uusimaa is representative of the Helsinki capital region.

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[51] https://helda.helsinki.fi/items/ce1866b9-eb28-46b3-9478-a531a2e736f7

Figure 2.43: Study region covering Uusimaa in southern Finland. The capital city of Helsinki is located at the coast, center of the selected region, marked with red circle. Figure adopted from Bounding Box Tool[52] *which gives coordinates for selected regions.*

Hazard

To study extreme precipitation events in Uusimaa/Helsinki, we followed the extreme precipitation workflow from the CLIMAAX Toolbox. We downloaded precipitation data from three EURO-CORDEX regional climate models from the Climate Data Store (CDS). These models, referred to as ICHEC-EC-EARTH/RACMO22E, MPI-M-MPI-ESM-LR/RCA4 and NCC-Nor-ESM1-M/HIRHAM5, have a horizontal resolution of 0.11° x 0.11° (approximately 12 km) in Europe. The historical data used spans 1976–2005, while the future projections cover 2041–2070 under the RCP 8.5 scenario, representing a worst-case pathway for future climate forcing. The highest temporal resolution available is 3 h. The precipitation flux represents the mean of the 3-hour aggregation period, meaning that the precipitation could have been constant rain during the 3 h period, or it could contain shorter periods of both even heavier precipitation and dry periods.

In the workflow, annual maximum precipitation amounts for 3-hour (Figure 2.44) and 24-hour (not shown) durations were analysed to produce return period distributions for the selected area. The frequency and magnitude of extreme precipitation events vary considerably across the models, even during the historical period (Figure 2.44 A, B, C). These differences in historical period and possibly even larger differences in the future period highlight the challenges in selecting the most suitable models for reliable projections for precipitation in the future (see also Section **Error! Reference source not found.**).

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[52] https://boundingbox.klokantech.com/

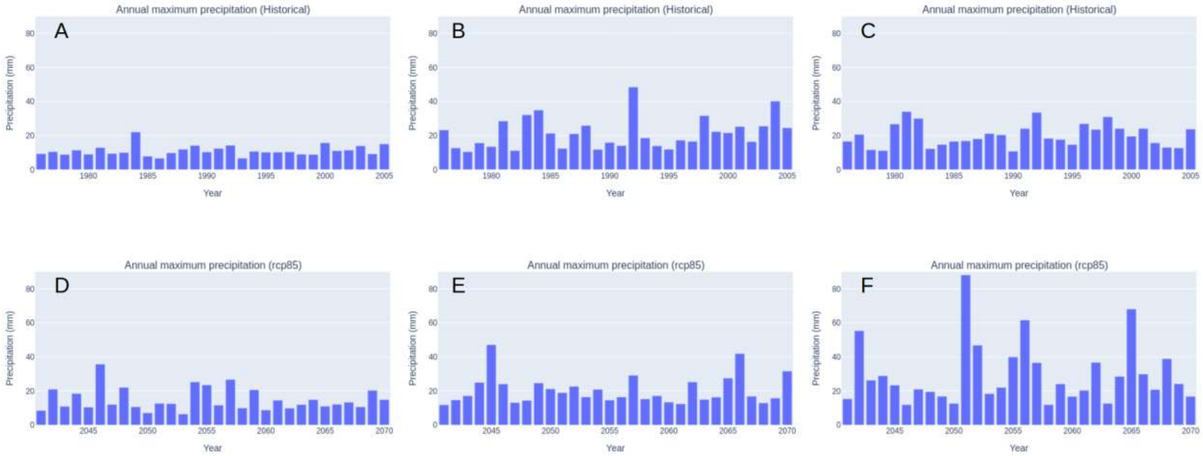

Figure 2.44: Histograms of annual maximum precipitation in Rautatientori, in Helsinki Uusimaa, in historic (A, B, C) and future periods (D, E, F). The regional climate models ICHEC-EC-EARTH_KNMI-RACMO22E (A,D), MPI-M-MPI-ESM-LR_SMHI-RCA4 (B, E) and NCC-Nor-ESM1-M_DMI-HIRHAM5 (C, F). Note that the years shown in the plots do not directly relate to real (historical or future) years but they do reflect the statistical averages and variation of the periods analysed.

