https://doi.org/10.7494/geom.2025.19.5.49

Valeriy Osypov[1], Nazar Filippov[2], Herman Mossur[3], Yurii Ahafonov[4], Oleg Skrynyk[5], Nataliia Osadcha[6], Volodymyr Osadchyi[7]

Climate Change Viewer: User-Friendly Web Tool for Climate Change Tracking in Ukraine

Abstract: An effective climate-change-adaptation strategy should be based on user-friendly and reliable climate services. Due to the lack of such services in Ukraine, this study aimed to develop a web tool called "Climate Change Viewer" (https://climate.uhmi.org.ua/) to visualize climate change in Ukraine and support the development of adaptation measures on a regional scale. The tool's temperature and precipitation data sets include gridded observation-based time series (1946–2020), climate ERA5-Land reanalysis (1981–2020), and high-resolution regional climate projections of the EURO-Cordex initiative (1981–2100). Regular grids of historical data sets and climate projections have been aggregated within the administrative units and main river basins of Ukraine. Climate Change Viewer shows that the observed warming trend across Ukraine remains within the projected range but exceeds the mean of the climate models' ensemble. The projected precipitation tends to increase in the northwestern and decrease in the southeastern parts of Ukraine through the end of the 21st century. The tool's user-friendly interface and regional binding can help increase the awareness of national and local authorities, businesses, and the public sector about future risks of warming and water availability. The further development of Climate Change Viewer also considers other environmental and sector-specific parameters.

Keywords: climate change, climate service, temperature, precipitation, Ukraine

Received: December 25, 2024; accepted: July 3, 2025

[1] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, email: valery.osypov@gmail.com (corresponding author), https://orcid.org/0000-0003-4853-8021
[2] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, https://orcid.org/0009-0001-5137-0074
[3] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, https://orcid.org/0009-0001-9838-6233
[4] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, https://orcid.org/0009-0007-2815-7893
[5] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, https://orcid.org/0000-0001-8827-0280
[6] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, https://orcid.org/0000-0001-6215-3246
[7] Ukrainian Hydrometeorological Institute, Kyiv, Ukraine, https://orcid.org/0000-0002-0428-4827

1. Introduction

Climate change affects Ukraine's biodiversity, agriculture, forestry, hydropower, water supply, infrastructure, tourism, health, insurance due to the more frequent droughts, heatwaves, wildfires, flooding in the Carpathians and Crimea, lower soil water, redistributed precipitation and water flow, higher eutrophication, and water-quality changes [1].

To sustain these challenges, Ukraine needs climate services that would be understandable for a wide range of end-users (businesses, national and local authorities, the public sector, and individuals), thus helping them increase their awareness, assess future risks, and develop cost-effective adaptation strategies. In an extended sense, "climate service is the transformation of climate-related data – together with other relevant information – into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large" [2].

Ukraine lacks a climate service that covers the whole country at the regional or basin scales [3, 4]. Climate-related information is mostly scattered across the scientific literature; it is not easily understandable and difficult to find for non-experts [5]. Currently, several global and pan-European web-atlases cover the Ukraine territory by a few parameters or indicators; however, only with a country-scale resolution (IPCC WGI Interactive Atlas [https://interactive-atlas.ipcc.ch/], IMPACT2C Web-Atlas [https://www.atlas.impact2c.eu/], Climate Change Knowledge Portal [https://climateknowledgeportal.worldbank.org/], Copernicus Interactive Climate Atlas [https://atlas.climate.copernicus.eu/atlas]). Overall, an analysis of the current situation shows the absence of an integrated and systematic approaches in climate change mitigation and adaptation strategies alongside the insufficient awareness of central and local authorities, business, and society [3, 5, 6]. International experience further underscores that, even where climate services exist, they are often underused due to their design shortcomings. One of the key barriers is the overwhelming complexity of many platforms, which are frequently developed using a capability-driven or science-informed approaches that prioritize data availability over user needs [7, 8]. Calvo et al. [9] highlighted that multi-layered visualizations and technical terminology can overload users' cognitive capacities, thus reducing both comprehension and trust. Their findings showed that simplifying the visual encoding and incorporating interactive elements can significantly reduce users' cognitive loads and improve usability. These insights underline the need for an intuitive, accessible, and user-informed design – especially, for national or regional platforms that are intended to support non-expert decision-makers in climate-adaptation planning.

This study aims to do the following: (1) bridge the gap between global climate data availability and regional adaptation needs by developing a climate service that is tailored to Ukraine's territorial and administrative structure; and (2) display historical and projected annual and seasonal mean air temperatures and total precipitation at the country, oblast, rayon, and territorial community levels as well as at the main Ukrainian river basin level. In contrast to a science-informed approach, this study draws on user-centered insights from existing climate services (particularly, the C3S Climate & Energy Education Demonstrator) to inform the interface layout and functionality [10]. The developed design allows for extensions to other environmental and sector-specific parameters in the future.

2. State of Problems

In recent years, the number of climate services has been growing rapidly – aiming to deliver information, manage climate-related risks, and build resilience to extreme events (aggregated at U.S. Climate Resilience Toolkit [https://toolkit.climate.gov/tools], UNFCCC Nairobi Work Programme [https://www4.unfccc.int/sites/NWPStaging/Pages/Home.aspx], Climate-ADAPT [https://climate-adapt.eea.europa.eu/en/countries-regions/countries]). A common problem is that researchers and developers tend to overestimate the abilities of end-users or decision-makers, thus assuming that complicated scientific information will be understood and accepted [11]. In their review, Hewitson et al. [12] pointedly summarized that "all of the climate information websites grossly overestimate their ease of use."

A desired climate service should be balanced between its simplicity and the robustness of the provided information. Several studies have synthesized barriers, requirements, and enablers for climate services based on interviews, webinars, and workshops with end-users [11–16] (Table 1). In the context of temperature and precipitation projections, Greis et al. [17] found that more-detailed representations of uncertainty did not necessarily improve decision-making; in fact, unfamiliar or overly complex visualizations were found to reduce both comprehension and trust. These findings highlighted the fact that the effective communication of climate projections requires clarity and alignments with users' mental models. At the same time, ensuring scientific robustness means that uncertainty should not be concealed. In this context, Kause et al. [18] demonstrated that line charts with medians and percentiles combined with plain-language labels (e.g., "high greenhouse gas emissions scenario" instead of "RCP8.5") could offer a reasonable compromise.

Goodess et al. [10] tackled several of the challenges that were highlighted above (such as the overcomplexity of interfaces, poor documentation, and a mismatch between user needs and presented information) during the development of the Copernicus Climate Change Service (C3S) Climate & Energy Education Demonstrator (C3S Edu Demo). They adopted an iterative user-driven approach that engaged stakeholders from the outset, allowing for co-design and regular feedback [10]. This process led to a platform that was user-friendly in both its functionality and supporting documentation, effectively narrowing the usability gap and improving the salience, credibility, and legitimacy of climate information.

