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Original research article

Building the scientific basis for the adaptation strategy of an Alpine region: The 'State of the climate in Trentino' report

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HIGHLIGHTS

- Widely accessible state-of-the-art climate information obtained through the collaboration of research and local institutions.
- Overview of the scientific literature availability on climate change impacts over the Trentino territory.
- Benefits and drawbacks of climate scenarios using dynamic and statistical downscaling

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ABSTRACT

Many regional administrations are currently developing tailored adaptation strategies, based on the unique characteristics of their territories, which includes local climate patterns and, more importantly, environmental and socioeconomic factors. Yet, exploiting this wealth of information to design effective climate strategies remains a challenge.

This study outlines the approach used to establish the basis for the climate strategy in the Autonomous Province of Trento, a mountainous region in northern Italy and part of the European Alps. The approach adopted by the regional government emphasizes the need for a multi-level, multi-stakeholder approach to shape the development of a regional adaptation strategy. Here, we present three major steps of this process, highlighting the collaborative effort between diverse entities: (1) Compilation of an up-to-date scientific review of the existing knowledge about climate change impacts in the region, (2) Creation of reference climate scenarios, and (3) Dissemination of a summary of the report to the general public.

The literature review revealed large heterogeneity across socioeconomic sectors in the scientific literature focusing on the impacts of climate change. This disparity was reflected in the informative report, which simplified and summarized the technical information without sacrificing scientific accuracy. The creation of climate scenarios had to balance multiple aspects, including mountain topography, data availability, and needs from stakeholders, by using a layered approach combining spatially aggregated results, statistical downscaling, and high-resolution convection-permitting models.

Practical implications

The climate is undergoing significant changes, profoundly affecting both the environment and society. These impacts include shifts in ecosystems, biodiversity, disruptions in human activities, economies, and livelihoods. The far-reaching consequences underscore the urgency of addressing the impacts of climate change.

1. *Local adaptation strategies are essential*: The case of the Autonomous Province of Trento (for brevity, Trentino hereafter) highlights the importance of regionally tailored climate adaptation strategies. It prioritizes localized planning that considers specific environmental and socioeconomic contexts, particularly in vulnerable regions like mountainous areas.

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2. *Collaboration enhances effectiveness:* Trentino's experience shows the benefits of involving interdisciplinary experts, scientific communities, and public administration. Such collaborative approaches foster communication across sectors and institutions with the aim to build a robust adaptation framework.
3. *Invest in knowledge transfer and public engagement:* Climate adaptation is more effective when scientific knowledge is made accessible to the general public. Trentino's efforts to disseminate information through a public report serves as a model for raising awareness and encouraging community engagement. Policy makers should support similar outreach initiatives to build public understanding and support.
4. *Address data fragmentation with coordinated efforts:* Italy's fragmented climate and meteorological systems pose challenges for coherent policy-making. Regional authorities could advocate for stronger coordination at the national level while continuing to develop their own high-quality climate datasets and make them easily accessible. Creating regional climate services with standardized methods can help bridge existing gaps.
5. *Use scientific assessments to inform funding and policy:* Identifying key climate risks and research gaps, as done in Trentino, provides a foundation for targeted investment and policy development. Decision-makers can use these assessments to direct funding toward research, infrastructure, and adaptive measures where they are most needed.
6. *Leverage state-of-the art data and methods:* Integrating validated climate scenarios with locally-tailored post-processing can strengthen the reliability of adaptation plans. This allows practitioners to build their strategies on high-quality data while tailoring applications to local needs.

1. Introduction

Scientific evidence for global climate change is extensively documented in numerous publications and technical reports, as synthesized in the recent Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019, 2013, 2023). To support the adoption and implementation of climate change adaptation measures, the 2021 European Adaptation Strategy calls on national and regional authorities to take decisive action (Rayner et al., 2023). In Italy, for instance, the National Adaptation Plan (Piano Nazionale di Adattamento ai Cambiamenti Climatici — PNACC) was only approved in 2023 (Ministero dell'Ambiente e della Sicurezza Energetica, 2023). According to PNACC (Ministero dell'Ambiente e della Sicurezza Energetica, 2023) recommendations and to the political mandate they received for elaborating both local policies and planning of actions, several Italian regions decided to develop their own adaptation strategies and plans, often engaging interdisciplinary experts and working groups (Pietrapertosa et al., 2021). As presented also by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) (ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale, 2023), this includes regions such as Sardegna (Regione autonoma della Sardegna, 2024)), Liguria (Regione Liguria, 2023), and Emilia-Romagna (Regione Emilia Romagna, 2018). Since a national meteorological and climate service is still under development in Italy, the collection and management of climate data is fragmented into regional and sub-regional offices, which adds a further layer of complexity to such efforts.

The territory of the Autonomous Province of Trento, hereinafter referred to as *Trentino* (Fig. 1), is a mountainous region in the south-eastern Alps particularly sensitive to the impacts of climate change. Like many mountain regions around the world, Trentino faces climate risks threatening both the environment and relevant socioeconomic sectors (Hock et al., 2019). Mountains are among the most vulnerable ecosystems to climate change, where local effects are amplified by complex orography. In particular, the Alpine region has already experienced significant shifts in temperature and precipitation patterns

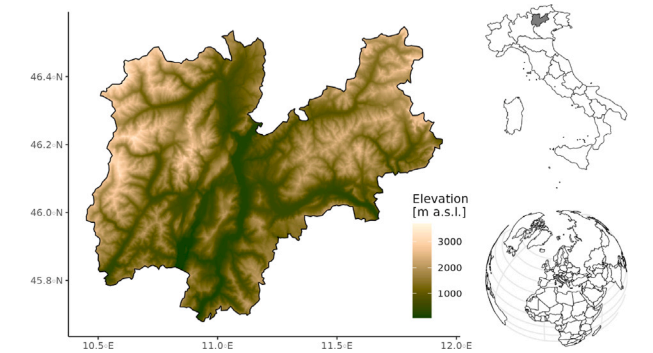

Fig. 1. The territory of the Autonomous Province of Trento (Trentino) in northern Italy.

depending on sub-region, season, and elevation (Kuhn and Olefs, 2020; Tudoroiu et al., 2016; Napoli et al., 2019).

Addressing the aforementioned challenges requires decision-makers to develop and implement targeted adaptation strategies. This process demands a multilevel, multi-stakeholder approach to ensure the effective design and implementation of regional adaptation plans (Gretter et al., 2024).

In 2021, the Autonomous Province of Trento approved the work program "Trentino Climate 2021-2023", which outlines the activities required to support the drafting of the "Provincial Strategy for Climate Change Mitigation and Adaptation", whose first version is expected before the end of 2025. The above-mentioned work program, whose implementation is coordinated by the Provincial Agency for Environmental Protection (APPA) of the Autonomous Province of Trento, includes scientific collaborations, communication activities targeted at the general public but also specifically at the youth, as well as participatory approaches for climate risk assessment and identification of possible adaptation measures based on the methodology of *climate impact chains* (Gretter et al., 2024; Zebisch et al., 2021).

In this study, the approach followed by the Autonomous Province of Trento is presented in Section 2 along with the methods implemented, Section 3 discusses the results obtained for the region, and Section 4 presents the main conclusions.

2. Methods

In the present work, we present the main results and challenges of three activities involving the collaboration between APPA, the Department of Civil, Environmental, and Mechanical Engineering at the University of Trento (DICAM), and the Science Museum of Trento (MUSE), namely:

1. A synthesis of existing studies on past and future climate change and its impacts in Trentino (scientific state-of-the-art knowledge base, Sections 2.1 and 3.1)
2. The development of reference climate scenarios for Trentino (future climate data for information and for impact studies, Sections 2.2 and 3.2)
3. The communication of key results in an informative report (outreach to the general public, Sections 2.3 and 3.3)

These activities were performed under the umbrella of a general agreement existing between the Provincial Government and the local research institutions for cooperation in environmental research and studies. A specific implementation agreement was signed by APPA and DICAM, identifying as a common area of interest and research the "Synthesis of studies on climate change and its impacts and elaboration of reference climate scenarios for Trentino", with the aim of supporting the development of the "Report on the State of the

Table 1
Overview of the sectors that were considered most important for the Trentino region.

Macro-area	Name	Impacts on:
Environment	Agroecosystems	Integrity of agroecosystems and health
Environment	Air	Large-scale circulations patterns and air quality
Environment	Aquatic ecosystems	Flora, fauna
Environment	Forests	Growth, dynamic, abiotic and biotic factors, ecosystem services
Environment	Snow, glaciers, and permafrost	Snow, glaciers and permafrost
Environment	Soil	Hydrological cycle, biogeochemical cycles, land use, peat bogs
Environment	Terrestrial ecosystems	Flora, fauna
Environment	Water	Runoff, quality, temperature of rivers, lakes, and groundwater
Socioeconomic	Agriculture	Agricultural productivity and techniques
Socioeconomic	Aquaculture, Livestock and food production	Techniques, productivity and food security
Socioeconomic	Cultural heritage	Cultural heritage, landscapes and traditions
Socioeconomic	Energy	Consumption, production, energy performance, infrastructure
Socioeconomic	Forest productivity and supply chain	Forest productivity
Socioeconomic	Health	Human health (direct impacts), allergies and diseases
Socioeconomic	Industries and infrastructure	Productivity and workers, small and medium-sized enterprises
Socioeconomic	Risk from natural hazards	Occurrence of extreme events (e.g. avalanches, fires, floods)
Socioeconomic	Security and social cohesion	Governance, security, activism, migration, social inequality
Socioeconomic	Settlements and urban areas	Urban planning/design, waste dumps, urban ecosystems
Socioeconomic	Tourism	Tourist influx, mountain huts
Socioeconomic	Transport and infrastructure	Reliability, efficiency and safety
Socioeconomic	Water resource management	Uses in agriculture, snowmaking and civil sector, hydropower

Climate in Trentino" in the context of the activities foreseen by the aforementioned "Trentino Climate 2021-2023" work program.

The process outlined in this study established the scientific basis for identifying potential climate risks (arising from climate change impacts described in the report) and for developing appropriate adaptation strategies in response. It does not tackle or identify the adaptation strategies themselves, which shall be performed in a subsequent phase. We do not yet present the feedback from the produced reports, since the report just has been published and it is too early to have gathered and analyzed feedback. Moreover, dedicated dissemination and communication initiatives have not yet been deployed by the Province of Trento.

2.1. Review of climate change impacts

A detailed and comprehensive literature review up to September 2023, was coordinated by DICAM with the objective of assessing the current state-of-the-art on the impacts of climate change in Trentino and more generally in the Alpine region, and the corresponding gaps of knowledge.

As a first step, the methodology examined climate change impacts in two different macro-areas, namely environmental vs. socioeconomic impacts, in analogy to the approach of the IPCC and its Assessment Reports (e.g., Hock et al., 2019; IPCC, 2023). For both areas, strategic sectors for Trentino were defined using information and categories from existing literature, and in particular the National Adaptation Strategy to Climate Change (Castellari et al., 2014), the National Climate Change Adaptation Plan (Ministero dell'Ambiente e della Sicurezza Energetica, 2023), and the South Tyrol Climate Report (Zebisch et al., 2018). Consequently, eight sectors related to environmental impacts and thirteen sectors related to socioeconomic impacts were selected (Table 1).