Return periods of 2, 5, 10, 20, 50, and 100-year were used in the analysis to capture a range of extreme precipitation scenarios. For shorter return periods, the rainfall distribution was narrower, and steeper (Figure 2.45 A, B, C) compared to longer return periods, such as 100 years, where the distribution becomes wider and flatter (Figure 2.45 D, E, F). Two of the models (ICHEC-EC-EARTH/RACMO22E and NCC-Nor-ESM1-M/HIRHAM5 (Figure 2.45 A, D and C, F, respectively)) project an increase in future extreme rainfall amounts, while one model (MPI-M-MPI-ESM-LR/RCA4, Figure 2.45 B, E) suggests no change or a slight decrease.

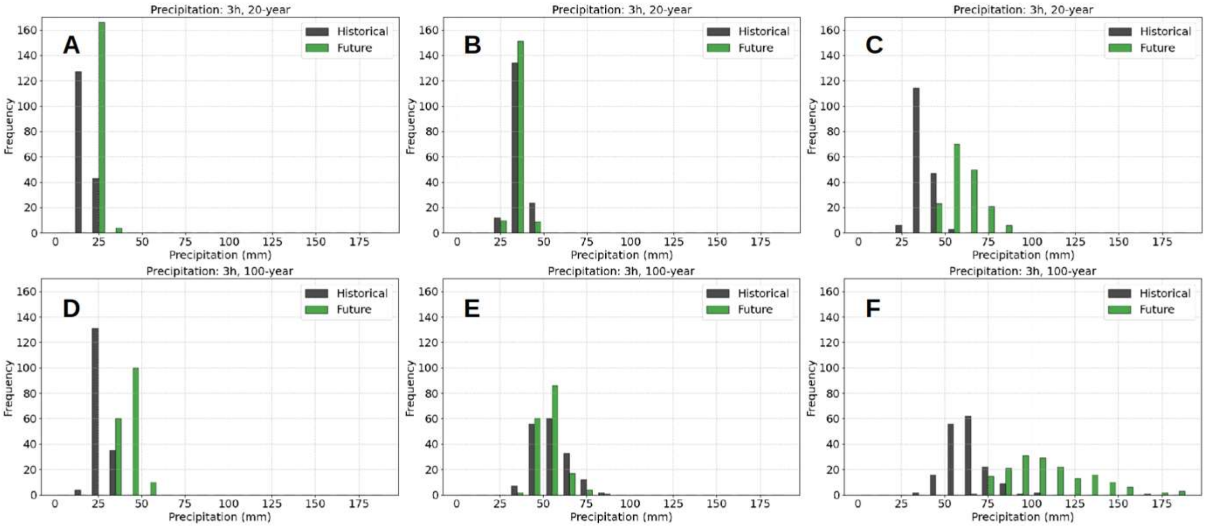

Figure 2.45: Histograms of accumulated precipitation amounts during 3h in Uusimaa region using 20-year return period (A, B, C) and 100-year return period (D, E, F) for historical (1976-2005, gray bars) and future (2041-2076, green bars) periods under RCP 8.5 scenario. The models used were ICHEC-EC-EARTH/RACMO22E (A,D), MPI-M-MPI-ESM-LR/RCA4 (B, E) and NCC-Nor-ESM1-M/HIRHAM5 (C, F).

Table 2-4: Median of accumulated precipitation (mm/3h) in Uusimaa region using five different return periods (2, 5, 10, 20, 50, and 100 years) in historical (1976-2005) and future (2041-2070) periods. The largest and the smallest values for each return period from the three climate models are highlighted with red and blue, respectively.

