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RESEARCH

Aligning local adaptation needs with ETCCDI indices in Freudenstadt, a German municipality

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Abstract

German municipalities are facing increasing challenges in terms of climate adaptation, not least because complex climate information is often difficult to translate into locally actionable knowledge. Although climate indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) provide a standardized and widely used framework for describing climate variability, they are originally defined primarily from a scientific perspective and may therefore not fully reflect local information needs. This study reverses the conventional workflow, using practitioners' perspectives as the starting point for selecting and interpreting indices. The municipality of Freudenstadt in Germany was used as a case study. Semi-structured interviews with municipal departments identified locally relevant climate-related impacts and opportunities, guiding the targeted selection of four ETCCDI indices capturing heavy precipitation, reduced snow, heat, and drought. These indices were calculated at district level using high-resolution regional climate model simulations with a resolution of 2.8 km for the period 1991–2020 and + 3 K global warming level. The results indicate an increase in heat and drought stress in the more densely populated eastern parts of the district, alongside with less frost and more frequent heavy precipitation events in mountainous areas. The experience-driven selection of high-resolution indices aligns with the perceptions of practitioners and provides a shared baseline to support dialogue and comparable adaptation planning. However, some planning-relevant climatic conditions are not fully captured by ETCCDI indices, suggesting the value of complementing them with tailored indices for a more comprehensive local assessment.

Keywords ETCCDI climate indices · Local knowledge · Municipal climate adaptation · Regional climate impacts · Regional climate modeling

Introduction

Global climate change has far-reaching regional and local consequences (Intergovernmental Panel On Climate Change 2023). In Central Europe, for example, the frequency and intensity of heatwaves have increased over the past two decades (Russo et al. 2014; Barriopedro et al. 2011), posing serious threats to the economy, ecosystems, and human health (Knutzen et al. 2025; Rousi et al. 2023; Poumadère et al. 2005). This is particularly the case in the Upper Rhine Valley, which is a heat hot spot in Germany (Winklmayer et al. 2023; Scholze et al. 2023). Across Europe, flash floods have more than doubled since the late 1980 s (EASAC 2018), leading to severe damage to infrastructure, economic losses, and fatalities (Meyer et al. 2022; WMO 2017). One of the most devastating recent events occurred in Germany's Ahr Valley in July 2021 (Mohr et al. 2023; Ludwig et al. 2023; Kahle et al. 2022),

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resulting in over 135 deaths and tens of billions of euros in economic losses (UN 2022). To minimize regional risks and protect ecosystems, economies, and communities, climate change adaptation has therefore become a key strategy. Timely and targeted adaptation can reduce damage and provide additional benefits, such as improvements to public health (Sharifi et al. 2021), integration into urban planning (Huber and Dunst 2021), and transformation within companies (Scholze et al. 2023).

Local governments play a central role in implementing these measures (Hackenbruch et al. 2017), as they manage key public services and infrastructure (Umweltbundesamt 2022). However, many municipalities face substantial constraints. A survey by the German Federal Environment Agency showed that 17% of the 1062 municipalities surveyed had researched adaptation measures but had not taken action. This proportion was higher among municipal associations (19%) and municipalities with fewer than 20,000 residents (22%). Smaller municipalities often lag behind larger ones (Umweltbundesamt 2024) due to economic, political, and structural barriers within a complex multilevel governance system (Fila et al. 2023; Fünfgeld et al. 2023; Lehmann et al. 2015; CorfeeMorlot et al. 2011; Measham et al. 2011). Common obstacles include limited staff capacity, financial constraints (Umweltbundesamt 2024; Hackenbruch et al. 2017), as well as information deficits (Lehmann et al. 2015). Scientific climate information can be difficult to interpret at the municipal level (Hackenbruch et al. 2017) and can also be financially inaccessible to smaller administrations (Fünfgeld et al. 2023).

Much of the climate information is still communicated in terms of standard meteorological parameters, such as temperature, precipitation, and wind. This can be difficult for decision makers to translate into locally actionable knowledge (Hackenbruch et al. 2017). Climate indices offer one way to enhance practical relevance (Schipper et al. 2019). These translate meteorological data into threshold-based indicators that capture specific climate characteristics. The Expert Team on Climate Change Detection and Indices (ETCCDI), established by the WMO and the WCRP, has defined 27 such indices to support global and regional analyses of climate extremes (Yin and Sun 2018; Karl et al. 1999). Since their introduction, ETCCDI indices have been widely used in regional climate impact, adaptation, and risk studies (Riach et al. 2023; Nugroho et al. 2023; Chervenkov and Slavov 2021; Gebrechorkos et al. 2019; Yin and Sun 2018; Zhang et al. 2011). In Germany, public institutions assess and provide several indices to support adaptation planning in national, regional, and sectoral contexts (e.g., KLIWAS, https://www.kliwas.de; ReKlies-De, https://www.hlnug.de; Klimaatlas-BW, https://www.klimaatlas-bw.de, DWD-Basisinformationen, https://www.dwd.de/DE/leistungen/klimaprojektionsdaten/).

To this aim, the use of high-quality and usable climate model data is key. Regional climate model simulations, like those produced in the scope of the EURO-CORDEX project (Jacob et al. 2014), have been used for a lot of climate assessment and impact studies over the years, but often provide insufficient spatial and time resolution. A recent step forward was the development of convective-permitting models (CPM) at 2–4 km, which provide a clear added value in terms of the representation of the local and regional weather and climate, and their extremes, particularly in urban and mountainous regions (e.g.,Hundhausen et al. 2024; Ban et al. 2021; Pichelli et al. 2021; Lucas-Picher et al. 2021; Prein et al. 2015). Recently, the first transient CPM ensemble simulations have been created, namely for the UK (Kendon et al. 2023), and Germany (Hundhausen et al. 2023). These datasets provide a robust new basis for climate assessment, particularly when combined with bias correction (Pinto et al. 2026).

Despite the broad application of climate model data and climate indices, challenges remain at the municipal level, where adaptation decisions are closely linked to locally experienced weather events and their impacts (Otto et al. 2025). Discrepancies can arise between climate data and the impact experiences of local decision-makers, highlighting the need to involve local stakeholders who can complement climate data with contextual knowledge, thereby better connecting these perspectives (UNFCCC 2020). This study addresses this issue by taking an experience-driven approach, whereby practitioner-identified climate impacts guide the selection of ETCCDI indices that reflect local experience and are analyzed for their projected development. While the study is relevant to many municipalities in Germany, it provides an initial assessment for Freudenstadt, a municipality and rural district (Landkreis) in the Black Forest. At the municipal scale, we identify key weather-related impacts and link them to ETCCDI indices. At the district scale, we analyze the selected indices using high-resolution regional climate model simulations, which are particularly valuable in heterogeneous terrain (Pinto et al. 2026; Hundhausen et al. 2023; Prein et al. 2015). Throughout the study, we examine the entanglement between the spatial scale of climate data and the spatial scale of municipal decision-making as a persistent challenge for research and practice. The study addresses the following objectives:

- Which climate-related challenges and opportunities are currently identified by local authorities in the city of Freudenstadt, and which are expected to arise in the future?
- How can climate experiences identified by practitioners guide the selection of ETCCDI indices, and what do these indices reveal about current and future climate trends in the district?