In collaboration with APPA, experts in each sector were identified based on their scientific publications, completed or ongoing research projects within the Autonomous Province of Trento, and technical responsibilities held within the Province Administration. Including all sectors, the total number of experts involved is 118, and all of them were initially invited to provide useful information for preparing the first draft of the document. Using online resources such as Google Scholar and websites specific to the Trentino region, the subsequent literature analysis was mainly carried out by DICAM on the basis of the input from the experts as an initial base of knowledge, and then further integrated the various chapters based on the level of detail obtained. The literature review considered scientific articles, research projects conducted in the territory, and technical documents produced by the Province Administration. When no scientific contributions specifically concerning Trentino were identified, useful information related to a wider area within the Alpine region was included.

The document with the initial literature review was subsequently reviewed by APPA and by the previously identified experts in order to elaborate the final draft of the report through an extensive collaborative process. Each sector (corresponding to a single chapter of the final report) was subdivided into common sub-sections:

- Literature Review: This paragraph reports all relevant studies (primarily referring to the Provincial territory) with a publication date before September 2023;
- Dataset: This paragraph lists the reference datasets used or potentially useful in sector studies;
- Impact Indicators: Here, if known, the indicators that may be useful for impact studies in the sector are defined;
- Gaps: This paragraph describes the knowledge gaps present in the territory; it is particularly useful for outlining possible future studies or activities to be conducted in Trentino;
- References: This section lists all the cited bibliographic references;

A summary of the key results from the review for the Water–Energy–Food-Ecosystems Nexus has been published separately (Napoli et al., 2025). The full report containing all sectors is written in Italian and will be available on the APPA website after the approval of the Provincial Strategy for Climate Change Mitigation and Adaptation.

2.2. Reference climatic scenarios

The reference climate scenarios were created in a sequential approach by first identifying available data and then selecting and analyzing it based on criteria identified by providers and users. We tried to accommodate as far as possible the needs of the different actor groups including climate data providers, impact modelers and societal users (Rössler et al., 2019). Constraints were the availability of data and the requirements of the provincial offices and other users, which included multiple emission scenarios, high spatial resolutions, and extensive coverage of the elevational gradients, given that Trentino has complex orography.

The available climate data included:

- GCMs (General Circulation Models) from CMIP5 (Coupled Model Intercomparison Project Phase 5) and CMIP6

- RCMs (Regional Climate Models) from the EURO-CORDEX initiative (European branch of the Coordinated Regional Climate Downscaling Experiment)
- Convection-permitting RCMs from the CORDEX-FPS (Flagship Pilot Studies) community and a continuous simulation for Italy (Raffa et al., 2023)
- A high-resolution (1 km) observational product of temperature and precipitation based on the interpolation of in-situ meteorological stations (Crespi et al., 2021)

The data selection and analysis was guided by expert knowledge, literature analysis, and continuous discussions with APPA. The added value from dynamical downscaling using RCMs (Jacob et al., 2020) was deemed essential for the study area. Furthermore, the usage of RCMs is corroborated by its widespread application across the European continent, such as in Switzerland (Fischer et al., 2022), the UK (Met Office Hadley Centre, 2018), or the Netherlands (van der Wiel et al., 2024).

Statistical downscaling was employed to further increase the spatial resolution of the raw EURO-CORDEX ensemble RCM output from approximately 12 km to 1 km. This was done using empirical quantile mapping, which has shown superior performance in a large comparison of downscaling methods (Gutiérrez et al., 2019). Technical details on how the quantile mapping was applied can be found in Appendices A.1 and A.4. Higher resolution and unbiased data are especially useful for other stakeholders, local users, and applications of climate scenarios (Yang et al., 2010). While bias adjustment and statistical downscaling are sometimes viewed controversial (Maraun, 2016), they were also found to improve climate change projections in certain cases (Iturbide et al., 2022; Gobiet et al., 2015).

Before statistical downscaling, the model ensemble was reduced for computational purposes but also because users often struggle with the concept of climate model ensembles (Rössler et al., 2019). Providing fewer but carefully chosen scenarios might make the data more approachable for local practitioners. We chose a pragmatic approach for sub-ensemble selection inspired by Dalelane et al. (2018), but not accounting for model inter-dependence, instead solely relying on maximizing the spread of future changes (Cannon, 2015). We acknowledge that this may introduce redundancy and an incomplete representation of structural variability.

Convection-permitting RCMs have shown wide significant improvements in the representation of precipitation by better resolving the physics (Ban et al., 2021) but also in many other climate variables through their higher spatial resolution (Lucas-Picher et al., 2021). We opted for a continuous simulation for Italy (Raffa et al., 2023) instead of the ensemble from the CORDEX-FPS (Flagship Pilot Studies) community, because the latter had (a) only 10-year time slices, which could be strongly affected by decadal variability, and (b) only the RCP8.5 (Representative Concentration Pathway) scenario, while APPA also required the consideration of other future scenarios like RCP2.6 or RCP4.5.

Finally, a layered approach was used to make the most of data availability and user needs:

- For aggregated climate information, we used the full EURO-CORDEX ensemble, thereby exploiting all available RCP scenarios and the large model ensemble available from the EURO-CORDEX community (Coppola et al., 2021). This type of information was provided as changes in climate anomalies of 30-year time periods. It provides the best estimate of scenario and ensemble spread. Moreover it is most useful for communication, general climate information, and government planning.
- For impact models and higher spatially resolved climate information, we employed statistical downscaling and bias adjustment. This gives high-resolution and unbiased data, mainly intended for applications like hydrological modeling. In the rest of the manuscript, this is labeled as BA-DS (bias adjusted and downscaled).
- Finally, data from one high-resolution convection-permitting simulation was processed, which has a transient run (i.e., complete time series, not only 10-year slices) until 2070 over Italy (Raffa et al., 2023). Note that the authors provide the period 1981–2070, contrary to what is mentioned in the original publication (1989–2050). This dataset provides (a) more meteorological variables than the above EURO-CORDEX dataset and (b) at the hourly scale, thus opening the possibility for other applications, such as energy-building simulations. This dataset is labeled VHR-PRO_IT.

Table 2
Overview of climate indices that were calculated. See Appendix A.5 and Table 5 for more info.

Group	Indices)
Heat and cold	FD (Frost Days), ID (Icing Days), SU (Summer Days), SU30 (Summer Days, 30 °C), TR (Tropical Nights)
Building energy demand	heatDD (Heating Degree Days), coolDD (Cooling Degree Days)
Precipitation	SDII (Simple Precipitation Intensity Index), Rx1day (Maximum 1-day precipitation), Rx5day (Maximum 5-day precipitation), RR1 (Wet Days), R10mm and R20mm (Very wet days, absolute thresholds), CDD (Consecutive Dry Days), R95p and R99p (Very Wet Days, percentile-based), R95pTOT and R99pTOT (Precipitation fraction due to very wet days)
Drought	SPI, SPEI (3, 6, 12, 24-month Standardized Precipitation (Evapotranspiration) Index)
Snow	HNd (Snowfall days), HN (Snowfall)
Other	Humidex3/4, EWS (Extreme Wind Speed)

Besides seasonal and annual averages of variables, a range of climatic indices was also calculated, to reflect different types of extremes (Table 2). The selection was based on the scientific literature, on their use in the PNACC (Ministero dell'Ambiente e della Sicurezza Energetica, 2023; PNACC, 2018), and on specific requests from APPA.

For more details on data and methods, see Appendix A in the appendix. Furthermore, a data usage guide is available as supplementary material.

2.3. Preparation of the informative report

The literature review report required a multidisciplinary approach, combining insights and data from various specialized departments of the Province administration. To ensure the report's accessibility to a wide audience, a methodical process was employed to simplify and synthesize technical information for dissemination purposes without sacrificing scientific accuracy.

We adopted a method based on three key principles combining simplification strategies, validation, and visualization. This method follows principles of effective science communication, relying on a practical approach rather than formal linguistic analysis:

1. Progressive simplification with iterative validation: starting from the technical text, the content was rewritten in a more accessible language, removing or explaining technical terms; each version was reviewed to assess clarity, with successive refinements until reaching accessibility for a wider audience than experts of the sector.
2. Comprehension testing with non-expert readers: a comprehension test has been done with 14 adult participants (all aged 18 or older) recruited at the MUSE among family members and professionals from other museum sectors. Following a short guided

visit, participants that had no specific background in climate science were given excerpts from the draft report to read and comment on. They were asked to highlight unclear language, technical jargon, and assess the clarity and tone of both text and visuals. Feedback from this "read–comment–revise" loop led us to simplify ambiguous sentences, better explain technical terms, and adapt visual elements for greater clarity. This iterative method is consistent with established best practices in science communication, which emphasize iterative feedback from real users to improve comprehension and engagement (Schuster et al., 2024).
3. Strategic use of visual elements and formatting: the studies by the IPCC (Gomis and Pidcock, 2022), and by Corner et al. (2015) provide validated and internationally recognized guidelines for the design of visual tools in climate reports. Based on these instructions, in our work we used charts, infographics, thematic maps, and photographs, which were selected to ensure accessibility even for non-experts. The structure was organized into concise paragraphs with clear headings and a well-defined visual hierarchy to enhance readability.

The received data and information were translated into more comprehensible language, specifically tailored for a non-expert public. This process involved careful rephrasing of technical terms and concepts, accompanied by visual aids to enhance understanding. We enriched the report with graphs, tables, and diagrams to visually convey trends, relationships, and key data points. These visuals were designed not only to support the text but also to be self-explanatory, such as to provide readers with digestible information at a glance.

Visual tools were designed collaboratively by a multidisciplinary team including climate scientists, data analysts, and a graphic designer/researcher experienced in science communication. The process followed a design-based research framework (Wang and Hannafin, 2005; Corner et al., 2015; Schuster et al., 2024), which involves iterative cycles of analysis, design, implementation, and evaluation. Specifically:

1. Identification of communication needs: The scientific and communication experts analyzed which complex concepts required visual support, such as future temperature projections and impact scenarios.
2. Design phase: The graphic designer created drafts of charts, infographics, and diagrams using tools like Adobe Illustrator and Tableau, with attention to visual hierarchy (e.g., size, color contrast, white space) to guide reader focus.
3. Implementation and feedback: Draft visuals were shared internally and with non-expert participants at MUSE during comprehension testing. Feedback addressed unclear labels, excessive detail ("chart junk"), and insufficient stand-alone explanatory captions.
4. Final refinement: Visuals were adjusted to improve clarity and autonomy by adding concise captions and decluttering non-essential elements.
5. Validation: Final versions were validated both by scientific experts for accuracy and by non-experts for comprehensibility, ensuring they meet both scientific rigor and public accessibility.

