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User-Driven Climate Resilience Across Southern European Regions

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Abstract: This study presents the ClimEmpower framework, a user-driven approach to enhancing climate resilience across five climate-vulnerable regions in Southern Europe: Costa del Sol (Spain), Central Greece, the Troodos Mountains (Cyprus), Osijek-Baranja County (Croatia), and Sicily (Italy). The project employs a region-specific methodology that integrates climate risk assessments, stakeholder engagement through Communities of Practice (CoPs), and the development of innovative climate services tailored to local needs. These regions, characterized by unique environmental and socio-economic vulnerabilities, face shared hazards such as droughts, heatwaves, and floods, alongside region-specific challenges like salinization and biodiversity loss. ClimEmpower identifies critical gaps in high-resolution data, cross-sectoral collaboration, and capacity-building efforts, underscoring barriers to effective adaptation. This work aims to provide a foundational resource, offering a comprehensive overview of the current situation, including needs, gaps, priorities, and expectations across the target regions. By establishing this baseline, it facilitates future research and comparative analyses, contributing to the development of robust, region-specific resilience strategies. The ClimEmpower framework offers scalable and replicable solutions aligned with the European Green Deal's climate resilience goals, advancing adaptation planning and providing actionable insights for broader European initiatives.

Keywords: climate resilience; regional adaptation; community of practice; climate risk assessment; climate data services; user-driven applications

1. Introduction

Climate change poses increasingly complex and significant risks to environmental, social, and economic stability across Europe [1–9]. These risks manifest through more frequent and intense extreme weather events, disruptions to ecosystems, and socio-economic challenges, particularly in vulnerable regions [10–12]. Climate resilience, defined as the capacity to anticipate, prepare for, and respond to hazardous events, has become essential for adapting and sustaining well-being under changing climatic conditions [13–19]. Recognizing this urgency, the European Union has emphasized resilience-building in its climate adaptation goals, particularly within regions highly exposed to climate extremes, as part of its broader efforts under the European Green Deal [20–23].

The ClimEmpower project, funded under the Horizon Europe program, directly addresses these resilience challenges by focusing on regional climate adaptation across Europe [24]. The project aims to empower local stakeholders by identifying gaps in data and services, leveraging existing datasets, and designing climate service architectures tailored to regional needs. The ultimate goal is to provide actionable insights and resilience-building tools that enhance regional climate adaptation planning.

Five case study regions were selected for ClimEmpower: Costa del Sol in Andalusia (Spain), Central Greece, the Troodos Mountains (Cyprus), Osijek-Baranja County (Croatia), and Sicily (Italy). These regions, located in Southern Europe (Figure 1), combine high levels of climate change risk with low coping capacities. They represent diverse climatic conditions and challenges: coastal areas experiencing water scarcity during tourist seasons, mountainous regions vulnerable to forest fires and erosion, and agricultural inland plains affected by unsustainable practices and shifting climatic patterns. These regions also face significant socio-economic issues, including economic stagnation, negative demographic trends, and high unemployment rates.

The primary aim of this paper is to present the framework developed by ClimEmpower to enhance the climate resilience of these regions. This includes identifying the current needs, gaps, priorities, and expectations of stakeholders while establishing a foundation for future research. The study also facilitates a comparative analysis between the five regions, enabling the development of scalable and replicable models for regional resilience.

To achieve these objectives, ClimEmpower employs a region-specific and community-driven approach. Central to this methodology is the establishment of regional Communities of Practice (CoPs), which bring together stakeholders from the quadruple helix—academia, industry, government, and civil society. CoPs facilitate stakeholder engagement, knowledge exchange, and co-creation of climate solutions, ensuring that regional insights and priorities shape the project's outputs. A comprehensive study was conducted to assess regional needs and data gaps through a structured questionnaire and stakeholder engagement. This questionnaire [25], designed by the ISTOS team from Cyprus, captured both quantitative and qualitative data, addressing issues such as climate risk perception, data usability, and adaptation priorities.

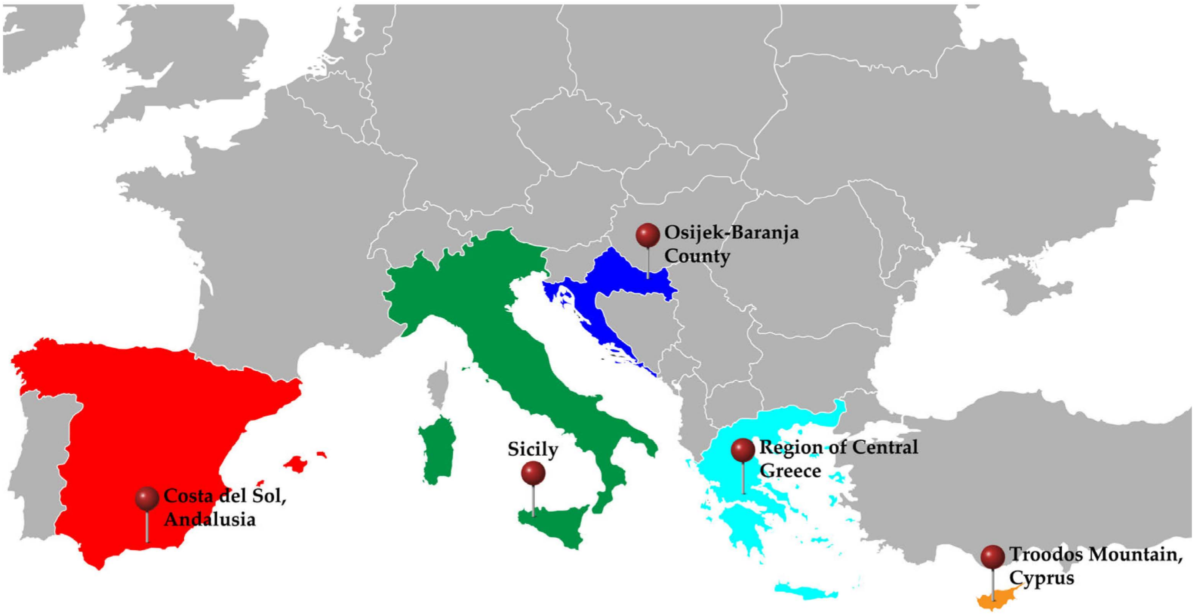


Figure 1. Geographical distribution of case study regions in Southern Europe.

The current climate resilience literature underlines the importance of region-specific assessments and adaptive frameworks, as climate risks vary significantly depending on factors such as geography, socio-economic conditions, and infrastructure resilience [26–30]. In Southern Europe, for example, areas like Sicily, Costa del Sol, and Cyprus face intensified threats from heat waves, droughts, and water scarcity, necessitating specialized strategies for localized risk management and resilience enhancement [31–36]. Research has consistently shown that effective adaptation relies on combining scientific climate data with community-specific insights, as this integration improves the relevance and acceptance of climate resilience initiatives.

Aligned with the European Union's Adaptation Strategy [37] the European Green Deal [38] and building on findings from previous projects such as CLIMAAX [39] and RESILOC [40], ClimEmpower integrates scientific data with local knowledge to ensure actionable outcomes. This combination of rigorous analysis and community insights enhances the relevance and acceptance of resilience-building strategies. By bridging gaps in data accessibility, usability, and decision-making relevance, ClimEmpower contributes to the broader European effort to mitigate climate risks and foster sustainable adaptation.

This paper is structured to outline the framework followed by ClimEmpower, the methodologies employed to gather and analyze regional data, and the findings from the comparative analysis of the five case study regions. It highlights the innovative application of climate services and regional insights, offering a foundation for future research and adaptation strategies.