The paper is structured as follows: the "Data and methods" section describes the interviews in Freudenstadt and datasets used. The "Results" section presents the key climate-related challenges and opportunities identified by the local authorities alongside the climate signals of the selected ETCCDI indices for the district of Freudenstadt. The "Discussion" section discusses the connections between local experiences and regional climate projections, and the "Conclusion and outlook" section concludes the paper with a summary and implications.

Data and methods

Data and data processing

Study area

The study region is the rural district of Freudenstadt in the north-eastern Black Forest in the state of Baden-Württemberg, Germany. Spanning approximately 870 km^2 (see Fig. 1a), the region had a population of around 122,000 in December 2023 (Statistik BW 2025). The municipality of Freudenstadt, the administrative center, has around 23,500 residents and is categorized as a medium-sized city. Such municipalities represent only 13.8% of all German cities, but account for 28.7% of the national population (Kah 2023). While district and city have developed climate mitigation concepts (Landkreis Freudenstadt 2025; Freudenstadt 2024), supported by dedicated climate managers, climate adaptation currently plays a more limited role, mainly being addressed through selected measures in development plans (Landkreis Freudenstadt 2024; Freudenstadt 2021). This is consistent with recent resilience assessments of rural areas and small-town municipalities in Baden-Württemberg, which highlight substantial inter-municipal variation in structural capacity, service provision, and governance arrangements that shape local implementation (Janoschka et al. 2024).

The district spans an elevation gradient, from 450 m a.s.l. in the east to 1150 m a.s.l. in the west (Fig. 1b). Forests covers 62% of the area, mainly in the central and western regions (Statistik-BW 2023). Settlements and agricultural land are concentrated in the east, accounting for 6% and 26% of the area (Fig. 1c). Five ski and winter sport resorts are located in the west, all below 1000 m a.s.l. The climate is cool and wet, with a mean annual temperature of 7.3 °C and mean annual precipitation of 1704.5 mm (1981–2010), based on data from a nearby weather station. July and August are the warmest months (16 to 17 °C), while January and February are the coldest (− 1 to 0 °C). Monthly precipitation exceeds 100 mm in all months, peaking in winter (DWD 2023).

This research used three data sources: the experience of municipal experts, observations, and regional climate simulations, which are described below.

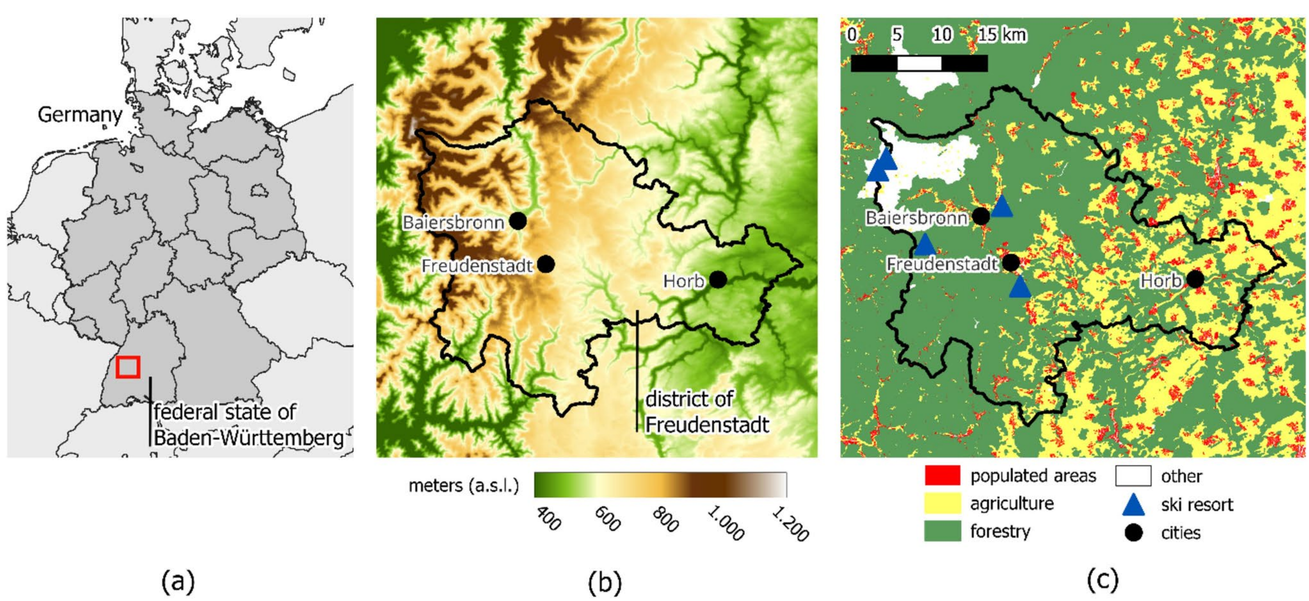


Fig. 1 Investigation area. **a** Red rectangle shows location of the district of Freudenstadt, **b** orography and cadastral boundaries, **c** land use in the area and three of the largest cities Baiersbronn, Freudenstadt, and Horb. Blue triangles show locations of ski resorts and other winter tourism offerings. White areas (other) show non-relevant protected zones and mountain regions. Projected coordinate reference system UTM Zone32N (source: GeoBasis-DE/Federal Agency for Cartography and Geodesy (BKG) (2024) and State Office for Geoinformation and Land Development Baden-Württemberg (LGL), www.lgl-bw.de, Figure created using QGIS 3.40.4)

Municipal experts' experience

To gain a detailed understanding of the role of how climate and weather influence the daily work of the local administration in Freudenstadt and how climate change is experienced in municipal practice, we employed a qualitative research design. Interviews were conducted with five local experts from different departments of the city who all served as designated contact persons within the shared project (see Table 1). As Freudenstadt is the only municipal partner in the project, the qualitative material is limited to this local administration. Interviews were carried out in spring 2024.