Model	Return period	Historical median [mm/3h]	Future median [mm/3h]	Median change [mm/3h]	Median change [%]

ICHEC-EC-EARTH/RACMO22E	2	10.6	12.4	1.7	15.3
MPI-M-MPI-ESM-LR/RCA4		18.6	18.2	-0.5	-2.7
NCC-Nor-ESM1-M/HIRHAM5		17.7	23.4	5.8	33.4
ICHEC-EC-EARTH/RACMO22E	5	13.5	17.1	3.4	25.2
MPI-M-MPI-ESM-LR/RCA4		25.0	24.1	-0.7	-2.7
NCC-Nor-ESM1-M/HIRHAM5		24.7	35.0	10.8	44.8
ICHEC-EC-EARTH/RACMO22E	10	15.9	21.3	5.1	32.3
MPI-M-MPI-ESM-LR/RCA4		29.7	29.1	-0.8	-2.7
NCC-Nor-ESM1-M/HIRHAM5		30.6	45.5	15.5	50.9
ICHEC-EC-EARTH/RACMO22E	20	18.6	26.4	7.3	38.9
MPI-M-MPI-ESM-LR/RCA4		35.5	34.7	-1.2	-3.0
NCC-Nor-ESM1-M/HIRHAM5		38.0	58.8	21.7	56.3
ICHEC-EC-EARTH/RACMO22E	50	22.7	34.5	11.1	48.3
MPI-M-MPI-ESM-LR/RCA4		44.6	43.6	-1.5	-3.5
NCC-Nor-ESM1-M/HIRHAM5		50.1	81.7	33.3	67.1
ICHEC-EC-EARTH/RACMO22E	100	26.5	42.2	14.9	56.2
MPI-M-MPI-ESM-LR/RCA4		53.0	51.7	-1.8	-3.5
NCC-Nor-ESM1-M/HIRHAM5		62.2	104.9	45.6	72.2

Risk

A critical impact rainfall threshold is defined as the amount of precipitation required to trigger unsustainable or unacceptable impacts. Projected changes in extreme precipitation could be used to estimate the magnitude and frequency of pluvial floods in the future.

To qualitatively estimate the possible effect of extreme precipitation in future we used results from HULEHENRI[53] project (Perttula et al., 2023) where a general pluvial flood hazard map has been developed for Finnish municipalities, identifying potential flood-prone areas in urban regions under two rainfall scenarios: 52 mm/hour and 80 mm/hour (Figure 2.46)[54]. These critical impact rainfall thresholds were based on observed rainfall data and 100-year return period, incorporating a 1.4 multiplier to account for expected climate change impacts on hourly extreme rainfall. Figure 2.46 represents the estimate of flooded areas (dark blue) in Rautatientori, city central of Helsinki, based on HULEHENRI pluvial flood modelling in the scenario where extreme rain of 80 mm/hour fell during the previous hour.

