University of Natural Resources and Life Sciences, Vienna

Ensemble of Bias Corrected Climate Change Scenarios for the Western Balkan Region

Methodical Background

Project ClimaProof - Deliverable 1.2.2

Version 2.3

Vienna, May 2022

This document presents the methodical background for the ensemble of bias-corrected climate scenarios and tools developed within the ClimaProof[1] project.

The scenarios are available for download via the CCCA Data Centre:

https://data.ccca.ac.at/group/climaproof

Additionally, a user guide on the handling of the scenarios as well as the tools developed is provided:

https://github.com/boku-met/climaproof-docs

Please note that in the course of further development, modifications and changes might occur. This document will be updated accordingly.

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[1] For information on the project please see page 5 or https://github.com/boku-met/climaproof-docs

The ClimaProof project

The project “**Enhancing Environmental Performance and Climate Proofing of Infrastructure Investments in the Western Balkan Region from an EU integration perspective” (ClimaProof)** is financed by the Austrian Development Agency and implemented by the United Nations Environmental Programme. ClimaProof will result in increased technical capacities of the relevant national authorities in the field of climate change adaptation, specifically climate proofing of road infrastructure, green infrastructure and evidence-based policy development in the field of climate change adaptation.

Furthermore, it aims at raising awareness of the relevant government officials in the Western Balkan region in regards to climate change in general, and in particular on climate change impacts on road infrastructure and the specific needs of the infrastructure sectors for increased resilience.

This will be achieved through the development of a regional strategy on climate resilient infrastructure, tailor-made training modules and development of guidelines, enhanced dialogue via regional communication tools as well as exchange of information, experiences and best practices via networking and training events.

The first component of the ClimaProof project focuses on **understanding the future climate and weather patterns in the target region**. This includes strengthening national capacities to understand climate change and climate change related risks in the region through **improvement of the information base.**

In order to do so the Institute of Meteorology and Climatology of the University of Natural Resources and Life Sciences, Vienna (BOKU-Met) evaluated available regional climate change projections (EURO-CORDEX, MED-CORDEX) compared it with observational data and generated an **ensemble of bias-corrected climate change scenarios for the Western Balkan Region**.

BOKU-Met further developed an **easy to handle program for bias correction** (ICC-OBS Tool) which allows the integration of additional local observations for further improvement of the scenarios on sub-regions (e.g. countries, river catchment, …), a model selection tool, as well as a downscaling tool.

The methods applied are presented in this document.

The climate change scenarios as well as the tools developed are freely available.

Table of Contents

1. Introduction

State of the art climate models simulate the climate quite well and produce appropriate climate projections. However, due to simplifications and limited spatial resolution, climate model output still deviates from real world climate, especially when looking at small-scale regional or local climates. Those systematic errors are called biases (Maraun & Widmann, 2018:p.4).

To remove the models biases and generate more accurate climate projections, the models output data can be processed with bias correction methods (Maraun & Widmann, 2018:pp.4–5). To represent the full range of predicted changes an ensemble of bias-corrected climate scenarios is produced that incorporates different combinations of global and regional climate models available for the Western Balkan region.

Within the ClimaProof project bias correction of the climate scenarios was accomplished by:

1) Selecting relevant models and observational datasets for bias correction
2) Regridding models and observations to a common grid with a resolution of 0.1°
3) Bias correction of the models using Scaled Distribution Mapping (SDM)

As guidance for the selection of a suitable model out of the ensemble of climate scenarios, the **ClimaProof Model Selection Tool** is provided. This easy-to-use tool compares climate change signals of the different models within a user-specific region.

Optionally, further modification of the provided dataset can be done by applying user-friendly tools that have been developed especially for the ClimaProof project:

a) Adding additional station data for improved bias correction (**ICC-OBS Tool**)
b) Downscaling to higher resolution (**ClimaProof Downscaling Tool**)

The following document gives a comprehensive summary on the methodical background leading to the final set of bias-corrected model scenarios and tools (Model Selection Tool, ICC-OBS Tool, Downscaling Tool). A user guide for the Tools with step-by-step instructions is provided in a separate document (available for download via https://github.com/boku-met/climaproof-docs).