Moreover, the report alternates various communication formats, such as text, tables, images, and schematic representations, with the intention of maintaining the audience's engagement. This alternation helps prevent cognitive overload while ensuring a dynamic flow of information. Particular attention was given to the aesthetic layout, making sure that the document was visually appealing, thus enhancing both its readability and its overall attractiveness to the audience.

The combination of these methods aimed at creating a balanced, user-friendly report that would effectively communicate complex climate-related data and information in an engaging, informative, and aesthetically pleasing manner.

A final round of validation by a smaller group of experts, chosen among those involved in the literature review stage, further ensured the scientific accuracy of the simplified content.

3. Results and discussion

3.1. Overview of the reviewed studies by sector and level of analysis

Based on our insights derived from the analysis of the conducted literature review, we present here a summary of the availability of climate change impact studies by sector. This summary is deliberately left broad and does not aim to give a whole account of the climate change impacts in the region, which would be beyond the scope of the current study. More detailed information on the impacts themselves, together with the respective references can be obtained, upon request from APPA directly, in the full report. Furthermore, the reader may refer to Napoli et al. (2025) for a synthesis of the climate change impacts on the Water–Energy–Food-Ecosystems nexus in the study region.

The literature review revealed a strong heterogeneity in the number of scientific contributions across different sectors regarding climate change impacts in Trentino (Fig. 2). Also the number of datasets and impact indicators varies considerably by sector. Moreover, these metrics are not correlated, which means that an abundance of literature does not imply an abundance of datasets or impact indicators.

The sectors most notable for the number of studies are in the macro-area of environmental impacts, namely "Water" (number of studies: 41), "Snow, glaciers, and permafrost" (30), "Forests" (29), "Agroecosystems" (24), "Terrestrial ecosystems" (28), and "Aquatic ecosystems" (18). This is not surprising, since they are the main focus of most mountain climate research worldwide, as also shown by the number of impact indicators defined globally (see Fig. 2). Moreover, these areas are among the most developed in the research bodies, universities, public agencies, and technical bureaus of the Province administration, besides corresponding to the most visible impacts of climate change in mountain regions. Although the sectors within the environmental area are in general better studied than the socioeconomic areas, partly thanks to the availability of public datasets, a few sectors, such as Ecosystems, are mainly characterized by non-public datasets. This limits the ability to gain deeper insights into these sectors.

Sectors characterized by significant knowledge gaps and limited literature are chiefly in the socioeconomic area. The most limited local impact number of studies were identified in sectors like "Cultural heritage" (5), "Security and social cohesion" (2), "Industries and infrastructure" (2), and "Transport and infrastructure" (1). On the contrary, "Risk from natural hazards" (23) and "Health" (18) are fairly well explored followed by "Water resource management" (17), "Tourism" (13), "Energy" (13), "Forest productivity and supply chain" (11), "Agriculture" (10), "Settlements and urban areas" (10), and "Aquaculture, livestock and food production" (10). These are again the primary research topics of scientific entities and technical bureaus of the Province administration. Compared with environmental sectors, socioeconomic sectors are characterized by fewer defined indicators and fewer publicly available datasets related to or usable for Trentino, once again highlighting the limited attention these sectors receive in mountain regions when assessing the impacts of climate change. Fostering coordinated actions to collect observations and generating easily accessible data products, that adhere to FAIR or similar standards (Wilkinson et al., 2016), would be a key step towards strengthening climate change adaptation capabilities at the regional scale.

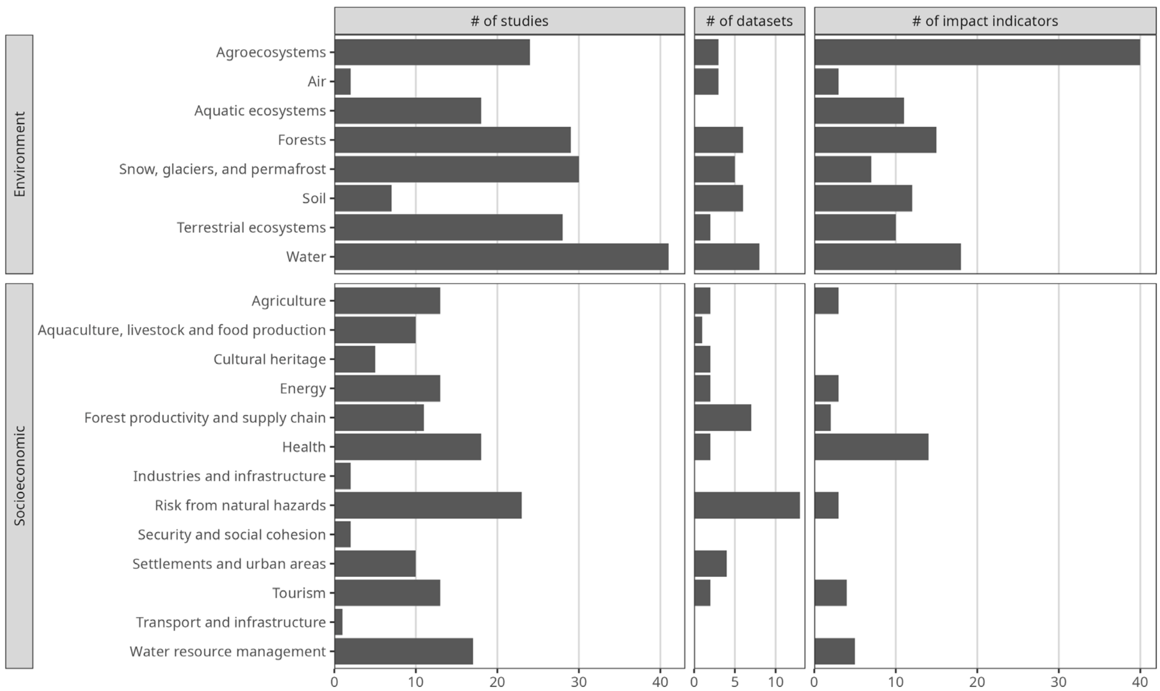

Fig. 2. Summary assessment of the availability of literature (# of studies) in the Trentino region on climate change (CC) impacts, public datasets (# of datasets) related to Trentino or usable by the Trentino region, and impact indicators (# of impact indicators) relative to the correspondent sector. The sectors are distinguished by socioeconomic and environmental macro-areas.

Analyzing these metrics (number of studies, datasets, and impact indicators) gives only a rough indication of the richness and exhaustiveness of the available research in each sector. For a thorough assessment, this would need to be complemented by an evaluation of the scientific clarity and maturity of studies on the topic, which however, would have to rely on the authors' judgement and on their subjective evaluation.

The report's scientific evidence is being used to shape the Trentino adaptation strategy in the way that the document established the necessary knowledge base for the identification of the sectoral and trans-sectoral climate change induced risks. Such risks have been analyzed and evaluated in order to define the adaptation measures which are to be included in the final Strategy document (this process is oriented on the methodology outlined by the Regional Adaptation Support Tool; link[2]). In fact, information and data from the report were used by APPA and other supporting actors to inform the sectoral risk and vulnerability analysis workshops that took place in 2023 and 2024 until early 2025, involving experts from different Provincial departments, scientific institutions, and stakeholders.

The review process stimulated the local scientific community by involving them in a collaborative effort to achieve a systematic overview of all the research carried out on the multifaceted topic of climate change impacts in Trentino allowing transferring scientific knowledge to the general public and citizens. Furthermore, the knowledge gaps highlighted by the report could also constitute preferential research directions for the future, with the possible activation of ad hoc study initiatives or research projects by different subjects.

In summary, for designing a climate change adaptation strategy at the regional level, a literature review of the main climate change impacts, like the one that was prepared for the present case, is a fundamental starting point (a) for the future implementation of more detailed studies related to climate change adaptation and (b) for deciding on the funding priority for specific projects and studies on climate change impacts in sectors lacking information.

[2] https://climate-adapt.eea.europa.eu/en/mission/knowledge-and-data/regional-adaptation-support-tool

3.2. Future climatic changes

The layered approach (consisting of multiple climate models and statistical downscaling, Section 2.2) in devising climate scenarios has also been used in creating the summary graphics. For example, Fig. 3 shows the temporal evolution of seasonally averaged daily temperature minima in winter (Dec–Feb) under the available RCP scenarios. The EURO-CORDEX ensemble spread is evaluated at the 5th and 95th percentiles, which corresponds roughly to the 90% coverage of trends used in the sub-ensemble of the bias adjusted and downscaled models. Models agree extremely well in the temporal evolution of temperature. Note that for the sake of comparison, in the temporal evolution, we also included the parent model of VHR-PRO_IT, namely COSMO_Italy, which has been used as a single reference for the national climate scenarios assessment (PNACC) (Ministero dell'Ambiente e della Sicurezza Energetica, 2023).

Besides temperature averages, precipitation extremes show a high agreement in the temporal evolution and magnitude of changes among models. However, compared to temperature variables, they exhibit a lower confidence in the projected results due to the wide ensemble spread. Nevertheless, precipitation intensity indices increase with higher greenhouse gas concentrations, i.e., towards the RCP8.5 scenario (Fig. 4). By the end of the century, the average daily precipitation intensity (SDII), based on the EURO-CORDEX ensemble, increases by 4% (2,12%; 5th and 95th percentile of model ensemble) for RCP2.6, by 6% (2,10%) for RCP4.5, and by 8% (−2,15%) for RCP8.5.

Differences between models emerge when looking at indices requiring absolute thresholds, such as the number of summer days above 30 °C (SU30, Fig. 5). SU30 increases, but the increase is limited to the lower elevations. With RCP4.5, the DS-BA ensemble predicts up to 50 days more summer days on average over the period 2041–2070, which is consistent with VHR-PRO_IT. However, the raw EURO-CORDEX ensemble, at its coarse resolution, is not able to capture these extremes (compare left panel to middle and right in Fig. 5), because the models at 0.11° spatial resolution do not resolve the low-elevation valleys due to orographic smoothing in the models (Matiu et al., 2020). Consequently,

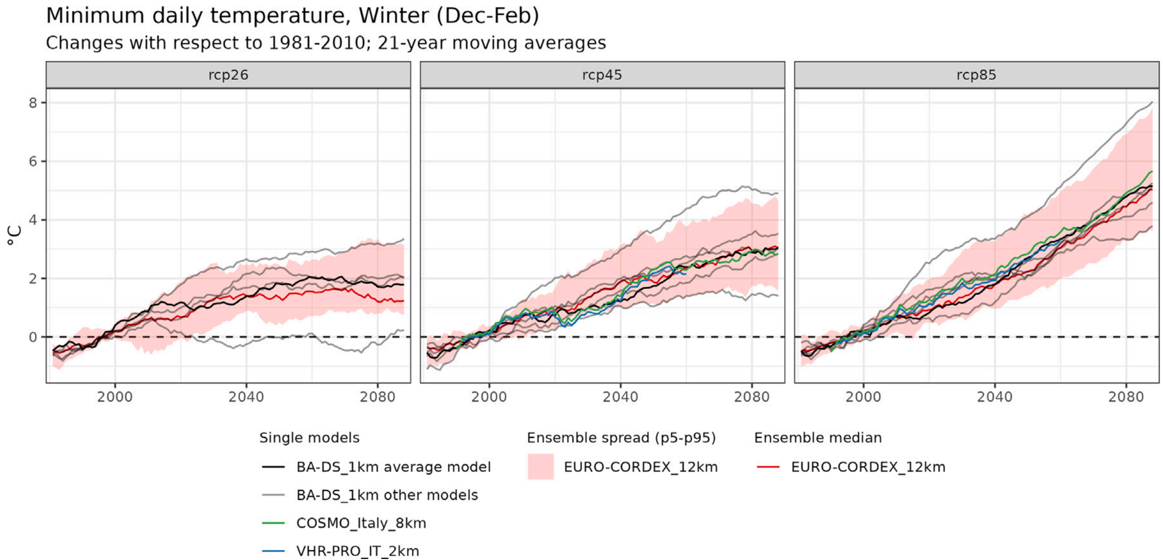

Fig. 3. Temporal evolution of seasonally averaged daily temperature minima in winter (Dec–Feb) relative to 1981–2010 under different scenarios (RCP2.6, RCP4.5, and RCP8.5) from diverse data sources: raw EURO-CORDEX ensemble (median and model spread using the 5th to the 95th percentile), bias adjusted and downscaled BA-DS (single models, the average model and the four to five others; average model is not an ensemble average), and high-resolution raw VHR-PRO_IT (together with its forcing model COSMO_Italy_8 km, used in the national assessment, single models). Time series are smoothed with a 21-year moving average.