2. Materials and Methods

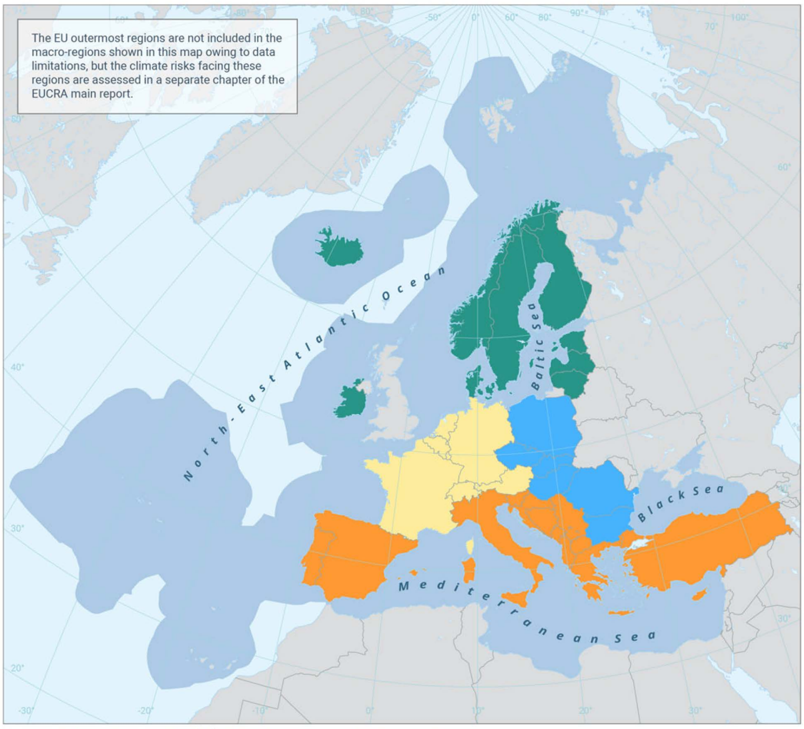
2.1. Data Collection and Assessment of Climate Resilience Needs

The ClimEmpower project utilized a multi-faceted methodology encompassing data collection, community engagement, and climate resilience assessment, designed to address the unique climate resilience needs of five diverse European regions: Costa del Sol in Andalusia (Spain), Central Greece, the Troodos Mountains (Cyprus), Osijek-Baranja County (Croatia), and Sicily (Italy). This section outlines the methodological approaches used to gather, analyze, and apply data within the project framework and describes the role of the Communities of Practice (CoPs) in facilitating stakeholder engagement and insight gathering. Additionally, it presents the climate resilience assessment framework, which integrates stakeholder feedback with data-driven approaches to create tailored regional adaptation strategies.

2.1.1. Climate Risk Assessments of the ClimEmpower Regions

Each ClimEmpower region has engaged in or is actively implementing climate risk assessments (CRAs) tailored to its specific environmental and socio-economic context. These assessments address multiple sectors, including agriculture, health, water resources, and biodiversity, to tackle climate hazards such as heat waves, droughts, and heavy precipitation. The CRAs are aligned with each region's national adaptation policies, with updates reflecting evolving climate data, such as Spain's statutory five-year review cycle and Croatia's recent comprehensive national CRAs.

Figure 2 presents the "EUCRA Land and Marine Regions", [41] categorizing ClimEmpower's regions within the broader Southern Europe zone, which is particularly susceptible to significant climate risks. This visual places the target regions within a larger European framework, highlighting common challenges across the Southern European zone, including heightened vulnerability to extreme weather patterns.



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commision – Eurostat/GISCO

Figure 2. The EUCRA land and marine regions.

Table 1 illustrates trends in critical climate-related hazards across four European macro-regions—Northern Europe, Western Europe, Central-Eastern Europe, and Southern Europe—encompassing heatwaves, heavy precipitation, and drought. Observed trends from the past (1952–2021) are presented alongside projections for the future (2081–2100) under both low-emission (SSP1-2.6) and high-emission (SSP3-7.0) scenarios.

Table 1. Observed and projected trends in key climatic related hazards in different European regions (2024) [42]. Notes: the blurred arrows are referred to projections with high uncertainty; the square is related to low-confidence projections.

Land Regions	**Northern Europe**			**Western Europe**			**Central-eastern Europe**			**Southern Europe**		
	Past	**Future**		**Past**	**Future**		**Past**	**Future**		**Past**	**Future**	
		Low	**High**		**Low**	**High**		**Low**	**High**		**Low**	**High**
Mean temperature	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
Heatwave days	□	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
Total precipitation	↗	↗	↗	↗	/	↘	↗	↗	/	/	↘	↘
Heavy precipitation	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
Drought	↗	↘	↘	↗	/	↗	↗	/	↗	↗	↗	↗

For past trends, mean temperature, heatwave days, total precipitation, heavy precipitation, and drought generally show an increase (↗) across most regions, with notable exceptions like the absence of significant change in heatwave days in Northern Europe (□). In future scenarios, mean temperature and heatwave days consistently increase across all regions under both low (↗) and high (↗) emission pathways. Total precipitation trends vary, showing increases (↗) in Northern and Western Europe but decreases (↘) under high-emission scenarios in Southern Europe. Heavy precipitation trends are projected to rise (↗) across all regions, while drought patterns indicate contrasting trends, with decreases (↘) in Northern Europe and increases (↗) in other regions under high-emission scenarios.

These comprehensive data, sourced from the Copernicus Climate Change Service (C3S), underscore the urgency of regional resilience planning, as Southern Europe is expected to experience some of the most pronounced climate shifts within the EUCRA framework. Together, Figure 1 and Table 1 contextualize the ClimEmpower regions within both their geographical and climatic risk profiles, illustrating the critical need for adaptive strategies to mitigate these projected impacts.

2.1.2. Climate Resilience: Differences Between Risk and Resilience Assessment

In climate resilience planning, it is essential to differentiate between risk assessment and resilience assessment, as each approach offers unique insights into managing climate challenges. Risk assessments focus on evaluating climate risks as a function of exposure, vulnerability, and hazards (Figure 3a), analyzing how these elements interact to contribute to the likelihood and potential severity of adverse impacts. This approach aligns with frameworks such as the IPCC's risk model [43], which defines risk through dynamic interactions between climate hazards, population vulnerability, and exposure levels in affected regions.

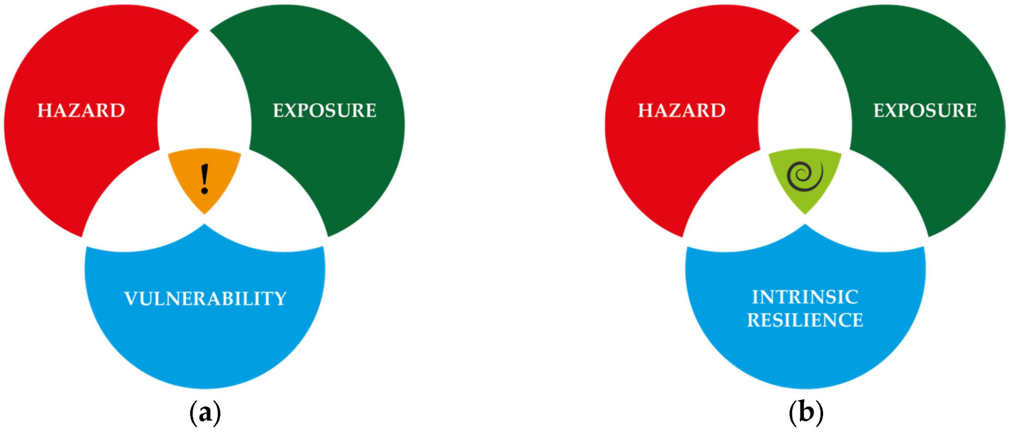


Figure 3. The concept of risk and resilience [40], (**a**) Risk = func (Hazard, Exposure, Vulnerability); (**b**) Resilience = func (Hazard, Exposure, Intrinsic Resilience).

In contrast, resilience assessments take a broader perspective, examining a community's intrinsic capacity to adapt, recover, and maintain well-being in response to climate disruptions. Resilience assessments go beyond immediate risk factors, focusing instead on factors like "intrinsic resilience" and "adaptive capacity"—key components that emphasize a community's inherent strengths and its ability to respond effectively to disruptions. This distinction highlights that resilience is not solely about mitigating risks, but also about enhancing adaptive capabilities within socio-ecological systems to sustain functionality and thrive despite climate pressures (Figure 3b).

Intrinsic resilience [41,44–47] represents a community's inherent ability to withstand shocks without severe loss of function, while adaptive capacity refers to the potential to reorganize, innovate, and adjust in response to changing conditions. Together, these resilience factors shift the focus from simply reducing risks to fostering long-term sustainability and adaptability. By integrating these resilience elements, the approach supports building robust climate resilience strategies that encompass both risk mitigation and adaptive growth, ultimately equipping communities to respond more effectively to both current and future climate challenges.

