SoftwareX 33 (2026) 102479

Contents lists available at ScienceDirect

SoftwareX

journal homepage: www.elsevier.com/locate/softx

CLIMB: Framework for CLIMate data bias-adjustment and downscaling

Jakub Śledziowski [a,*], Paweł Terefenko [a], Andrzej Giza [a], Kamran Tanwari [a], Dominik Paprotny [a,b]

[a] Institute of Marine and Environmental Sciences, University of Szczecin, Mickiewicza 16, 70-383 Szczecin, Poland
[b] Research Department Transformation Pathways, Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam 14473, Germany

ARTICLE INFO

Keywords:
ERA5 reanalysis
ERA5-Land
Python
Bias adjustment and downscaling
Climate data processing
Event attribution

ABSTRACT

Modern climate impact and attribution science requires timely, high-resolution meteorological and hydrological data. The CLIMB workflow is an open-source framework integrating state-of-the-art datasets and methods for operational generation of high-resolution climate datasets tailored for attribution studies of floods, droughts, heatwaves, and other extremes. We show that global climate reanalysis can be efficiently bias-adjusted and downscaled, and further converted into readily-usable climate indicators. The choice of variables and formatting of the data enables direct application in hydrological models. The workflow implements a fully scripted pipeline that can be automated via cron scheduling, providing daily meteorological outputs. We show an application of the workflow for operational monitoring weather extremes in Poland.

Metadata

Nr	Code metadata description	*Metadata*
C1	Current code version	*1.1*
C2	Permanent link to code/ repository used for this code version	https://github.com/HORIZON-COMPASS/Integration-of-datasets-and-models
C3	Permanent link to reproducible capsule	https://zenodo.org/records/17176667
C4	Legal code license	*MIT License*
C5	Code versioning system used	*git*
C6	Software code languages, tools and services used	*Python, bash, jupyter notebook*
C7	Compilation requirements, operating environments and dependencies	Tested under Ubuntu 22.04 (also via WSL2 on Windows) with Python 3.11.6, CDO 2.2.3, NetCDF4 1.7.1, xarray 2024.7.0, pandas 2.2.2, shapely 2.0.5, Cartopy 0.23.0, scipy 1.14.0, cdsapi 0.7.0, and LISVAP with PCRaster 4.4.1. Complete Conda environment files are provided in the repository (environment.yml and environment-lisvap.yml).
C8	If available, link to developer documentation/manual	https://github.com/HORIZON-COMPASS/Integration-of-datasets-and-models/blob/main/step-by-step-guide.ipynb
C9	Support email for questions	jakub.sledziowski@usz.edu.pl

1. Motivation and significance

The increasing frequency, intensity, and complexity of climate-related extreme events poses significant challenges for risk assessments and decision-making [1]. Understanding the role of climate change in driving these events and their impacts on human and natural systems requires robust, scalable frameworks for event attribution that combine multiple data sources and modelling approaches [2,3]. Over the past two decades, the field of extreme event attribution has advanced rapidly, with new methods being developed and applied, notable improvements in physical modelling, the rise of impact attribution, and the growing use of different tools for climate change analysis [4–6].

While methodological developments are crucial for advancing extreme events attribution towards practical and operational applications, reliable and high-resolution climate data are also essential to this purpose. They enable resolving local processes and extremes strongly influences the reliability of attribution statements. Recent studies highlight that improvements in spatial and temporal resolution of reanalysis and model data enhance the detection, simulation, and quantification of climate change signals in extreme weather events [2, 7].

Several existing frameworks provide advanced tools for climate data post-processing, bias adjustment and statistical downscaling, such as the R-based climate4R bundle (including downscaleR and transformeR), the

---

* Corresponding author.
E-mail address: jakub.sledziowski@usz.edu.pl (J. Śledziowski).

https://doi.org/10.1016/j.softx.2025.102479
Received 29 September 2025; Received in revised form 17 November 2025; Accepted 2 December 2025

Python framework pyESD for empirical–statistical downscaling, the ibicus package for multi-method bias adjustment, and climdex-kit for climate index calculation and analysis [8–11]. In contrast, CLIMB is not a general-purpose method library but an executable, end-to-end workflow that connects Copernicus reanalyses (ERA5 / ERA5-Land) and EMO-1 observations to application-ready, bias-adjusted daily fields for a fixed domain, including hydrological pre-processing and automated updates. Its focus is on operational deployment and reproducibility in a specific service context, and it can in principle make use of alternative bias-adjustment engines (e.g. ibicus) within the same scripted pipeline.