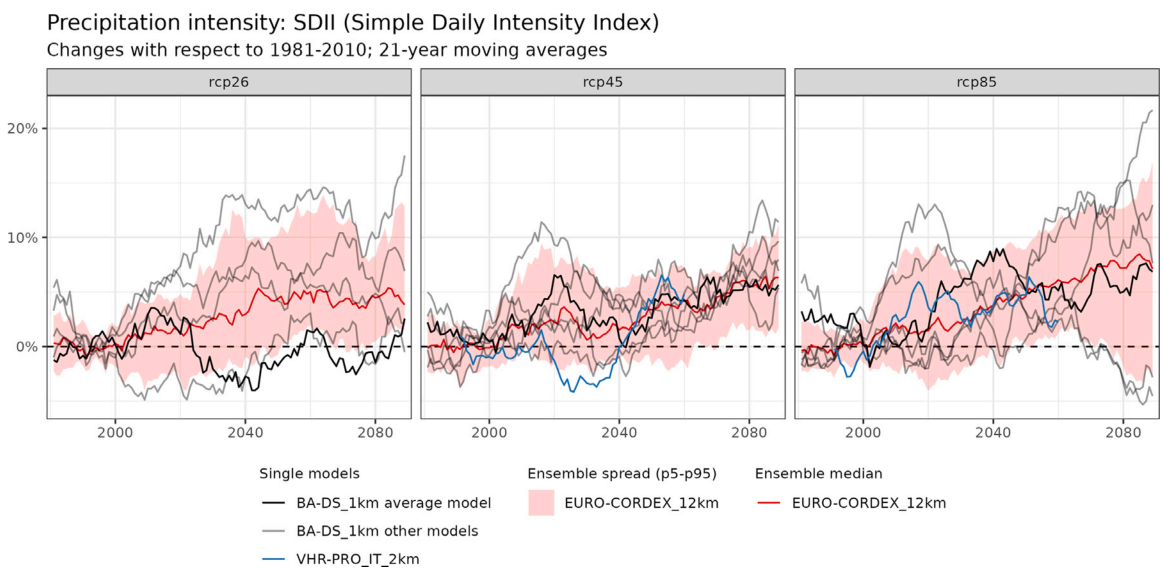

Fig. 4. Temporal evolution of SDII (daily precipitation intensity) relative to 1981–2010 under RCP2.6, RCP4.5, and RCP8.5 scenarios from diverse data sources: raw EURO-CORDEX ensemble (median and model spread using the 5th to the 95th percentile), bias adjusted and downscaled BA-DS (single models, the average model and the four to five others; average model is not an ensemble average), and high-resolution raw VHR-PRO_IT (single model). Time series are smoothed with a 21-year moving average.

indices such as SU30 that have a strong dependency on temperature, and thus elevation, require the use of statistical downscaling or high-resolution RCMs to properly identify future changes in complex terrain (Soares et al., 2024).

The last example concerns the number of snowfall days (HNd, Fig. 6), an index of particular importance for mountain regions. We observe an overall reduction of HNd over the entire territory, which is, in relative terms, stronger at the lower elevations. Over the period 2041–2070, only at the highest elevations are the changes zero or minimal in the RCP4.5 scenario. By comparing the different model ensembles, both EURO-CORDEX and VHR-PRO_IT show lower decreases than BA-DS in the central valley of Trentino, which is likely not only related to the coarser resolution of these datasets but also to the lack of bias adjustment. As RCMs can have non-negligible biases in temperature and precipitation (Matiu et al., 2024; Vautard et al., 2021), this can have strong impacts on climate indices that rely on fixed thresholds. For instance, a cold bias in RCMs would not only increase the absolute number of frost days (FD, i.e., days with maximum temperatures below 0 °C) in any given period, but it would also make the change signals implausible.

To conclude, the above-mentioned layered approach was found highly useful in creating reference climate scenarios. The coarse-resolution and large EURO-CORDEX ensemble provides the opportunity to assess scenario uncertainty at the regional scale and inter-model agreement, which can be an indication of confidence in the projections. The raw ensemble is refined using bias adjustment and statistical downscaling to finer resolutions to provide climate information at the local

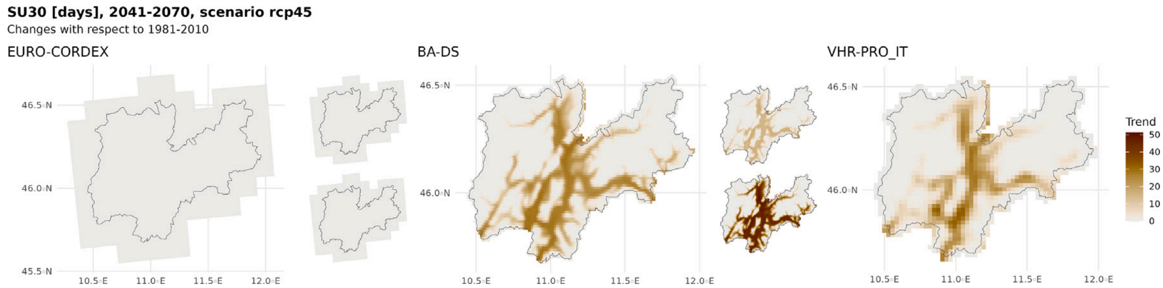

Fig. 5. Spatial distribution of changes in SU30 (summer days, maximum temperatures above 30 °C) for the period 2041–2070 relative to 1981–2010 under RCP4.5 from diverse data sources (raw EURO-CORDEX ensemble, bias adjusted and downscaled BA-DS, and high-resolution raw VHR-PRO_IT).

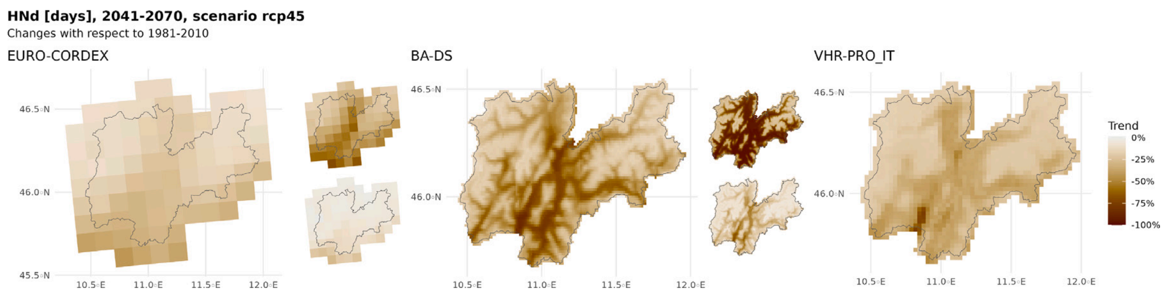

Fig. 6. Spatial distribution of changes in HNd (days with snowfall, i.e., mean temperatures below 2 °C and precipitation above 1 mm) for the period 2041–2070 relative to 1981–2010 under RCP4.5 from diverse data sources (raw EURO-CORDEX ensemble, bias adjusted and downscaled BA-DS, and high-resolution raw VHR-PRO_IT).

scales, which is unbiased and covers extreme indices that might not be resolved by coarser resolution. Finally, a high-resolution simulation confirms and further validates results from the statistical downscaling and enables us to derive even more indices, such as extreme winds, or to reach finer temporal scales, such as hourly values of Humidex.

3.3. Informative report

The development of the Trentino informative report was a key step in communicating the study's findings to the general public. As can be inferred from Fig. 7, which shows some example pages, the report presents key data in the form of explanatory images, photos, graphs, and infographics facilitating the understanding of climate trends, important concepts, and possible adaptation strategies. Alternating short texts, summary diagrams, and images helped to maintain readers' attention, making the document an effective awareness-raising tool.

This experience highlights the importance of clear and scientifically accurate communication tools to facilitate the understanding of climate change and stimulate an informed dialogue between citizens and policymakers. The Italian informative report was officially approved in April 2025 and is now available on the APPA website.[3]

The news of the report approval and publication has been published not only on the institutional websites of the Autonomous Province of Trento, APPA and MUSE, but also on the national adaptation platform (https://climadat.isprambiente.it/) managed by ISPRA (Italian Institute for Environmental Protection and Research) and in the newsletter of SNPA (national system of regional environmental protection agencies).

As of November 2025, preliminary statistics on the access to the APPA webpage that hosts the report are available: 1646 page-views, 1294 unique page-views, 457 downloads since the date of publication (April 16th, 2025). Despite the shorter time span, the page is among the most consulted on APPA website compared to those already online since 1st January 2025.

User feedback is still being gathered and analyzed (as of November 2025). For the future, it will be worthwhile to gather more feedback to this report and analyze it. Thus potential areas for improvement could be identified, as well as, new research contributions and needs for data collection and monitoring for future updates of the document. In addition, the results from participatory climate risk analyses and related studies will lead to the production of a Vulnerability and Risk Assessment technical document which will bridge knowledge about the impacts of climate change (synthesized in the report) to the choice of the most appropriate adaptation measures (the core of the future provincial Strategy).

4. Conclusions

The fragmentation of bodies in charge of meteorological monitoring in Italy, along with the absence of a unique national meteorological or climatological service, has some implications for the development of climate services. One downside is the lack of institutional capacity to derive consistent climate scenarios to support the formulation of climate policies, unlike what was done in other European countries. On the other hand, regional assessments can better consider the diverse climatic and socioeconomic conditions across the Italian territory, from both environmental and socioeconomic point-of-view. Nonetheless, it remains a challenge to merge efforts and confront results with neighboring territories, which more likely share somewhat similar climatic and socioeconomic challenges than more distant regions.