Table 1. Barriers to, enablers of, and requirements for uses of climate services

Barriers
Lack of awareness of climate information
Tradition of performing historical variability analysis (barrier for climate change or seasonal forecast services)
Unfamiliar terminology and/or methods
Complicated navigation (e.g., related data is spread across multiple sections)
Lack of explanations about displayed data (e.g., data-generation method, robustness)
Too many options to choose
Poor or unclear guidance
Enablers
User-friendly and intuitive interfaces
Accessible and jargon-free language
Useful form of information – not merely different types of climate information
Easy to access and download
Freely available (no cost)
Easy to use and/or compatible with organization's software
Explanation or indicator(s) of potential impacts on sector
Access to user support
Building communities of practice and knowledge-brokering
Requirements
Scientific quality and robustness
Credibility of data source
Explanation or visualization of data uncertainty
Guidance on how to choose
Explanations about restrictions of data usage (e.g., accuracy of downscaling method)
No more than three clicks from initial website

Source: compiled from [11–16]

3. Material and Methods

3.1. Historical Monthly Air Temperature and Precipitation Data

Observational data such as station time series of essential climate variables must be the main reference to evaluate any model simulations and calculations – including gridded reanalysis products or climate model historical simulations.

In our pilot climate service project, we utilized station time series of monthly air temperatures (mean, minimum, and maximum) and monthly sums of the atmospheric precipitation that was collected at all of the available 178 temperature and 224 precipitation meteorological stations in Ukraine during the period of 1946–2020. Due to the Second World War (1939–1945), almost all of the Ukrainian weather stations have been missing for several years; therefore, it would be problematic to perform a thorough quality control and relative homogenization of the time series with a longer observational period (as compared to 1946–2020). The sources of the data and a detailed methodology of their quality control and homogenization by means of HOMER software [19] are presented in [20].

Since precipitation records often omit wind-induced undercatch corrections, we calculated this based on the Bryazgin methodology [21]. Developed specifically for monthly precipitation data, this methodology relies on wind speeds and the forms of precipitation (liquid, mixed, and solid). The average monthly wind speed at a height of 10 m was determined using sub-daily observations for the period of 1976–2020 [22]. For the period of 1961–1975, long-term monthly wind speeds were used at the weather stations. Due to the absence of wind measurements at 46 stations, these wind speeds were obtained from the nearest weather stations with similar physical and geographical conditions. Lastly, we assumed that those months with observed blizzards were those where the average monthly wind speed exceeded 6 m/s – the threshold at which blowing snow begins to enter the rain gauge receiver [21].

Quality controlled and homogenized station time series were gridded by MISH interpolation software [23] (developed at the Hungarian Meteorological Service). The MISH algorithm adopts the ideas of geostatistical spatial modeling (like, e.g., krigging) while taking advantage of the valuable climatological/statistical information that is contained in long homogenized data series. Terrain elevation, local topography components, and distances from the Black Sea and the Sea of Azov seashores have been used as additional deterministic predictors. Gridded time series were obtained with a spatial resolution 0.1° × 0.1°.

In addition to the observation-based gridded data sets, we utilized climate ERA5-Land reanalysis [18] for river basins, as the observational data did not cover the transboundary parts of the river basins.

3.2. Climate Projections of Temperature and Precipitation

The selections of regional climate models (RCMs) and general circulation models (GCMs) in this study were based on the standardized multi-model ensemble that was developed under the EURO-CORDEX initiative [25, 26], which included simulations that were forced by the RCP4.5 and RCP8.5 greenhouse gas concentration scenarios [27] (Table 2). The ensemble included simulations with a consistent spatial resolution (0.11° grid), bias correction techniques [28–31], and a diverse combination of RCM–GCM chains to span the main sources of uncertainty; namely, the scenario, model, and internal variability [25]. This ensemble has become a standard reference for impact and adaptation research in Europe. While our study does not introduce a new selection method, it therefore relies on the best-available peer-reviewed ensemble that was constructed to maximize the scientific robustness and relevance for regional-scale impact studies.

Grid nodes were averaged within the Ukrainian border, administrative oblasts, rayons, territorial communities, and river basins (including the transboundary parts of the Dnipro, Don, and Dniester basins). The spatial aggregation of climate projections within the administrative and river basin polygons did not introduce additional uncertainty beyond that which was already present in the climate model ensemble. On the contrary, the ensemble means over the defined spatial units tended to smooth out any local-scale variability and reduce any random noise; this potentially enhanced the robustness of the regional signals [32]. While this process can obscure local extremes or microclimatic effects, it remains appropriate for regional adaptation planning (where decision-making typically occurs at the administrative or basin-wide levels).

Table 2. List of regional climate models (RCMs) forced by general circulation models (GCMs) used in Climate Change Viewer

General circulation model	Ensemble member (per model)	Regional climate model	Bias-correction method
CNRM-CM5	r1i1p1	CCLM4-8-17	v1-SMHI-DBS45-MESAN
CNRM-CM5	r1i1p1	ARPEGE51	v1-IPSL-CDFT21-WFDEI
CNRM-CM5	r1i1p1	ARPEGE51	v1-IPSL-CDFT22-WFDEI
CNRM-CM5	r1i1p1	RCA4	v1-SMHI-DBS45-MESAN
CNRM-CM5	r1i1p1	RCA4	v1-IPSL-CDFT21-WFDEI
CNRM-CM5	r1i1p1	RCA4	v1-IPSL-CDFT22-WFDEI
EC-EARTH	r12i1p1	CCLM4-8-17	v1-SMHI-DBS45-MESAN
EC-EARTH	r12i1p1	RCA4	v1-SMHI-DBS45-MESAN
EC-EARTH	r12i1p1	RCA4	v1-IPSL-CDFT21-WFDEI
EC-EARTH	r12i1p1	RCA4	v1-IPSL-CDFT22-WFDEI
EC-EARTH	r1i1p1	RACMO22E	v1-IPSL-CDFT21-WFDEI
EC-EARTH	r1i1p1	RACMO22E	v1-IPSL-CDFT22-WFDEI
EC-EARTH	r1i1p1	RACMO22E	v1-SMHI-DBS45-MESAN
EC-EARTH	r3i1p1	HIRHAM5	v1-IPSL-CDFT21-WFDEI
EC-EARTH	r3i1p1	HIRHAM5	v1-IPSL-CDFT22-WFDEI
EC-EARTH	r3i1p1	HIRHAM5	v1-SMHI-DBS45-MESAN
IPSL-CM5A-MR	r1i1p1	WRF331F	v1-IPSL-CDFT21-WFDEI
IPSL-CM5A-MR	r1i1p1	WRF331F	v1-IPSL-CDFT22-WFDEI
IPSL-CM5A-MR	r1i1p1	RCA4	v1-SMHI-DBS45-MESAN

Table 2. cont.

IPSL-CM5A-MR	r1i1p1	RCA4	v1-IPSL-CDFT21-WFDEI
IPSL-CM5A-MR	r1i1p1	RCA4	v1-IPSL-CDFT22-WFDEI
HadGEM2-ES	r1i1p1	CCLM4-8-17	v1-SMHI-DBS45-MESAN
HadGEM2-ES	r1i1p1	RACMO22E	v1-IPSL-CDFT22-WFDEI
HadGEM2-ES	r1i1p1	RACMO22E	v1-SMHI-DBS45-MESAN
HadGEM2-ES	r1i1p1	RCA4	v1-SMHI-DBS45-MESAN
HadGEM2-ES	r1i1p1	RCA4	v1-IPSL-CDFT21-WFDEI
HadGEM2-ES	r1i1p1	RCA4	v1-IPSL-CDFT22-WFDEI
MPI-ESM-LR	r1i1p1	CCLM4-8-17	v1-SMHI-DBS45-MESAN
MPI-ESM-LR	r1i1p1	REMO2009	v1-IPSL-CDFT21-WFDEI
MPI-ESM-LR	r1i1p1	REMO2009	v1-IPSL-CDFT22-WFDEI
MPI-ESM-LR	r1i1p1	RCA4	v1-SMHI-DBS45-MESAN
MPI-ESM-LR	r1i1p1	RCA4	v1-IPSL-CDFT22-WFDEI

Source: [19]

3.3. Climate Change Viewer's Technical Environment

From a development perspective, Climate Change Viewer represents a lightweight Web GIS portal that integrates climate data with geospatial layers through a responsive browser-based interface; the set of technologies is illustrated in Figure 1. The project source code is freely available from the GitHub repository [33].