Global reanalysis products, such as ERA5, provide consistent long-term records but remain limited in spatial resolution and biased compared to local observations. ERA5-Land offers an improved land-surface representation but still inherits systematic biases from ERA5. To address these shortcomings, regional observational datasets such as EMO-1 [12] have been developed but limited by the length of timeseries.

Some initiatives have developed methods and tools to address parts of this challenge. The ISIMIP framework [13] introduced standardized bias adjustment and statistical downscaling methods in a Python-based library BASD [3]. The method was applied to provide 1 arc-minute (∼1.8 km) inputs for the European hydrological model LISFLOOD [14] to generate 6-hourly river discharge back to 1950 [15] and further create a catalogue of historical impactful floods [16]. Still, a gap remains for a fully automated, end-to-end pipeline that combines reanalysis data, observational references, bias correction and adjustment, and hydrological pre-processing into reproducible, user-ready outputs.

The CLIMB workflow addresses this gap by implementing a scripted pipeline that integrates ERA5, ERA5-Land, and EMO-1 datasets. It generates 1 arc-minute daily climate data suitable for both use in LISFLOOD [14] and direct translation into climate impacts. Bias adjustment and downscaling are performed using ISIMIP3BASD method, described in validated by Lange [13], followed by hydrological pre-processing in LisVAP [17].

This development is part of the COMPASS project (COMPound extremes Attribution of climate change: towardS an operational Service), which aims to establish harmonized frameworks for attributing complex extremes, including compound, sequential, and cascading events. Recognizing the growing climate risk in Poland, which is already experiencing the consequences of climate change through more frequent and intense heatwaves and droughts [18], we applied the workflow to continuous monitoring of those extremes in Poland.

2. Software description

2.1. Software architecture

The workflow is organized into eleven sequential steps (Fig. 1), each implemented as a dedicated script stored in the SCRIPTS/ folder of the GitHub repository. Input, intermediate, and output data are organized into separate directories (Step_1–Step_11), which ensures transparency and reproducibility. Additional dependencies include the ISIMIP3BASD library (bundled in the repository) and the LisVAP hydrological preprocessor (used as an external tool configured via Step 11).

The overall architecture follows a modular pipeline design:

- Step 1–4: data acquisition and preprocessing of ERA5, ERA5-Land, and EMO-1 datasets, including GRIB-to-NetCDF conversion.
- Step 5–7: preparation and harmonization of ERA5-Land and EMO-1 for bias adjustment, including dimensional scaling and merging.
- Step 8–10: bias adjustment and statistical downscaling (ISIMIP3BASD) and post-processing to standardized NetCDF formats.
- Step 11: computation of hydrological variables (potential evapotranspiration) using LisVAP.

The CLIMB workflow is implemented as a sequence of Bash scripts, each corresponding to a single processing step (e.g. data download, preprocessing, bias adjustment, post-processing, hydrological preparation). This step-wise design reflects the intended operational use of the framework, where the scripts are executed sequentially (e.g. via a cron job or a wrapper script) and individual steps can be re-run or modified independently. This keeps the implementation transparent, facilitates debugging and extension, and allows users to adjust only those parts of the workflow that are relevant to their specific application.

Folder structure

The overall workflow directory is structured as follows:

```
Framework
├── Isimip3basd-master
├── SCRIPTS
```