To accommodate the interviewees' different roles and availability, two modes of interview were used: oral and written. One in-person, semi-structured interview was conducted with two key contacts from the municipal public utility company. This interview was audio-recorded and transcribed, and followed an open-ended interview guide that enabled interactive dialogue (Muhar et al. 2018). The interviews provided detailed insights into the sensitivity of local water resources and the energy system to climate impacts, implemented or planned adaptation strategies, and the role of weather and climate in routine operational tasks. A follow-up interview with one of these experts was conducted online to clarify and supplement the initial findings.

Written interviews were conducted via email with three experts from the tourism department, the department of construction operations, and the urban development office. Respondents were asked to answer open-ended questions about the role of climate or weather in their work, and about emerging challenges and opportunities (see the Supplement Information for the full set of questions). The written format was chosen to reduce barriers to participation, as these experts were involved in the project to a lesser extent. Using two modes of interview may have influenced the depth and spontaneity of the responses; however, both formats followed the same thematic structure to ensure comparability of the results.

Expert selection was based on the interviewees' formal role as project partners or designated contact persons, as well as their relevance, as identified by the project team. While the interviews provide context-specific insights into local governance they but limit generalization beyond the city. Views from other parts of the district, such as agricultural actors and winter tourism operators, are not included. These gaps shape the scope of the qualitative findings and should be considered when interpreting the results.

Observational datasets

We use the high-resolution gridded observational dataset HYRAS ("HYdrologische RASterdaten") (Razafimaharo et al. 2020; Rauthe et al. 2013) from the German Weather Service (DWD). The dataset has a temporal resolution of one day and a spatial resolution of 5 km for near-surface temperature and 1 km for precipitation, and they were interpolated onto the 2.8 km grid of the climate simulation ensemble. Additionally, a height correction of the temperature was performed, underlying a vertical gradient of 0.0065 K/m (Hundhausen et al. 2023). The HYRAS dataset was also used for the bias-correction of the climate simulation data. In this study, we used the climate period 1991–2020.

Climate model data

The climate model data used in this study comes from the KIT-KLIWA convective-permitting ensemble (Hundhausen et al. 2023). This four-member ensemble is based on the regional climate model COSMO-CLM (version COSMO5.0 CLM9) developed by the German Weather Service (Rockel et al. 2008). Each simulation chain is driven by a different global climate model from CMIP5, which provides the boundary conditions (Taylor et al. 2012). All simulations follow the RCP8.5 emission scenario from 2006 onward (Van Vuuren et al. 2011). The ensemble has a 2.8-km horizontal resolution and covers the period 1968–2100 (Hundhausen et al. 2023). For the current study, daily variables are used. Further details on the KIT-KLIWA ensemble can be found in Hundhausen et al. (2023) and Pinto et al. (2026).

To correct systematic biases between model output and observations (Cannon et al. 2015; Sillmann et al. 2013; Mearns et al. 2012), the ensemble was bias-corrected

Table 1 Overview of expert interviews in Freudenstadt, including department affiliation, number of participants and interview format

Interview ID	Department/office	No. of experts interviewed	Interview format	Reason for format selection
1	Public utility company	2	Oral (recorded)	Key project partner
2	Public utility company	1	Online meeting (not recorded, with protocol)	Key project partner
3	Tourism department	1	Written (email)	Associated partner
4	Construction operation department	1	Written (email)	Associated partner
5	Urban development office	1	Written (email)	Associated partner

for daily minimum temperature, maximum temperature, and precipitation using Quantile Delta Mapping (QDM). QDM adjusts model distributions to match observations from the HYRAS dataset. Further details are provided in Hundhausen et al. (2023) and Pinto et al. (2026). The KIT-KLIWA ensemble has been evaluated and validated in detail for heat extremes (Hundhausen et al 2023) and precipitation extremes (Hundhausen et al. 2024, 2025). Moreover, Pinto et al. (2026) assessed in detail the results for 16 climate indices (including the four considered here) both regarding the validation against observations and the quantification of the climate change signals for Central and Southern Germany. The transient CPM ensemble simulations allowed the analysis of climate-change signals using the Global Warming Level (GWL) concept, which is widely used in recent climate studies and IPCC assessments (e.g., Pinto et al. 2026; Moemken et al. 2022; Tebaldi et al. 2021). A GWL corresponds to a 30-year period in which global mean surface temperature exceeds a given threshold relative to the 1881–1910 baseline. This study uses two GWLs: the recent past (1991–2020, GWL 0.95 K), chosen to enhance local relevance, and a future 3 K warming level (GWL 3.0 K), representing mid- to late-century conditions. The GWL approach supports comparability across scenarios because warming-level responses remain broadly consistent across emissions pathways (Diez-Sierra et al. 2023; Seneviratne and Hauser 2020; Wartenburger et al. 2017). High-risk scenarios such as RCP8.5 are widely used to explore changes under strong warming (Pinto et al. 2026; Riach et al. 2023; Klimaatlas-BW) and help avoid underestimating future impacts.

Data analysis

Qualitative content analysis

The expert interviews were analyzed using qualitative content analysis, which is suited for systematically examining transcripts through categorization and interpretation (Mayring 2022). The interview materials were coded manually to identify statements related to past or expected weather and climate events that influence decision-making and day-to-day tasks. Three inductively derived categories guided the subsequent analysis: climate/weather event (e.g., heavy precipitation, heat), Impact (e.g., limited winter tourism, reduced groundwater recharge), and Adaptation (e.g., irrigation, shading). The climate/weather event category was further differentiated into 13 specific phenomena to enable the subsequent linkage to the climatological analysis.

The analysis proceeded in three steps. First, we applied a case-oriented frequency count across the three main categories. Each category was counted once per topic and department to reduce bias from varying interview lengths. This step provided an overview of the relative prominence of events, impacts, and adaptation measures in the municipal accounts. Second, an intensity-oriented frequency count was conducted for the 13 climate and weather events. Each phenomenon was counted in total for each department to identify which events were considered most relevant for different administrative areas. Third, we conducted a framing analysis for the five most frequently mentioned events: heavy precipitation, reduced snow, heat, dry periods, and cool nights. Using the inferred interpretation approach (Mayring 2022), each phenomenon was classified as perceived positively, negatively, or neutrally based on evaluative language, described consequences, and emotional wording. Because interviewees referred to both heat and the absence of heat, this category was split into heat and no heat to ensure precise interpretation.

Although the interview data represent the municipal perspective of the city of Freudenstadt, the ETCCDI analysis was conducted at district level. The spatial resolution of the climate data does not support analyses of specific sites within urban areas, and the district-scale domain provides a larger set of grid cells for a more detailed assessment of climate signals. The study addresses this mismatch between the scale of municipal decision-making and the scale of climate information as a key methodological consideration.