We adopted the MVW (model-view-whatever) architectural design pattern to enable the easier scaling and maintenance of the platform while also accelerating its development [34, 35]: *Model* represents the data that is retrieved from the database via client-server communication and implemented through an API (application programming interface) using HTTPS requests and responses; *View* refers to the rendered web page, including components such as maps, graphs, menus, timeline sliders, dropdown menus, and pop-up windows; and *Whatever* acts as the logic layer that responds to user interactions (e.g., button clicks or slider movements) and potentially updates *View* with new data from *Model*.

To implement the MVW pattern, we selected the Vue.js open-source JavaScript framework. Vue supports the architectural approach by clearly separating the data-handling (*Model*), user interface rendering (*View*), and interaction logic (*Whatever*). It also provides a well-organized project structure upon its initialization, along with preconfigured scripts for running, testing, and building the application; this can typically be executed with minimal setup through one or two commands, thus reducing the reliance on extensive terminal input [36].

Vue also facilitates the development of single-page applications (SPAs); this offer a more seamless and responsive user experience as compared to traditional multi-page applications (MPAs). Unlike MPAs (which reload entire pages with each user action), SPAs dynamically render the content within a single page. This results in faster navigation, a simplified application structure (with one .html file serving multiple components), and the more efficient use of resources such as dynamic imports and real-time updates [37].

We used the Leaflet JavaScript library to enable an interactive web-map interface (which supports actions like zooming, panning, and clicking on polygons) and to integrate base maps and vector overlays. Its extensive plugin ecosystem allows for the incorporations of additional features such as tile layers, layer controls, legends, and custom markers; these enhance both the usability and functionality [38]. The vector layers are prepared in the GeoJSON format, which is natively supported by Leaflet. While the attribute tables of these GeoJSON files contain pre-calculated data for ten-year periods, the annual and seasonal values for the individual years are retrieved from the server dynamically when a polygon is clicked.

For creating interactive charts, we utilized Chart.js; this leverages an HTML5 canvas for better performance and provides robust compatibility across all modern browsers.

To enable client-server communication through API, we employed the Axios JavaScript library because of its capability to centrally intercept HTTPS requests and responses as well as its automatic JSON data transformation.

The climate data sets were located in a PostgreSQL database within a Docker container in order to enhance the scalability and streamline the deployment (Fig. 1). A Caddy web server handled HTTPS connections and route requests as a reverse proxy. The application was developed in Python using the Flask-RESTful extension; this simplified the creations of RESTful APIs to retrieve data from the PostgreSQL database and serve it to the clients. This architecture provided a scalable and transferable solution for the web platform.

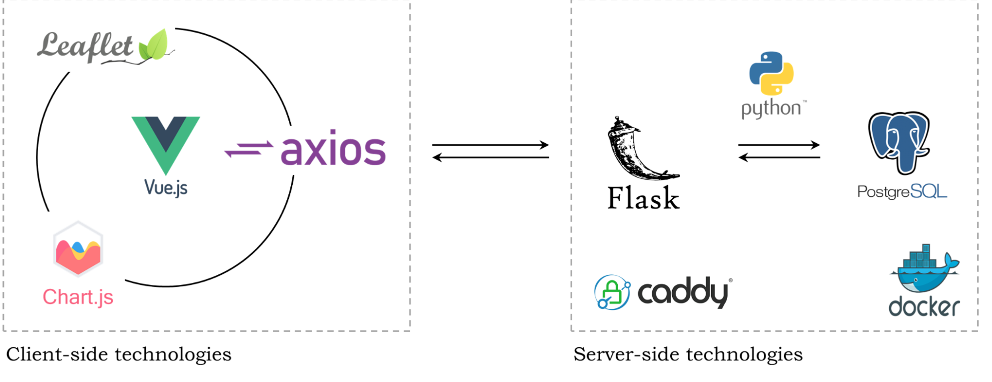


Fig. 1. Climate Change Viewer's technical environment

The data structure within the database follows a three-tier hierarchy: schema – table – column. *Schema* groups tables by data type, distinguishing between historical and projected climate data as well as by spatial references such as polygonal vector layers (e.g., oblasts, rayons) or point-based data (e.g., meteorological stations). Each table corresponds to a specific spatial unit (e.g., Kyivska Oblast or the Chernihiv meteorological station), while the columns represent the associated attributes (including the year, season, percentile, and parameter [temperature or precipitation]).

3.4. Climate Change Viewer's Interface Design

To overcome cognitive barriers and reduce information overload, Climate Change Viewer's interface is designed with several user-friendly features:

- light and recognizable interface (including full-screen map, left-side menu, standard icons, and timeline slider);
- single webpage layout (for maintaining user's attention);
- tooltips that explain scientific terminology (thus, making data more accessible);
- 'ready-to-use' design (meaning that users can access tool without undergoing complex setup procedures).

We relied on C3S Edu Demo's insights on which climate change information should be displayed: anomalies for all polygons on a map, and yearly graphs for a selected polygon in a chart [10].

The interface functionality includes a menu (for selecting the parameters), a ten-year time slider (for choosing the displayed period on a map), dropdown menus (for selecting the season and emission scenario), a layer's panel (for switching between geometry files), and a button (for downloading a JPG file of the map) (Fig. 2).

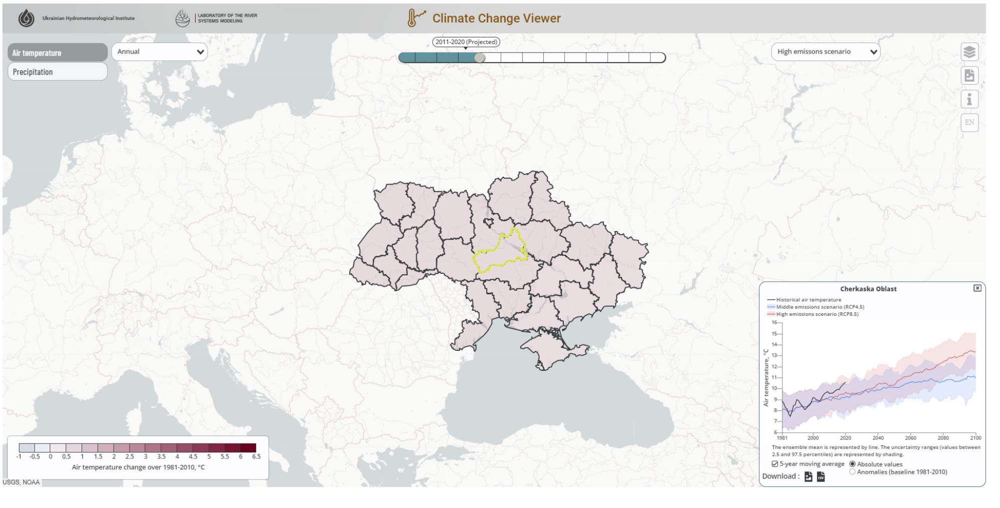


Fig. 2. Climate Change Viewer's interface (https://climate.uhmi.org.ua/)

Clicking on a polygon opens the yearly graphs, which show the ensemble of climate models (mean and spread) as well as any observed values. Users can display absolute values or anomalies, apply a five-year moving average for smoothing, and remove desired lines by clicking on the corresponding items in the legend.