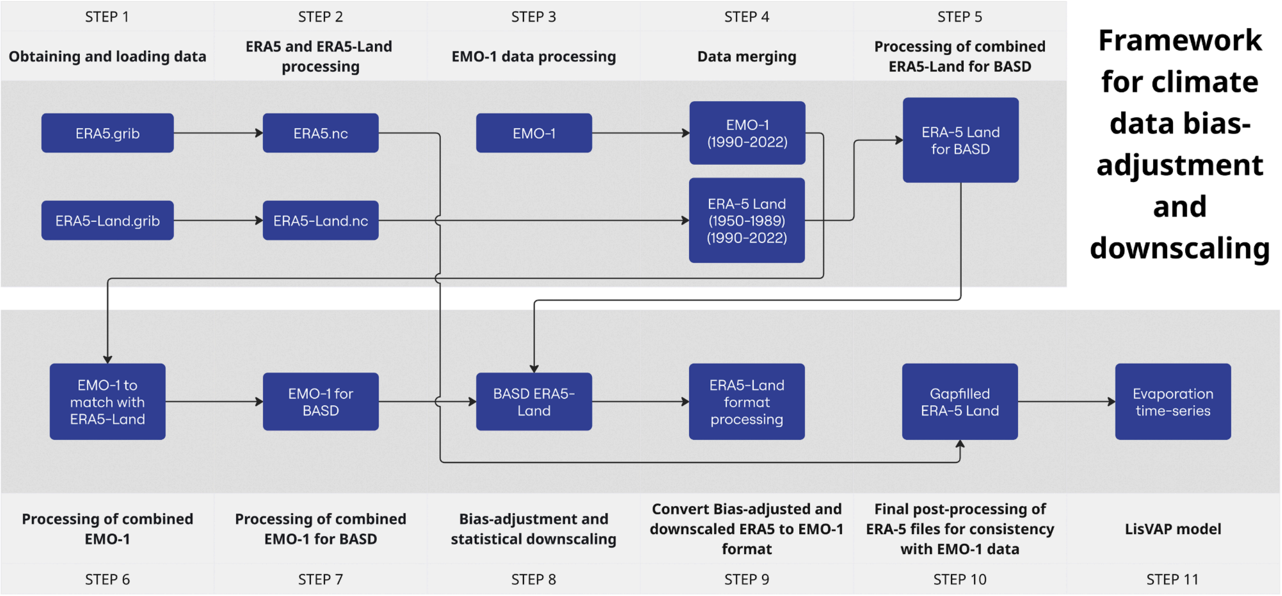

Fig. 1. Structure of the CLIMB framework for climate data bias-adjustment and downscaling. The workflow consists of eleven steps: data acquisition and conversion (Steps 1–2), EMO-1 processing (Step 3), merging of ERA5, ERA5-Land, and EMO-1 datasets (Step 4), bias-adjustment and statistical downscaling (Step 5, Step 8), format conversion and consistency checks (Steps 6–9), and final time-series generation for all variables and with using the LisVAP model (Step 10–11).

├─── Step_1/ to Step_11
├─── Step-by-step-guide.ipynb

Below is a detailed breakdown of each step:

Framework contains scripts and inputs/outputs of each workflow step for designing and developing an automated event attribution for heatwaves and droughts.

