Bridging Climate Information and Stakeholder Decisions: A Co-Design Approach for Regional Climate Change Adaptation

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ABSTRACT

Climate change poses a significant threat to communities at both regional and global scales, with adaptation being particularly urgent for small- and medium-sized communities. However, a persistent knowledge gap limits their capacity to adapt effectively. The lack of accessible, tailored climate information and services further increases vulnerability. This study therefore aims to address this gap by developing effective science communication strategies using a co-design approach, with a focus on the regional scale through the implementation of Regional Climate Information Platforms. The selected case study area, Oberland (Upper Bavaria, Germany), is characterized by complex terrain encompassing Alpine and Pre-Alpine regions, where three distinct climate zones occur in close proximity. This diverse topography presents specific challenges, as climate change impacts may vary spatially, particularly with regard to hydro-meteorological extremes. In addition, the region is highly dependent on tourism, rendering it economically sensitive to changing climate conditions and increasing extreme events such as heavy precipitation, flooding, summer heatwaves, and decreasing snowfall affecting tourism-related activities. The study follows a comprehensive workflow, beginning with the identification of stakeholder needs and followed by the analysis of relevant climate information. The resulting climate information on hydro-meteorological extremes will provide essential input for stakeholders and decision-makers. These results will be visualized as maps and integrated into the digital decision support system Platform Oberland within the KARE (Klimawandelanpassung auf regionaler Ebene) project. Beyond its scientific objectives, the study emphasizes stakeholder interaction and co-design to ensure the relevance and usability of the generated information. Furthermore, it aims to identify best-practice approaches for translating scientific workflows and results into actionable climate adaptation measures for small- and medium-sized communities. The case study may serve as a regional model for effective science communication and adaptation strategies addressing hydro-meteorological extremes.

KEYWORDS: Climate information, science communication, co-design, floods, extreme heat

1 INTRODUCTION

In recent decades, there has been a significant advancement in scientific understanding of climate change and its regional impacts, in parallel with technological and computational developments (Pan et al., 2022), (Karetnikov and Ruth, 2014), (IPCC, 2023). Despite the increasing body of knowledge, a persistent gap remains between climate research and its effective application in policy and decision making, particularly among small and medium-sized communities (Selseng and Gjertsen, 2024), (Fünfgeld et al., 2023), (Ricciardi et al., 2023), (Buschmann et al., 2022), (Fila et al., 2024). Key barriers include the disconnect between researchers and policymakers (Thompson et al., 2017), (Briley et al., 2015), the limited accessibility and relevance of climate information, institutional and financial constraints (Fila et al., 2024), and the lack of participatory processes that involve local stakeholders in the design and implementation of adaptation measures (Ricciardi et al., 2023), (Jones et al., 2017), (Thompson et al., 2017). Although small and medium-sized municipalities are not less affected by climate change, they are underrepresented in research, in contrast to larger cities and metropolitan areas (Ricciardi et al., 2023). In particular, the gap between the production of climate information and how it is used in the real world is a major challenge in developing resilient and inclusive climate adaptation strategies (Mabon, 2020), (Lemos and Rood, 2010). Local and regional stakeholders often find it difficult to incorporate scientific climate information into their planning and decision-making processes. This difficulty arises from several interrelated factors. Firstly, climate information is often presented in formats that are too technical or abstract for non-experts to interpret and apply directly (Mabon, 2020), (Briley et al., 2015). The use of specialized indices, probabilistic language, and complex visualizations can lead to confusion or underestimate of climate risks. Secondly, the relevance of the information is not always clear as scientific studies often focus on broad or global scales, whereas local stakeholders require insights that are tailored to their specific context (Briley et al., 2015), (Roberts et al., 2018). Third, the channels through which climate knowledge is communicated may not align with local actors' information seeking behaviours (Thompson et al., 2017), (Briley et al., 2015), further reducing the likelihood that available information will influence local decision-making (Jones et al., 2017), (Lemos and Rood, 2010). These challenges have highlighted the need for easy-to-use and decision-relevant climate information, which could also help bridging the gap between scientific production and practical application.