The data is available for meteorological stations and grid points and are aggregated at the country, oblast, rayon, territorial community, or main river basin levels.

4. Results

4.1. Historical Air Temperature and Precipitation

Climate Change Viewer tracks temperature and precipitation changes across Ukraine (including its administrative regions and river basins) from 1946 to the present day. For instance, the recent climate norm (1991–2020) shows an average warming of 1.2°C across Ukraine relative to the period of 1961–1990, with greater increases in the winter and summer (1.5°C each) and lesser increases in the spring (1.1°C) and autumn (0.7°C) (Fig. 3). The warming was more pronounced in the north and west than it was in the east and south. For example, the Autonomous Republic of Crimea and the Luhansk region observed a warming level of 1.0°C, while the Kyiv and Lviv regions experienced warming levels of 1.3°C and 1.2°C, respectively.

The average change in precipitation across Ukraine was negligible, with a 2% loss during the 1991–2020 period relative to 1961–1990. However, there were surpluses in the spring (4%) and autumn (11%) and decreases in the winter (−9%) and summer (−8%).

4.2. Climate Projections of Air Temperature and Precipitation

Under both the RCP4.5 and RCP8.5 emissions scenarios, all of the climate models project a warmer climate for Ukraine (Fig. 4). In the near future (2021–2050), both scenarios exhibit a similar trend – a warming trend of around 1.4°C as compared to the period of 1981–2010, with the highest increases in the winters (at 1.6°C). In the distant future (2071–2100), projected temperature increases are 2.3°C and 4.2°C under RCP4.5 and RCP8.5, respectively, with the greatest warming occurring in the winters (2.7°C and 4.9°C, respectively). However, the current warming rate in Ukraine already exceeds the mean of the RCM ensemble (Fig. 4), with an average increase of 0.58°C per decade for the period 1991–2020 as compared to the 0.43°C per decade that was expected under RCP8.5.

The annual total precipitation may change in both directions; most likely, it will show a slight increase for the year as a whole but with no major changes in the summer (Fig. 5). In the near future (2021–2050), the ensemble mean of total precipitation is projected to increase by 6% under both RCP4.5 and RCP8.5 as compared to the period of 1981–2010, with the greatest rises in the winter (10%) and the lowest in the summer (1%). In the distant future (2071–2100), the expected changes indicate surpluses of 9% and 11% but losses of 2% and 3% in the summers under RCP4.5 and RCP8.5, respectively.

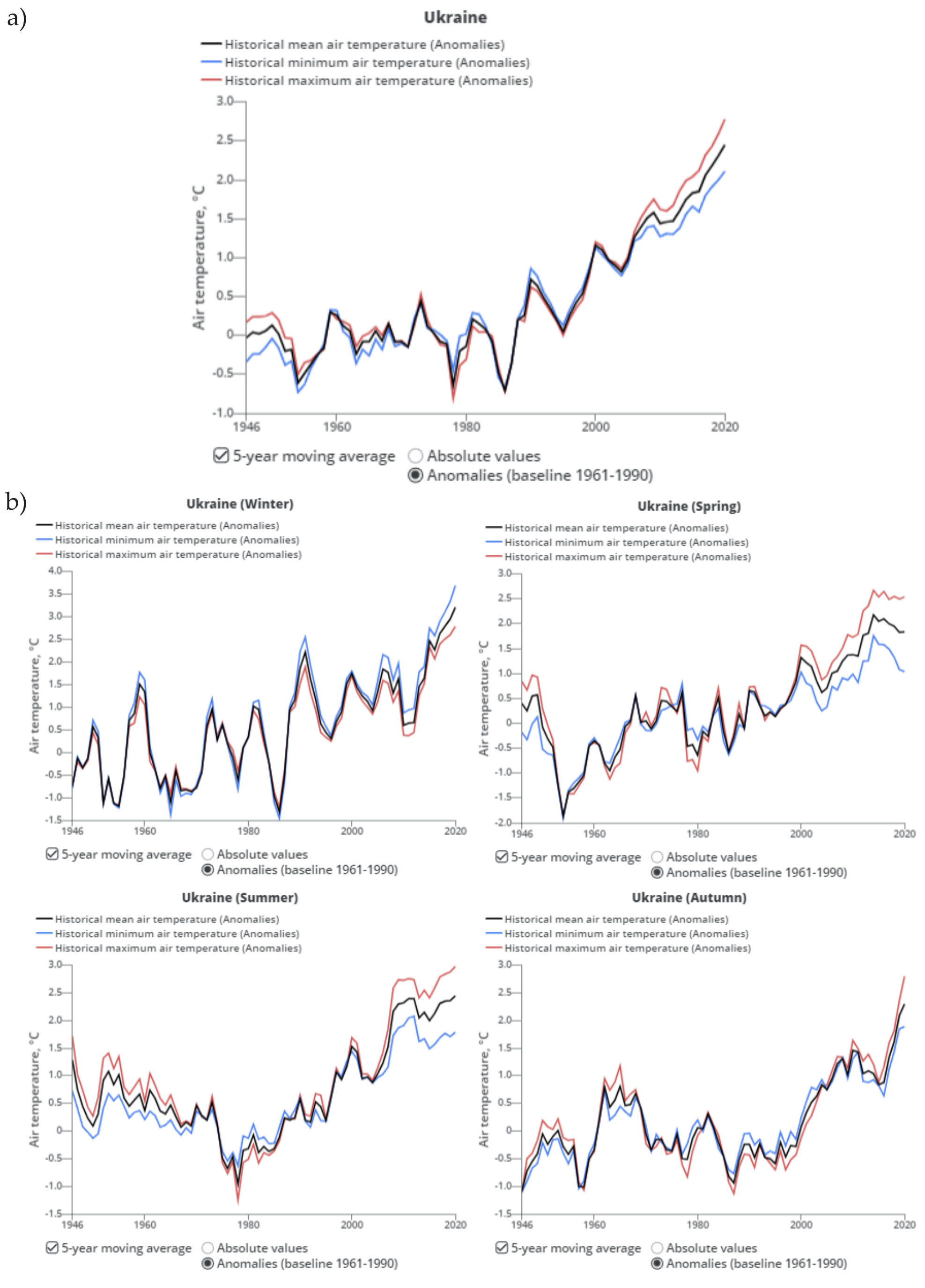


Fig. 3. Annual (a) and seasonal (b) mean, minimum, and maximum air temperatures in Ukraine for period of 1946–2020

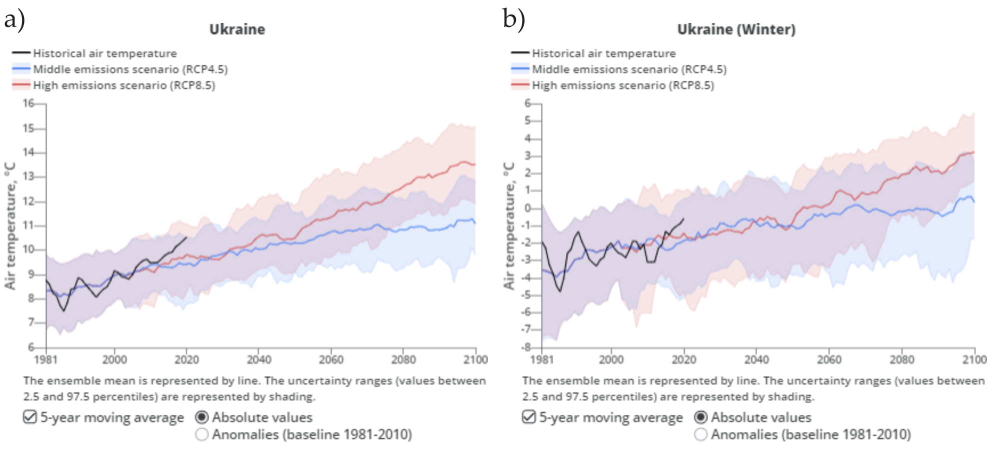


Fig. 4. Annual (a) and winter (b) mean air temperatures projected by regional climate model (RCM) ensemble within Ukraine (1981–2100) and observed by ground stations (1981–2020)