1. **Isimip3basd-master/** - contains the bias-adjustment and downscaling model scripts developed by Stefan Lange [3].
2. **SCRIPTS/** - contains all the necessary scripts required to complete the workflow. The scripts are named according to the workflow step, for example: step_1.sh, step_2.sh.
   - **Step_1/** - contains all the downloaded ERA5 reanalysis and ERA5-Land data in GRIB format. As shown in the example below, the files conventions are divided into 12 segments for each year representing different months.
     - ERA5_(year)_1.grib
     - ERA5_(year)_2.grib
   - **Step_2/** - Conversion of monthly GRIB files into daily NetCDF4 files representing each year as a single NetCDF4 file.
     - ERA5_for_gapfill/ - contains ERA5 reanalysis data converted into yearly NETCDF4 format.
     - ERA5_land_daily/ - contains ERA5-Land data converted into yearly NETCDF format.
   - **Step_3/** - Contains EMO-1 downloaded dataset for each variable and downscaled to the size of the region of interest.
     - **emo_data/** - contains the downloaded emo dataset with each folder inside representing separate variables.
   - **Step_4/** - Contains merged data for EMO-1 from 1990–2022 and ERA5-Land from 1950–2022.
     - **Merge_emo1/** - contains merged EMO-1 data in single file for each variable from 1990–2022.
     - **Merge_ERA5/** - contains merged ERA5-Land data in two files for each variable from 1950–1990 and 1990–2022.
   - **Step_5/** - contains processed ERA5-Land for BASD script by modifications in dimensions of the NetCDF file to make it compatible with the ISIMIP3BASD script. The folder contains both the ERA5-Land modified files and EMO-1 merged files. For example, the file conventions are as follows:
     - EFAS_hurs_1990_2022.nc
     - ERA5_hurs_ERA5_1950_1990.nc
   - **Step_6/** - This step contains the remapped EMO-1 data to match the resolution of ERA5-Land data. For example, the file conventions are as follows and are similar for each variable:
     - hurs_1990_2022_t_aggregate.nc
     - pr_1990_2022_t_aggregate.nc
   - **Step_7/** - The remapped EMO-1 was similarly pre-processed for change in dimensions to be suitable for ISIMIP3BASD script. The output is provided in this step. For example, the file conventions are as follows and each variable is accompanied by an aggregate file:
     - EFAS_hurs_1990_2022.nc
     - EFAS_hurs_1990_2022_aggregate.nc
   - **Step_8/** - The folder contains the output of BASD performed with the ISIMIP3BASD scripts. The file conventions after the output are as follows:
     - ERA5_hurs_ERA5_1950_2022.nc
     - ERA5_sfcWind_ERA5_1990_2022.nc
   - **Step_9/** - The folder contains output of bias-adjusted and downscaled ERA5-Land which is converted to EMO-1 format. The output is back to yearly for each variable per file to match with the EMO-1 format back in Step_3. The file conventions after the output are as follows:
     - pd_1950.nc …. pd_2022.nc
     - pr_1950.nc …. pr_2022.nc
   - **Step_10/** - Step_10/ – The folder contains the gap-filled, post-processed ERA5-Land fields for 1990–2022. In this step, ERA5 is used only to fill coastal and sea grid cells where ERA5-Land is undefined, while all other values remain taken from the bias-adjusted ERA5-Land. The file conventions follow those of Step_9 (one NetCDF file per year and variable).
   - **Step_11/** - The folder contains configuration and example output of potential reference evapotranspiration calculated with the LISVAP model. The LISVAP code itself is not redistributed; instead, this folder provides:
     - basemap/ - a basemap directory prepared for Poland (land/sea mask and static maps required by LISVAP).
     - **config.xml** - a sample LISVAP configuration file adapted to the CLIMB workflow
     - **Lisflood-lisvap/** - create this folder to upload scripts for running LISVAP model.
     - **output/** - The output of LISVAP is saved in this folder
     - **readme.**txt – instructions on how to install LISVAP and PCRaster from the official sources and how to run LISVAP with this configuration.

The entire workflow is modular and reproducible. It can be adapted for other regions and hazards with minimal modifications. The workflow is organised in four processing blocks that communicate exclusively via NetCDF files. Block A (Steps 1–2) downloads and preprocesses ERA5 / ERA5-Land on the target grid. Block B (Steps 3–7) prepares the observational reference dataset; in the present implementation this is EMO-1, but the same block can be replaced by analogous preprocessing for national or regional gridded datasets as long as the resulting fields follow the same grid and variable naming conventions. Block C (Step 8) applies the ISIMIP3BASD bias-adjustment and downscaling, which only assumes that it receives a "model" (reanalysis) and a "reference" NetCDF file in the BASD input format. Block D (Steps 9–11) performs post-processing and hydrological preparation. This structure allows users to insert additional intermediate steps or to substitute individual blocks (e. g. using another reference dataset) without changing the rest of the pipeline, provided that the expected NetCDF structure is preserved.

Each processing step is documented in detail in the Jupyter Notebook (step-by-step-guide.ipynb) included in the GitHub repository. This notebook contains explanations, code snippets, and usage examples for all steps of the workflow, serving as both a user manual and training material for new users.

2.2. Software functionalities

The major functionalities of the workflow are:

- Automated data download from the Copernicus Climate Data Store API (ERA5, ERA5-Land) and integration with EMO-1.
- Preprocessing and conversion of GRIB files into daily NetCDF, including variable derivation (e.g. temperature range, skewness).
- Bias adjustment and downscaling using ISIMIP3BASD to align ERA5-Land data with EMO-1 observational references.
- Hydrological modelling with LisVAP to compute potential reference evapotranspiration.
- Output generation in standardized NetCDF format, enabling straightforward use in subsequent analyses such as drought detection or event attribution studies.
- Automation and reproducibility through fully scripted steps, modular folder structure, and cron-based scheduling ready.