Climate indices

To describe and contextualize climate and weather events in a climatological perspective, ETCCDI climate indices were selected based on municipal experts' experience. As heat, low temperatures and precipitation were the dominant answers; the indices were analyzed accordingly and provided clear definitions for subjective statements, ensuring a structured, objective quantification of climatological trends. The ETCCDI index closely related to heat is summer days, defined as a day with a maximum temperature $T_{day,max} > 25$ °C. It is commonly used to assess increasing heat and its impacts on human health and infrastructure. Further temperature-related events from the experts' experience are snow and black ice. Therefore, the ETCCDI climate index frost days, defined as a day with a minimum temperature $T_{day,min} < 0$ °C, was used. They also mentioned heavy precipitation as a relevant topic. This is captured by the ETCCDI index heavy precipitation days, defined as a day with total precipitation $P_{day,sum} > 20$ mm. This index offers insights into flood risks and potential stress on infrastructure systems. Furthermore, drought was mentioned and is represented by the ETCCDI index dry days, defined as a day with a precipitation sum $P_{day,sum} < 1$ mm, reflecting changes in drought risk and water availability, with implications for agriculture, forestry, and water resource management. The annual totals of these indices and the corresponding climate change signals are presented in the next chapter. Other topics mentioned by experts, mild winters, air quality, solar radiation, and wind, fall outside the scope of available ETCCDI indices and were therefore excluded. We calculated the indices for each grid point within the district using observational data from 1991–2020 (GWL 0.95 K). We then assessed the climate change signal as the difference between GWL 3.00 K and GWL 0.95 K for each ensemble member. Confidence in the simulations was supported by comparison with observational data, which showed only minor differences after bias correction (Pinto et al. 2026). To evaluate projection reliability, we performed a robustness test for each index following Pfeifer et al. (2015). First, we assessed model agreement and required at least 75% of the models to show the same direction of change. Second, we applied the Mann–Whitney–Wilcoxon *U*-test (Pettitt 1985) to test differences between GWL 0.95 K and GWL 3.00 K at the 0.95 significance level. Both tests were performed pixelwise. We classified a signal as robust only when both criteria were met. Maps for all indices display robust signals, while non-robust areas appear in gray.

Results

Municipal climate risks and opportunities

The qualitative content analysis identified three main categories, with impacts on infrastructure mentioned most frequently (32 mentions), followed by the triggering climate and weather events (25 mentions). This pattern suggests that administrators perceive climate change primarily through its operational consequences, as single events such as heavy precipitation can lead to multiple impacts, including water turbidity, sewage overflow, and stress on urban greenery (see Table S1 in the Supplementary Information for an overview). Adaptation measures were mentioned least often (19 mentions), indicating that systematic adaptation is still limited or not yet embedded in routine practice.

Interviewees mentioned 13 climate and weather events (Table 2). Heavy precipitation was the most relevant event, reported six times across three departments. Four mentions described negative impacts, as displayed in Fig. 2. The public utility company noted that heavy rainfall following droughts increases water turbidity and can reduce treatment effectiveness, causing temporary shutdowns. The construction operations department reported that heavy rainfall does not sufficiently irrigate urban greenery and can cause sewage overflow. In contrast, the public utility company viewed steady rain as beneficial because it replenishes water reserves. To address both risks and benefits, the urban development office planned several adaptation measures, including a new sponge-city district designed to absorb and reuse rainwater.

Table 2 Climate- and weather-related events and impacts in Freudenstadt, their total frequency of mentions, the frequency mentioned by each department and corresponding quotes from the interviews. *PUC*, public utility company; *TD*, tourism department; *COD*, construction operation department; *UDO*, urban development office. Quotes were translated from the original quotes in German language

Climate/weather events	Total frequency	PUC	TD	COP	UDO	Example quote
Heavy precipitation	6	2	-	2	2	"Due to the heavy rainfall, there is a risk of sewer system flooding" (COP)
Reduced snow	5	-	1	3	1	"We have reduced snow in winter, which leads to […] a limited winter tourism offering." (COP)
Heat	4	2	1	-	1	"In those months or years when it was very hot, we also have a higher water consumption." (PUC)
Dry periods	4	1	-	2	1	"We measure the spring discharges during dry periods, and they decrease significantly." (PUC)
Cool nights	4	1	2	-	1	"A quick cooling […] and consistent ventilation is […] creating […] cool temperatures at night during the summer." (UDO)
Mild summers	2	-	2	-	-	"[…] many guests come in summer because our temperatures are still pleasant, and tourists can sleep at night." (TD)
Mild winters	2	1	-	1	-	"Due to the generally mild winters that we have, we see a decrease in gas sales." (PUC)
Solar radiation and wind	2	2	-	-	-	"During peak times […] we need to transport the excess power through a downstream grid." (PUC)
No humid weather	1	-	1	-	-	"In summer, it is comfortably warm with […] little humidity." (TD)
Warm and wet weather	1	-	-	1	-	"warm, wet weather means faster grass growth" (COP)
Black ice	1	-	-	1	-	"In winter, we have to deal more with black ice rather than snow" (COP)
Steady rain	1	1	-	-	-	"This steady rain we have now […] is optimal for the water reserves." (PUC)
Air quality	1	-	1	-	-	"Freudenstadt […] has high air quality." (TD)

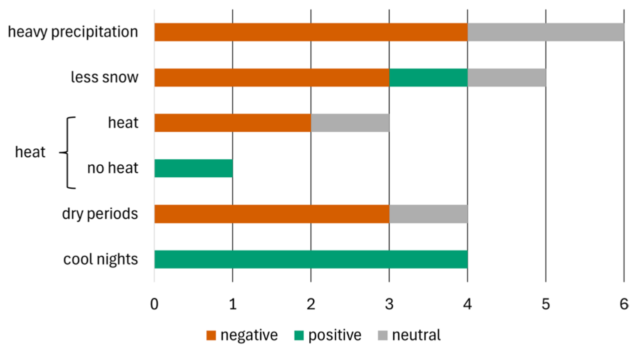


Fig. 2 Results from the interviews with Freudenstadt's experts. Inferred interpretation of the five most frequently mentioned climate and weather events and their corresponding impacts: heavy precipitation, reduced snow, heat/no heat, dry periods, and cool nights. The event heat was subdivided into heat and no heat, to enhance interpretative accuracy. The numbers indicate how often each event was perceived as negative (red), positive (green), and neutral (gray) (figure created using Microsoft Excel version 2408)

Reduced snowfall was the second most frequently mentioned event ($n=5$), mostly by the construction operations department ($n=3$). Three mentions described it as a challenge, and one mentioned a benefit (Fig. 2). The department highlighted that a lack of prolonged frost reduces predictability for winter services and complicates staff planning and procurement of salt and vehicles (Schipper et al. 2016). Longer frost-free periods also extend the pruning season for urban trees. The tourism and urban development departments expressed concern about declining day tourism due to fewer snowy days. In response, they are developing winter offerings that do not rely on snow and expanding weather-independent attractions such as the leisure pool.