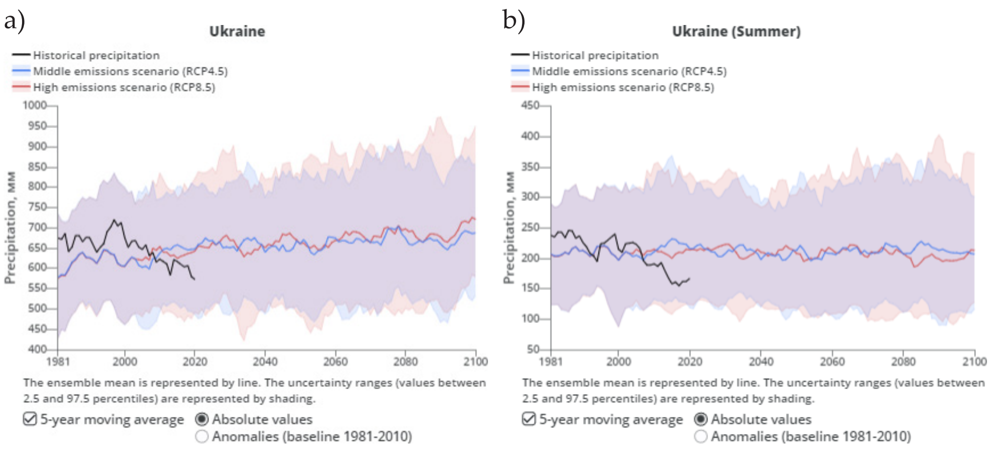


Fig. 5. Annual (a) and summer (b) total precipitation projected by regional climate model (RCM) ensemble within Ukraine (1981–2100) and observed by ground stations (1981–2020)

Since 2015, the observed air temperatures in Ukraine have consistently exceeded the ensemble mean of the regional climate model projections, while the observed precipitation has shown a decreasing trend. However, it is still too early to determine whether these patterns represent a sustained trend, as a period of 5–10 years is too short for robust climate signal detection. As reviewed by Jose et al. [39], uncertainties in climate projections stem from multiple sources, including the model structure, emission scenarios, downscaling techniques, and internal climate variability. The observed divergence in temperature may reflect a complex interaction between global drivers and regional amplification mechanisms that are not fully captured by the ensemble mean. Nevertheless, the full range of the model projections has reliably encompassed observed variability, thus indicating that the utilized ensemble remains a credible basis for climate-informed planning and risk assessment.

5. Discussion

We developed a novel climate service in Ukraine – the web-based climate-change-tracking platform called Climate Change Viewer. The platform was based on high-resolution RCMs that are aggregated within administrative units from the country to the territorial community levels as well as within the main river basins of Ukraine. This layout aimed to support regional climate-change-adaptation policy as well as adaptation strategies in river-basin-management plans.

We implemented native design, tooltips, and simplified scientific language into the Climate Change Viewer interface to overcome the cognitive barriers of end-users. On the other hand, the completeness of the provided information – 32 RCMs forced by the two more probable boundary greenhouse gas emission scenarios (RCP4.5 and RCP8.5) [40] – enables a risk-informed decision analysis, which means considering a possible range of future scenarios. Compared to global-scale portals, Climate Change Viewer provides a more accessible and localized user experience – particularly, for non-expert audiences. For example, the Copernicus Interactive Climate Atlas limits users to country-level selections even though it also includes high-resolution EURO-CORDEX projections (https://atlas.climate.copernicus.eu/); sub-national exploration is only possible via manual polygon drawing. More critically, international tools often overwhelm users with a wide range of data sets and choices, thus requiring technical knowledge to distinguish among multiple climate models, scenarios, or bias-correction methods. As was demonstrated by Calvo et al. [9], such complexity leads to higher cognitive loads, causing users to discontinue their use rather than consult the documentation to gain an understanding of the data structure. In contrast, Climate Change Viewer enables immediate one-click access to temperature and precipitation projections for clearly defined administrative and river basin units in Ukraine. Its native-language interface, simplified parameter selection, and familiar geographic layouts help reduce decision fatigue, thus making it far more usable for local authorities and stakeholders who lack technical climate expertise.

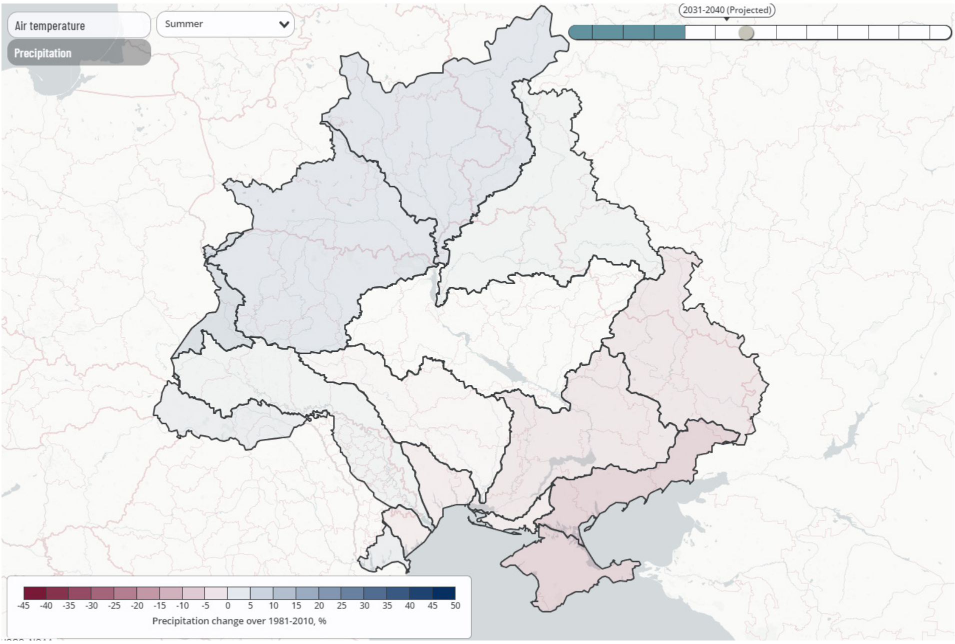
The presented spatial and temporal changes in temperature and precipitation can serve as a basis for raising awareness and identifying those risks that are related to heat stress, water availability, and water quality. For example, Figure 6 shows that, despite the overall annual increase, precipitation will likely decrease in the summers across the Crimean Rivers basin, the Azov Sea River basin, the Black Sea River basin, the Lower Dnipro, and the Don River basin, thus causing water and temperature stresses for crops, water-supply risks for households and irrigation, aquatic contamination due to higher eutrophication, and lower dissolving abilities of the rivers. As highlighted by Snizhko et al. [41], Ukraine's water security is being increasingly compromised not only by climate change but also by the wartime destruction of the water infrastructure. The projected reductions in river discharges – especially in the southern regions – pose serious risks to irrigation, drinking water, and energy generation in those areas that are already vulnerable to drought and conflict. In this context, the availability of gridded climate projections and historical baselines that are aggregated to administrative and hydrological units can support more-effective risk-informed planning.