2. Ensemble of bias-corrected climate scenarios

2.1. Features

temporal resolution	daily
spatial resolution	**0.1°or (0.01° on request)**
temporal extent	1981 – 2099/2100 (depending on the model)

geographic extent:	Western Balkan Region (Albania, Bosnia and Herzegovina, Croatia, Kosovo*, Montenegro, North Macedonia, Serbia) (see Figure 1) * Reference to Kosovo shall be understood to be in the context of Security Council Resolution UNSCR 1244/99
data format	netCDF

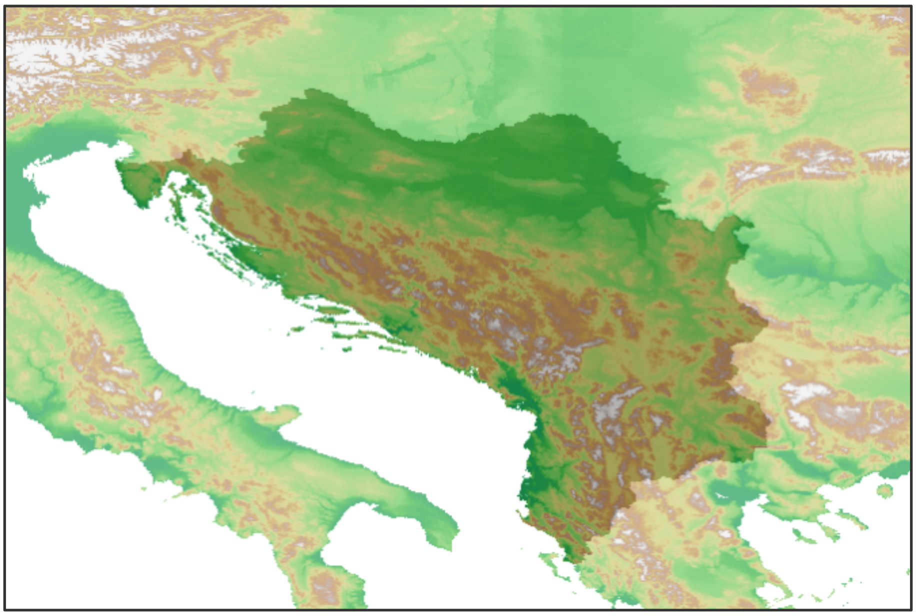

Figure 1: Map of the area covered by the ensemble of bias-corrected climate scenarios (illustrated by BOKU-Met, Datasource: ESRI, Diva-gis)

2.2. Variables and indicators

Table 1 shows the meteorological variables, which are available using the process described below. Apart from the standard parameters temperature and precipitation additional parameters were chosen to be included in the dataset: radiation, 10-m wind speed and relative humidity. This set of variables is adequate for calculating derived variables like evapotranspiration and providing necessary input to climate change impact models.

Table 1: Climatological variables included in the bias-corrected scenarios

Variable	Unit	Description
tasmax	**°C**	**daily maximum near-surface air temperature**
tasmin	**°C**	**daily minimum near-surface air temperature**
pr	**mm/day**	**total daily precipitation**
rsds	**W/m²**	**surface downwelling shortwave radiation**
sfcWind	**m/s**	**daily mean 10-m wind speed**
hurs	**%**	**daily mean near-surface relative humidity**

In addition to the meteorological parameters, several relevant climate indicators were computed. The indicators were determined in an online survey with experts and authorities working in the fields of infrastructure development, planning, construction, maintaining and operating.

Update May 2022: The final list of indicators is currently being developed and will be included in this document as soon as it is finalised. The indicator datasets will be made available along with the other ClimaProof data on the CCCA Data Centre.

2.3. Availabilty

The ensemble of bias-corrected climate scenarios is available for download via the CCCA Data Centre (https://data.ccca.ac.at/group/climaproof). The dataset is available free of charge.

Every scenario provided can be downloaded separately as a netCDF file (for a full list of models see chapters 2 and 3). To help with the selection of the climate models, the ClimaProof Model Selection Tool is provided (for more details see chapter 5.1).