2.1.3. Climate Risk Assessment (CRA) Approach

ClimEmpower's CRA approach, aligned with IPCC standards, conceptualizes climate risk as a dynamic interaction between hazards, exposure, and vulnerability, allowing each region to adapt assessments to local conditions. By integrating resources like the European Drought Risk Atlas [48], which provides data on long-term drought trends, the CRA prioritizes regional risks and supports targeted resilience strategies. Informed by frameworks like the European Climate Risk Assessment (EUCRA) [49], ClimEmpower utilizes a structured model to evaluate risk severity, confidence, and policy readiness. The EUCRA model, with its "risk urgency matrix", enables regions to align risk assessments with adaptive, multi-hazard policies that reflect both immediate and projected climate threats. Through this comprehensive approach, ClimEmpower ensures that each region can apply resilience measures that are both timely and tailored to specific regional needs.

2.2. Community of Practice (CoP) Engagement and Methodology

To capture local insights and foster collaboration, ClimEmpower established a Community of Practice (CoP) in each target region. The CoP framework was based on established methodologies from previous EU projects that emphasized participatory processes and stakeholder engagement. Each CoP included representatives from regional authorities, local organizations, research institutions, and other stakeholders affected by climate change.

The objective was to facilitate collaborative learning, enable stakeholders to share local knowledge, and gather feedback on climate resilience needs specific to each region.

The engagement process within each CoP followed a structured schedule of meetings and interactive sessions, beginning with an introductory phase to build a common understanding of resilience challenges and project goals. The CoP activities included discussions on data accessibility, identification of region-specific resilience challenges, and participatory mapping of climate hazards. Interactive tools, such as surveys and real-time polling, were employed to collect and prioritize stakeholder needs.

The Community of Practice (CoP) framework within ClimEmpower is built on a collaborative model that integrates diverse stakeholders, aligning with the conceptual components of a CoP as shown in Figure 4. This figure, adapted from Wegner-Trayner's model [50], outlines the core elements that shape each CoP: a shared domain of climate resilience, a community of stakeholders who actively participate, and shared practices aimed at addressing regional climate challenges.

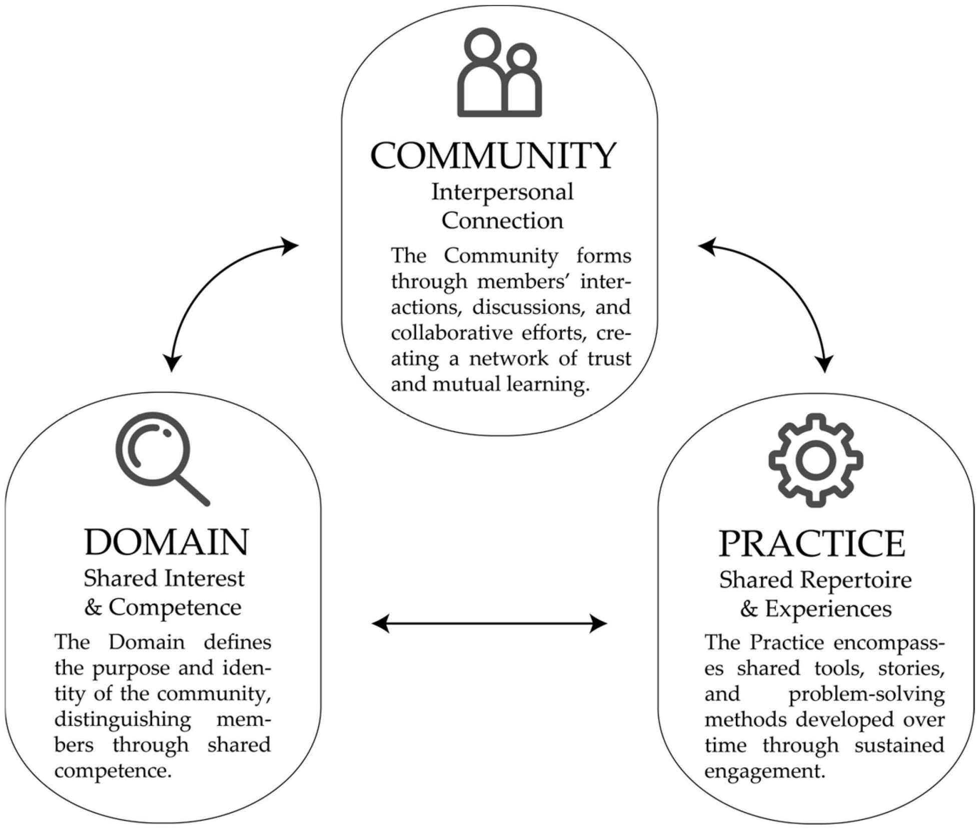


Figure 4. Components of the Communities of Practice.

Furthermore, Figure 5 introduces the quadruple helix innovation framework, which expands stakeholder engagement by incorporating perspectives from public authorities, academia, industry, and civil society. This approach ensures that solutions developed within the CoP reflect a balanced understanding of technical, societal, and economic impacts, fostering broader acceptance and integration of climate resilience initiatives. Together, these figures illustrate how ClimEmpower structures its CoP to promote inclusive, multisectoral engagement essential for sustainable climate adaptation efforts.

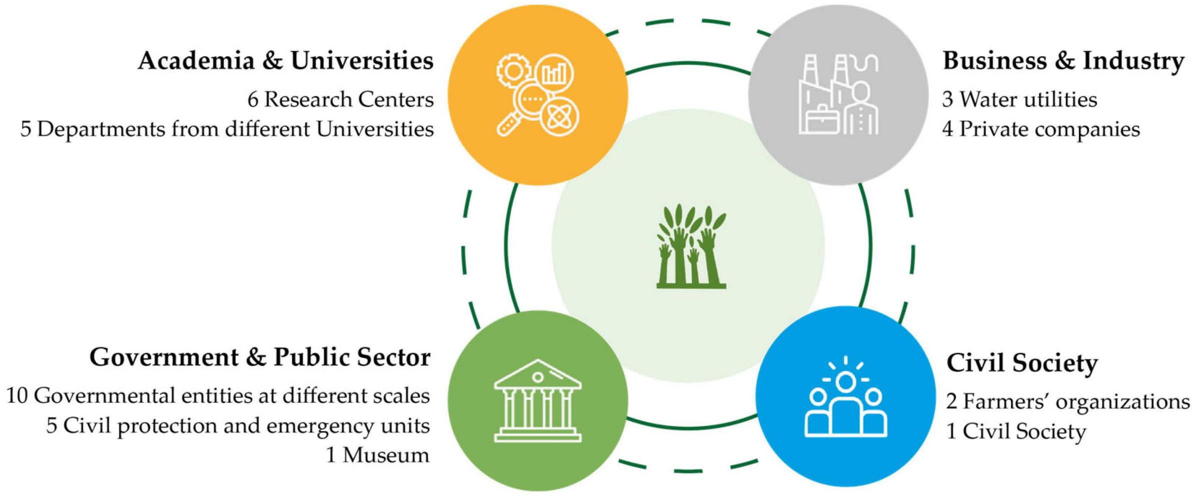


Figure 5. Quadruple helix framework—participants in the first CoP meeting across all regions.

2.3. Climate Resilience Assessment Framework (Clim-RA)

The climate resilience assessment (Clim-RA) framework in ClimEmpower is designed to address the specific resilience needs of diverse European regions through a two-pronged approach: climate risk assessment (CRA) and resilience assessment. Initially, the CRA component identifies key climate hazards, exposure levels, and vulnerability factors, establishing a foundation for resilience planning tailored to regional contexts. This phase leverages data to map out both immediate and projected climate risks, enabling a focused assessment of each region's risk profile.

The framework then progresses to resilience assessment, which evaluates adaptive capacity and resilience factors that go beyond conventional risk metrics. This phase addresses social resilience, economic stability, and infrastructure robustness, focusing on the community's inherent strengths and ability to respond to and recover from climate stressors. Figure 6 visually represents this modular approach by detailing the dimensions, indicators, and proxies used to assess resilience in the RESILOC project. Drawing on the great amount of existing research articles and reviews, the Clim-RA framework provides a comprehensive view of each region's adaptive capacity, allowing stakeholders to prioritize resilience-building measures suited to their specific socio-economic and environmental conditions (Table 1, Section 3.2.1). The more pronounced these components are, the more resilient a city/region is to weather-related stresses and shocks.