Since Ukrainian legislation requires the development of climate-adaptation strategies at the level of administrative-territorial units, Climate Change Viewer provides the necessary spatial granularity to enable evidence-based decision-making by local authorities. This function is aligned with the requirements that are outlined in the official methodological recommendations [42] for the development of regional environmental-protection programs. Furthermore, the same ensemble of climate projections that is used in the viewer has been applied in the national assessments of climate threats [43], which identified those regional hazards that are associated with temperature and precipitation changes. Since the data in Climate Change Viewer is aligned with the paper report, this enables users to go further by exploring and downloading the underlying projections for their own follow-up research.

This potential is already being realized in practice. For example, Kireitseva et al. [44] used Climate Change Viewer to obtain temperature projections for the Zhytomyr territorial community under the RCP4.5 and RCP8.5 scenarios and conducted multivariate statistical analyses to inform local adaptation strategies. Their work demonstrates how the tool can serve as a data gateway for conducting localized assessments of climate risks, validating long-term temperature trends, and identifying those patterns that are relevant to municipal climate-resilience planning.

We acknowledge that the global trend in climate services is shifting from simple data provision toward fully co-produced decision-support tools [45, 46]. However, the number of open-access web-based climate services remains limited in the Ukrainian context. Therefore, the current version of Climate Change Viewer focuses primarily on the technical environment, spatial structure, and user interface design for delivering reliable climate data in an accessible format. The viewer was developed using open-source technologies such as Vue.js, Leaflet, Flask-RESTful, and PostgreSQL; these allowed for fast, flexible, and low-cost implementation. This development approach demonstrated a scalable and transferable model that could be adopted by other low- and middle-income countries that are facing similar budgetary and institutional limitations. At the same time, we emphasize that future improvements to Climate Change Viewer should move toward a more fully co-produced service [46]. As resources will allow, comprehensive user experience research, usability testing, and early stakeholder engagement should be integrated into the development process in order to ensure that the platform effectively meets diverse user needs and policy contexts.

a)



b)

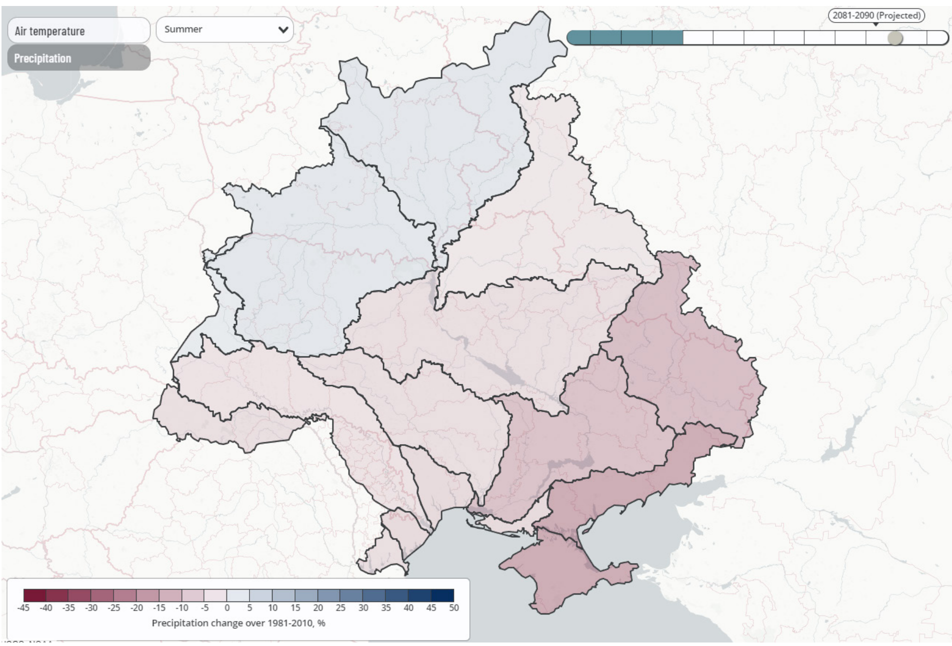


Fig. 6. Total precipitation anomalies [%] in summers projected by regional climate model (RCM) ensemble across Ukrainian river basins, including transboundary parts of Dnipro, Don, and Dniester basins in near (2031–2040) (a) and distant futures (2081–2090) (b) compared to period of 1981–2010

In the future, the methodology could be applied to visualize changes in weather parameters (e.g., wind speed, solar radiation, and relative humidity), weather extremes (e.g., heatwaves, tropical nights, freeze-thaw days, and cold-spell durations), hydrological parameters (discharge, soil water, surface/groundwater flow, etc.), water-quality parameters (sediment, nitrogen/phosphorus loads, etc.), and other derived sector-specific indicators [47]. Water-sector-related parameters are particularly relevant in the Ukrainian context, where the water supply and sanitation sector was identified as the most vulnerable to climate change by 67% of the surveyed local governments [5]. Despite the frequent mentions of water-related risks such as droughts, floods, and reduced river flows, Ukrainian municipalities currently lack the necessary tools for accessing high-resolution projections of hydrological variables. Extending Climate Change Viewer to include discharge and evapotranspiration projections would directly address this gap and support evidence-based planning for local adaptations and water-resource management.

6. Conclusion

Climate Change Viewer is a web-based platform that disseminates historical and projected climate changes in Ukraine at the country, regional, and river basin levels (https://climate.uhmi.org.ua/). Its current initial release includes air temperature and precipitation as the main drivers of our economic and environmental processes. The interface enables analyses of spatial, temporal, and seasonal variations and uncertainties, as it displays a map of anomalies for selected geometries (administrative units or river basins) and an annual graph of ensemble means and ensemble spreads for selected polygons.

All climate models project a warmer climate for Ukraine – an increase of 1.4°C in the near future (2021–2050) compared to 1981–2010 under both RCP4.5 and RCP8.5, with increases of 2.3°C and 4.2°C in the distant future (2071–2100) under RCP4.5 and RCP8.5, respectively.

Under both RCP4.5 and RCP8.5, the total precipitation is expected to increase by 6% (the ensemble mean within Ukraine) in the near future (2021–2050) and by 9% and 11%, respectively, in the distant future (2071–2100) as compared to the period of 1981–2010. However, the model spread shows that a slight decrease in precipitation is also possible. Moreover, the precipitation is likely to decrease in the summers in the southern and eastern parts of Ukraine, enhancing the risks to agriculture and fresh-water supplies.

The initial version of Climate Change Viewer was focused on a scalable and user-friendly design for visualizing climate variables and their related indicators in time and space. The platform can be expanded to include meteorological, hydrological, hydrochemical, agrometeorological, and agricultural variables. By bridging the gap between global data sets and local decision-making needs, the viewer offers a practical low-cost example of how open-source tools can provide high-impact climate services in resource-constrained contexts. Its regional granularity, intuitive interface, and accessibility make it especially valuable for supporting adaptation planning across Ukraine's administrative and hydrological units.

Funding

The software development, specifically the creation of the web interface, was funded by the EURIZON project, which is supported by the European Union under Grant Agreement No. 871072.

CRediT Author Contribution

V. O.: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft preparation, writing – review and editing, visualization, supervision.