The scenarios will be provided on a regular grid with a horizontal resolution of 0.1°x0.1° (~11 km). They can be downloaded for the whole area (see Figure 1) or for selected areas on a sub-regional level (e.g. selecting a specific country or specifying latitude and logitude of a bounding box). If required, the downloaded scenarios can further be downscaled to a 0.01° grid (~1 km) using the ClimaProof Downscaling Tool (for more details see chapter 5.3).

Additional own (higher resolved) observational data can be used to further improve the bias-corrected dataset by using the ICC-OBS Tool developed by BOKU-Met (detailed description see chapter 5.2).

A user guide for the ClimaProof Tools is provided for download via

https://github.com/boku-met/climaproof-docs

The guide enables all interested meteorological and climate change experts to use the provided tools.

3. Data sources

The ensemble of bias-corrected climate scenarios for the Western Balkan Region produced within the ClimaProof project is based only on freely available climate model and observational data.

3.1. Regional Climate Models: EURO- and MED-CORDEX

Regional climate model (RCM) scenarios from EURO-CORDEX2 and MED-CORDEX experiments (see Ruti et al., 2016) are the basis for the ensemble of bias-corrected climate scenarios.

[2]We acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups (listed in Table 2 of this paper) for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S.

EURO-CORDEX is part of the worldwide CORDEX initiative and provides regional climate change projections for Europe at a 0.44° and 0.11° resolution. The projections are based on the internationally coordinated framework for improving regional climate scenarios by the WCRP Coordinated Regional Downscaling Experiment (published in Giorgi, Jones & Asrar, 2009) (Jacob et al., 2014:p.564).

MED-CORDEX, also part of the CORDEX initiative, coordinates regional climate modeling activities addressing the specific conditions of the Mediterranean basin. MED-CORDEX models specifically address the characteristics of the Mediterranean sea as a basin by implementing strong air-sea coupling in order to model intense weather phenomena (e.g. mistral and bora winds) and consequences of Saharan dust outbreaks (Ruti et al., 2016:pp.1187–1188). Due to the set-up of the MED-CORDEX experiments, it is expected to see more realistic moisture fluxes in the Mediterranean area leading to more realistic precipitation fields. MED-CORDEX comprises 12 fully-coupled RCMs, 13 stand-alone atmospheric and 10 stand-alone ocean models (Ruti et al., 2016:p.1190).

3.1.1. Representative Concentration Pathways (RCP)

All CORDEX-models are operated with the RCP (Representative Concentration Pathway) scenario set. The scenarios represent pathways that lead to a range of radiative forcing levels in the year 2100, ranging from 2.6 W/m² to 8.5 W/m² (van Vuuren et al., 2011:p.5). The number indicates the additional radiative forcing level at the end of the pathway e.g. RCP 4.5 represents a scenario that leads to a 4.5 W/m² higher radiative forcing level in 2100 compared to pre-industrial.

The RCP scenario set provides a wide range of potential future emissions and concentration pathways for future climate scaling between the different RCP-Scenarios (Weyant et al., 2009). RCP 8.5 is a highly energy-intensive scenario (strong reliance on fossil fuels) as a result of high population growth and a lower rate of technological development (Moss et al., 2010). In contrast, the RCP 2.6 scenario requires very aggressive emission reductions early in the century and deployment of negative emission technologies later in the century to achieve additional radiative forcing of only 2.6 W/m^2 in 2100.

3.1.2. Selection of models

Due to the great number of climate models available, only a subset of relevant models was selected for bias correction within the ClimaProof project. The selection was based on the following criteria:

- availability (only freely available scenarios are used - status as of April 2018),
- domain (models covering the Western Balkan Region),
- daily temporal resolution
- horizontal grid-resolution of 0.11°.

While a great number of EURO-CORDEX models are available with a horizontal resolution of 0.11°, there are only few scenarios of MED-CORDEX available with the same resolution. Furthermore, not

Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

all parameters are available for all models (status April 2018). 2 and 3 show all EURO-CORDEX and MED-CORDEX models used within the ClimaProof project with their original resolution and available parameters (relevant for the project).

All EURO-CORDEX models used are available for the RCP 4.5 and 8.5 scenarios - five of them are additionally available for the RCP 2.6 scenario. Out of the MED-CORDEX models with a resolution of 0.11°, one model uses the RCP 4.5 scenario and two models the RCP 8.5 scenario.