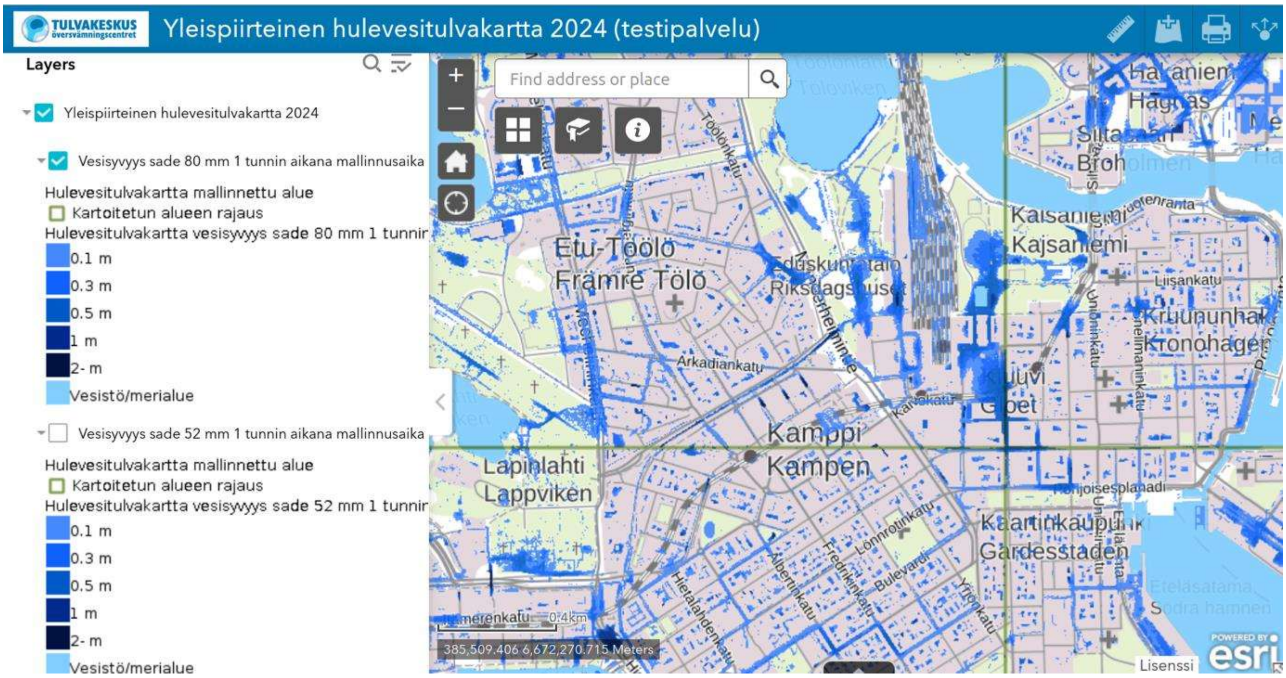

Figure 2.46: Estimate of pluvial floods (dark blue) in Rautatientori in the capital city of Helsinki in Uusimaa Finland with critical impact rainfall threshold of 80 mm/h.

In the modelling of urban flooding in the HULEHENRI project, a constant runoff reduction rate of 10 mm/hour was applied to account for the capacity of stormwater drainage systems. This simplified estimate represents the average capacity of drainage infrastructure, though significant local variability exists. For instance, areas with well-maintained drainage systems may handle rainfall better, while others with older or insufficient infrastructure are more vulnerable. Additionally, terrain plays a role; locations at the base of hills are more prone to flooding compared to elevated areas. Seasonal factors, such as fallen leaves in autumn or snow in winter, can further affect drainage efficiency.

To assess the possible pluvial flood risk in Helsinki in the future, we compared the critical impact rainfall thresholds to the median precipitation values with different return period levels from the climate model scenarios. Due to the highest temporal resolution of 3 hours and relatively coarse horizontal resolution of 12 km in CORDEX regional climate model data, which can smoothen out the

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[53] https://wwwi9.ymparisto.fi/i9/fi/hulevesitulva/info_kunnille_2024_01/Tietopohjaa%20alustavan%20arvioinnin%20tueksi_Yleispiirteinen%20hulevesitulvakartta_MikkoHuokuna_16012024_update.pdf

[54] https://syke.maps.arcgis.com/apps/webappviewer/index.html?id=aa63362413914688b20b29b98f14f456

largest precipitation amounts, we assume here that the 3h accumulation roughly corresponds to the hourly critical impact thresholds used in HULEHENRI pluvial flood modelling.

Assessing the median precipitation values in the historical period the critical impact rainfall threshold of 52 mm/h was exceeded with two models (MPI-M-MPI-ESM-LR/RCA4 and NCC-Nor-ESM1-M/HIRHAM5) when 100-year a return period was applied (Table 2-4). None of the models exceeded the higher threshold of 80 mm/h in the historical period. In the future period, only one model (NCC-Nor-ESM1-M/HIRHAM5) exceeded the threshold of 52 mm/hour, but it occurred already with 20-year return period (compared to 100-year in historical period), meaning that the extreme precipitation events causing pluvial floods could be more frequent than in the historical period. Nevertheless, in two of the three tested climate models the median of extreme precipitation with different return period levels were not high enough to cause pluvial floods in Helsinki (Table 2-4). However, the maximum precipitation in the study region exceeded the 52 mm/3h at least once in the Uusimaa region for all the models when computing a 100-year return period in the future (Figure 2.45). The large variation between the three climate models (Table 2-4) highlights the need for model validation and use of larger model ensembles to ensure reliable heavy precipitation estimates for the future.