N. F.: methodology, software, validation, visualization.

H. M.: methodology, software, validation.

Y. A.: methodology, software, validation.

O. S.: writing – original draft preparation, writing – review and editing, validation.

N. O.: writing – original draft preparation, writing – review and editing, supervision.

V. O.: supervision.

Declaration of Competing Interests

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.

Data Availability

Public Data: all data are freely available for download at Climate Change Viewer web tool [https://climate.uhmi.org.ua/].

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

Acknowledgements

This project has received funding through the EURIZON project, which is funded by the European Union under Grant Agreement No. 871072.

References

[1] Wilson L., New S., Daron J., Golding N.: *Climate Change Impacts for Ukraine*. Met Office, Exeter, Devon, UK 2021.

[2] European Commission. Directorate-General for Research and Innovation: *A European Research and Innovation Roadmap for Climate Services*. Publications Office of the European Union, Luxembourg 2015. https://doi.org/10.2777/702151.

[3] Soloviy V., Dubovich I.: *Ecological-social-economic analysis of urban climate governance based on climate plans and reports of Ukraine's cities of regional significance*. Proceedings of the Forestry Academy of Sciences of Ukraine, no. 21, 2020, pp. 157–172. https://doi.org/10.15421/412036.

[4] Osadchyi V.I.: *Climate program of Ukraine as a basis of integral ecological policy of the state in the conditions of climate change*. Visnyk of the National Academy of Sciences of Ukraine, no. 6, 2021, pp. 81–84. https://doi.org/10.15407/visn2021.06.081.

[5] Pavliuk S., Prystupa M., Kovalchuk I., Zozulia A., Riabyka M., Popfalushi D.: *Ukrayins'ki hromady ta adaptatsiya do zminy klimatu: Zvit za rezultatamy onlayn-opytuvannya* [Ukrainian communities and adaptation to climate change report based on the results of an online survey]. 2022. https://enefcities.org.ua/upload/files/Publications/Analytics/zvit_climateadapt.pdf [access: 10.06.2025].

[6] Verkhovna Rada Ukrainy*: Pro skhvalennia Stratehii ekolohichnoi bezpeky ta adaptatsii do zminy klimatu na period do 2030 roku.* Rozporyadzhennya Kabinetu Ministriv Ukrainy [Verkhovna Rada of Ukraine: On approval of the Strategy of environmental security and adaptation to climate change for the period up to 2030. Order of the Cabinet of Ministers of Ukraine]. Document no. 1363-2021-p, October 20, 2021. https://zakon.rada.gov.ua/laws/main/l510497.

[7] Hewitt C.D., Stone R.: *Climate services for managing societal risks and opportunities.* Climate Services, vol. 23, 2021, 100240. https://doi.org/10.1016/j.cliser.2021.100240.

[8] Boon E., Body N.S., Biesbroek R.: *Developing and testing an evaluation framework for climate services for adaptation*. Climate Services, vol. 38, 2025, 100549. https://doi.org/10.1016/j.cliser.2025.100549.

[9] Calvo L., Christel I., Terrado M., Cucchietti F., Pérez-Montoro M.: *Users' cognitive load: A key aspect to successfully communicate visual climate information*. Bulletin of the American Meteorological Society, vol. 103(1), 2022, pp. E1–E16. https://doi.org/10.1175/BAMS-D-20-0166.1.

[10] Goodess C.M., Troccoli A., Acton C., Añel J.A., Bett P.E., Brayshaw D.J., De Felice M., Dorling S.R., Dubus L., Penny L., Percy B., Ranchin T., Thomas C., Trolliet M., Wald L.: *Advancing climate services for the European renewable energy sector through capacity building and user engagement*. Climate Services, vol. 16, 2019, 100139. https://doi.org/10.1016/j.cliser.2019.100139.

[11] Palutikof J.P., Street R.B., Gardiner E.P.: *Decision support platforms for climate change adaptation: an overview and introduction*. Climatic Change, vol. 153, 2019, pp. 459–476. https://doi.org/10.1007/s10584-019-02445-2.

[12] Hewitson B., Waagsaether K., Wohland J., Kloppers K., Kara T.: *Climate information websites: an evolving landscape*. WIREs Climate Change, vol. 8(5), 2017, e470. https://doi.org/10.1002/wcc.470.

[13] Davis M., Lowe R., Steffen S., Doblas-Reyes F., Rodó X.: *Barriers to using climate information: Challenges in communicating probabilistic forecasts to decision-makers*, [in:] Drake J., Kontar Y., Eichelberger J., Rupp T., Taylor K. (eds.), *Communicating Climate-Change and Natural Hazard Risk and Cultivating Resilience*, Advances in Natural and Technological Hazards Research, vol. 45, Springer, Cham 2016. https://doi.org/10.1007/978-3-319-20161-0_7.

[14] Bruno Soares M., Dessai S.: *Barriers and enablers to the use of seasonal climate forecasts amongst organizations in Europe*. Climatic Change, vol. 137, 2016, pp. 89–103. https://doi.org/10.1007/s10584-016-1671-8.

[15] Alexander M., Bruno Soares M., Dessai S.: *Multi-sector requirements of climate information and impact indicators across Europe: Findings from the SECTEUR European-wide survey – Part 1. Deliverable 2.3 for the "SECTEUR" project: Sector Engagement for the Copernicus Climate Change Service (C3S) – Translating European User Requirements*. 2017. https://doi.org/10.13140/RG.2.2.18132.81282.

[16] European Environment Agency: *Overview of climate change adaptation platforms in Europe*. European Environment Agency Technical Report 5/2015, Publications Office, Copenhagen 2015. https://doi.org/10.2800/400414.

[17] Greis M., Ohler T., Henze N., Schmidt A.: *Investigating representation alternatives for communicating uncertainty to non-experts*, [in:] Kurosu M. (ed.), *Human-Computer Interaction: Interaction Technologies*, Springer, Cham 2015, pp. 256–263. https://doi.org/10.1007/978-3-319-22723-8_21.

[18] Kause A., Bruine de Bruin W., Fung F., Taylor A., Lowe J.: *Visualizations of projected rainfall change in the United Kingdom: An interview study about user perceptions*. Sustainability, vol. 12, 2020, 2955. https://doi.org/10.3390/su12072955.

[19] Mestre O., Domonkos P., Picard F., Auer I., Robin S., Lebarbier E., Bohm R., Aguilar E., Guijarro J., Vertachnik G., Klancar M., Dubuisson B., Stepanek P.: *HOMER: a homogenization software – methods and applications*. Idojaras (Quarterly Journal of Hungarian Meteorological Service), vol. 117, 2013, pp. 47–67. https://doi.org/10.3402/polar.v24i1.6254.

[20] Osadchyi V., Skrynyk Olesya, Palamarchuk L., Skrynyk O., Osypov V., Oshurok D., Sidenko V.: *Dataset of gridded time series of monthly air temperature (min, max, mean) and atmospheric precipitation for Ukraine covering the period of 1946–2020*. Data in Brief, vol. 44, 2022, 108553. https://doi.org/10.1016/j.dib.2022.108553.

[21] Aleksandrov Y.I., Bryazgin N.N., Førland E.J.: *Seasonal, interannual and long-term variability of precipitation and snow depth in the region of the Barents and Kara seas*. Polar Research, vol. 24(1–2), 2005, pp. 69–85. https://doi.org/10.3402/polar.v24i1.6254.

[22] Central Geophysical Observatory: *Archives of meteorological data [dataset], 1976–2020*. Kyiv.