The approach adopted by the Autonomous Province of Trento exemplifies this situation by focusing on sectors of local significance, such as water, glaciers and snow, forests, health, agriculture, and tourism, which also resonate strongly with the public. At the same time, it integrates climate scenarios based on well-established international data while taking into account the region's complex orography. To conclude this work, an informative report was prepared to disseminate knowledge and raise public awareness.

The process has been extremely valuable in connecting the different institutions and entities active in Trentino, such as science and public administration, promoting and strengthening their collaboration on

3 https://www.appa.provincia.tn.it/Documenti-e-dati/Documenti-tecnici-di-supporto/Lo-stato-del-clima-in-Trentino

Fig. 7. Example pages of the Italian informative report. (a) Cover page; (b) Section division; (c) Highlighting temperature changes with simple graphics and images; (d) Explaining more complex concepts (global warming potential and CO_2 equivalents) in separate text boxes and drawings; (e) Easing reader flow by alternating between graphics, text, boxes, and images; (f) Showing raw observed data and statistics.

climate adaptation issues. In fact, the entire process was developed through continuous feedback between scientists and policy-makers, which included technicians and experts from the departments of the Autonomous Province of Trento, who provide the technical support to the adaptation strategy development and to policy formulation in the different sectors. This iterative process particularly focused on topics that are often difficult to interpret, such as uncertainty of future scenarios, the definition and interpretation of climate indicators, and the spatial and temporal resolution of the model data. An internal document (not included here) was circulated among the Autonomous Province of Trento that contained graphs and data specifically focused on their practical use. It was the responsibility of APPA and the other provincial technical structures to act as mediators towards higher-level policy- and decision-makers, to convey and ensure a thorough understanding of scenario-based supporting information. Furthermore, an open-data online platform for the climate scenarios is currently under development. This platform shall include guidelines focused on their practical application based on the existing internal documents that shall explain how this information can be used and interpreted.

Code and data availability

All code will be made available under https://github.com/tnclima/. Generated data can be made available by the authors upon request.

CRediT authorship contribution statement

Anna Napoli: Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Michael Matiu:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Lavinia Laiti:** Writing – review & editing, Methodology, Conceptualization. **Roberto Barbiero:** Writing – review & editing, Project administration, Methodology. **David Tombolato:** Writing – original draft, Methodology. **Silvia Scarian Monsorno:** Writing – review & editing, Methodology. **Alberto Bellin:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Dino Zardi:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Bruno Majone:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve writing and summarize content. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Data and methods for the reference climate scenarios

A.1. Observational data

The observational data used in this study includes a gridded product at 1 km *x* 1 km spatial resolution for daily temperature minima and maxima, and precipitation over Trentino Alto-Adige, elaborated by using 243 and 311 daily records of precipitation and temperature (maximum and minimum), respectively, retrieved from gauging stations (Crespi et al., 2021). The dataset covers the period from 1981 to 2020.

A.2. Model data

We used the ensemble of GCM-driven EURO-CORDEX RCMs downloaded from ESGF servers in January 2023. We focused on high resolutions as the region lies in mountain terrain, so we used only the EUR-11 simulations, which have a horizontal spacing of 0.11°, equivalent to approximately 12 km horizontal resolution.

The list of RCMs used in the present study is shown in Table 3. We used daily data for precipitation (pr), mean temperature (tas), minimum temperature (tasmin), and maximum temperature (tasmax). The ensemble consisted of only one member per GCM-RCM combination. The ensemble size for tasmin and tasmax was one less than for tas and pr because there was no tasmin and tasmax available for RMIB-UGent-ALARO-0. The available GCM-RCM combinations were 52 for RPC8.5, 29 for RCP4.5, and 23 for RCP2.6.

This represents an ensemble of opportunity, which means that it does not include all CMIP5 GCMs and that the GCM-RCM matrix, i.e., the combination of driving GCMs (in total 8) and different RCMs (in total 12) is far from complete (see also Table 3). Additionally, the different RCP scenarios had different ensemble sizes of different GCM-RCM combinations. We checked if results would change after reducing the ensemble to GCM-RCM combinations that had all three RCPs in common, which means the same ensemble of GCM-RCMs for all RCP scenarios. However, we found that the mean changes and the inter-model ranges over Trentino were very similar in both cases (results not shown here). Consequently, we did not select only common GCM-RCMs to all RCPs, but kept the full ensemble that different by RCP.

Besides the daily RCM data from EURO-CORDEX, we also extracted information from the Very High Resolution Projections for Italy (VHR-PRO_IT). These are dynamically downscaled simulations from the CMCC-CM GCM using the COSMO-CLM RCM at 2.2 km resolution and covering a transient period over 1981–2070 (Raffa et al., 2023). The dataset is available for 1981–2070, contrary to the period mentioned in the original publication (1989–2050). The variables of interest were temperature, precipitation, humidity, downward shortwave radiation, surface snow amount, u and v wind velocity components (eastward and northward). We only did a basic pre-processing (download from a data delivery system, cropping to the region of interest, reprojecting from a rotated pole to a standard long lat reference system) to make it easier for future users to directly work with the data. Otherwise, no post-processing, especially no bias adjustment, was performed.

A.3. Ensemble reduction

The large EURO-CORDEX ensemble has been reduced before statistical downscaling in order to reduce computational load and data size requirements, and make the scenarios easier to use. The last point has been the most influential in the decision, as users often struggle with the concept of climate model ensembles and how to apply it in practice (Fischer et al., 2022). Users often expect or want to use the *one best model*, something that cannot be achieved as there is no *best* model (Vautard et al., 2021). As model ensembles are often used to address correspondent spread, we took an approach that tries

Table 3
Overview of regional climate models used. RCMs in rows, and GCMs in columns. The cell value is the downscale realization for the different RCPs in the form RCP2.6/RCP4.5/RCP8.5, where a dash (-) means no simulation available. RCM abbreviations: crCLIM-v1-1 is COSMO-crCLIM-v1-1, HadREM3 is HadREM3-GA7-05. GCM abbreviations: CM5 is CNRM-CM5, EC is EC-EARTH, GFDL is GFDL-ESM2G, Had is HadGEM2-ES, CM5A-LR is CM5A-LR, CM5A-MR is IPSL-CM5A-MR, MPI is MPI-ESM-LR, and Nor is NorESM1-M. The GCM ensemble was always r1i1p1 except for EC-EARTH with r12i1p1.

	CM5	EC	GFDL	Had	CM5A-LR	CM5A-MR	MPI	Nor
ALADIN63	v2/v2/v2			-/-/v1			-/-/v1	-/-/v1
ALARO-0	v1/v1/v1							
CCLM4-8-17	-/v1/v1	v1/v1/v1		-/v1/v1			-/v1/v1	
crCLIM-v1-1	-/-/v1	-/-/v1		-/-/v1			-/-/v1	-/-/v1
HIRHAM5	-/-/v2	-/-/v1		v2/v2/v2		-/-/v1	-/-/v1	-/v3/v3
HadREM3	-/-/v2	v1/-/v1		v1/-/v1			-/-/v1	-/-/v1
RACMO22E	v2/v2/v2	v1/v1/v1		v2/v2/v2		-/-/v1	v1/-/v1	v1/-/v1
RCA4	-/v1/v1	v1/v1/v1		v1/v1/v1		-/v1/v1	v1a/v1a/v1a	v1/v1/v1
REMO2009							v1/v1/v1	
REMO2015	v2/-/v2		v1/-/-		v1/-/-	-/-/v1		v1/v1/v1
RegCM4-6	-/-/v2	-/-/v1		v1/-/v1			v1/-/v1	v1/-/v1
WRF381P	-/-/v2	-/-/v1		-/-/v1		-/v1/v1	-/-/v1	-/-/v1

Table 4
Selected models in sub-ensemble.

experiment	model_number	gcm	institute_rcm	ensemble	ds
rcp26	1	NCC-NorESM1-M	GERICS-REMO2015	r1i1p1	v1
	2	MOHC-HadGEM2-ES	SMHI-RCA4	r1i1p1	v1
	3	NOAA-GFDL-GFDL-ESM2G	GERICS-REMO2015	r1i1p1	v1
	4	ICHEC-EC-EARTH	MOHC-HadREM3-GA7-05	r12i1p1	v1
	5	ICHEC-EC-EARTH	SMHI-RCA4	r12i1p1	v1
rcp45	1	CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN63	r1i1p1	v2
	2	MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	r1i1p1	v1
	3	MOHC-HadGEM2-ES	SMHI-RCA4	r1i1p1	v1
	4	IPSL-IPSL-CM5A-MR	SMHI-RCA4	r1i1p1	v1
	5	IPSL-IPSL-CM5A-MR	IPSL-WRF381P	r1i1p1	v1
	6	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	r1i1p1	v1
rcp85	1	CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN63	r1i1p1	v2
	2	MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	r1i1p1	v1
	3	MOHC-HadGEM2-ES	SMHI-RCA4	r1i1p1	v1
	4	NCC-NorESM1-M	GERICS-REMO2015	r1i1p1	v1
	5	IPSL-IPSL-CM5A-MR	IPSL-WRF381P	r1i1p1	v1
	6	NCC-NorESM1-M	CNRM-ALADIN63	r1i1p1	v1

to minimize the number of models preserving uncertainty in future projections.

Specifically, we followed the same approach that has been applied to GCMs, exploiting the initialization step of k-means clustering (Cannon, 2015). It is a sequential algorithm that selects the (k-1) elements of the ensemble that are the farthest from the global centroid in the space of the results (Fig. 8). In other words, this approach aims at identifying the uncertainty bounds as the envelope of a smaller number of points (models). In our case, we applied this procedure to seasonal changes in winter (DJF) and summer (JJA) temperature and precipitation for the time window 2071–2100 versus the reference 1981–2010, thereby resulting in a four-dimensional input matrix to the algorithm: (1) winter temperature, (2) summer temperature, (3) winter precipitation, and (4) summer precipitation. The procedure was applied separately to each RCP since the ensembles were different, with the constraints of covering at least 90% of the full spread (uncertainty) in expected changes, which was achieved by using k = 5 to 6 models, depending on the RCP (see Table 4 and Fig. 9).

The main benefit for users of this approach is that each of the 5–6 models can be labeled on the basis of the expected future changes. Model 1, the centroid, is always the mean expected change. Then, for instance, for RCP8.5, model 2 is the one exhibiting much warmer and much drier summers, model 3 much warmer and wetter winters, as well as warmer but not drier summers, and similarly for the other models and RCPs (Fig. 10). Consequently, users can explore different possibilities of future climates, simulating both the best and the worst scenarios, which may differ depending on the sector of application.