2.6.5 Future Plans

2.6.5.1 Wildfire

For wildfires, we will continue with the development of the models with possible new layers – e.g. a company called Arbonaut has maps which include also ground steepness gradients and indicators for moistness. This is important as there are a total of 9.3 million hectares of bogs and peatlands in Finland, or a third of the land area. About half of the bogs have been drained for forestry use, about 250,000 hectares are in agricultural use and about 50,000 hectares are in active peat production. Of the current marsh area, 1.2 million hectares, or about 13 percent, have been protected.[55] This is a major factor in the development of forest fires.

With the results, we hope to identify high-risk wildfire areas. This would allow us to use the information in various ways:

- In terms of general public: We are able to increase awareness of the risks during forest fire season.
- In terms of fire departments (wellbeing services counties): We are able to increase preparedness in the most high-risk areas.
- In terms of health care units (wellbeing services counties): We are able to address the health impacts of wildfires.
- In terms of cities and municipalities: We are able to plan restriction lines between wildland and urban areas.
- In terms of Forest Centre: We are able to promote forestry to choose fewer flammable trees, to do proper forestry management and to do prescribed burnings in the most sensitive areas.

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[55] https://mmm.fi/en/nature-and-climate/mires-and-peatlands

2.6.5.2 Urban flooding

We intend to make use of the methods and tools developed in the CLIMAAX consortium to evaluate models on a regional scale once they become available (in fact, FMI participates in the development and testing of these tools) and will repeat the analysis with the so identified best set of models. The results of the precipitation intensities will be communicated to stakeholders (i.e., the cities belonging to the Helsinki capital region) and other research institutes. For instance, the Finnish Environment Institute SYKE performs urban flood modelling based on given precipitation amounts.

4 Lessons learnt

4.1 Planning

The CLIMAAX project is very ambitious both in terms of content and timing. It is also very novel in terms of its conception and structure. Therefore, it was almost a given that some problems would arise along the way. During the pilot phase we encountered numerous challenges, which, on the one hand, show that the work of the CLIMAAX project is necessary and useful, but on the other hand also led to various deviations from the original project plan, both in terms of timing and content.

What became apparent very early on during the project implementation was that the schedule of the first phase of the project was overall too tight. The time and person months were not so much of an issue, but many work packages and tasks depend critically on each other and often one work package had to wait for another one to deliver before work could continue. This was especially an issue with the pilots, which were scheduled to start in August 2023 and last for 10 months. Most of these issues were resolved by extending the pilot phase by 6 months until the end of 2024. This also includes a staged submission of this deliverable: The first version was submitted June 2024, while this version will be submitted in February 2025.

Fortunately, the Third Parties (60+ regions supported by the cascading fund of CLIMAAX) have 22 months to conduct their CRAs. Next to the use of the CLIMAAX tools they can include local datasets and expertise. Finally, as the CRA Framework and Toolbox have been improved significantly during the past half year based on the feedback from the pilots, it can be assumed that the given 22 months can also be used much more efficiently by the Third Parties.

4.2 Need for local technical support and regional optimization

In addition to the timing issues lined out above, there were also some conceptual challenges in the pilots. The original plan of the CRA Toolbox was to provide generalised workflows which can be run in any European region and produce results without greater technical effort or input of own, regional data. The idea then had been for the pilots to adapt these general workflows to their own local needs, using own, high-resolution data where necessary. This, however, turned out to be a larger challenge than originally anticipated.

While each pilot had a technical partner, the core competences of the technical partners (in terms of, e.g., climate hazards) did not always align with the needs of the pilots. This was solved by involving a lot of other partners in the work done with the pilots, often the ones who developed the original, European-scale workflows for the CRA Toolbox in WP2. The machine learning fire workflow has a complex approach, requiring multiple data from the local region and, in most cases, technical support from the developers. For exploration objectives, it was more helpful to develop a simplified fire workflow that provides insights in the expected risks. Also, as workflow development became more focused on certain regions, the amount of support that individual partners received was not well balanced. Part of the Third Parties who applied for the CLIMAAX funding have applied together with a technical partner or sub-contractor, which will greatly benefit their CRAs.