2.3. Data sources and core tools

- ERA5 [19] is the fifth-generation global reanalysis from ECMWF, providing consistent climate and weather data since 1950. ERA5 integrates model simulations with observations through data assimilation, producing a long-term, continuous record of essential variables such as temperature, precipitation, radiation, and wind. For this workflow, ERA5 served as the global reference dataset covering 1950–2024.

- ERA5-Land [20] is a high-resolution (9 km) replay of the ERA5 land-surface component, optimized for terrestrial applications. It provides hourly output for variables including temperature, precipitation, radiation, and wind, with oceanic regions masked to reduce data volume. ERA5-Land formed the primary input dataset in this workflow.
- EMO-1 [12] is a gridded European meteorological observation dataset providing sub-daily and daily data for temperature, precipitation, wind, radiation, and humidity. Based on quality-controlled ground observations, EMO-1 serves here as the observational reference for bias adjustment and downscaling of ERA5-Land due to its higher resolution.
- ISIMIP3BASD [13] is a Python-based tool for bias adjustment and statistical downscaling, applying parametric quantile mapping methods to correct distributional biases while preserving long-term trends. In this workflow, it was used to align ERA5-Land data with the observational reference EMO-1.
- LisVAP [17] is a preprocessing tool for the LISFLOOD [14] hydrological model, designed to compute potential reference evapotranspiration (ET_0), as well as potential evaporation from bare soil and open water. Within the workflow, LisVAP was used to derive ET_0 from bias-adjusted ERA5-Land inputs.

In this study we use ERA5-Land as the primary meteorological forcing, complemented by ERA5 only for consistency checks and occasional gap filling. ERA5-Land provides a higher effective horizontal resolution over land ($0.1^\circ \approx 9$ km compared to $0.25^\circ \approx 31$ km in ERA5) and was specifically developed to improve the representation of the terrestrial water and energy cycles for land applications, including hydrology and water resources management. This choice is consistent with existing Copernicus and JRC workflows (e.g. EMO-1 and GloFAS-ERA5-Land) and closely matches the spatial scale of the EMO-1 observational grid, thereby reducing the amount of spatial downscaling required prior to bias adjustment. In coastal regions, ERA5-Land occasionally exhibits missing values at the land–sea boundary due to differences in the land–sea mask. In Step 10 we therefore use ERA5 as an auxiliary gap-filling dataset restricted to these cells: whenever a grid point is undefined in ERA5-Land, the corresponding value from ERA5 is inserted, while all other ERA5-Land values remain unchanged. This approach restores a continuous field over the full target domain and provides a basic synoptic description over adjacent marine areas, while preserving the higher-resolution, bias-adjusted ERA5-Land product as the primary forcing over land.

In the current implementation, the workflow has been tested on a core set of meteorological variables essential for event attribution and hydrological analysis: 10 m u-component of wind, 10 m v-component of wind, 2 m dewpoint temperature, 2 m air temperature, surface solar radiation downwards, and total precipitation. These variables cover thermal, radiative, hydrological, and dynamical aspects of climate extremes. While the workflow was validated on this subset, its modular structure allows users to easily adapt the scripts to additional variables depending on project requirements, making it suitable for a wide range of applications in climate impact studies.

2.4. Workflow implementation

The workflow is implemented as a series of modular Bash scripts that coordinate data processing steps in a repeatable manner. Each step invokes dedicated external libraries and tools for handling climate data available within `PIP` or the `Conda` environment.

The workflow has been tested under Ubuntu 22.04 (also via WSL2 on Windows) with Python 3.11.6 and the following library versions: CDO 2.2.3, cdsapi 0.7.0, NetCDF4 1.7.1, xarray 2024.7.0, pandas 2.2.2, shapely 2.0.5, Cartopy 0.23.0, scipy 1.14.0, among others (see repository for full requirements). Hydrological variables are computed with LisVAP, which depends on PCRaster (4.4.1).

In Step 8 we apply the ISIMIP3BASD trend-preserving bias-adjustment and statistical downscaling method to daily ERA5-Land fields using EMO-1 as the reference. We employ the official ISIMIP3BASD code in its recommended trend-preserving configuration for daily data, without modifications to the underlying algorithm. For each variable, the method is calibrated on the full multi-decadal overlap between ERA5-Land and EMO-1 (1990–2022) and subsequently applied to the entire reanalysis period 1950–2024. In practice, the 1950–1989 and 1990–2022 segments are processed separately as “future” periods, but both use the same 1990–2022 calibration. Our choices are limited to the selection of variables, the spatial domain, and the definition of this calibration period; all other settings follow the ISIMIP3BASD defaults.