A.4. Statistical downscaling

We evaluated different methods for statistical downscaling from the family of MOS (model output statistics) approaches (Gutiérrez et al., 2019). Specifically, we tested first the gain obtained by applying multivariate bias adjustment of temperature and precipitation with respect to a bias adjustment that treats each variable of interest separately (Cannon, 2018). We did not find a substantial benefit from the multivariate approach, although in principle it was expected to provide better results. Improvements achieved by the multivariate snowfall index were negligible, probably because the correlation is inherited from the model and the correlation between temperature and precipitation is weak. Potentially different results could be obtained if other variables, such as humidity, were to be bias adjusted. Moreover, another drawback of the multivariate adjustment is that it requires a temporal shifting to preserve correlations and, as such, introduces speckle or noise in a spatial application. This is an inherent limitation of the univariate approach, while the multivariate approach could preserve spatial and inter-variable correlations, thus improving inter-variable and inter-site properties. However, consequences could be computational instability or that temporal properties might suffer (François et al., 2020; Robin and Vrac, 2021).

Based of the above consideration, we compared two different downscaling approaches for precipitation and four for temperature. The first included the trend-preserving variant of the widely used quantile mapping algorithm (Cannon et al., 2015). The second is a spatially explicit method based on principal components analysis (PCA) (Frei et al., 2015; Hiebl et al., 2024). The third, only used for temperature,

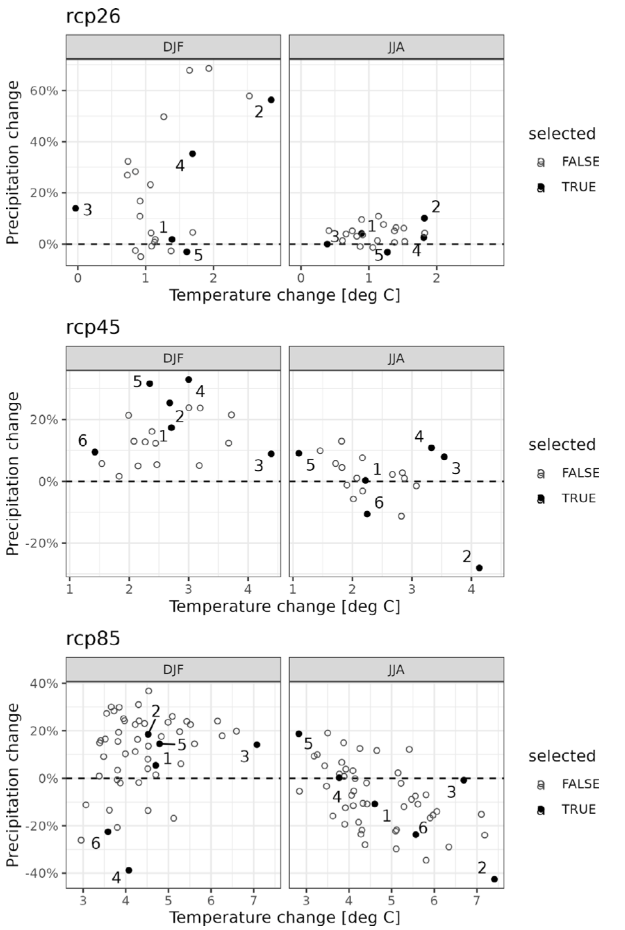

Fig. 8. Sub-ensemble selection for the three RCP scenarios (RCP2.6, RCP4.5, RCP8.5). The labels refer to the same model in the two selected seasons (DJF and JJA), but differ between the RCPs.

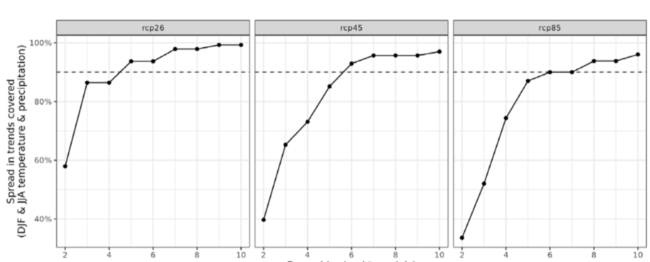

Fig. 9. Spread of trends covered by sub-ensemble as a function of sub-ensemble size.

is a linear lapse-rate adjustment, albeit with different lapse rates per month and variable. The fourth, also applied only to temperature, is a 3-D interpolation of RCM surface temperatures using generalized additive models, assuming independence between the 2-D horizontal field and the 1-D vertical component, which is able to consider non-linear elevation lapse-rates. The detailed results can be found in a separate study (Matiu et al., in preparation).

The final choice was to use univariate quantile delta mapping (QDM), since it provided the highest accuracy in reproducing the past climatology for both temperature and precipitation, even though the spatial PCA-based approach was found slightly superior for precipitation (but not for temperature). This confirms previous assessments showing that empirical quantile mapping has the highest accuracy (Gutiérrez et al., 2019) and corroborates its widespread use in climate change assessments (Fischer et al., 2022).

The methodological steps for creating the scenarios are as follows. First, RCMs were bilinearly remapped to a regular lon-lat grid of the same resolution (0.11°). Then, the high-resolution observation grid cells were matched to coarse RCM scale grid cells by selecting the RCM grid cell to which the observational cell belongs. In the case of overlaps, the cell with minimal distance from the cell center was selected. For the trend-preserving aspect of QDM, we chose the time window 1981–2010 as a reference using additive trends for temperature and relative trends for precipitation. QDM was finally applied point-by-point, month-by-month, and decade-by-decade. For each month and decade, the mapping was performed using a training window of ±1 month and ±1 decade. For example, to derive the values of January 2041–2050, the quantile mapping function was estimated using past observed values from December to February 1981–2010, past model simulations from December to February 1981–2010, and future model simulations from December to February 2031–2050. This resulted in a continuous time series for the future with fewer breaks between months and decades.

A.5. Climate indices

The detailed description of climate indices is presented in Table 5. The period 1981–2010 was used as a reference period for the indices that required one. All indices were calculated based on full solar years (January to December). Below are some further clarifications not reported in the Table:

heatDD, coolDD Note that definitions of heatDD and coolDD could vary in different studies, making the comparison not always easily possible. For example, for coolDD (heatDD) the PNACC (Italian level) uses 21 °C, but only for days that exceed 24 °C (18° and 15° for heatDD), while the EEA (European Environment Agency) uses 22 °C for heatDD and 15.5° for coolDD, respectively, and the EEA uses tmin, tmean, and tmax for the calculation. Here, we used the thresholds 22° and 18 °C, which were also used in the PEAP (Piano Energetico Ambientale Provinciale) (PAT and APRIE, 2022), which is the most locally relevant report.

Humidex3/4 Combined heat index based on temperature and humidity. Category 3 (humidex > 30 °C) corresponds to some discomfort, category 4 (humidex > 40 °C) to great discomfort and recommendation to avoid exertion. Category 5 (humidex > 45 °C), which corresponds to dangerous conditions and heat strokes quite possibly, was never reached in the analyzed data. Humidex3/4 index is computed as follows: $T_{air} + \frac{5}{9}\left[6.11 \cdot \exp\left(c\left(\frac{1}{273.15} - \frac{1}{273.15+T_{dew}}\right)\right) - 10\right]$, where $c = 5417.7530$, T_{air} is air temperature in ° C and T_{dew} is dewpoint temperature in ° C. Humidex was calculated only for hourly data of VHR-PRO_IT.

SPI, SPEI Calculated based on monthly precipitation with the R-package SPEI and default values (log–logistic distribution for SPEI and Gamma for SPI). Potential evapotranspiration (PET) for SPEI was calculated with the Thornthwaite approximation, which requires monthly mean temperature and latitude (here fixed to 46,07° N).

HN, HNd Snowfall amount (HN) and days (HNd) index based on the daily mean temperature (tmean) and daily precipitation (pr), assuming a fixed fresh snow density of 100 kg/m^3; HN = pr · 100 kg/m^3, only if tmean < 2 °C. The temperature threshold of 2 °C was found to fit best to observed data (Zubler et al., 2014). For snowfall days (HNd), the pr threshold of 1 mm was taken in accordance with the ETCCDI definition of wet days.

experiment	model_number	tas_DJF	tas_JJA	pr_DJF	pr_JJA
rcp26	1	1.4	0.9	1.8%	4.1%
	2	2.9	1.8	56.3%	10.1%
	3	-0.0	0.4	13.9%	-0.0%
	4	1.7	1.8	35.3%	2.5%
	5	1.6	1.3	-3.1%	-3.2%
rcp45	1	2.7	2.2	17.4%	0.3%
	2	2.7	4.1	25.4%	-28.1%
	3	4.4	3.5	8.9%	7.9%
	4	3.0	3.3	32.9%	10.8%
	5	2.3	1.1	31.6%	9.1%
	6	1.4	2.2	9.4%	-10.6%
rcp85	1	4.7	4.6	5.4%	-10.8%
	2	4.5	7.4	18.5%	-42.5%
	3	7.1	6.7	14.1%	-0.8%
	4	4.1	3.8	-38.8%	0.2%
	5	4.8	2.8	14.5%	18.7%
	6	3.6	5.6	-22.6%	-23.8%

Fig. 10. Seasonal changes of selected models (sub-ensemble) 2071–2100 versus 1981–2010. Tas is daily mean temperature, pr is precipitation, DJF is winter (Dec–Feb), and JJA is summer (Jun–Aug). Color bars are a visualization help, where the length and color of the bars indicate the magnitude of change: for temperature, yellow (low increase) to black (strong increase); for precipitation, brown (decrease) to blue (increase).

Table 5
Detailed explanation of calculated climate indices. Abbreviations: tmean/tmin/tmax is daily mean/minimum/maximum temperature, pr is daily precipitation.

Index	Description
FD	Days with tmin < 0 °C
ID	Days with tmax < 0 °C
SU	Days with tmax > 25 °C
SU30	Days with tmax > 30 °C
TR	Days with tmin > 20 °C
heatDD	Sum of the difference between 18 °C and tmean, only when tmean < 18 °C
coolDD	Sum of the difference between tmean and 22 °C, only when tmean > 22 °C
Humidex3/4	Sum of hours with humidex > 30 °C (cat 3) or > 40 °C (cat 4)
SDII	Mean daily precipitation on wet days only (pr ≥ 1mm)
Rx1day	Maximum of daily precipitation
Rx5day	Maximum of 5-day consecutive precipitation sums
RR1	Number of days with pr ≥ 1 mm
R10mm	Number of days with pr ≥ 10 mm
R20mm	Number of days with pr ≥ 20 mm
CDD	Maximum number of consecutive days with pr < 1mm
R95p	95th percentile of pr, calculated on wet days (pr ≥ 1mm) in the reference period
R99p	99th percentile of pr, calculated on wet days (pr ≥ 1mm) in the reference period
R95pTOT	Total precipitation above the 95th percentile, calculated on wet days (pr ≥ 1mm) in the reference period
R99pTOT	Total precipitation above the 99th percentile, calculated on wet days (pr ≥ 1mm) in the reference period
HNd	Number of days with tmean < 2 °C and pr ≥ 1mm
HN	$\text{pr} \cdot 100 kg/m^3$, only when tmean < 2 °C
EWS	98th percentile of daily maximum wind speed

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.cliser.2025.100629.

Data availability

Data will be made available on request.