In order to enhance access to climate data and support adaptation planning, a number national and regional institutions in Germany have developed climate information platforms and services. At the national level, institutions such as the Deutscher Wetterdienst (DWD, 2025a), the Climate Service Center Germany (GERICS, 2025) and the German Environment Agency (UBA, 2025a) provide essential climate datasets, projections, and adaptation tools. These services are underpinned by high-resolution observational data and downscaled climate projections derived from international ensembles such as EURO-CORDEX (UBA, 2025b). The Climate Data Center (CDC) of DWD (DWD, 2025b), for instance, supplies gridded climate variables, while GERICS supports decision-making in sectors such as urban planning through tailored regional scenarios and vulnerability assessments (GERICS, 2025a; 2025b). At federal state level, Bavaria has developed its own specialised services to address the impacts of climate change at a more localised level. The Bavarian Climate Information System (BAYKIS), which is operated by the Bayerisches Landesamt für Umwelt (LfU), provides downscaled climate projections and impact indicators via a central platform (LFU, 2025). These datasets are statistically refined using outputs from the EURO-CORDEX regional climate model, DWD observations and LfU post-processing techniques. The LfU's portal also disseminates complementary tools, such as municipal climate checks and adaptation guidelines, facilitating the integration of climate considerations into local and regional governance structures (LFU, 2025). In addition to these services, several regional initiatives based on different research projects provide place-based climate information tailored to urban and sub-regional contexts for different federal states in Germany (i.e. KliVO Portal Hessen, Klimaatlas BW, Umweltatlas Berlin, etc.) (UBA, 2025c; LUBW, 2025, Landes Berlin, 2025). ReKIS (Regionales Klimainformationssystem), for example, is a regional climate information platform providing climate information to the eastern German states of Saxony, Saxony-Anhalt and Thuringia (REKIS, 2025). It provides high-resolution climate data and projections related to extreme weather events and long-term trends, as well as indicators. Similarly, The NRW Climate Atlas (Klimaatlas Nordrhein-Westfalen) provides regional climate change projections with a focus on temperature, precipitation, and extreme events across North Rhine-Westphalia Landesamt für Natur, Umwelt und Klima Nordrhein-Westfalen (LANUK, 2025).

Despite the wide range of climate information platforms and services available in Germany, they remain limited in their practical applicability for small and medium-sized communities. The multitude of providers, diverse data formats and differing methodological assumptions and time periods often cause confusion which pose challenges for non-specialist users in local administrations. Furthermore, while many existing services rely on downscaled regional climate projections with different ensembles, these are often insufficiently detailed to capture local extreme events and locally relevant impacts, which are critical for municipal-level adaptation planning. Therefore, this study aims to address these limitations using NUKLEUS - Nutzbare lokale Klimainformationen für Deutschland, high-resolution, user-oriented climate information specifically tailored to the needs collected during the transfer meetings of medium- and small-sized communities. By bridging the gap between national and regional climate services and local decision-making requirements, the study aims to make climate data easily understandable, more usable, and relevant to effective, place-based adaptation planning.

2 STUDY AREA, DATA & METHODS

2.1 Study Area

The study area, Oberland, is located in the southern German province of Upper Bavaria, which is characterised by the presence of three distinct climate zones within the Alpine foreland. The area is renowned for its high level of tourism (for example, ski tourism) and is economically dependent on tourism due to its scenic landscape. Moreover, the region is considered to be one of the most economically dynamic areas in the country. However, the region is also known for its frequency of extreme convective precipitation events, which have been responsible for numerous floods in the past. Climate predictions indicate a continuation of the observed trend of rising event frequency, suggesting that the impacts of climate change are already evident and are expected to intensify further in the region.

2.2 Data

The NUKLEUS dataset is a comprehensive, high-resolution ensemble of regional climate model simulations developed within the "NUKLEUS - Nutzbare Lokale Klimainformationen für Deutschland" project, a cross-cutting activity of the RegIKlim research initiative. The core objective of NUKLEUS is to generate, evaluate, and provision spatially and temporally refined climate information tailored to regional climate impact assessments, adaptation planning, and climate service applications for Germany. The dataset under consideration comprises dynamically downscaled climate projections derived from multiple combinations of global climate models (GCMs) and regional climate models (RCMs). Initially, three CMIP6 GCMs (e.g., EC-EARTH3-Veg, MIROC6, MPI-ESM1-2-HR) are downscaled to an intermediate European grid (EUR-11, ~12 km), and subsequently to a convection-permitting scale (~3 km; CEU-3) over Germany via RCMs including COSMO-CLM, ICON-CLM, and REMO. The simulation types include evaluation runs against ERA5 reanalysis, historical runs, and future transient scenario projections under standardized SSP forcing pathways (NUKLEUS, 2025).