Additionally, the MED-CORDEX model developed and used by the University of Belgrade (MED-44i_MPI-ESM-LR_rcp85_r1i1p1_UNIBELGRADE-EBUPOM2c_v1) is used. Although it runs on a resolution of 0.44°, it is expected to provide relevant additional information on the very specific meteorological and climatological processes within the Western Balkan Region. It is further the only fully-coupled RCM.

Table 2: List of EURO-CORDEX model scenarios compiling the bias-corrected ensemble

EURO-CORDEX Models	Res.	Variables
CNRM-CERFACS-CNRM-CM5_rcp26_r1i1p1_CNRM-ALADIN53_v1	**0.11°**	**pr**
CNRM-CERFACS-CNRM-CM5_rcp45_r1i1p1_CNRM-ALADIN53_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs**
CNRM-CERFACS-CNRM-CM5_rcp85_r1i1p1_CNRM-ALADIN53_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs**
CNRM-CERFACS-CNRM-CM5_rcp45_r1i1p1_CLMcom-CCLM4-8-17_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
CNRM-CERFACS-CNRM-CM5_rcp85_r1i1p1_CLMcom-CCLM4-8-17_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
CNRM-CERFACS-CNRM-CM5_rcp45_r1i1p1_SMHI-RCA4_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
CNRM-CERFACS-CNRM-CM5_rcp85_r1i1p1_SMHI-RCA4_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp26_r12i1p1_CLMcom-CCLM4-8-17_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp45_r12i1p1_CLMcom-CCLM4-8-17_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp85_r12i1p1_CLMcom-CCLM4-8-17_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp26_r12i1p1_KNMI-RACMO22E_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp45_r12i1p1_KNMI-RACMO22E_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp85_r12i1p1_KNMI-RACMO22E_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp45_r1i1p1_KNMI-RACMO22E_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp85_r1i1p1_KNMI-RACMO22E_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**
ICHEC-EC-EARTH_rcp26_r3i1p1_DMI-HIRHAM5_v1	**0.11°**	**tasmin, tasmax, pr, rsds, hurs, sfcWind**

EURO-CORDEX Models	Res.	Variables
ICHEC-EC-EARTH_rcp45_r3i1p1_DMI-HIRHAM5_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
ICHEC-EC-EARTH_rcp85_r3i1p1_DMI-HIRHAM5_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
IPSL-IPSL-CM5A-MR_rcp45_r1i1p1_IPSL-INERIS-WRF331F_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
IPSL-IPSL-CM5A-MR_rcp85_r1i1p1_IPSL-INERIS-WRF331F_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
IPSL-IPSL-CM5A-MR_rcp45_r1i1p1_SMHI-RCA4_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
IPSL-IPSL-CM5A-MR_rcp85_r1i1p1_SMHI-RCA4_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp26_r1i1p1_SMHI-RCA4_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp45_r1i1p1_SMHI-RCA4_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp85_r1i1p1_SMHI-RCA4_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp45_r1i1p1_CLMcom-CCLM4-8-17_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp85_r1i1p1_CLMcom-CCLM4-8-17_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp45_r1i1p1_KNMI-RACMO22E_v2	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MOHC-HadGEM2-ES_rcp85_r1i1p1_KNMI-RACMO22E_v2	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp45_r1i1p1_CLMcom-CCLM4-8-17_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp85_r1i1p1_CLMcom-CCLM4-8-17_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp45_r1i1p1_MPI-CSC-REMO2009_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp85_r1i1p1_MPI-CSC-REMO2009_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp45_r2i1p1_MPI-CSC-REMO2009_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp85_r2i1p1_MPI-CSC-REMO2009_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp26_r1i1p1_SMHI-RCA4_v1a	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp45_r1i1p1_SMHI-RCA4_v1a	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MPI-M-MPI-ESM-LR_rcp85_r1i1p1_SMHI-RCA4_v1a	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
NCC-NorESM1-M_rcp45_r1i1p1_DMI-HIRHAM5_v2	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind

EURO-CORDEX Models	Res.	Variables
NCC-NorESM1-M_rcp85_r1i1p1_DMI-HIRHAM5_v2	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind

Table 3: List of MED-CORDEX model scenarios compiling the bias-corrected ensemble

MEDCORDEX Model (Atmosphere RCM)	Res.	Variables
MED-11_ICTP-RegCM4_rcp85_r1i1p1_ICTP-RegCM4-3_v1	0.11°	tasmin, tasmax, rsds, hurs
MED-11_CNRM-CM5_rcp45_r8i1p1_CNRM-ALADIN52_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MED-11_CNRM-CM5_rcp85_r8i1p1_CNRM-ALADIN52_v1	0.11°	tasmin, tasmax, pr, rsds, hurs, sfcWind
MEDCORDEX Model (Fully-Coupled RCM)		
MED-44i_MPI-ESM-LR_rcp85_r1i1p1_UNIBELGRADE-EBUPOM2c_v1	0.44°	pr, rsds

3.1.3. Comparison of MED-CORDEX and EURO-CORDEX

Due to the very limited availability of MED-CORDEX model data, a comprehensive comparison between the two experiments could not be made.

A comparison between precipitation data of the only similar model combination of GCM and RCM was made for the models CNRM-CERFACS-CNRM-CM5_r1i1p1_CNRM-ALADIN53_v1 and MED-11_CNRM-CM5_r8i1p1_CNRM-ALADIN52_v1 for the historical period (1981-2010) and the RCP 8.5 scenario for the period 2070-2100.

When comparing yearly precipitation sums (Figure 4) of the historical model data with the observations, one can see a distinct wet bias of both models. The differences between the model for both, the historical as well as the future period are small (Figure 4 and 5).

In the comparison by season both models show an overestimation of precipitation in spring and summer as well as an underestimation in autumn and winter (Figure 2 and 3).