Heat was mentioned four times (Table 2). Although Freudenstadt's elevation and surrounding forests buffer extreme heat, heat-related impacts still occur during particularly warm periods (Fig. 2). The public utility company reported increased water demand during the hot summer of 2020. The paved market square, a major tourist attraction, becomes a heat hotspot and is often avoided on cloud-free days. Shading or greening has been discussed but not implemented. The utility company also expects higher electricity demand due to increased air-conditioning use. In contrast, cool nights were described positively ($n=4$). Ventilation from surrounding forests moderates heat and supports nighttime cooling. Freudenstadt, a certified climatic health resort (Freudenstadt 2025), benefits from high air quality ($n=1$), mild summers ($n=2$), and low humidity ($n=1$). Authorities actively promote these advantages to attract tourists and new residents but acknowledge that rising global temperatures may reduce these benefits over time, even though the city remains one of the cooler locations in Baden-Württemberg.

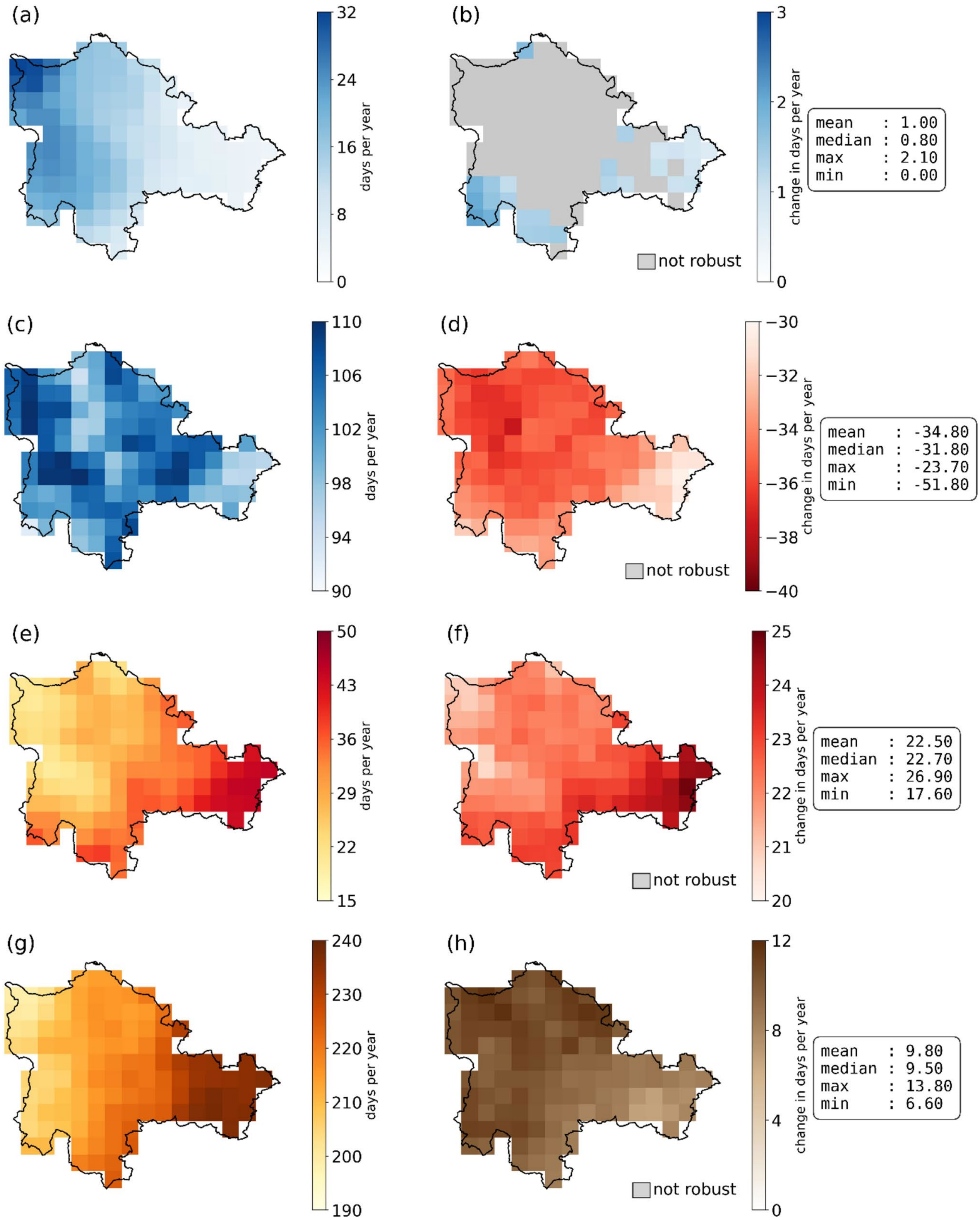
Drought was mentioned four times, three of which referred to negative impacts (Table 2, Fig. 2). The public utility company reported that prolonged dry periods reduce spring discharge, and hardened soils decrease groundwater recharge (Schimel et al. 2007). The construction operations department observed increasing drought stress in urban trees, though increased irrigation currently serves as an adequate response. While immediate water scarcity is not expected, authorities consider drought the greatest long-term risk to water supply stability, especially as recurring droughts become more likely (Moemken and Pinto 2022), particularly in combination with heavy rainfall events.

Climate change signal of the indices

This chapter presents the spatial distribution of the annual number of days for each climate index across the district in Fig. 3 for the historical period (GWL 0.95 K) and projected changes in GWL 3.0 K based on the mean of the climate model ensemble. To represent model spread and uncertainty, we include box–whisker plots in Fig. 4 that show the median and interquartile range for the two GWLs. Across all indices, model ensemble means match closely with the observations at GWL 0.95 K, indicating good agreement, reliable representation of climate conditions and successful bias correction. Heavy precipitation shows a spatial mean of 14.89 (model) and 14.99 (observed) days; frost days 102.7 and 103.3 days; summer days 30.4 and 30.5 days; and dry days 218.2 and 217.8 days.

The HYRAS dataset shows that heavy precipitation days occur primarily in the mountainous northern and southwestern parts of the district, with up to 32 days annually, depicted in Fig. 3a. In contrast, these events are rare in the low-lying eastern areas. This pattern reflects orographic effects, with higher elevations experiencing more frequent heavy precipitation events. In a 3 K warmer climate, the ensemble projects only a slight increase of one to two days per year in the southern and eastern parts (Fig. 3b), which aligns with broader evidence that extreme precipitation intensifies with warming (Papalexiou and Montanari 2019; Alfieri et al. 2017; Winsemius et al. 2016; Ludwig et al. 2023). However, the projected changes are generally not robust, which reflects high uncertainty in precipitation modeling. Pinto et al. (2026) likewise report that strong year-to-year variability dominates projections of both total and extreme precipitation. Figure 4 a shows that the four-member model ensemble shows only small differences in the increases, except for CNRM-CM5, which projects a larger increase. Its median is 17 days compared with 15 days in the other models, a relative deviation of 11.8%.