[23] Szentimrey T., Bihari Z.: *Manual of Interpolation Software MISHv1.03*. Hungarian Meteorological Service, Budapest 2014.

[24] Copernicus Climate Change Service (C3S): *ERA5-Land hourly data from 1950 to present*. 2021. https://doi.org/10.24381/cds.e2161bac.

[25] Jacob D., Petersen J., Eggert B., Alias A., Christensen O.B., Bouwer L.M., Braun A., Colette A., Déqué M., Georgievski G., Georgopoulou E., Gobiet A., Menut L., Nikulin G., Haensler A., Hempelmann N., Jones C., Keuler K., Kovats S., ..., Yiou P.: *EURO-CORDEX: New high-resolution climate change projections for European impact research*. Regional Environmental Change, vol. 14(2), 2014, pp. 563–578. https://doi.org/10.1007/s10113-013-0499-2.

[26] Taylor K.E., Stouffer R.J., Meehl G.A.: *An overview of CMIP5 and the experiment design*. Bulletin of the American Meteorological Society, vol. 93, 2012, pp. 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

[27] Moss R.H., Edmonds J.A., Hibbard K.A., Manning M.R., Rose S.K., van Vuuren D.P., Carter T.R., Emori S., Kainuma M., Kram T., Meehl G.A., Mitchell J.F.B., Nakicenovic N., Riahi K., Smith S.J., Stouffer R.J., Thomson A.M., Weyant J.P., Wilbanks T.J.: *The next generation of scenarios for climate change research and assessment*. Nature, vol. 463, 2010, pp. 747–756. https://doi.org/10.1038/nature08823.

[28] Weedon G.P., Balsamo G., Bellouin N., Gomes S., Best M.J., Viterbo P.: *The WFDEI meteorological forcing data set: WATCH forcing data methodology applied to ERA-Interim reanalysis data*. Water Resources *Research*, vol. 50(9), 2014, pp. 7505–7514. https://doi.org/10.1002/2014WR015638.

[29] Vrac M., Noël T., Vautard R.: *Bias correction of precipitation through singularity stochastic removal: Because occurrences matter*. Journal of Geophysical Research: Atmospheres, vol. 121, 2016, pp. 5237–5258. https://doi.org/10.1002/2015JD024511.

[30] Landelius T., Dahlgren P., Gollvik S., Jansson A., Olsson E.: *A high-resolution regional reanalysis for Europe. Part 2: 2D analysis of surface temperature, precipitation and wind*. Quarterly Journal of the Royal Meteorological Society, vol. 142, 2016, pp. 2132–2142. https://doi.org/10.1002/qj.2813.

[31] Yang W., Andréasson J., Graham P.L., Olsson J., Rosberg J., Wetterhall F.: *Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies*. Hydrology Research, vol. 41(3–4), 2010, pp. 211–229. https://doi.org/10.2166/nh.2010.004.

[32] 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., ..., Zubler E.M.: *Climate scenarios for Switzerland CH2018 – Approach and implications*. Climate Services, vol. 26, 2022, 100288. https://doi.org/10.1016/j.cliser.2022.100288.

[33] Climate Change Viewer source code. https://github.com/StormInside/ClimateChangeViewer-Frontend-UHMI/tree/localize-end_2023-Herman [access: 30.06.2025].

[34] Scott E.A., Jr.: *SPA Design and Architecture: Understanding Single-Page Web Applications*. Black & White, 2015.

[35] Jánki Z.R., Bilicki V.: *Rule-based architectural design pattern recognition with GPT models*. Electronics, vol. 12(15), 2023, 3364. https://doi.org/10.3390/electronics12153364.

[36] Filipova O.: *Learning Vue.js 2*. Packt Publishing, Birmingham 2016.

[37] Kowalczyk K., Szandala T.: *Enhancing SEO in single-page web applications in contrast with multi-page applications*. IEEE Access, vol. 12, 2024, pp. 11597–11614. https://doi.org/10.1109/ACCESS.2024.3355740.

[38] Edler D., Vetter M.: *The simplicity of modern audiovisual web cartography: An example with the open-source JavaScript library leaflet.js*. KN – Journal of Cartography and Geographic Information, vol. 69, 2019, pp. 51–62. https://doi.org/10.1007/s42489-019-00006-2.

[39] Jose D.M., Dwarakish G.S.: *Uncertainties in predicting impacts of climate change on hydrology in basin scale: a review*. Arabian Journal of Geosciences, vol. 13, 2020, 1037. https://doi.org/10.1007/s12517-020-06071-6.

[40] Mora C., Frazier A.G., Longman R.S., Dacks R.S., Walton M.M., Tong E.J., Sanchez J.J., Kaiser L.R., Stender Y.O., Anderson J.M., Ambrosino C.M., Fernandez-Silva I., Giuseffi L.M., Giambelluca T.W.: *The projected timing of climate departure from recent variability*. Nature, vol. 502, 2013, pp. 183–187. https://doi.org/10.1038/nature12540.

[41] Snizhko S., Didovets I., Bronstert A.: *Ukraine's water security under pressure: Climate change and wartime*. Water Security, vol. 23, 2024, 100182. https://doi.org/10.1016/j.wasec.2024.100182.

[42] Verkhovna Rada Ukrayiny: *Pro zatverdzhennya Metodychnykh rekomendatsiy shchodo zmistu rozroblennya rehionalnykh prohram z okhorony dovkillya*. Nakaz Ministerstva Okhorony Navkolyshn'oho Seredovyshcha ta Pryrodnykh Resursiv Ukrayiny [Verkhovna Rada of Ukraine: On the approval of the Methodological recommendations on the content of developing regional environmental protection programs. Order Ministry of Environmental Protection and Natural Resources of Ukraine]. Document no. 486, July 11, 2023. https://zakon.rada.gov.ua/rada/main/en/l534130 [access: 10.06.2025].

[43] Krakovska S., Kryshtop L.: *Overall climate change impact assessment for Ukraine*. Deutsche Gesellschaft für Internationale Zusammenarbeit, Bonn and Eschborn 2024. https://doi.org/10.13140/RG.2.2.34337.31840.

[44] Kireitseva H., Tsyhanenko-Dziubenko I., Khomenko S., Lehenchuk R.: *Application of multivariate statistical methods for analysis of climate projections*. Scientific Journal Metinvest Polytechnic. Series Technical Sciences, no. 3, 2025, pp. 26–33. https://doi.org/10.32782/3041-2080/2025-3-3.

[45] Jacobs K.L., Street R.B.: *The next generation of climate services*. Climate Services, vol. 20, 2020, 100199. https://doi.org/10.1016/j.cliser.2020.100199.

[46] Fleming A., Bohensky E., Dutra L.X.C., Lin B.B., Melbourne-Thomas J., Moore T., Stone-Jovicich S., Tozer C., Clarke J.M., Donegan L., Hopkins M., Merson S., Remenyi T., Swirepik A., Vertigan C.: *Perceptions of co-design, co-development and co-delivery (Co-3D) as part of the co-production process – Insights for climate services*. Climate Services, vol. 30, 2023, pp. 100364. https://doi.org/10.1016/j.cliser.2023.100364.

[47] Preuschmann S., Hänsler A., Kotova L., Dürk N., Eibner W., Waidhofer C., Haselberger C., Jacob D.: *The IMPACT2C web-atlas – Conception, organization and aim of a web-based climate service product*. Climate Services, vol. 7, 2017, pp. 115–125. https://doi.org/10.1016/j.cliser.2017.03.005.