For the analysis of this study, ICON-CLM, EC-EARTH3-Veg, CEU-3 simulations were used due to the availability of three different future transient scenario projections under standardized SSP forcing pathways (SSP2-4.5, SSP3-7.0, SSP8-5.5) under two different global warming levels (GWL) (GWL2K, GWL 3K).

2.3 Method

Global warming, driven primarily by anthropogenic greenhouse gas emissions, exerts profound influences on regional climate dynamics through changes in key meteorological and hydrological variables. To assess these impacts and evaluate the associated risks to small- and medium-sized communities that are often characterized by limited adaptive capacity, resource constraints, and strong dependence on local ecosystems, it is essential to examine variations in air temperature, precipitation, and snow depth, which serve as fundamental indicators of regional climate change. Air temperature is a primary metric due to its direct link to the enhanced greenhouse effect, whereby increased atmospheric concentrations of greenhouse gases trap outgoing longwave radiation and raise surface temperatures. At the regional scale, this manifests as amplified warming trends, including more frequent and intense heatwaves. For small- and medium-sized communities, which often lack robust cooling infrastructure or diversified economic structures, such warming poses significant risks, including increased heat-related mortality, reduced agricultural productivity through altered growing seasons, and higher energy demand for cooling. Precipitation represents another critical climate variable, as global warming intensifies the hydrological cycle. Warmer air masses can hold more moisture, leading to shifts toward more extreme precipitation regimes—characterized by heavier rainfall events in some regions and prolonged droughts in others. These changes affect water availability, flood frequency, and soil moisture, with cascading impacts on food security, infrastructure resilience, and public health. Small- and medium-sized communities are particularly vulnerable due to their reliance on rain-fed agriculture and local water resources. For example, increased flood frequency can overwhelm drainage systems and cause urban flooding, while drought conditions may lead to water scarcity that directly constrains agricultural and domestic water use. Snow depth, particularly in the Alpin region, provides insights into cryospheric responses to warming, including accelerated snowmelt and reduced accumulation. Global warming diminishes snowpack through elevated freezing levels and earlier spring thaw, altering seasonal hydrology and water storage. In addition, reduced snow cover affects winter economies (e.g., tourism) and ecosystems, potentially triggering feedback loops such as albedo reduction that further amplify regional warming.

Apart from the changes in the average annual temperature, precipitation, and winter average snow depth, we focus on the occurrence of extreme events, including yearly extreme heat days, heatwaves, heavy rain days, and snow days. Extreme heat days are defined as those days with daily maximum temperature exceeding 30°C. A heatwave event is defined as at least consecutive 3 days with daily mean temperature exceeding 95% of the historical reference temperature derived using CEU-3 output. Heavy rain days and snow days are defined as those days with precipitation exceeding 30 mm and with snow depth exceeding 1 cm, respectively.

The indicators and the final output formats were determined based on the results of a mini survey titled 'Climate Information Requests and Data Formats' that was conducted with all stakeholders in the project area during a project meeting on 20 June 2024. The research questions were then determined in line with this using a co-design approach.

3 RESULTS

The future climate projections for the Oberland region were evaluated under multiple SSP (SSP245, SSP370, and SSP585) and at two GWLs, +2K and +3K relative to pre-industrial conditions. Accordingly, annual mean temperature shows a linear and consistent increase across all SSP scenarios as the level of global warming increases; for example, in the SSP245 scenario, increases at low warming levels remain around +1.4°C (+3K), while in the SSP585 scenario, this increase exceeds +4 °C at high warming levels (+3K) (Table 1). Maximum temperatures and hot extremes respond more strongly than the average; increases in the number of hot days reach 12 days average in the high emissions scenario. In contrast, with the increase in minimum temperatures, cold extremes are decreasing significantly; for example, the number of cold days or cold nights decreases by a few days per year even at low warming levels, and by more than 20 days at high warming levels (SSP585, +3K) (Table 1).