The frost days index is also strongly elevation-dependent. Most areas experience 100–110 Frost Days per year (Fig. 3c). A band-shaped structure in the central and far


(a)
32
24
16
8
0
days per year
(b)
3
2
1
0
change in days per year
mean : 1.00
median : 0.80
max : 2.10
min : 0.00
not robust
(c)
110
106
102
98
94
90
days per year
(d)
−30
−32
−34
−36
−38
−40
change in days per year
mean : -34.80
median : -31.80
max : -23.70
min : -51.80
not robust
(e)
50
43
36
29
22
15
days per year
(f)
25
24
23
22
21
20
change in days per year
mean : 22.50
median : 22.70
max : 26.90
min : 17.60
not robust
(g)
240
230
220
210
200
190
days per year
(h)
12
8
4
0
change in days per year
mean : 9.80
median : 9.50
max : 13.80
min : 6.60
not robust

◂**Fig. 3** Observed absolute annual number of each Expert Team on Climate Change Detection and Indices (ETCCDI) climate index in Global Warming Level 0.95 K (left column) and mean expected changes from the model ensemble in a 3 K warmer climate (right column) for **a**, **b** heavy precipitation days ($P_{day,\ sum}$ > 20 mm), **c**, **d** frost days ($T_{day,\ min}$ < 0 °C), **e**, **f** summer days ($T_{day,\ max}$ > 25 °C), and **g**, **h** dry days ($P_{day,\ sum}$ < 1 mm). The boxes on the right show the spatially averaged mean, median, maximum, and minimum values of the model ensemble (figure created using Python3/2023.01 and matplotlib 3.10.1)

eastern parts, corresponding to valleys, shows only about 92 frost days. This pattern persists under future climate conditions. In mountainous areas, frost days are projected to decline on average by 35 days (from 110 to 72), while lower regions show a smaller decline of 20 days (from 92 to 72) (Fig. 3d). These reductions are robust across the entire district and are driven by rising temperatures. Individual models show different magnitudes of change. CNRM-CM5 projects only 51 frost days annually, whereas MPI-ESM-LR projects 79 days (Fig. 4b). The relative deviation of 35.4% is the highest among all indices.

Observations show a gradual spatial increase in summer days from 20 days per year in the northwest to 45 days in the east (Fig. 3e), clearly linked to elevation. The ensemble projects robust increases in Summer Days for all grid cells, with an additional 20–25 days per year (Fig. 3f). The largest absolute increase of + 25 days per year (from 45 to 70) is expected in the low-lying east. The mountainous region shows the highest relative increase of + 100% (from 20 to 40 days). Figure 4 c shows that CNRM-CM5 again projects the smallest increase (18 days), while HadGEM2-ES shows the largest (27 days). The relative deviation of 33.3% is, together with frost days, the highest of all indices.

Dry days increase from 199 days in the northwest to 238 days in the east, mirroring the spatial pattern of summer days (Fig. 3g). This distribution also reflects elevation effects. In a 3 K warmer climate, the mountainous region shows the largest increase, with + 12 dry days per year (from 199 to 211), while lower areas increase by + 7 days (from 238 to 245) (Fig. 3h). In contrast to heavy precipitation days, these changes are robust across the study area, even though both indices are derived from precipitation data. The differences between individual models are smaller for dry days than for heavy precipitation days, ranging from 225 dry days (CNRM-CM5) to 233 (HadGEM2-ES) with a relative deviation of only 3.4%, which is the lowest of all indices (Fig. 4d).

Discussion

This study links locally experienced climate events with ETCCDI indices, allowing local knowledge and climatological data to be interpreted together using an experience-driven approach. Interviews with local representatives in the city of Freudenstadt revealed key climate-related challenges and opportunities. Based on these insights, four ETCCDI indices were selected to reflect experiences of heavy precipitation, reduced snowfall, heat, and drought. The historical and projected development of these indices was then assessed.

Identified climate trends and implications

Heavy precipitation is perceived as a pressing challenge, not least because recent floodings in other municipalities have made the associated risks more tangible for local authorities. Projections indicate a modest increase in Heavy Precipitation Days, with significant increases confined to parts of the east and south of the district. In these areas, settlements and infrastructure are concentrated, making them sensitive to changes in precipitation extremes. The absence of robust increases across most of the district likely reflects uncertainties in precipitation modeling and the variability of heavy precipitation, similar to findings in Pinto et al. (2026). However, they found significant changes for higher thresholds (daily precipitation > 25 mm and > 40 mm), especially in the Black Forest. This underlines the importance of municipal interpretation considering a range of plausible outcomes rather than focusing on a single deterministic signal, similar to applications provided by the public institutions (e.g., DWD-Basisinformationen, Klimaatlas-BW). In terms of adaptation planning, this highlights the importance of transparent communication of uncertainty, for instance when prioritizing sewer upgrades or nature-based retention measures (Müller and Döll 2024).

Milder winters and reduced snowfall emerged as a major concern across departments. The district-wide decline in frost days is particularly relevant around local ski resorts, where winter sports remain an important part of the regional tourism industry. Together with heavy precipitation, these cold-related issues align with the climate risk archetype 1a identified for Baden-Württemberg by Riach et al. (2023), in which municipalities are categorized based on recurring climatic hazards, exposure, and vulnerability. Freudenstadt's classification into an archetype characterized by precipitation-related risks and higher-elevation climate sensitivities closely aligns with the insights shared by local experts in this study. Interviewees also reported increasing uncertainty and reduced predictability of snow conditions, resulting in high vulnerability to shorter winter periods. In Freudenstadt, this is reflected in a decreasing number of day visitors following several winters with reduced and unpredictable snow cover. Local authorities are already adapting by