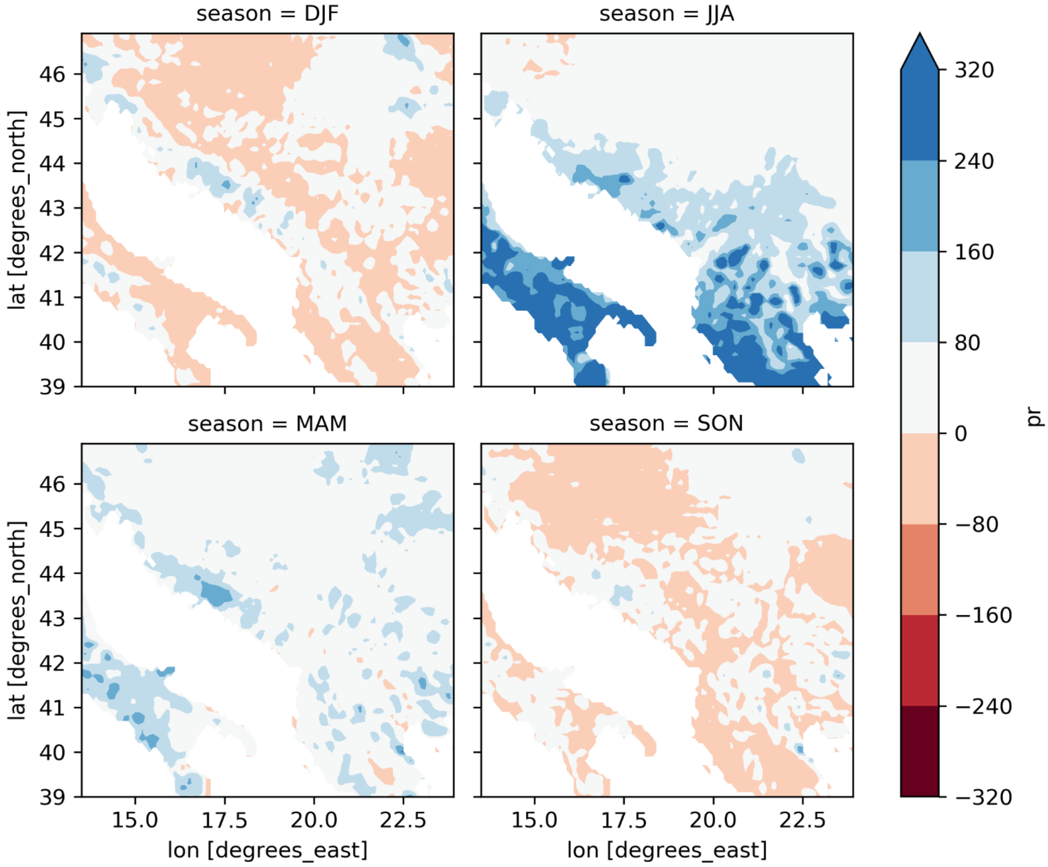

Figure 2: Relative difference in % of mean seasonal precipitation sum of EURO-CORDEX and Observations for the historical period 1981-2010.

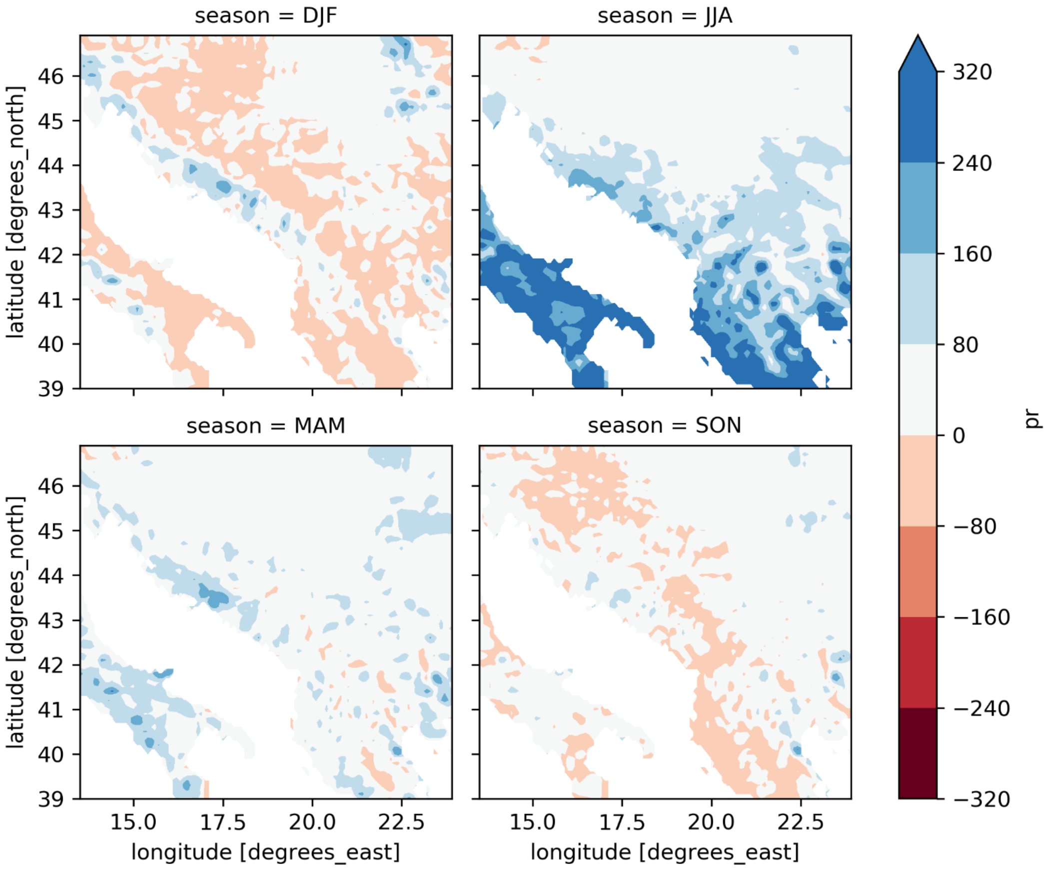

Figure 3: Relative difference in % of mean seasonal precipitation sum of MED-CORDEX and Observations for for the historical period 1981-2010.