The precipitation analysis based on NUKLEUS projections for Oberland shows that, annual total precipitation increases in relative terms across all SSPs and warming levels. We can see the strongest relative increase for SSP370 reaching up to %10.5 (+2K) and %5.5 (+3K), but with a large inter-model spread (up to %40, +3K) (Table 1). When we look at the seasonal precipitation changes, we can see that spring and autumn mean precipitation have a constant increase up to %25 (SSP245, +3K), where the change in autumn has high variability. The results for winter and summer precipitation values give more mixed responses and highly uncertain. Mean precipitation in winter decreases under SSP245 (%12.6, +2K), where it has near neutral changes for SSP370, and has a consistent decrease under SSP585. For summer, mean changes are comparatively small or negative for SSP245 and SSP585, where they are positive for SSP370 scenario (Table 1). Large min-max ranges (up to %70) shows high uncertainty and indicate strong model disagreement.

Table 1. Changes of climate indicators in Oberland region based on NUKLEUS data (ICON-CLM, EC-EARTH3-Veg, CEU-3)

	Historical	SSP245						SSP370						SSP585					
		GWL-2K			GWL-3K			GWL-2K			GWL-3K			GWL-2K			GWL-3K		
	Mean	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Annual Mean Temperature (°C)	6.82	1.93	0.9	3.02	2.85	1.39	4.02	1.77	0.26	3.74	3.07	0.63	4.58	1.94	0.64	3	3.41	1.97	4.95
Winter (DJF) Mean Temperature (°C)	-1.41	2.42	0.79	5.38	2.77	-0.39	4.81	1.89	-1.5	4.2	3.07	0.76	5.46	2.4	0.24	4.47	3.6	0.95	6.18
Spring (MAM) Mean Temperature (°C)	6.26	1.12	-2.46	3.23	1.73	-1.24	3.56	1.14	-3.11	4.3	2.43	-1.22	4.53	1.33	-0.73	3.75	2.62	-0.27	5.63
Summer (JJA) Mean Temperature (°C)	14.83	2.39	0.34	4.78	3.84	1.9	6.03	2.22	-0.05	4.86	3.87	1.61	6.03	1.9	0.37	4.04	3.93	1.1	7.07
Autumn (SON) Mean Temperature (°C)	7.44	1.79	0.34	4.78	3.05	1.9	6.03	1.84	-0.05	4.86	2.92	1.61	6.03	2.11	0.37	4.04	3.5	1.1	7.07
Number of Summer Days (Tmax > 25°C) per Year	16.03	15.47	-0.03	40.97	29.17	4.97	65.97	15.43	-4.03	47.97	28.87	1.97	65.97	11.67	-6.03	38.97	31.9	8.97	77.97
Number of Heat Days (Tmax > 30 °C) per Year	1.03	3.6	-16.03	6.97	10.3	-14.03	18.97	4.03	-16.03	8.97	9.3	-15.03	10.97	3.3	-16.03	-2.03	12.1	-15.03	29.97
Number of Tropical Nights (Tmin > 20°C) per Year	0	0.1	-16.03	-14.03	1.13	-16.03	-7.03	0.4	-16.03	-12.03	1.2	-16.03	-9.03	0.13	-16.03	-14.03	2.07	-16.03	-4.03
Number of Heatwaves per Year	7.73	-0.8	-13.03	-0.03	-0.77	-13.03	-5.03	-0.07	-11.03	-5.03	-1.13	-13.03	-6.03	-0.9	-12.03	-2.03	-0.43	-12.03	-1.03
Number of Cold Days per Year	20.67	22.53	9.97	49.97	40.37	19.97	76.97	22.07	2.97	52.97	40.97	16.97	85.97	18.33	0.97	45.97	42.6	18.97	84.97
Number of Heating Days (Tmean > 15°C) per Year	309.1	-32.1	228.97	287.97	-50.87	223.97	265.97	-29.7	230.97	287.97	-53.4	205.97	272.97	-29.4	231.97	299.97	-54.97	193.97	271.97
Number of Frost Days (Tmin < 0°C) per Year	124.17	-27.7	45.97	116.97	-40.67	31.97	94.97	-26.6	47.97	122.97	-46.87	29.97	122.97	-29.6	34.97	100.97	-52.67	17.97	90.97