3. Illustrative examples

To illustrate the capabilities of the CLIMB framework, we applied the pipeline to ERA5, ERA5-Land, and EMO-1 datasets for Poland. Input data were downloaded via the Copernicus Climate Data Store API and processed through the complete workflow, covering the period 1950–2024. The pipeline produced daily NetCDF files containing a set of key variables: maximum temperature (TX), minimum temperature (TN), precipitation (PR), wind speed (WS), solar radiation (RG), and humidity (PD).

Fig. 2 presents illustrative outputs for selected variables and years. The left panels show daily time series of maximum temperature (TX), minimum temperature (TN), and reference evapotranspiration (ET_0), with smoothed 7-day means, uncertainty ranges, and long-term linear trends. The right panels illustrate corresponding daily spatial fields over Poland, demonstrating the framework’s ability to generate both high-resolution maps and temporally consistent series from the same workflow.

By combining automated data processing with reproducible scripts, the workflow ensures that high-resolution climate information is accessible not only for research but also for operational contexts, such as drought early warning, heatwave attribution, or regional climate impact modelling.

Beyond the case study for Poland, the repository includes a step-by-step tutorial notebook that mirrors the bash-based workflow and explains how to visualize and inspect the resulting NetCDF files (e.g. via a reusable Python plotting function and standard GIS tools).

4. Impact

The CLIMB workflow has several important impacts for climate research and applications. First, it enables new research questions to be addressed by providing long, bias-adjusted daily time series at high spatial resolution. Such datasets allow for the systematic attribution of droughts, heatwaves, and other extremes over multi-decadal periods, making it possible to assess changes in frequency, intensity, and duration of events since 1950 [11].

Second, the workflow improves the pursuit of existing research questions by lowering technical and computational barriers. Instead of manually downloading and processing GRIB and NetCDF files, often terabytes in size, users can run a fully scripted pipeline that automatically performs data harmonization, bias adjustment, and hydrological variable computation. This facilitates reproducibility and accelerates the time from data acquisition to analysis-ready outputs, which are exported in CSV format suitable for direct use in statistical or machine learning models.

Third, the workflow changes daily research practice by providing a transparent and automated solution that can be scheduled to update continuously via cron. This allows researchers and institutions to