This climate resilience assessment is also fully aligned with the outputs from the EU CASCADES project [51], in which they define resilience as the capacity to absorb shocks, avoid tipping points, navigate surprise, and keep options alive, and the ability to innovate and transform in the face of crises and traps [52]. This more dynamic understanding implies that European resilience to cascading climate risk is contingent upon:

- The capacity to learn from events and about plausible futures;
- Sufficiently diverse sources of inputs and resources;
- Diverse ways of achieving its objectives (i.e., avoiding over-reliance on systems that might fail);
- Strong links and connectivity with other systems, such as countries, supply chains, markets, and ecosystems;
- Stores and spare capacity to cope with shocks and surprises;
- The stability of Europe's neighborhood (the EU's neighboring regions, both in the south and in the east);

- The capacity to work with other countries and actors and to learn from and influence them effectively;
- Methods for including all of society in decision-making and planning to ensure equity.

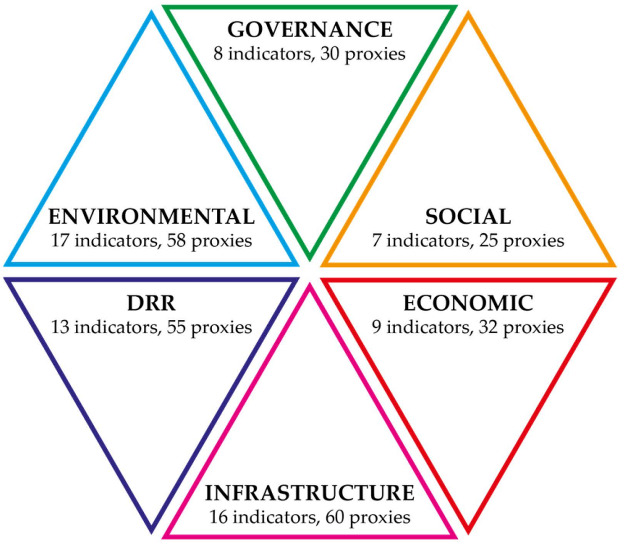


Figure 6. RESILOC dimensions, indicators, and proxies for resilience assessment [53].

Appendix A provides a structured framework for regions to comprehensively evaluate and enhance their climate resilience. This annex offers essential insights, practical resources, and key recommendations to guide regions through the multifaceted dimensions of resilience. Each section addresses critical aspects of climate adaptation, ensuring a holistic approach to preparing for climate-related stresses and shocks.

Key topics include strategies for enhancing robustness and adaptiveness, methodologies for evaluation and monitoring, and tools for scaling resilience across various geographic and administrative levels. It emphasizes the importance of interdisciplinary collaboration, learning from experience, and fostering innovation. The annex also underscores the value of information transparency, the integration of natural and built environments, and the development of networked governance systems. Finally, it advocates for prioritizing equity and justice, ensuring inclusivity in resilience-building efforts.

This guideline serves as a vital resource for regions to assess their current capabilities and implement strategies that not only address immediate risks, but also build long-term adaptive capacities for a sustainable future.

2.4. Application Architecture and Implementation

The implementation of ClimEmpower's climate resilience services relies on a modular application architecture that is designed to be both scalable and adaptable to meet the specific climate resilience needs of diverse regions. This architecture includes a data services layer, processing and indicator services, and a user-facing graphical interface (GUI). The GUI is designed to provide users—including policymakers, local authorities, and the general public—with streamlined access to climate data, resilience indicators, and visual insights. This interface facilitates informed decision-making by displaying actionable resilience metrics tailored to each region's context.

The data services layer plays a crucial role in ensuring interoperability by aggregating climate data from multiple sources, both local and international. This structured data access allows for comprehensive resilience assessments that account for each region's unique climate challenges. Processing services are responsible for generating resilience indicators, which are then visualized within the GUI, enabling stakeholders to make region-specific, data-driven resilience decisions. Designed for flexibility, this architecture (Figure 7) supports rapid prototyping and allows regions to customize features and integrate the application with their existing systems for broader adaptability.

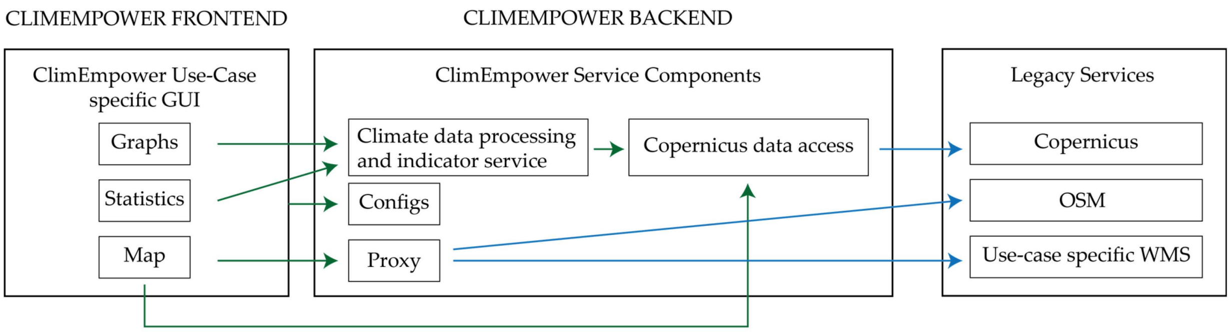


Figure 7. ClimEmpower architecture—component view.

In summary, the ClimEmpower methodology integrates rigorous data collection, stakeholder engagement through Communities of Practice (CoPs), and a specialized resilience assessment framework to provide a comprehensive approach to climate resilience planning. This structured yet adaptable methodology is designed to capture region-specific resilience needs, translating them into tailored climate adaptation strategies. The following section presents the results derived from these approaches, showcasing key findings on data gaps, resilience priorities, and actionable insights identified for each target region. These results highlight the practical outcomes of ClimEmpower's commitment to supporting regionally driven climate resilience initiatives.

3. Results

To systematically evaluate the usability and relevance of climate data and services, a structured approach was implemented. This process encompassed expertise assessment, dataset collection, local data integration, and the identification and evaluation of climate services. However, the initial data review proved insufficient for addressing the specific needs of end-users due to the extensive diversity of climate services available. To refine the analytical framework, a comprehensive literature review on climate service typologies was conducted. This review identified a typological framework, presented in Figure 8, that categorizes services along two dimensions: Customization (generic vs. customized) and Integration (focused vs. integrated). This framework provided the foundation for the analyses conducted for each region.

To operationalize the framework and capture stakeholder needs effectively, a detailed questionnaire was utilized. Designed and proposed by the ISTOS team from the Cypriot region, the questionnaire consisted of 21 questions, strategically divided into two sections: the first 15 aimed at enabling quantitative analysis, and the remaining 6 designed to elicit qualitative insights. The quantitative section focused on measurable attributes such as expertise, priorities, and expectations, while the qualitative section sought to explore context-specific challenges, perceptions, and opportunities. This dual approach ensured a comprehensive understanding of both statistical trends and nuanced stakeholder perspectives, forming a robust basis for subsequent analyses.

The survey was distributed among stakeholders participating in the Community of Practice (CoP), representing the quadruple helix model of academia, industry, government, and civil society. This diverse representation ensured that the collected responses reflected a broad spectrum of expertise, priorities, and perspectives, fostering a holistic understanding of regional needs. CoP representatives facilitated the distribution of the questionnaire, consulting regional partners to ensure informed and representative responses. The analysis of survey responses, reflecting the data and needs as of 2024, provided valuable initial insights into regional priorities and requirements.

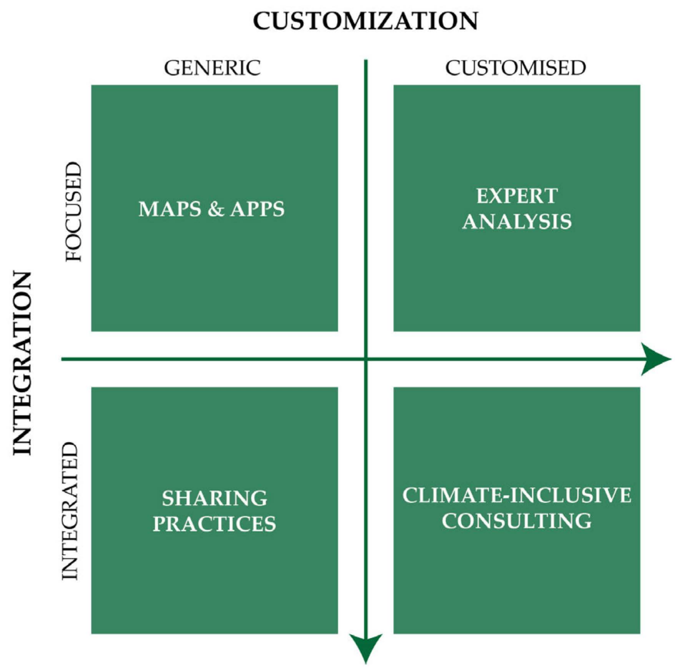


Figure 8. A comprehensive framework for climate services.