Number of Ice Days (Tmax < 0°C) per Year	35.97	-16.63	-15.03	30.97	-19.9	-15.03	25.97	-12.17	-9.03	45.97	-20.3	-13.03	16.97	-16.67	-12.03	24.97	-24.37	-13.03	19.97
Annual Total Precipitation	1511.96 mm	4.62%	-22.99%	25.80%	6.55%	-30.88%	32.53%	10.53%	-14.51%	36.77%	5.49%	-20.94%	43.97%	5.51%	-25.13%	31.80%	2.06%	-17.96%	33.25%
Winter (DJF)Total Precipitation	353.03 mm	-12.61%	-60.45%	39.17%	-2.12%	-47.58%	85.70%	0.81%	-55.67%	74.32%	-0.64%	-52.26%	71.23%	-9.26%	-50.22%	32.04%	-4.41%	-48.94%	32.05%
Spring (MAM)Total Precipitation	378.72 mm	16.11%	-21.51%	73.46%	25.03%	-26.40%	77.96%	15.95%	-42.89%	77.75%	15.54%	-32.72%	47.84%	12.17%	-34.41%	68.85%	9.68%	-44.35%	59.65%
Summer (JJA)Total Precipitation	475.99 mm	-1.24%	-34.98%	55.23%	-9.21%	-47.25%	37.42%	9.84%	-45.68%	66.96%	1.18%	-44.00%	72.31%	3.38%	-50.62%	53.28%	-7.86%	-56.55%	44.03%
Autumn (SON)Total Precipitation	304.22 mm	19.49%	-51.63%	96.39%	18.26%	-43.00%	116.13%	16.11%	-59.33%	76.59%	6.84%	-57.05%	99.91%	17.69%	-29.93%	96.44%	15.63%	-33.72%	92.66%
Before Growing Season Total Precipitation	445.16 mm	8.22%	-27.46%	33.56%	13.33%	-28.01%	64.75%	18.87%	-21.54%	65.23%	15.99%	-18.81%	54.16%	9.76%	-25.62%	61.92%	5.16%	-55.14%	76.28%
After Growing Season Total Precipitation	415.63 mm	4.03%	-52.74%	62.72%	-7.80%	-63.02%	48.96%	9.86%	-35.69%	62.75%	-4.00%	-68.60%	37.43%	3.16%	-53.54%	49.63%	-8.66%	-57.61%	49.61%
Number of Heavy Rain Days per Year	3.3	2.1	-3.3	7.7	2.2	-2.3	6.7	2.77	-1.3	6.7	1.4	-2.3	7.7	2.2	-2.3	6.7	1.9	-3.3	5.7
Number of Dry Days per Year	6.23	0.23	-2.23	4.77	1.3	-2.23	6.77	-0.2	-5.23	5.77	0.43	-4.23	3.77	0.43	-3.23	5.77	0.87	-3.23	3.77
Number of Dry Days Before Growing Season per Year	0.67	-0.03	-0.67	2.33	0.4	-0.67	2.33	-0.23	-0.67	1.33	0.03	-0.67	1.33	0.3	-0.67	3.33	0.57	-0.67	2.33
Number of Dry Days After Growing Season per Year	1.67	-0.1	-1.67	2.33	0.9	-0.67	3.33	-0.03	-1.67	2.33	0.3	-1.67	2.33	0.17	-1.67	1.33	0.4	-1.67	3.33
Number of Wet Days per Year	0.83	0.07	-0.83	3.17	0.47	-0.83	3.17	0.3	-0.83	2.17	0.17	-0.83	1.17	-0.13	-0.83	2.17	0.23	-0.83	4.17
Number of Wet Days Before Growing Season per Year	0.27	-0.07	-0.27	1.73	0.37	-0.27	1.73	0.27	-0.27	2.73	0.13	-0.27	0.73	0.03	-0.27	1.73	0.17	-0.27	2.73
Number of Wet Days After Growing Season per Year	0.33	0.03	-0.33	1.67	0.07	-0.33	1.67	0.07	-0.33	1.67	-0.03	-0.33	1.67	-0.07	-0.33	0.67	-0.03	-0.33	1.67
Mean Snow Depth (cm)	21.96	-12.81	-82.7	12.28	-13.27	-89.63	4.43	-10.02	-88.29	40.92	-11.41	-88.69	35.81	-12.08	-90.34	3.78	-15.77	-90.41	-43.49
Number of Snow Days per Year	87.77	-7.6	-26.77	3.23	-8.03	-32.77	3.23	-6.53	-26.77	3.23	-15	-45.77	2.23	-6.47	-48.77	3.23	-17.47	-48.77	3.23
Number of Heavy Snow Days per Year	23.6	-20.73	-23.6	2.4	-20	-23.6	14.4	-15.6	-23.6	28.4	-15.33	-23.6	22.4	-19.97	-23.6	8.4	-23.2	-23.6	-20.6
Number of Snowstorm Days per Year	2.07	0.33	-1.07	2.93	0.03	-2.07	1.93	0.1	-2.07	2.93	-0.33	-2.07	1.93	0.33	-2.07	2.93	0.6	-1.07	3.93