References

Ban, N., Caillaud, C., Coppola, E., Pichelli, E., Sobolowski, S., Adinolfi, M., Ahrens, B., Alias, A., Anders, I., Bastin, S., Belušić, D., Berthou, S., Brisson, E., Cardoso, R.M., Chan, S.C., Christensen, O.B., Fernández, J., Fita, L., Frisius, T., Gašparac, G., Giorgi, F., Goergen, K., Haugen, J.E., Hodnebrog, O., Kartsios, S., Katragkou, E., Kendon, E.J., Keuler, K., Lavin-Gullon, A., Lenderink, G., Leutwyler, D., Lorenz, T., Maraun, D., Mercogliano, P., Milovac, J., Panitz, H.-J., Raffa, M., Remedio, A.R., Schär, C., Soares, P.M.M., Srnec, L., Steensen, B.M., Stocchi, P., Tölle, M.H., Truhetz, H., Vergara-Temprado, J., de Vries, H., Warrach-Sagi, K., Wulfmeyer, V., Zander, M.J., 2021. The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation. Clim. Dyn. 57 (1), 275–302. http://dx.doi.org/10.1007/s00382-021-05708-w.

Cannon, A.J., 2015. Selecting GCM scenarios that span the range of changes in a multimodel ensemble: Application to CMIP5 climate extremes indices. J. Clim. 28 (3), 1260–1267. http://dx.doi.org/10.1175/JCLI-D-14-00636.1, URL https://journals.ametsoc.org/view/journals/clim/28/3/jcli-d-14-00636.1.xml, Publisher: American Meteorological Society Section: Journal of Climate.

Cannon, A.J., 2018. Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables. Clim. Dyn. 50 (1), 31–49. http://dx.doi.org/10.1007/s00382-017-3580-6.

Cannon, A.J., Sobie, S.R., Murdock, T.Q., 2015. Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes? J. Clim. 28 (17), 6938–6959. http://dx.doi.org/10.1175/JCLI-D-14-00754.1, URL https://journals.ametsoc.org/doi/10.1175/JCLI-D-14-00754.1.

Castellari, S., Venturini, S., Denti, A.B., Bigano, A., Bindi, M., Bosello, F., Carrera, L., Chiriacò, M.V., Danovaro, R., Desiato, F., Filpa, A., Gatto, M., Gaudioso, D., Giovanardi, O., Giupponi, C., Gualdi, S., Guzzetti, F., Lapi, M., Luise, A., Marino, G., Mysiak, J., Montanari, A., Ricchiuti, A., Rudari, R., Sabbioni, C., Sciortino, M., Sinisi, L., Valentini, R., Viaroli, P., Vurro, M., 2014. Rapporto sullo stato delle conoscenze scientifiche su impatti, vulnerabilità ed adattamento ai cambiamenti climatici in Italia. Min. dell'Ambiente e della Tutela del Territorio e del Mare, URL https://iris.unive.it/handle/10278/3661003?mode=simple#. Accepted: 2015-08-31T09:26:09Z.

Coppola, E., Nogherotto, R., Ciarlo', J.M., Giorgi, F., Meijgaard, E.v., Kadygrov, N., Iles, C., Corre, L., Sandstad, M., Somot, S., Nabat, P., Vautard, R., Levavasseur, G., Schwingshackl, C., Sillmann, J., Kjellström, E., Nikulin, G., Aalbers, E., Lenderink, G., Christensen, O.B., Boberg, F., Sørland, S.L., Demory, M.-E., Bülow, K., Teichmann, C., Warrach-Sagi, K., Wulfmeyer, V., 2021. Assessment of the European climate projections as simulated by the large EURO-CORDEX regional and global climate model ensemble. J. Geophys. Res.: Atmospheres 126 (4), e2019JD032356. http://dx.doi.org/10.1029/2019JD032356, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JD032356, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019JD032356.

Corner, A., Webster, R., Teriete, C., 2015. Climate Visuals: Seven principles for visual climate change communication (based on international social research). Technical Report, Climate Outreach, Oxford, URL https://climateoutreach.org/reports/climate-visuals-seven-principles-for-visual-climate-change-communication/.

Crespi, A., Matiu, M., Bertoldi, G., Petitta, M., Zebisch, M., 2021. A high-resolution gridded dataset of daily temperature and precipitation records (1980–2018) for Trentino-South Tyrol (north-eastern Italian Alps). Earth Syst. Sci. Data 13 (6), 2801–2818. http://dx.doi.org/10.5194/essd-13-2801-2021, URL https://essd.copernicus.org/articles/13/2801/2021/, Publisher: Copernicus GmbH.

Dalelane, C., Früh, B., Steger, C., Walter, A., 2018. A pragmatic approach to build a reduced regional climate projection ensemble for Germany using the EURO-CORDEX 8.5 ensemble. J. Appl. Meteorol. Clim. 57 (3), 477–491. http://dx.doi.org/10.1175/JAMC-D-17-0141.1, URL https://journals.ametsoc.org/view/journals/apme/57/3/jamc-d-17-0141.1.xml, Publisher: American Meteorological Society Section: Journal of Applied Meteorology and Climatology.

Fischer, A.M., Strassmann, K.M., Croci-Maspoli, M., Hama, A.M., Knutti, R., Kotlarski, S., Schär, C., Schnadt Poberaj, C., Ban, N., Bavay, M., Beyerle, U., Bresch, D.N., Brönnimann, S., Burlando, P., Casanueva, A., Fatichi, S., Feigenwinter, I., Fischer, E.M., Hirschi, M., Liniger, M.A., Marty, C., Medhaug, I., Peleg, N., Pickl, M., Raible, C.C., Rajczak, J., Rössler, O., Scherrer, S.C., Schwierz, C., Seneviratne, S.I., Skelton, M., Sørland, S.L., Spirig, C., Tschurr, F., Zeder, J., Zubler, E.M., 2022. Climate scenarios for Switzerland CH2018 – approach and implications. Clim. Serv. 26, 100288. http://dx.doi.org/10.1016/j.cliser.2022.100288, URL https://www.sciencedirect.com/science/article/pii/S2405880722000061.

François, B., Vrac, M., Cannon, A.J., Robin, Y., Allard, D., 2020. Multivariate bias corrections of climate simulations: which benefits for which losses? Earth Syst. Dyn. 11 (2), 537–562. http://dx.doi.org/10.5194/esd-11-537-2020, URL https://esd.copernicus.org/articles/11/537/2020/, Publisher: Copernicus GmbH.

Frei, C., Willi, M., Stöckli, R., Dürr, B., 2015. Spatial analysis of sunshine duration in complex terrain by non-contemporaneous combination of station and satellite data. Int. J. Climatol. 35 (15), 4771–4790. http://dx.doi.org/10.1002/joc.4322, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.4322, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/joc.4322.

Gobiet, A., Suklitsch, M., Heinrich, G., 2015. The effect of empirical-statistical correction of intensity-dependent model errors on the temperature climate change signal. Hydrol. Earth Syst. Sci. 19 (10), 4055–4066. http://dx.doi.org/10.5194/hess-19-4055-2015, URL https://hess.copernicus.org/articles/19/4055/2015/, Publisher: Copernicus GmbH.

Gomis, M.I., Pidcock, R., 2022. IPCC visual style guide. URL https://www.ipcc.ch/site/assets/uploads/2022/09/IPCC_AR6_WGI_VisualStyleGuide_2022.pdf.

Gretter, A., Nikologianni, A., Betta, A., Lugli, L., Laiti, L., Barbiero, R., 2024. A multi-approach and collaborative pathway towards designing climate strategies: The case of trentino, a mountainous region in Italy. Sustainability 16 (10), 4198. http://dx.doi.org/10.3390/su16104198, URL https://www.mdpi.com/2071-1050/16/10/4198, Number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

Gutiérrez, J.M., Maraun, D., Widmann, M., Huth, R., Hertig, E., Benestad, R., Roessler, O., Wibig, J., Wilcke, R., Kotlarski, S., San Martín, D., Herrera, S., Bedia, J., Casanueva, A., Manzanas, R., Iturbide, M., Vrac, M., Dubrovsky, M., Ribalaygua, J., Pórtoles, J., Räty, O., Räisänen, J., Hingray, B., Raynaud, D., Casado, M.J., Ramos, P., Zerenner, T., Turco, M., Bosshard, T., Štěpánek, P., Bartholy, J., Pongracz, R., Keller, D.E., Fischer, A.M., Cardoso, R.M., Soares, P.M.M., Czernecki, B., Pagé, C., 2019. An intercomparison of a large ensemble of statistical downscaling methods over Europe: Results from the VALUE perfect predictor cross-validation experiment. Int. J. Climatol. 39 (9), 3750–3785. http://dx.doi.org/10.1002/joc.5462, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.5462, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/joc.5462.

Hiebl, J., Bourgeois, Q., Tilg, A.-M., Frei, C., 2024. Daily sunshine grids for Austria since 1961 – combining station and satellite observations for a multi-decadal climate-monitoring dataset. Theor. Appl. Climatol. 155 (8), 8337–8360. http://dx.doi.org/10.1007/s00704-024-05103-5.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., Steltzer, H., 2019. High mountain areas. In: Pörtner, H.-O., Roberts, D., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegrí a, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,

IPCC, 2019. Summary for policymakers. In: Pörtner, H.-O., Roberts, D., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegrí a, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. (in press).

IPCC, 2023. Climate Change 2023: Synthesis report. In: Core Writing Team, Lee, H., Romero, J. (Eds.), Contribution of Working Groups I, II and III To the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale, 2023. Climate change adaptation strategies and plans. URL https://va.mite.gov.it/en-GB/Oggetti/Documentazione/7726/11206?RaggruppamentoID=1044. (Accessed: 14 November 2025).

Iturbide, M., Casanueva, A., Bedia, J., Herrera, S., Milovac, J., Gutiérrez, J.M., 2022. On the need of bias adjustment for more plausible climate change projections of extreme heat. Atmospheric Sci. Lett. 23 (2), e1072. http://dx.doi.org/10.1002/asl.1072, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/asl.1072, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/asl.1072.

Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M., Benestad, R., Boberg, F., Buonomo, E., Cardoso, R.M., Casanueva, A., Christensen, O.B., Christensen, J.H., Coppola, E., De Cruz, L., Davin, E.L., Dobler, A., Domínguez, M., Fealy, R., Fernandez, J., Gaertner, M.A., García-Díez, M., Giorgi, F., Gobiet, A., Goergen, K., Gómez-Navarro, J.J., Alemán, J.J.G., Gutiérrez, C., Gutiérrez, J.M., Güttler, I., Haensler, A., Halenka, T., Jerez, S., Jiménez-Guerrero, P., Jones, R.G., Keuler, K., Kjellström, E., Knist, S., Kotlarski, S., Maraun, D., van Meijgaard, E., Mercogliano, P., Montávez, J.P., Navarra, A., Nikulin, G., de Noblet-Ducoudré, N., Panitz, H.-J., Pfeifer, S., Piazza, M., Pichelli, E., Pietikäinen, J.-P., Prein, A.F., Preuschmann, S., Rechid, D., Rockel, B., Romera, R., Sánchez, E., Sieck, K., Soares, P.M.M., Somot, S., Srnec, L., Sørland, S.L., Termonia, P., Truhetz, H., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2020. Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. Reg. Environ. Chang. 20 (2), 51. http://dx.doi.org/10.1007/s10113-020-01606-9.