To deepen the understanding of these results and address region-specific contexts, bilateral online discussions were conducted with each region. These discussions enabled a detailed examination of survey responses, offering further insights into regional priorities, challenges, and opportunities. This iterative engagement process also facilitated the identification of gaps between existing climate services and the needs of regional stakeholders, ensuring a focused approach to addressing these discrepancies.

This rigorous and region-specific methodology ensured a detailed and contextualized understanding of the usability of climate services. By aligning the services with the requirements of local stakeholders, this approach supports the development of actionable strategies for enhancing climate resilience.

3.1. Qualitative Analysis of CoP Expectations and Hazards

3.1.1. Regional CoP Expectations

Across the regions, CoP participants highlighted a need for accessible data, adaptable models, and training resources tailored to local conditions. Common themes included drought resilience, tools for climate risk awareness, and user-friendly interfaces to bridge technical gaps. Regional expectations were as follows:

- Costa del Sol, Andalusia: Stakeholders prioritized models and predictive tools addressing water scarcity and drought resilience, with an emphasis on inter-agency coordination and user-friendly access;
- Region of Central Greece: Tools with both mitigation and educational functionalities were emphasized, aiming to enhance public climate awareness through accessible data;
- Troodos Mountains, Cyprus: Strategies focused on managing mountain-specific hazards like wildfires and ecosystem preservation, with a need for accessible data on vulnerable agricultural and natural areas;

- Osijek-Baranja: Tools addressing the social impacts of climate migration were central, as stakeholders called for resilience strategies to strengthen local support networks;
- Sicily: The CoP has focused on urban areas, as they host the majority of the regional population and are more exposed to risks such as pluvial flooding, heatwaves, and water scarcity.

While each region's unique challenges were reflected in specific expectations, shared goals emerged, including the development of user-friendly tools, improved data accessibility, and regional adaptation capabilities suited to local needs.

3.1.2. Hazard Identification and Sectoral Vulnerabilities

The analysis of hazards and sectoral vulnerabilities revealed both common and unique climate threats across the ClimEmpower regions. Common hazards identified included droughts, extreme heat, floods, and wildfires, with each region exhibiting specific characteristics:

- Shared Hazards: Drought and heatwaves posed significant risks across Costa del Sol, Sicily, and Osijek-Baranja, impacting water resources, agriculture, and health. Flooding was also a common concern, affecting urban infrastructure and agricultural areas in Central Greece, Andalusia, and Sicily.
- Unique Hazards:
- Costa del Sol, Andalusia: Desertification and salinization emerged as distinctive challenges, reflecting the region's exposure to extreme aridity and water scarcity.
- Troodos: The Troodos Mountains face the unique challenge of Saharan dust, which poses risks to public health and biodiversity. However, it is not the region's most pressing concern.
- Sicily: Extreme heatwaves, with the new record for the hottest temperature ever recorded in Europe experienced in the region (48.8 °C on 11 August 2023 recorded in Siracusa); pluvial floods and water scarcity aggravated by irregular extreme precipitation event patterns; inadequate drainage systems; and extensive soil sealing.

Recognizing these common and unique hazards enables ClimEmpower to pursue cross-cutting solutions where possible, while also tailoring specific interventions to regional needs.

3.1.3. Sectoral Representation and Stakeholder Insights

The CoPs followed a quadruple helix framework, aiming for balanced representation from public authorities, industry, academia, and civil society. However, regional differences in sectoral representation influenced the focus and priorities in resilience planning:

- Costa del Sol, Andalusia: Public administration dominated the stakeholder composition, with significant involvement from regional and provincial bodies. The private sector, particularly water utilities, had a presence, while academia and civil society were underrepresented. Stakeholders emphasized predictive models, accessible tools, and training programs. Identified gaps included data accessibility, challenges in transferring model results, and seasonal population increases that strain resources. Costa del Sol's experience in climate projects provides a solid foundation, though stakeholders expressed concerns over software licensing costs and tool accessibility;
- Region of Central Greece: This region showed balanced representation from academia, public administration, and the private sector, with limited civil organization involvement. This balanced structure supported integrating technical expertise, policy insights, and industry perspectives into climate discussions. Stakeholders prioritized user-friendly technology, data access, and tools with dual functionality in hazard

forecasting and education. Challenges included limited funding, coordination barriers among agencies, and technological knowledge gaps.

- Troodos: Public administration was the dominant sector, with minimal representation from academia and an absence of industry and civil society stakeholders. This imbalance may limit diverse perspectives, particularly those of industry and community organizations essential for holistic adaptation strategies. Key challenges included insufficient funding, limited inter-agency coordination, and a need for training to effectively utilize technological solutions. Stakeholders demonstrated a willingness to share data, though practical implementation is hampered by financial and knowledge constraints.
- Osijek-Baranja County: Representation leaned towards academia and public administration, with minimal involvement from the private sector and civil society. This focus on research and policy suggests potential gaps in industry insights and community engagement. Stakeholders were particularly interested in practical models for drought prediction and flood management. Barriers included limited public data, restrictive data-sharing policies, and a tendency to focus on strategy over actionable tools. Accessibility and user-friendly models for end-users were highlighted as essential needs.
- Sicily: This first phase is composed of public administration stakeholders and technical experts at regional and metropolitan scales; additional stakeholders will be involved in a second phase to ensure that diverse perspectives, including specific socio-economic and environmental priorities at the local level, are adequately incorporated in the climate resilience strategies. Stakeholders emphasized the need for tools to support climate-proofing in planning and infrastructure. Challenges included the lack of access to detailed data suitable for urban to neighborhood scale analysis, and the complexity of incorporating a multipurpose perspective into climate adaptation within infrastructure projects. Feedback underscored the proactive stance of stakeholders regarding data sharing, but pointed to a need for practical training and improved data accessibility.

Across regions, the prevalence of public administration indicates a policy-driven approach to stakeholder engagement. Academia, industry, and civil society were often underrepresented, which could restrict interdisciplinary solutions tailored to specific regional needs. Common themes included the need for accessible, user-friendly technology, effective training, and improved data accessibility. Barriers like limited funding and inter-agency coordination gaps were noted consistently. This analysis underscores the importance of balanced sectoral representation and stakeholder collaboration to enhance regional climate resilience.

3.1.4. Barriers and Data Gaps Identified Across Regions

The CoP discussions revealed several common barriers to climate resilience efforts:

- Data Accessibility and Resolution: Many regions reported limited access to high-resolution, localized data, particularly for socio-economic vulnerabilities and specific hazards like urban flooding. For instance, Sicily stakeholders noted that existing flood models lack the spatial detail needed for effective urban planning.
- Technical Capacity and Knowledge Gaps: In regions such as Troodos and Osijek-Baranja, a need for capacity-building programs emerged to help stakeholders use advanced climate tools and data effectively. Limited knowledge of technological solutions was cited as a barrier to effective resilience implementation.
- Inter-agency Coordination: Enhanced collaboration among public agencies was a recurring theme across all regions, with stakeholders citing fragmentation as an obstacle to cohesive resilience planning.

These barriers highlight the need for targeted capacity-building initiatives and integrated data-sharing efforts across sectors, which could strengthen each region's ability to implement and sustain effective resilience measures.

3.2. Regional Climate Resilience Assessment

3.2.1. Integration of Identified Hazards and Potential Resilience Measures Across Regions

The ClimEmpower project highlights how diverse climate hazards—both shared and region-specific—intersect with regional vulnerabilities across Southern Europe. While hazards like droughts, wildfires, and floods are widespread, their specific manifestations and impacts vary significantly, demanding tailored resilience strategies. The measures summarized in Table 2 reveal a rich interplay of technological, ecological, and societal approaches to adaptation, offering not just solutions but also insights into the broader challenges of fostering climate resilience.

Table 2. Resilience strategies for diverse climate hazards.