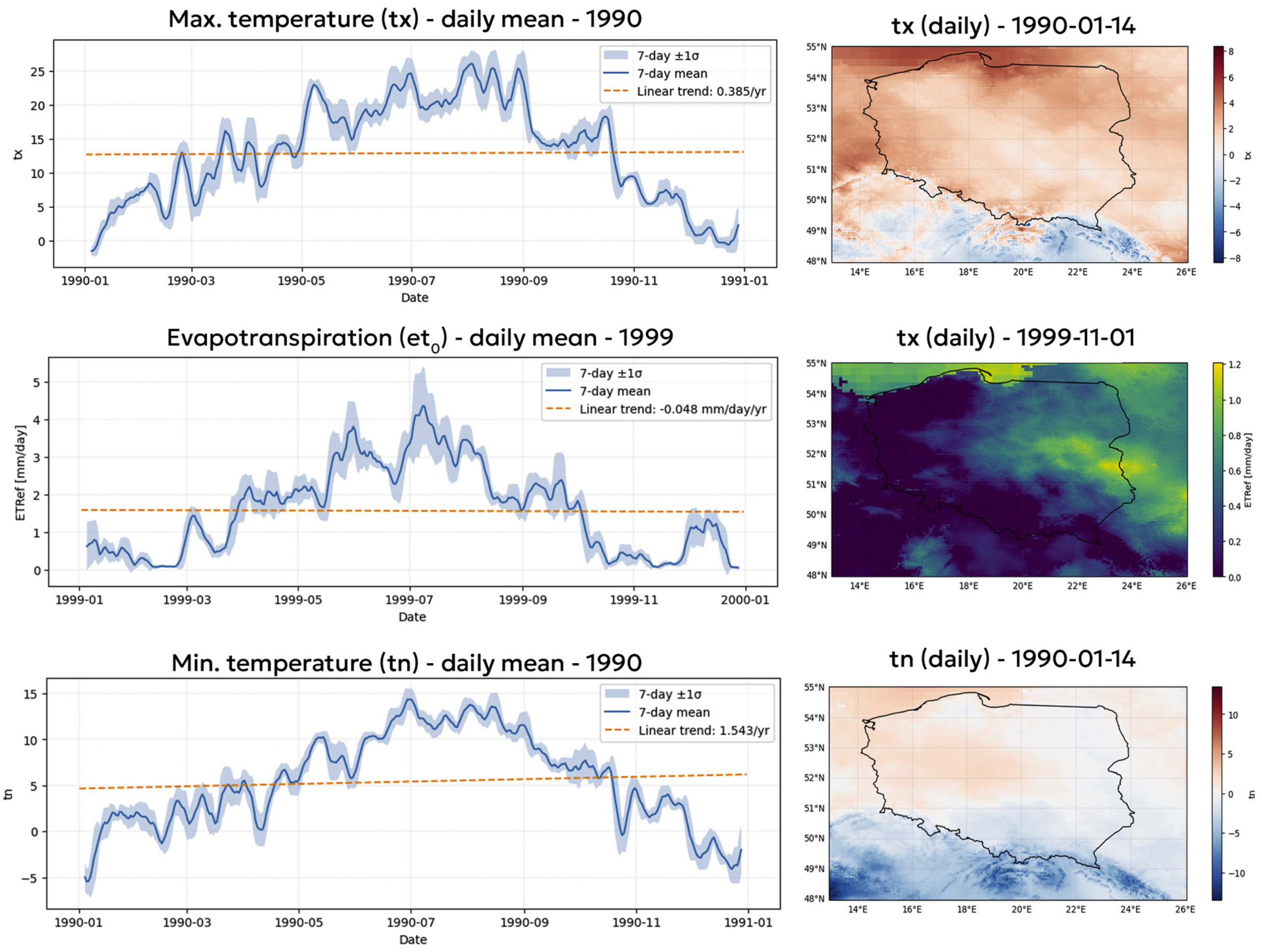

Fig. 2. Example outputs from the CLIMB framework for Poland. Left panels: daily mean time series of maximum temperature (TX, 1990), minimum temperature (TN, 1990), and reference evapotranspiration (ET_0, 1999) with 7-day averages, uncertainty bands, and linear trends. Right panels: corresponding daily maps showing spatial variability for selected dates.

maintain up-to-date climate datasets for their regions of interest, bridging the gap between reanalysis archives and operational applications such as drought monitoring, agricultural impact modelling, or climate risk assessment.

The software has been used on Polish climate data (1950–2024) but can be adapted to other European regions or even global domains. Its modular design and open-source license (MIT) ensure that it can be reused, extended, and combined with other frameworks. Within the COMPASS project, the workflow contributes to the operationalization of event attribution by producing harmonized datasets that support the study of compound and cascading extremes [17]. Beyond research, it has potential relevance for government agencies, NGOs, and commercial stakeholders seeking robust, high-resolution climate information for adaptation planning and risk management.

Although the workflow was validated on six core climate variables (temperature, dewpoint, precipitation, radiation, and wind components), its modular design enables extension to other variables, ensuring adaptability across diverse research and application domains.

The original purpose of EMO-1, and hence this workflow was to provide all necessary inputs for European-scale hydrological modelling in LISFLOOD model. We particularly based our workflow on Tilloy et al. (2025), which was so far limited to 1950–2020, but an update is planned to bring this hydrological dataset to current year with the help of our CLIMB implementation.

5. Conclusions

The development of the CLIMB workflow demonstrates how large and complex climate datasets can be transformed into user-ready information through automation, reproducibility, and open access. Rather than focusing solely on methodological innovation, the framework emphasizes usability: it bridges the gap between reanalysis archives in GRIB/NetCDF format and the practical needs of researchers and practitioners who require daily, bias-adjusted, and spatially refined datasets.

By validating the workflow on more than seven decades of climate data for Poland, the study shows both the feasibility and the value of a scripted, modular approach to climate data processing. The framework is not confined to a single case study: its design allows users to adapt it to new regions, variables, or hazard types with minimal modification.