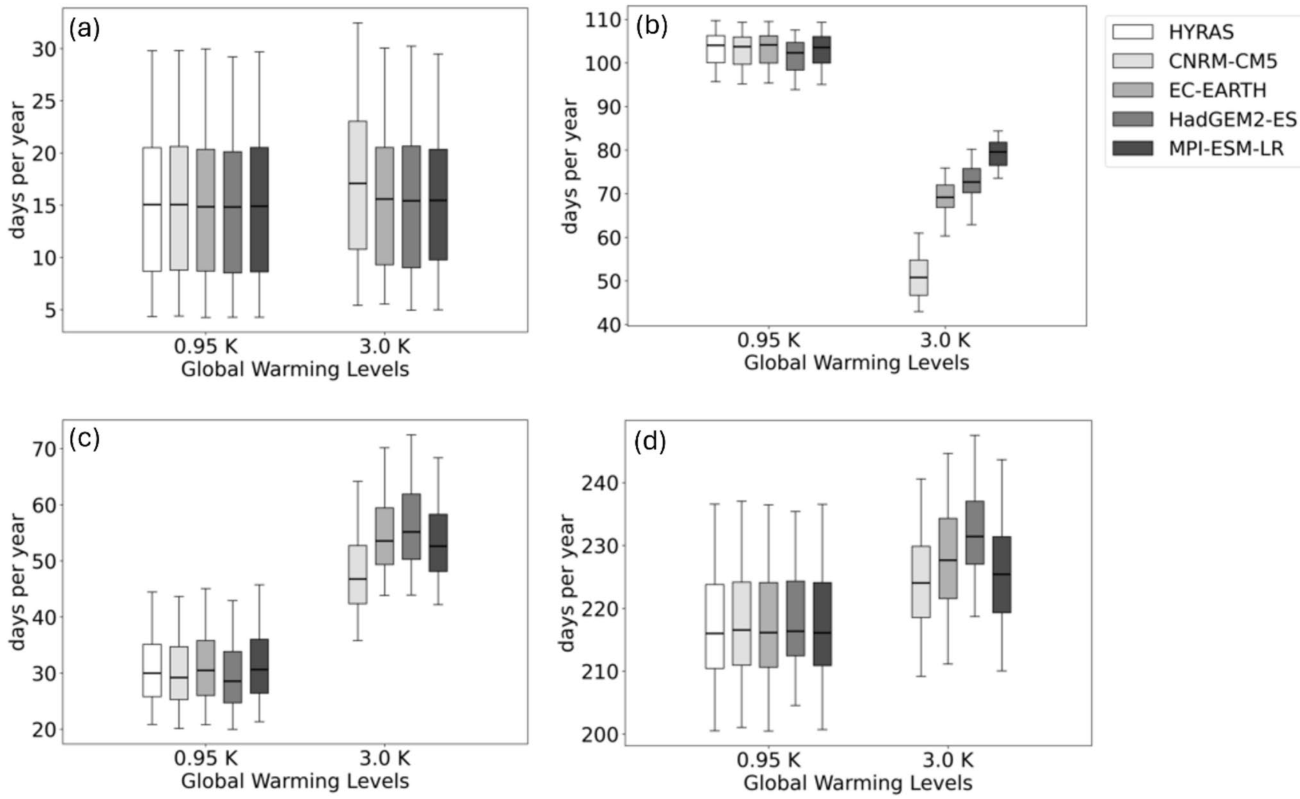


Fig. 4 Box-Whisker plot of absolute numbers of **a** heavy precipitation days, **b** frost days, **c** summer days and **d** dry days for the historical period (GWL 0.95 K) and the 3 K Global Warming Level shown for each model of the ensemble and the observations. All values represent the spatial average over the investigation area, the district of Freudenstadt. The box shows the interquartile range (25th to 75th percentiles) with the median (50th percentile) as bold line. Whiskers extend to the 2.5th and 97.5th percentiles (figure created using Python3/2023.01 and matplotlib 3.10.1)

diversifying winter packages and moving away from a reliance on snow conditions, an adjustment that has been well documented in climate tourism research (e.g., Endler and Matzarakis 2011; Schmidt et al. 2012, Demiroglu 2016). Against this background, the frost days index provides a longer-term climatic perspective on recent experiences of low-snow winters, supporting the interpretation of observed changes as part of a broader emerging trend.

Prolonged summer heat is an increasingly relevant issue for public health and urban planning. This is reflected in both the interviews and in the projected increase in Summer Days, particularly in the more strongly populated eastern residential areas on lower above-sea levels. The transition from heat exposure to heat risk depends on vulnerability factors such as urban structure, demographic composition, and land cover (Morris et al. 2022), alongside the exposure of housing to the sun and the quality of window shadows and ventilation. Considering public space, paved central squares with limited vegetation cover, such as the market square in Freudenstadt, are especially vulnerable to overheating due to the properties of the materials used and their ability to store heat (Gutiérrez et al. 2015). In terms of summer days, future conditions in Freudenstadt may become more comparable to those currently observed in warmer areas, such as the Upper Rhine Valley (Pinto et al. 2026; Hundhausen et al. 2023). As heat already accounts for a significant proportion of climate-related impacts on enterprises (Scholze et al. 2023) and municipalities in this region, the summer day index offers a quantifiable metric that enables local stakeholders to contextualize projected changes against current reference conditions and develop targeted measures, such as implementing a heat action plan (Karlsruhe 2021), particularly to safeguard the high proportion of vulnerable, often elderly populations that are especially prominent in Freudenstadt.

Drought was another frequently mentioned concern, particularly in relation to decreasing groundwater recharge. An increasing number of dry days indicates a growing relevance of drought risks, especially in the already comparatively dry eastern part of the district. As most agricultural land is concentrated there, this trend implies growing challenges for the agricultural sector. In the district, approximately half of the agricultural land consists of permanent grassland, which is primarily used for grazing dairy cattle (StatistikBW 2023). While rising temperatures could potentially boost forage productivity (Iglesias et al. 2012), this benefit is limited by drought stress and soil-related constraints (BMEL-D 2022). The dry days index thus provides useful additional information for assessing changing climatic exposure in agriculture. However, translating this information into concrete adaptation planning will require further sector-specific expertise.

A methodological challenge arises from the difference between the spatial scale of climate indices (district level) and the highly localized nature of many adaptation needs. While municipal concerns often refer to specific sites (i.e., particular squares or infrastructure elements), available climate data typically only exists at a coarser scale. In rural contexts, this scale mismatch is intensified by differences in implementation capacity, service provision, and governance arrangements. Resilience assessments identify these as the main factors that determine whether climate information can be translated into effective local action (Janoschka et al. 2024). Nevertheless, adaptation processes can advance when climate data are complemented with local practitioner knowledge (UNFCCC 2020), a guiding principle of this study. Emerging machine-learning approaches may further reduce scale discrepancies in selected domains (i.e., meter-scale urban heat stress mapping) (Briegel et al. 2025), although their transferability to other variables and decision contexts remains an area for future research as we pinpoint subsequently.