Identified Hazard	Region	Potential Resilience Measure		
		Measure #1	Measure #2	Measure #3
Drought	Andalusia, Central Greece, Troodos Mountain, OBZ	Implement Drought Monitoring and Early Warning Systems	Assess Drought Vulnerability and Risk	Implement Drought Risk Mitigation Measures
Salinization	Andalusia, Central Greece, Troodos Mountain, OBZ	Promote Sustainable Irrigation Practices	Enhance Soil Management	Cultivate Salt-Tolerant Crops
Wildfires	Andalusia	Implement Fire-Resilient Landscaping	Enhance Early Warning Systems	Promote Community Education and Preparedness
Desertification	Andalusia, Central Greece, Troodos Mountain, Sicily	Restore Degraded Lands	Adopt Sustainable Land Management Practices	Strengthening Policy Frameworks
Floods	Andalusia	Develop Integrated Water Resource Management (IWRM	Construct Flood Defense Structures	Enhance Urban Planning
Heatwaves	Andalusia, Central Greece, OBZ, Sicily	Establish Early Warning Systems	Promote Urban Greening	Structural Solutions for Heatwaves
Water Contamination	Andalusia, Central Greece, Troodos Mountain, OBZ, Sicily	Enhance Water Treatment Facilities	Implement Source Protection Measures	Promote Public Awareness
Saharan dust	Central Greece	Monitor Air Quality	Implement Building Design Adaptations	Promote Public Health Measures
Hail	Troodos Mountain	Promote Agricultural Protective Measures	Community Preparedness	Enhance Building Codes
Biodiversity loss	Sicily	Establish Protected Areas	Promote Sustainable Land Use Practices	Implement Restoration Projects

The synthesis underscores that resilience to climate risks requires integrated approaches rather than isolated actions. Effective strategies combine early warning systems, community-driven initiatives, and nature-based solutions to address the complexity of climate hazards. For instance, drought monitoring systems provide critical data for managing water scarcity, but their effectiveness is enhanced when combined with sustainable land use practices and initiatives to engage local communities in conservation efforts. This integration represents a shift toward anticipatory and systemic resilience-building approaches.

Shared hazards, such as wildfires and floods, affect multiple regions but require context-specific responses. Fire management benefits from widely applicable early detection systems, yet regions such as the Troodos Mountains or Sicily, with distinct ecological and social contexts, demand adaptive measures like fire-resilient landscaping and community preparedness initiatives. Similarly, flood management must extend beyond infrastructure-based interventions to include integrated water resource management and urban planning strategies that promote long-term sustainability.

The measures also emphasize the critical role of governance and policy frameworks in facilitating adaptation. Integrating resilience planning into broader policy systems is essential to address systemic vulnerabilities, such as desertification in Andalusia or biodiversity loss in Sicily. Without robust policy support, efforts like reforestation, ecosystem restoration, or sustainable irrigation practices risk being insufficient to address the cascading impacts of climate change.

Fostering adaptive capacities within communities is another key theme. Initiatives such as public education on wildfire safety, participatory planning for flood resilience, and community preparedness for hailstorms reframe resilience as a societal process, rather than a purely technical or ecological issue. Embedding resilience within local knowledge systems ensures that immediate risks are mitigated while simultaneously building the social capital necessary for long-term adaptation.

Region-specific hazards, such as Saharan dust in the Troodos Mountains or salinization in Andalusia, further highlight the importance of tailoring interventions to local contexts. These examples demonstrate how resilience planning must consider the intersection of environmental, cultural, and socio-economic factors. Such a tailored approach aligns with the growing emphasis in climate adaptation research on place-based strategies that are designed to resonate with local realities and priorities.

Overall, the measures outlined in Table 2 illustrate the dynamic and multi-dimensional nature of resilience. While technological innovations, such as air quality monitoring and early warning systems, provide critical tools, their success depends on integration with ecological restoration efforts and meaningful community engagement. This interplay among technical, ecological, and social dimensions underscores the need for collective, interdisciplinary approaches to resilience-building that are rooted in science, policy, and local action.

3.2.2. Comparative Resilience Insights

The ClimEmpower project's climate resilience assessment across five regions leveraged a structured methodology based on 10 resilience dimensions. These dimensions—ranging from robustness, adaptiveness, and environmental resilience to learning and innovation, social equity, and transparency—allowed for a comprehensive comparison of each region's strengths and vulnerabilities. The assessment provided insights into resilience-building opportunities tailored to each region's unique challenges.

Figure 9 visually summarizes the resilience scores from Table 3, comparing each region's performance across resilience dimensions. These values, calculated by averaging scores for each region across dimensions, highlight that regions generally excelled in environmental resilience, transparency, and learning and innovation—areas benefiting from data availability and local engagement efforts. Conversely, dimensions such as robustness, adaptiveness, and transformative capacity scored lower, indicating a need for enhanced collaboration between sectors, increased funding for region-specific tools, and systematic training for local stakeholders.

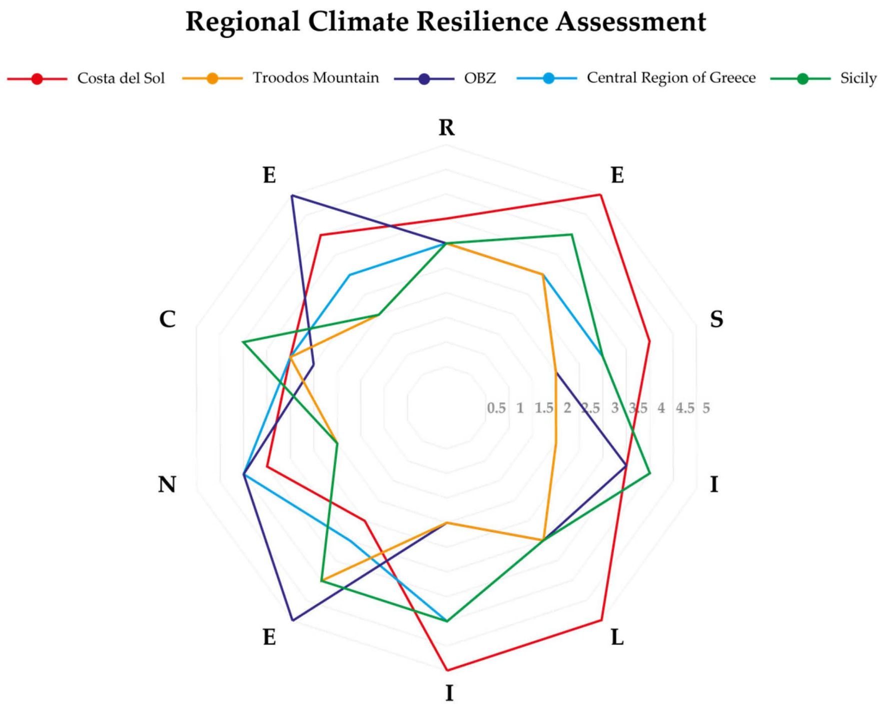


Figure 9. Regional climate resilience evaluation results across all regions. Notes: R = Robustness and adaptiveness to climate related stresses and shocks; E = Evaluation and Monitoring: resilience as a process; S = Scale (Countries, Regions, Cities, Neighborhoods, Individual); I = Interdisciplinarity: resilience as an umbrella for different sectors; L = Learning and innovation; I = Information and transparency: resilience as a participation tool; E = Environment (natural and built up); N = Networked systems and actors (multilevel governance); C = Capacity to transform after disturbance but maintain self-organization; E = Equity and Justice: resilience measurements must not exclude others.

Table 3. Regional climate resilience evaluation results (individual scores) by dimensions and regions. Legend: ES = Costa del Sol sub-region, Costa del Sol, Spain; CY = Troodos Mountains, Cyprus, HR = OBZ, Croatia, EL = PSTE, Greece, and IT = Sicily, Italy.