Looking ahead, the workflow provides a solid foundation for integration with downstream applications such as crop yield models, hydrological forecasting, or operational climate services. Its openness and flexibility ensure that it can evolve in parallel with emerging datasets and analytical needs, supporting both fundamental research and practical adaptation planning in the face of climate extremes.

CRediT authorship contribution statement

Jakub Śledziowski: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Conceptualization. **Paweł Terefenko:** Writing – review

& editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis. **Andrzej Giza:** Writing – review & editing, Validation, Formal analysis. **Kamran Tanwari:** Writing – review & editing, Writing – original draft, Validation, Software. **Dominik Paprotny:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paweł Terefenko reports financial support was provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by COMPASS project (Grant Agreement No 101135481) under the European Union's HORIZON Research and Innovation Actions Programme. Co-financed by the Minister of Science under the "Regional Excellence Initiative" Program for 2024-2027 (RID/SP/0045/2024/01).

References

[1] Seneviratne SI, et al. Weather and climate extreme events in a changing climate. in *climate change 2021 – the physical science basis*. Camb Univ Press 2023:1513–766. https://doi.org/10.1017/9781009157896.013.

[2] van Oldenborgh GJ, et al. Attribution of the Australian bushfire risk to anthropogenic climate change. Nat Hazards Earth Syst Sci 2021;21:941–60.

[3] Trenberth KE, Fasullo JT, Shepherd TG. Attribution of climate extreme events. Nat Clim Chang 2015;5:725–30.

[4] Otto FEL, et al. Climate change increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan. Environ Res 2023;2:025001.

[5] Perkins-Kirkpatrick SE, et al. Frontiers in attributing climate extremes and associated impacts. Front Clim 2024;6.

[6] Strauss BH, et al. Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. Nat Commun 2021;12:2720.

[7] Stott PA, et al. Attribution of extreme weather and climate-related events. WIREs Clim Change 2016;7:23–41.

[8] Iturbide M, et al. The R-based climate4R open framework for reproducible climate data access and post-processing. Environ Model Softw 2019;111:42–54.

[9] Boateng D, Mutz SG. pyESDv1.0.1: an open-source Python framework for empirical-statistical downscaling of climate information. Geosci Model Dev 2023; 16:6479–514.

[10] Spuler FR, Wessel JB, Comyn-Platt E, Varndell J, Cagnazzo C. Ibicus: a new open-source Python package and comprehensive interface for statistical bias adjustment and evaluation in climate modelling (v1.0.1). Geosci Model Dev 2024;17:1249–69.

[11] Campalani P, Crespi A, Pittore M, Zebisch M. Climdex-kit: an open software for climate index calculation, sharing and analysis towards tailored climate services. Environ Model Softw 2025;190:106442.

[12] Thiemig V, et al. EMO-5: a high-resolution multi-variable gridded meteorological dataset for Europe. Earth Syst Sci Data 2022;14:3249–72.

[13] Lange S. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). Geosci Model Dev 2019;12:3055–70.

[14] Van Der Knijff JM, Younis J, De Roo APJ. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. Int J Geogr Inf Sci 2010;24:189–212.

[15] Tilloy A, et al. HERA: a high-resolution pan-European hydrological reanalysis (1951–2020). Earth Syst Sci Data 2025;17:293–316.

[16] Paprotny D, et al. Merging modelled and reported flood impacts in Europe in a combined flood event catalogue for 1950–2020. Hydrol Earth Syst Sci 2024;28: 3983–4010.

[17] Burek P, Ntegeka V, Knijff van der J. LISVAP, evaporation pre-processor for the lisflood water balance and flood simulation model – revised user manual. Publications Office; 2013. 10.2788/26160.

[18] Marsz AA, Sobkowiak L, Styszyńska A, Wrzesiński D. Causes and course of climate change and its hydrological consequences in the Greater Poland region in 1951-2020. Quaest Geogr 2022;41:183–206.

[19] Hersbach H, et al. The ERA5 global reanalysis. Q J R Meteorol Soc 2020;146. 1999–2049.

[20] Muñoz-Sabater J, et al. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. Earth Syst Sci Data 2021;13:4349–83.