When we look at the extremes, heavy rain days increase robustly across all SSPs. Number of heavy precipitation days increase of 2-3 days per year in average, with maxima up to 7.7 days. This situation might indicate the intensification of extreme precipitation, even where total rainfall changes are moderate. When we analyse the changes in number of dry days, we see slight increases in total dry days especially under SSP245, +3K (6.7 days). However, seasonally change in number of dry days shows high variability but no strong systematic trend (Table 1). Number of wet days have positive changes in overall (< 0.5 days per year) suggesting that increased precipitation is driven more by intensity than frequency.

In addition to changes in temperature and precipitation, projected warming also affects snow-related variables. Winter snow conditions are projected to decrease under all warming levels and emission scenarios. Mean snow depth is reduced by about 10–16 cm on average, with mean changes ranging from −12.8 to −15.8 cm across scenarios and warming levels, and with some model projections showing much larger reductions, indicating that seasonal snow cover could become very limited under warmer conditions. The number of snow days per year also becomes lower, with mean reductions of about −6 to −17 days per year, corresponding to losses of approximately 7 to 17 snow days per year compared to the historical period. Heavy snow days show the strongest response, with average reductions of roughly −15 to −21 days, and some projections suggesting the complete loss of heavy snowfall events (Table 1). In contrast, changes in the number of snowstorm days are small, with mean changes between 0 and +0.6 day and a wide uncertainty range, indicating that snowstorms may still occur but will contribute less to overall snow accumulation.

Overall, the results show that the Oberland region will become steadily warmer, with more frequent heat extremes, heavier rainfall events, and a strong decline in snow cover, while seasonal precipitation changes remain uncertain, highlighting increasing climate-related challenges under higher warming levels and emission scenarios.

4 DISCUSSION

The projections indicate that rising temperatures, together with changing precipitation patterns, lead to more frequent heat extremes, stronger rainfall intensity, and substantially weaker snow conditions under future warming. A shift toward more intense but less evenly distributed precipitation, characterized by wetter springs and autumns, uncertain summers, and more frequent heavy rainfall events, particularly under intermediate to high forcing scenarios. This pattern suggests enhanced precipitation intensity and seasonality rather than uniform wetting, increasing the likelihood of hydrological extremes such as flooding and seasonal water stress, especially during and after the growing season. These conditions are significant for this region, which currently experiences heavy rainfall and has suffered flooding on numerous occasions. In parallel with the expected increase in rainfall intensity, short-term extreme rainfall, combined with the topography of this region at the foothills of the Alps, makes it more prone to flooding.

The analysis also shows that a systematic decline in snow accumulation, duration, and intensity, with snow depth and heavy snowfall being particularly sensitive to warming. While isolated snowstorm events may persist, the overall snow regime shifts toward shallower, shorter-lived, and less intense snow conditions, especially under higher warming levels. These conditions could pose a long-term risk for the local population, which is particularly dependent on ski tourism during the ski season in the region.