Beyond expert team on climate change detection and indices (ETCCDI) indices and targeted complements

Beyond individual extremes, interviews indicated that adaptation-relevant risks also arise from compound events: for example, heavy precipitation occurring during or shortly after extended droughts. Such sequences are projected to increase in parts of Europe (Steensen et al. 2025) and could impact local water management by increasing water turbidity and compromising the quality of spring water, as well as putting stress on treatment infrastructure (Moreira et al. 2023). The relevance of drought also varies across sectors: short dry spells are critical for maintaining urban green spaces, whereas prolonged droughts affect water resource management through delayed impacts on recharge and water availability (Van Loon 2015; Hisdal and Tallaksen 2000). To reflect these different decision contexts, it may be useful to complement ETCCDIs Consecutive Dry Days (CDD) analysis with additional drought indices, such as Standardized Precipitation Index (SPI), Relative Drought Index (RDYI), or Cumulative Drought Index (CDY), which capture both short-term deficits and long-term drought conditions (Moemken and Pinto 2022). As a counterbalance to drought, steady low-intensity rainfall is especially beneficial for recharging groundwater, yet this precipitation type is expected to decline (Hundhausen et al. 2024). Developing a steady-rain index and including drought and compound-event indices would offer a more holistic representation of regional water balance dynamics. Seasonal analyses may further increase relevance, given that climate change is altering the seasonal distribution of precipitation (Calvin et al. 2023). This information is particularly important for public utilities in Freudenstadt and in neighboring districts, which are reporting increasing pressure on water supplies (Schwarzwald-Baar-Kreis.de 2025).

For tourism and winter sports activities, stakeholders require clearer information about future snowfall patterns and reliability. Snow cover at mid-elevations between 500 and 1000 m a.s.l. is expected to decline (Schneider and Schönbein 2005), likely shortening ski seasons across the Black Forest (Endler and Matzarakis 2011; Schmidt et al. 2012). As Freudenstadt's slopes are exclusively below 1000 m a.s.l. altitude, these trends present challenges for winter tourism. Additionally, the risk of black ice depends on factors beyond freezing conditions, including fog, freezing rain, and melt–refreeze cycles (Hong et al. 2022). For winter services, the duration of consecutive hazardous episodes is operationally relevant because it affects staffing, salt use, and vehicle preparation (Venäläinen and Kangas 2003). Including additional indicators alongside frost days, such as snowfall- and winter-service-related indices (i.e., salting days and winter service days, see Pinto et al. 2026; Schipper et al. 2019), would offer a more comprehensive representation of the winter climate for both tourism and maintenance operations.

Local authorities also expressed a need for more detailed information on prolonged heat periods and summer warming, including the implications for water consumption and electricity demand (i.e., air conditioning). A range of established heat-related indices could be considered in future work, such as those used by, e.g., the DWD-Basisinformationen (2025), including hot days, heatwave metrics, cooling degree days, and tropical night-based heat stress indicators. These metrics could improve assessments of whether future summers will resemble current conditions in warmer regions and could be valuable for public utilities, strategic planning, and city marketing initiatives capable of attracting tourists and new residents by promoting climatic comfort in summer. This could have transferable outcomes for other higher-elevation regional settings across Germany, like the Swabian Jura, the Alpine region, and German Central Uplands. Furthermore, administrators emphasized the importance of natural night-time cooling, which supports thermal comfort, reduces energy use, and mitigates health risks (Fischer et al. 2012; Amaripadath et al. 2023; Liu et al. 2025). However, while the ETCCDI index "Tropical Nights" captures the frequency of very warm nights, it provides limited insight into night-time cooling dynamics at the level of settlements and neighborhoods (e.g., Amaripadath et al. 2023; Ramponi et al. 2014a and 2014b; Geros et al. 2005), lacking relevant information for practitioners. Therefore, complementing ETCCDI indices with practice-oriented tools (i.e., assessments of nocturnal cold-air flows and settlement-level thermal load, as provided in Klimaatlas BW) would improve their relevance for local adaptation planning.

Conclusion and outlook

This study shows that linking municipal experience with climate indices improves the practical use of climate information in adaptation planning. In Freudenstadt, impacts from heavy precipitation, low snowfall, heat, and drought were identified. These practitioner-identified impacts guided the selection of four ETCCDI climate indices that match local experience. High-resolution, bias-corrected, convective-permitting simulations then revealed long-term changes and spatial differences in potential climatic impacts across the district.

As well as documenting change, the indices help to translate climate projections into locally meaningful signals. The projected increase in summer days indicates growing heat stress risks relevant to urban planning and public health. The decline in frost days highlights challenges for snow-dependent tourism and winter services, while the increase in dry days suggests rising drought impacts, particularly for agriculture. Regarding heavy precipitation days, the simulations indicate heterogeneous spatial changes, with increases in the eastern and southern areas, and partly non-robust signals, highlighting the importance of transparent communication of uncertainty. By expressing climate change in terms of indices that reflect observed impacts, this approach enables local stakeholders to relate their everyday experience to longer-term projections. As ETCCDI indices are widely used, they facilitate intermunicipal comparisons and provide a shared baseline for discussing region-specific adaptation approaches.

However, the findings also highlight that the need for adaptation-related information is often department-specific, and that additional indicators are required to capture planning-related conditions that are not fully represented by standard ETCCDI indices. Some locally significant impacts are not directly tied to discrete extremes, yet remain important for strategic planning. Therefore, complementing the selected ETCCDI indices with more tailored indicators can increase their overall usability. Indices capturing night-time cooling or prolonged heat can support urban development, while indices capturing snowfall, snow reliability, and black ice indices can strengthen the information base for tourism and winter maintenance. For long-term water management, indicators capturing extended droughts, persistent rainfall, and compound events can help public utility companies to assess changing water balance conditions.

Future studies could strengthen the connection between climate information and local needs by involving scientists, stakeholders, and decision-makers in co-design processes from the onset. Previous work has highlighted the benefits of such an approach (Schipper et al. 2016; Abegg et al. 2021). Integrating socioeconomic alongside climatic indicators could further increase the relevance of climate indices for strategic adaptation planning (Riach et al. 2023; Vogel et al. 2020). This is particularly pertinent in rural and small-town contexts, where adaptive capacity depends not only on exposure to hazards but also on structural capacity, service provision, and governance arrangements, all of which vary substantially across municipalities. In such settings, building resilience is most effective when scientific climate information is combined with local knowledge and systematic monitoring to support implementation (Janoschka et al. 2024). Overall, an experience-driven and co-designed use of climate indices can make climate information more actionable for municipalities and support effective, data-informed adaptation aligned with local priorities.

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Data availability The KIT-KLIWA simulation data are available on request from the authors. The HYRAS dataset is available from the German Weather Service.

Declarations

Informed consent All interview participants provided informed consent about the use and publication of their answers.

Conflict of interest The authors declare no competing interests.

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