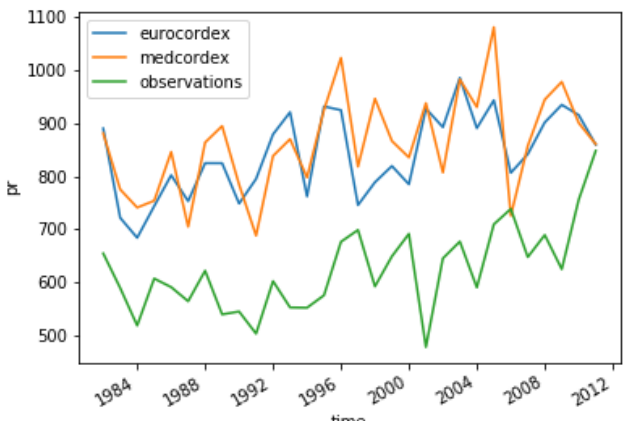

Figure 4: Comparison of annual precipitation sum (mean of the domain) for the historical period.

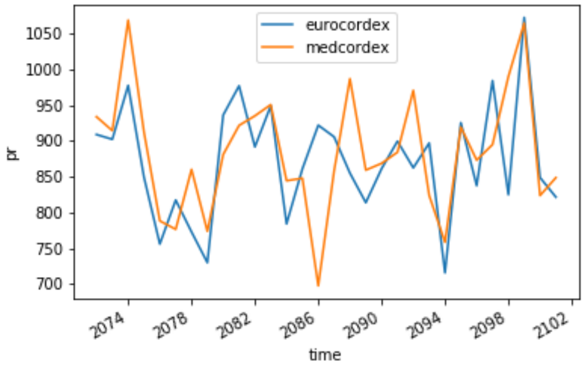

Figure 5: Comparison of annual precipitation sum (mean of the domain) for the end of the 20th century.

3.2. Observational data

The selected climate projections (see chapters 2 and 3) have been bias-corrected with open and freely available observational data. The selection of the datasets for bias correction was based on the criteria quality and resolution. All datasets used are described below. Chapter 4 gives an additional overview.

3.2.1. Carpatclim & Danubeclim

A high quality, homogeneous, high-resolution gridded observational dataset was developed by the CARPATCLIM project. Daily data is provided on a grid with a resolution of 0.1° for the years 1961 - 2010. CARPATCLIM covers the larger Carpathian Region between latitudes 44°N and 50°N, and longitudes 17°E and 27°E (CARPATCLIM, s.a.), thus only covering a small part of the ClimaProof project area, in particular the northern part of Serbia and the north-eastern area of Croatia.

Recently, the same methodology has been applied within the DANUBECLIM project. DANUBECLIM covers the entire area of Serbia, Montenegro and the Srpska Republic (entity of Bosnia and Herzegovina) (European Commission - JRC, 2015). This resulted in a high quality dataset of observational data provided for a great part of the ClimaProof project area.

At the moment however we have no height information for the DANUBECLIM data. Therefore only precipitation is used from the DANUBECLIM dataset. All other variables have a strong height dependency and hence cannot be used without correct underlying height information.

In conclusion, additional data sources need to be used to perform bias correction for the part of the ClimaProof project area, not covered by CARPATCLIM and DANUBECLIM. Figures 7 and 8 show a map with an overview of the datasets used for precipitation and temperature.

3.2.2. E-OBS

E-OBS is a freely available gridded daily dataset for temperature (minimum, maximum, mean), precipitation amount and sea level pressure for the period of 1950-01-01 to 2017-08-31. Within ClimaProof data from Version 17 (released in April 2018) was used. (Download via: https://www.ecad.eu/download/ensembles/download.php (ECA&D, 2018)).

The dataset is based on the European Climate Assessment and Data set (ECA&D) complemented by data from other projects and data provided by national Meteorological and Hydrological Services (Haylock et al., 2008:p.2). However, the quality of the E-OBS dataset is limited by the number of station data provided by each country (most countries do not provide data from all of their stations, and the number of stations varies highly) (Haylock et al., 2008:p.2) (see Figure 6).

A 1x1 km downscaled version of E-OBS (Moreno & Hasenauer, 2016) is also available. After validation of this dataset with SPARTACUS, a high-quality gridded observational dataset for Austria (Hiebl & Frei, 2018), it was concluded that there is no genuine added value in the downscaled version. Once again it was shown that the downscaling procedure does not compensate for the lack of measurements - especially in areas with complex terrain. Therefore, the downscaled E-OBS dataset is not used within the ClimaProof project.