Acronym	Explanation	Specific Question for the Region	Climate Resilience Evaluation					Average Value
			ES	CY	HR	EL	IT	
R	Robustness and adaptiveness to climate related stresses and shocks	What is the degree of robustness and adaptiveness to climate related stress and shocks in your region?	3.5	3	3	3	3	3.10
E	Evaluation and Monitoring: resilience as a process	Is there some public methodology to easily assess climate-related risks and identify potential adaptation measures?	5	3	3	3	4	3.60
S	Scale (Countries, Regions, Cities, Neighborhoods, Individual)	What is the level of spatial disaggregation of climate related risks?	4	2	2	3	3	2.80
I	Interdisciplinarity: resilience as umbrella for different sectors	Are all the critical sectors involved in climate resilience/risk assessment plans and strategies?	3.5	2	3.5	4	4	3.40

Table 3. *Cont.*

Acronym	Explanation	Specific Question for the Region	Climate Resilience Evaluation					Average Value
			ES	CY	HR	EL	IT	
L	Learning and innovation	The public administration provides to society free-of-charge resources and materials to learn on expected climate change impacts and potential adaptation measures. Does your region actively participate in R&D projects?	5	3	3	3	3	3.40
I	Information and transparency: resilience as participation tool [it is linked to the "L" score]	Does your region have some national or sub-national online climate services portal, with information aggregate as climate indicators?	5	2	2	4	4	3.40
E	Environment (natural and built up)	Do you think that there are enough natural protected areas (NPAs) to buffer the potential impacts of climate change and conserve ecosystem services—e.g., water provisioning?	2.5	4	5	3	4	3.70
N	Networked systems and actors (multilevel governance)	Is there good coordination and collaboration between the different stakeholders (public authorities, water utilities, NGOs, SMEs, etc.) of your region for fostering climate resilience?	3.5	2	4	4	2	3.10
C	Capacity to transform after disturbance but maintain self-organization (it is linked to the "R" dimension)	What is the "community-level recovery" from extreme weather events?	3	3	2.5	3	4	3.10
E	Equity and Justice: resilience measurements must not exclude others	Are climate resilience/risk adaptation measures taking into account all people?—Leave no one behind approach	4.2	2	5	3	2	3.64
			3.9	2.6	3.3	3.3	3.3	

3.2.3. Key Findings by Region

The resilience assessment highlighted notable strengths and challenges in each region:

Costa del Sol, Spain demonstrated high resilience in evaluation and monitoring, supported by a quantitative climate risk assessment framework. The Costa del Sol Portal on Climate Change further bolsters learning and innovation by providing climate adaptation resources to the public and local authorities, fostering community engagement. However, lower scores in environmental protection and community-level recovery point to a need for initiatives that reinforce ecological sustainability and improve community response to extreme weather.

Central Greece (PSTE) scored well in learning and innovation, partly due to the development of integrated environmental management systems and sustainability platforms. These platforms aim to consolidate climate data to support policy planning and business operations. Nonetheless, the region requires improvements in multi-level governance and sectoral collaboration to further strengthen its resilience framework.

Cyprus displayed strong environmental resilience, benefiting from the NATURA 2000-protected Troodos National Forest Park, which supports biodiversity and ecological stability. However, lower scores in interdisciplinarity and social equity suggest a need for broader stakeholder engagement and integration of various sectors to enhance resilience comprehensively.

The Croatian region has initiated the use of GIS and crowd-sourced data to develop hazard models for droughts, heatwaves, and floods. Despite these efforts, the assessment revealed a lack of formal climate services, underscoring an opportunity to establish structured tools for climate adaptation planning that address regional vulnerabilities effectively.

Sicily showed strong performance in information transparency, supported by regional and national data platforms. Overcoming the diversity in terms of spatial resolution presents a barrier. For the different relevant datasets included in exposure, vulnerability, risk/impact, and resilience analysis, the ongoing effort in developing a downscaled, region-specific climate framework will significantly enhance adaptation efforts across the island. Moreover, Sicily is working to establish an interdisciplinary committee to supervise the process for the production of the Climate Change Regional Adaptation Plan. A new tool has been released to evaluate the impact of both new infrastructure and retrofitted structures on resilience.

From a disaster risk management perspective, the strong capacity at national and regional levels of the Italian Civil Protection Department allows the rapid deployment of response measures based on the local civil protection plans and established procedure at the national level for early warning and emergency management operation.

The shared gaps across robustness, adaptiveness, and transformative capacity reflect underlying challenges in multisectoral coordination, resource limitations, and the need for targeted capacity-building. Addressing these barriers could enhance the regions' adaptive capacity to manage future climate risks and improve overall resilience. By examining these results, the ClimEmpower project underscores the importance of tailored interventions. This approach promotes resilience-building measures that leverage each region's strengths while addressing their specific vulnerabilities, ensuring an adaptive and localized response to climate challenges.

3.3. Data Availability

In assessing climate resilience, ClimEmpower gathered a comprehensive set of datasets relevant to climate hazards, exposure, vulnerability, and impacts across target regions. This review revealed strengths and gaps in data coverage and availability at the regional level, impacting the precision and applicability of resilience planning.

From the 126 datasets analyzed, a majority (approximately 70%) were classified as hazard-related data, with exposure and vulnerability datasets constituting smaller portions (16% and 11%, respectively). This contribution shows a substantial focus on hazard information—such as temperature, precipitation, and drought projections—while exposure and vulnerability indicators, essential for socio-economic resilience assessments, remain comparatively sparse.

Most datasets cover broad geographic scopes, with 68% representing national or European levels, and only 10% specific to the ClimEmpower regions. This situation highlights the challenge of addressing unique local needs with generalized datasets. National and

European datasets, though comprehensive, often lack the granularity necessary for local adaptation strategies. For example, many European datasets omit Cyprus, affecting regional analyses for the Troodos Mountain CoP.

Figures such as Figure 10 (spatial coverage of datasets) and Figure 11 (distribution of data types by region and country) visually summarize these findings, illustrating the prevalence of hazard data over vulnerability and exposure data across regions.

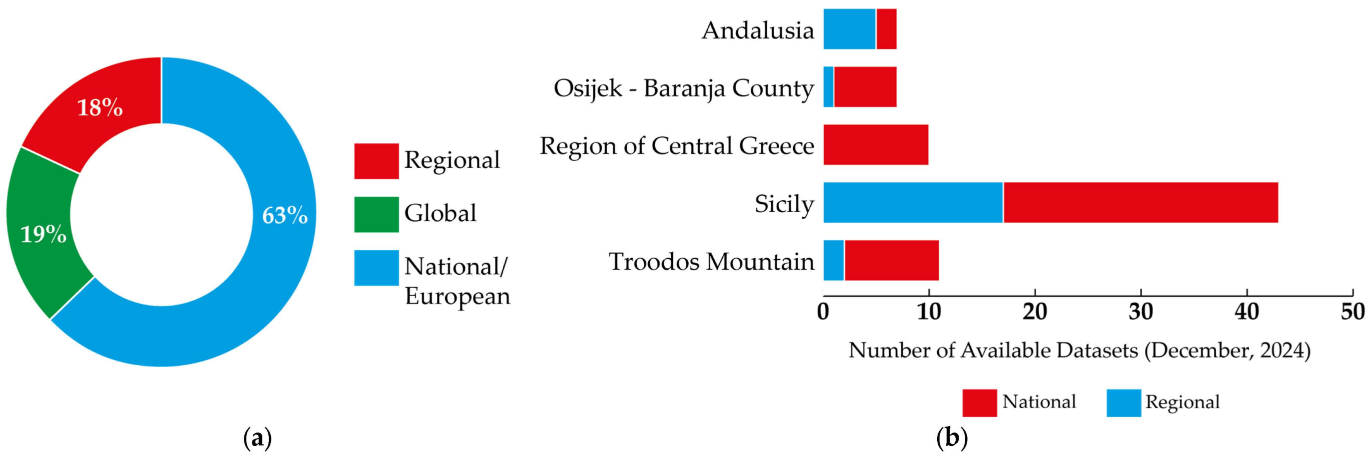


Figure 10. Spatial coverage of available data: (**a**) level of spatial coverage; (**b**) data by country and region.