4.3 Advance knowledge and expectations

Contrary to the assumptions of the scientific partners, many of the pilot partners did not have a lot of previous experience with CRA or climate issues in general. For this reason, the pilot partners often struggled with the material provided to them, because they were not familiar with, e.g., concepts, terminology and technical solutions which belong to the standard repertoire of the climate researcher community. This also caused delays in the regional CRA execution of the pilots. On the other hand, the diverse backgrounds of the pilot partners in terms of entry level, interest, and expertise made it possible to test the CLIMAAX tools from very many different viewpoints: some partners are very technical and had few problems with the CRA Toolbox but could instead give technical feedback on the workflows. Other partners had a long history in climate change adaptation and climate risk prevention and could directly compare their methodologies to the one presented in the CRA framework. Also, the different backgrounds helped collect a list of terms and issues to be added to the Glossary and Frequently Asked Questions sections of the CRA Handbook, as well as helped shape the documentation throughout the CRA Handbook. The experience was also beneficial for the pilot partners, as they learned from each other and the participation in the project altogether. As the Third Parties to be funded by the CLIMAAX cascading fund are expected to be at least as diverse as the pilots, the input and experiences from the pilot phase is expected to greatly ease the start of the second phase of the project.

Another problem that arose was that the expectations of the pilots concerning the functionality and outcomes of the CRA Toolbox workflows were different from what the toolbox developers had originally planned. Due to the very technical nature of the workflows, the pilot partners needed much more technical support than originally anticipated. This issue was solved by restricting the number of hazards to be assessed by each of the pilots. Also, additional, optional elements for visualisation of the workflow results were concepted based on the feedback received from the pilots. These elements will be implemented as technical solutions in the CRA Toolbox.

4.4 Cross-pilot interaction and learning

After the 2nd CLIMAAX GA in Setúbal, WP3 started organising weekly technical meetings with the pilots and all interested partners of the CLIMAAX project (before, meetings were mainly bilateral between the pilots and the WP3-lead and other partners). In these meetings different topics were discussed, including the CRA Framework, different CRA Toolbox workflows, and discussions on climate scenario use. These meetings proved to be a very efficient platform to facilitate dialogue between different CLIMAAX partners, in particular between scientists, technical, and non-technical partners. This triggered a lot of self-organised interaction between the pilots as well. For instance, some of the pilots initiated bilateral dialogue to discuss common issues with the CRA Framework and Toolbox. To provide the support for and to ensure the dialogue between the Third parties, these technical meetings will be continued for the full group of regions.

4.5 Other aspects

As already mentioned before, the regions across Europe are very diverse. This does not only include climatic zones and the connected climate hazards and risks, but also the backgrounds of the people and institutes performing CRA. While some regions may benefit greatly from the tools provided by CLIMAAX, others may find the offered material too complex or even overwhelming. Yet other regions may have already performed very advanced CRAs which already exceed what CLIMAAX have to offer.

Also, it has become clear, that most regional CRA cannot be performed at the resolutions which pan-European or global datasets have to offer. To perform a CRA at a NUTS3 or smaller level, most cases will require higher-resolution and possibly local data. However, such data may not always be readily available and ways to acquire or produce such data must be explored to further support this initiative.

To be able to support all possible end users, the CLIMAAX concept of standardised flexibility must be at the forefront. We are doing our best to make this goal a reality, learning from the advanced regions and teaching and supporting the ones who need it the most.

5 Conclusions

This deliverable reports on the regional climate risk assessments (CRA) performed by the five CLIMAAX pilots during the first stage of the CLIMAAX project. To this end, each pilot reports both on the process of performing the CRA as well as its final results after the CLIMAAX CRA Framework had been applied and the workflows of the CRA Toolbox had been adapted to the special needs of the pilot region in question.

This deliverable also contains a Lessons Learnt section, which reflects on what worked and what could be improved in the project. This is very important because the second phase of the CLIMAAX project will fund 60+ European regions to perform a regional CRA using the tools developed by CLIMAAX. The experiences gained through the involvement of the pilots has greatly helped to shape the CLIMAAX tools into their current form and thereby making them as useful as possible for the 60+ regions to follow in their footsteps.

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