On the other hand, the results show that model uncertainty differs between variables and generally becomes larger at higher warming levels. Changes in annual and seasonal mean temperature are consistent across models, indicating good agreement on the overall warming trend. In contrast, temperature extremes, such as the number of summer days, heat days, and tropical nights, show a much wider range of projections, reflecting higher uncertainty. Precipitation changes are more uncertain, especially at the seasonal scale, where models project both strong increases and decreases, leading to low confidence in the direction of change. Precipitation extremes, represented by the number of heavy rain days, are more consistent across models and point to an increase in rainfall intensity. Snow-related variables show the highest uncertainty, with very large reductions in some projections and smaller changes in others, reflecting the strong sensitivity of snow to temperature. Overall, while the warming trend is robust, the size of changes in precipitation and snow becomes increasingly uncertain at higher warming levels. Climate indices obtained through NUKLEUS simulations provide information about the region's future. However, since these results are model-dependent, any uncertainty should also be taken into account when communicating with stakeholders.

In order to improve the practical use of the presented indicators for decision-making purposes, it is also crucial to explicitly link projected climate changes with sector-specific adaptation measures. Despite uncertainties mentioned above in seasonal mean precipitation, the robust increase in heavy precipitation days suggests an intensification of short-duration rainfall events. For the Oberland region, which is characterised by complex topography and documented flood exposure, this translates into heightened risk of flash flooding and pluvial flooding. Adaptation responses should therefore prioritise the creation of flood retention areas, the enhancement of drainage infrastructure, the implementation of nature-based solutions and the improved integration of early warning systems into municipal planning tools. Similarly, the projected increase in extreme heat days and heatwave frequency implies elevated risks of heat stress, particularly for vulnerable populations (such as kids or elderly people) and outdoor workers. Municipal adaptation strategies may therefore include developing heat action plans, expanding urban green infrastructure to mitigate the urban heat island effect, integrating cooling centres into emergency planning and incorporating passive cooling standards into building regulations considering the vulnerable groups and climate information together. The projected decline in snow depth and days under all warming levels has significant implications for winter tourism, a key economic pillar of the region. Therefore, adaptation strategies may involve diversifying towards year-round tourism concepts, investing in climate-resilient infrastructure, and engaging in strategic economic planning to reduce dependence on snow-reliant activities. By linking quantified climate indicators into clearly defined risk factors and adaptation options, the study could help to provide more relevant information on regional scale for municipal authorities.

5 CONCLUSION & OUTLOOK

This study demonstrates the added value of combining high-resolution regional climate modelling in the region for the first time using the NUKLEUS dataset with a co-design approach to support climate change adaptation at regional and municipal levels. The analysis of the Oberland region as a case study reveals robust warming trends, an obvious increase in heat extremes and heavy precipitation events, and a significant decrease in snow depth and days with snow under all considered warming levels and emission scenarios. These changes highlight an increasing risk of heat stress, flooding, issues with water management and problems with winter tourism. This is particularly relevant for small and medium-sized communities with limited adaptive capacity and a strong dependence on local environmental conditions.

The results provide climate information that is relevant for decision-making and can directly support stakeholders and policymakers in regional planning and adaptation processes. By translating complex climate projections into specific indicators, such as the number of days with extreme heat, heavy precipitation, and snow-related metrics, the study enables an assessment of climate risks and supports the prioritization of adaptation measures in sectors such as disaster risk management, infrastructure planning, tourism, and land use. The co-design process ensures that the selected indicators and data formats align with stakeholder needs, thereby increasing their usability and trustworthiness and the likelihood of their integration into practical decision-making processes.

As a next step, the derived climate indicators will be visualized in the form of maps and to integrate them into the digital decision-support system within the KARE project. Beyond the regional scale, the methodology and results will be transferred and upscaled to the federal state level of Bavaria, and then to the national level in Germany. The objective is to ensure consistency across governance levels while preserving regional characteristics, thereby contributing to a more consistent and applicable climate information framework. Conducting this analysis will also facilitate the comparison of those previously conducted at national and federal state levels with analyses using NUKLEUS data, thereby providing a comparative overview. This approach can provide a transferable example for strengthening the interface between science and policy and for improving climate adaptation planning in regions with diverse climatic and socio-economic conditions.

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Author contributions

GK: Funding acquisition, conceptualization, methodology, writing - original draft, writing - review and editing.

CL: Methodology; formal analysis; writing – review and editing.

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