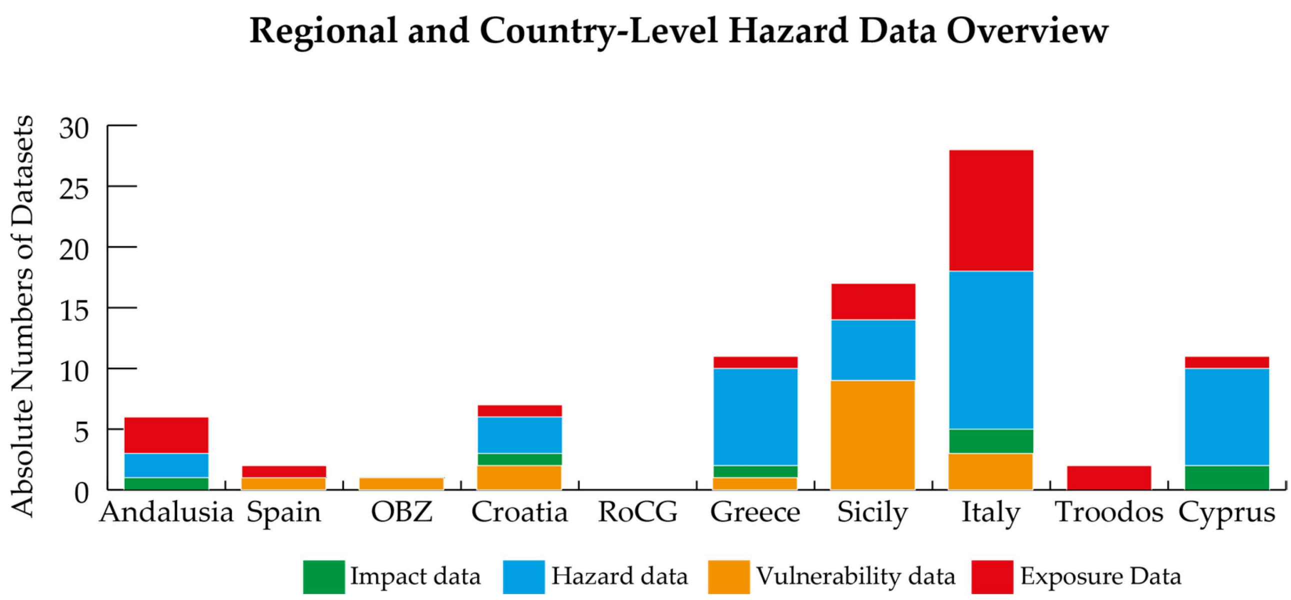


Figure 11. Hazard-, exposure-, vulnerability-, and impact-related data per region and country.

The distribution of data by format is equally noteworthy. Gridded data, vital for localized climate assessments, constitutes nearly half of the data formats analyzed (47%), whereas point data, important for fine-scale spatial analysis, comprises the remaining portion. Georeferenced formats, such as ESRI shapefiles, dominate the event-based datasets, supporting GIS-based applications and enabling interoperability for high-resolution spatial analysis. These formats facilitate adaptability across GIS platforms, critical for assessing population, infrastructure, and hazard-prone areas at regional levels.

3.4. Climate Service Gaps

Despite extensive efforts in data collection, substantial gaps in climate services continue to hinder effective adaptation strategies across regions. These gaps highlight the limited availability of localized, actionable data and services that are essential for building robust climate resilience.

One critical need is for drought and heatwave prediction tools, especially in Croatia, where the absence of regionally tailored models has created challenges for agricultural adaptation. Current datasets and services lack the predictive precision required to support effective planning in this climate-sensitive sector.

Another major gap is the limited regional specificity in vulnerability data. Vulnerability datasets, particularly those capturing socio-economic dimensions, are sparse in regions like the Troodos Mountains, making it difficult to accurately evaluate climate risks affecting vulnerable populations. With vulnerability data primarily available at broader geographical scales, there is a pressing need for metrics that reflect community-level risks and conditions.

The need for interoperable climate services that facilitate cross-sectoral integration is also clear. Many of the existing climate services, such as data visualization tools and case study repositories, lack the adaptability necessary for resilience-building across multiple sectors. Services tailored to specific needs in areas like agriculture, infrastructure, or public health remain scarce, as the majority of available resources focus on generalized climate information rather than sector-specific tools.

In addition, there are significant gaps in training and support resources for adaptation needs. For example, in Central Greece, stakeholders lack adequate training resources to interpret and effectively apply climate data within resilience strategies. Expanding training options would strengthen the capacity of decision-makers and practitioners to use this data in adaptive planning.

Lastly, regions like the Troodos Mountains and Sicily face an acute need for localized data on infrastructure resilience. Stakeholders emphasize the importance of infrastructure-specific data for managing drought and flood risks, particularly for critical systems such as water supply and transportation networks that are vulnerable to climate extremes.

4. Discussion and Conclusions

The ClimEmpower project demonstrates the critical importance of user-centered, region-specific approaches to climate resilience. This study highlights that effective adaptation strategies must integrate high-resolution climate data with local knowledge and foster multi-stakeholder collaboration. The findings from five diverse Southern European regions illustrate that resilience needs and priorities vary significantly, influenced by local environmental, socio-economic, and cultural contexts.

A key insight from the project is the shared demand for accessible, actionable data tailored to specific regional challenges, such as drought monitoring in Costa del Sol, heatwave management in Sicily, and flood resilience in Central Greece. However, critical gaps in data availability, particularly for socio-economic vulnerabilities and localized infrastructure impacts, remain a significant barrier. Addressing these gaps will require coordinated efforts to improve data granularity and accessibility across sectors.

The engagement of stakeholders through the quadruple helix model—academia, industry, government, and civil society—has been central to ClimEmpower's success. By leveraging the Community of Practice (CoP) framework, the project facilitated knowledge exchange, co-creation of solutions, and alignment of resilience strategies with regional priorities. This participatory approach underscores the importance of inclusivity and shared ownership in climate adaptation planning.

Despite its successes, ClimEmpower reveals systemic barriers to resilience-building, including limited inter-agency coordination, insufficient funding, and knowledge gaps. These challenges emphasize the need for capacity-building programs to empower stakeholders to utilize advanced climate tools and foster cross-sectoral collaboration.

In conclusion, the ClimEmpower framework provides a replicable model for region-specific climate adaptation. Its user-driven methodology aligns with European climate policies, offering scalable solutions to enhance resilience across diverse regions. Future efforts should focus on advancing high-resolution data systems, expanding capacity-building initiatives, and strengthening interdisciplinary collaboration to ensure sustainable and inclusive climate resilience strategies across Europe.

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Appendix A

In this appendix, some resources, insights, and recommendations for regional climate resilience assessment are briefly described below.

- **[R] Robustness and adaptiveness to climate related stresses and shocks:**
  - Redundancy in infrastructure in different sectors (water, energy, etc.) can provide a higher value of this resilience dimension.
  - The robustness refers to short-term response skills (e.g., operational Early Warning Systems).
  - The adaptiveness is more focused on mid/long term response skills (e.g., multisectoral regional climate action plan, including diverse strategic areas: water resources; flood prevention; Agriculture/Fishery/; Urbanism; Tourism; Energy; among others).
- **[E] Evaluation and Monitoring**: (Resilience as a process.) The existence of a robust, tested and validated national or regional methodology to assess (quantitatively or semi-quantitatively) climate risks and their contributions to building resilience.
- **[S] Scale (Countries, Regions, Cities, Neighborhoods, Individual)**: Does the region have some climate service or product in which you can filter climate risks projections at different spatial scales—Basin, municipality/city, region/province, boundary box/etc.?
- **[I] Interdisciplinarity**: Resilience as an umbrella for different sectors: to investigate the level of participation (including diversity) of public/private sectors and

stakeholders during the preparation of existing climate strategic plans, strategies, and methodologies.

- **[L] Learning and innovation**:
    - Learning from past experiences at government and politician scales is also a significance point of view.
    - Learning from "failures" must be a mandatory issue.
    - How can on-going/finished/planned R&D projects contribute to regional climate goals?
- **[I] Information and transparency—resilience as participation tool**: Making a catalogue of existing climate platforms and services in each region can be a good proxy to evaluate this dimension.
- **[E] Environment (natural and built-up)**: Based on the number of natural protected areas (NPAs) in the region:
    - The percentage of land cover referred as NPA with respect to total area.
    - Resource (NATURA 2000 DATA—the European network of protected sites [54]).

A complementary approach to evaluate this dimension is referred to the number of nature-based solutions (NBSs) already implemented or projected in the short-term (not assessed in the current version of the methodology).

- **[N] Networked systems and actors (multilevel governance)**: One recommended proxy can be the "Regional Authority Indicator (RAI)"—a scale ranging between 1 and 30—for each region or regional tier. It measures the authority in self-rule and shared rule exercised by regional governments. Self-rule refers to autonomy, and hence the extent to which sub-national units (Länder, cantons, states, provinces, autonomous communities, etc.) are free in deciding, financing, and implementing their own policies. Shared rule is defined as the extent to which sub-national units can participate in decisions that concern the whole political community and not just their region. Resources:
    - RAI-MLG [55].
    - Causes and consequences of multilevel governance [56].
- **[C] Capacity to transform after disturbance but maintain self-organization:**
    - Skills to anticipate the impact (indicator-based management).
    - Maintaining self-organization = governance capabilities (EQI−Data).
    - Resource: European Quality of Government Index (EQI) [57].
- **[E] Equity and Justice**: (Resilience measurements must not exclude others.) The equity and justice score must be coherent with those related to climate resilience dimensions "Scale", "Interdisciplinarity", "Learning", "Information & transparency", and "Networked systems".

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