Kuhn, M., Olefs, M., 2020. Elevation-dependent climate change in the European alps. In: Oxford Research Encyclopedia of Climate Science. Oxford University Press, http://dx.doi.org/10.1093/acrefore/9780190228620.013.762, URL https://oxfordre.com/climatescience/view/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-762.

Lucas-Picher, P., Argüeso, D., Brisson, E., Tramblay, Y., Berg, P., Lemonsu, A., Kotlarski, S., Caillaud, C., 2021. Convection-permitting modeling with regional climate models: Latest developments and next steps. WIREs Clim. Chang. 12 (6), e731. http://dx.doi.org/10.1002/wcc.731, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/wcc.731, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.731.

Maraun, D., 2016. Bias correcting climate change simulations - a critical review. Curr. Clim. Chang. Rep. 2 (4), 211–220. http://dx.doi.org/10.1007/s40641-016-0050-x.

Matiu, M., Napoli, A., Bellin, A., Zardi, D., Majone, B., 2025. Statistical downscaling of daily temperature and precipitation from regional climate models in complex mountain terrain. Int. J. Climatol. (in preparation).

Matiu, M., Napoli, A., Kotlarski, S., Zardi, D., Bellin, A., Majone, B., 2024. Elevation-dependent biases of raw and bias-adjusted EURO-CORDEX regional climate models in the European Alps. Clim. Dyn. http://dx.doi.org/10.1007/s00382-024-07376-y.

Matiu, M., Petitta, M., Notarnicola, C., Zebisch, M., 2020. Evaluating snow in EURO-CORDEX regional climate models with observations for the European alps: Biases and their relationship to orography, temperature, and precipitation mismatches. Atmosphere 11 (1), 46. http://dx.doi.org/10.3390/atmos11010046, URL https://www.mdpi.com/2073-4433/11/1/46.

Met Office Hadley Centre, 2018. UKCP18 regional projections on a 12km grid over the UK for 1980–2080. URL https://catalogue.ceda.ac.uk/uuid/589211abeb844070a95d061c8cc7f604/.

Ministero dell'Ambiente e della Sicurezza Energetica, 2023. Piano nazionale di adattamento ai cambiamenti climatici - (PNACC). URL https://va.mite.gov.it/en-GB/Oggetti/Documentazione/7726/11206?RaggruppamentoID=1044.

Napoli, A., Crespi, A., Ragone, F., Maugeri, M., Pasquero, C., 2019. Variability of orographic enhancement of precipitation in the Alpine region. Sci. Rep. 9 (1), 13352. http://dx.doi.org/10.1038/s41598-019-49974-5, URL https://www.nature.com/articles/s41598-019-49974-5, Publisher: Nature Publishing Group.

Napoli, A., Matiu, M., Laiti, L., Barbiero, R., Bellin, A., Zardi, D., Majone, B., 2025. Review on climate change impacts on the water-energy-food-ecosystems (WEFE) nexus in the north-eastern Italian alps. Clim. Change 178 (3), 41. http://dx.doi.org/10.1007/s10584-025-03890-y.

PAT, APRIE, 2022. Piano Energetico Ambientale Provinciale 2021–2030. URL https://www.provincia.tn.it/Documenti-e-dati/Documenti-di-programmazione/Piano-Energetico-Ambientale-Provinciale-2021-2030.

Pietrapertosa, F., Salvia, M., De Gregorio Hurtado, S., Geneletti, D., D'Alonzo, V., Reckien, D., 2021. Multi-level climate change planning: An analysis of the Italian case. J. Environ. Manag. 289, 112469. http://dx.doi.org/10.1016/j.jenvman.2021.112469, URL https://www.sciencedirect.com/science/article/pii/S0301479721005314.

PNACC, 2018. Piano Nazionale di Adattamento ai Cambiamenti Climatici. Technical Report, Ministero dell'ambiente e della tutela del territorio e del mare.

Raffa, M., Adinolfi, M., Reder, A., Marras, G.F., Mancini, M., Scipione, G., Santini, M., Mercogliano, P., 2023. Very High Resolution Projections over Italy under different CMIP5 IPCC scenarios. Sci. Data 10 (1), 238. http://dx.doi.org/10.1038/s41597-023-02144-9, URL https://www.nature.com/articles/s41597-023-02144-9, Number: 1 Publisher: Nature Publishing Group.

Rayner, T., Szulecki, K., Jordan, A.J., Oberthür, S., 2023. The global importance of EU climate policy: an introduction. In: Handbook on European Union Climate Change Policy and Politics. Edward Elgar Publishing, pp. 1–21, URL https://www.elgaronline.com/edcollchap-oa/book/9781789906981/book-part-9781789906981-11.xml, Section: Handbook on European Union Climate Change Policy and Politics,

Regione autonoma della Sardegna, 2024. Strategia regionale di adattamento ai cambiamenti climatici. URL https://portal.sardegnasira.it/web/sardegnaambiente/strategia-regionale-di-adattamento. (Accessed: 14 November 2025).

Regione Emilia Romagna, 2018. Integrating climate change adaptation processes at regional and local scales in Emilia-Romagna. URL https://ambiente.regione.emilia-romagna.it/it/cambiamenti-climatici/strategia-mitigazione-adattamento. (Accessed: 14 November 2025).

Regione Liguria, 2023. Strategia regionale di adattamento ai cambiamenti climatici. URL https://www.regione.liguria.it/homepage-ambiente/cosa-cerchi/sviluppo-sostenibile/strategia-adattamento-cambiamenti-climatici.html. (Accessed: 14 November 2025).

Robin, Y., Vrac, M., 2021. Is time a variable like the others in multivariate statistical downscaling and bias correction? Earth Syst. Dyn. 12 (4), 1253–1273. http://dx.doi.org/10.5194/esd-12-1253-2021, URL https://esd.copernicus.org/articles/12/1253/2021/, Publisher: Copernicus GmbH.

Rössler, O., Fischer, A.M., Huebener, H., Maraun, D., Benestad, R.E., Christodoulides, P., Soares, P.M.M., Cardoso, R.M., Pagé, C., Kanamaru, H., Kreienkamp, F., Vlachogiannis, D., 2019. Challenges to link climate change data provision and user needs: Perspective from the COST-action VALUE. Int. J. Climatol. 39 (9), 3704–3716. http://dx.doi.org/10.1002/joc.5060, URL https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.5060, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/joc.5060.

Schuster, R., Gregory, K., Möller, T., Koesten, L., 2024. "Being simple on complex issues" – accounts on visual data communication about climate change. IEEE Trans. Vis. Comput. Graphics 30 (9), 6598–6611. http://dx.doi.org/10.1109/TVCG.2024.3352282.

Soares, P.M.M., Careto, J.A.M., Cardoso, R.M., Goergen, K., Katragkou, E., Sobolowski, S., Coppola, E., Ban, N., Belušić, D., Berthou, S., Caillaud, C., Dobler, A., Hodnebrog, Ø., Kartsios, S., Lenderink, G., Lorenz, T., Milovac, J., Feldmann, H., Pichelli, E., Truhetz, H., Demory, M.E., de Vries, H., Warrach-Sagi, K., Keuler, K., Raffa, M., Tölle, M., Sieck, K., Bastin, S., 2024. The added value of km-scale simulations to describe temperature over complex orography: the CORDEX FPS-Convection multi-model ensemble runs over the Alps. Clim. Dyn. 62 (6), 4491–4514. http://dx.doi.org/10.1007/s00382-022-06593-7.

Tudoroiu, M., Eccel, E., Gioli, B., Gianelle, D., Schume, H., Genesio, L., Miglietta, F., 2016. Negative elevation-dependent warming trend in the Eastern Alps. Environ. Res. Lett. 11 (4), 044021. http://dx.doi.org/10.1088/1748-9326/11/4/044021.

van der Wiel, K., Beersma, J., van den Brink, H., Krikken, F., Selten, F., Severijns, C., Sterl, A., van Meijgaard, E., Reerink, T., van Dorland, R., 2024. KNMI'23 climate scenarios for the netherlands: Storyline scenarios of regional climate change. Earth's Futur. 12 (2), e2023EF003983. http://dx.doi.org/10.1029/2023EF003983, URL https://onlinelibrary.wiley.com/doi/abs/10.1029/2023EF003983, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2023EF003983.

Vautard, R., Kadygrov, N., Iles, C., Boberg, F., Buonomo, E., Bülow, K., Coppola, E., Corre, L., van Meijgaard, E., Nogherotto, R., Sandstad, M., Schwingshackl, C., Somot, S., Aalbers, E., Christensen, O.B., Ciarlo, J.M., Demory, M.-E., Giorgi, F., Jacob, D., Jones, R.G., Keuler, K., Kjellström, E., Lenderink, G., Levavasseur, G., Nikulin, G., Sillmann, J., Solidoro, C., Sørland, S.L., Steger, C., Teichmann, C., Warrach-Sagi, K., Wulfmeyer, V., 2021. Evaluation of the large EURO-CORDEX regional climate model ensemble. J. Geophys. Res.: Atmospheres 126 (17), e2019JD032344. http://dx.doi.org/10.1029/2019JD032344, URL https://onlinelibrary.wiley.com/doi/abs/10.1029/2019JD032344. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2019JD032344.

Wang, F., Hannafin, M.J., 2005. Design-based research and technology-enhanced learning environments. Educ. Technol. Res. Dev. 53 (4), 5–23.

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3 (1), 160018. http://dx.doi.org/10.1038/sdata.2016.18, URL https://www.nature.com/articles/sdata201618, Number: 1 Publisher: Nature Publishing Group.

Yang, W., Andréasson, J., Phil Graham, L., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. Hydrol. Res. 41 (3–4), 211–229. http://dx.doi.org/10.2166/nh.2010.004.

Zebisch, M., Schneiderbauer, S., Fritzsche, K., Bubeck, P., Kienberger, S., Kahlenborn, W., Schwan, S., Below, T., 2021. The vulnerability sourcebook and climate impact chains – a standardised framework for a climate vulnerability and risk assessment. Int. J. Clim. Chang. Strat. Manag. 13 (1), 35–59. http://dx.doi.org/10.1108/IJCCSM-07-2019-0042, URL https://www.emerald.com/insight/content/doi/10.1108/ijccsm-07-2019-0042/full/html, Publisher: Emerald Publishing Limited.

Zebisch, M., Vaccaro, R., Niedrist, G., Schneiderbauer, S., Streifeneder, T.P., Weiß, M.L., Troi, A., Renner, K., Pedoth, L., Baumgartner, B., Bergonzi, V., 2018. Rapporto sul clima Alto Adige 2018. Technical Report, Eurac Research, Bolzano.

Zubler, E.M., Scherrer, S.C., Croci-Maspoli, M., Liniger, M.A., Appenzeller, C., 2014. Key climate indices in Switzerland; expected changes in a future climate. Clim. Change 123 (2), 255–271. http://dx.doi.org/10.1007/s10584-013-1041-8.