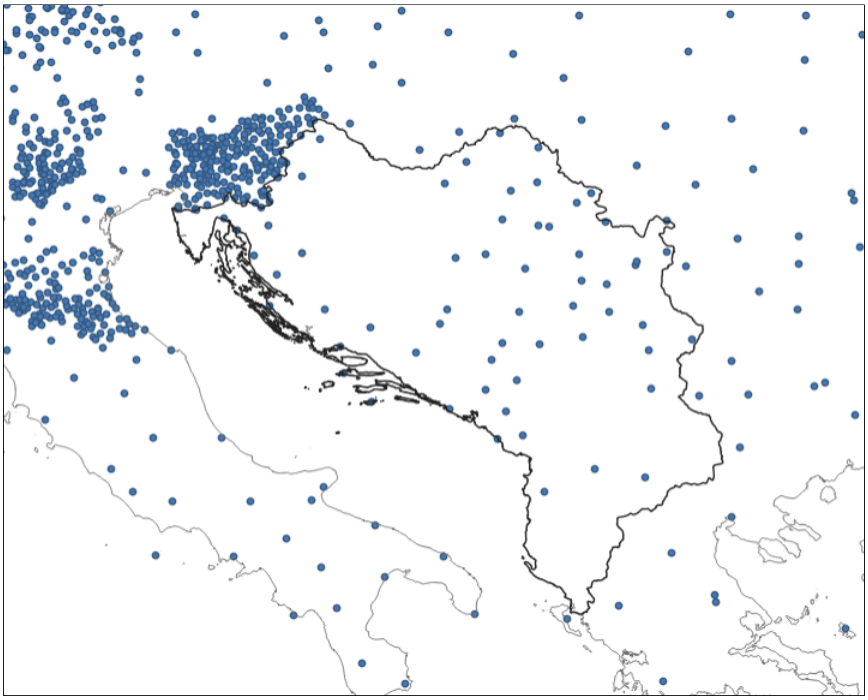

Figure 6: Map of observational stations included in the E-OBS dataset within the projected area.
Illustration by BOKU-Met; Datasource: Eurostat, DivaGis, E-OBS

3.2.3. ERA5

ERA5 is the fifth generation ECMWF climate reanalysis, replacing ERA-Interim. The global reanalysis covers the period from 1979 onwards with a resolution of 0.28° and is available since

January 2019 (Copernicus Climate Change Service (C3S), 2017). It is used for the bias correction of 10-m wind speed and relative humidity (calculated from temperature and dew point temperature).

3.2.4. CHIRPS

CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) is a quasi-global dataset on precipitation with a horizontal resolution of 0.05°. CHIRPS incorporates satellite information on sparsely gauged locations as well as Cold Cloud Duration (CCD) based precipitation estimates and blends station data (Funk et al., 2014:pp.1–2).

3.2.5. SARAH-2

SARAH-2 is the second edition of a satellite-based dataset of surface solar radiation. The data is derived from "satellite-observations of the visible channels of the MVIRI and the SEVIRI instruments on-board the geostationary Meteosat satellites". The data is provided as monthly and daily means as well as 30-minute instantaneous data (Pfeifroth et al., 2017).

Table 4: Observational datasets used for bias correction

Dataset	Variables used within the Project	Horizontal Resolution	Expansion of original dataset	Download
Carpatclim (Szalai et al, 2013; European Commission JRC, 2013)	**tasmax, tasmin, pr, rsds, sfcWind, hurs**	**0.1°**	**44°N - 50°N, 17°E - 27°E**	http://www.carpatclim-eu.org/
Danubeclim (Szalai et al, 2013; European Commission JRC, 2015)	**pr**	**0.1°**	**Serbia, Montenegro and Srpska Republic**	http://www.carpatclim-eu.org/danubeclim
E-OBS (Haylock et al, 2008; ECA&D, 2018)	**tasmax, tasmin**	**0.25°**	**25°N -75°N 40°W-75°E**	https://www.ecad.eu/download/ensembles/download.php
CHIRPS (Funk et al, 2015)	**pr**	**0.05°**	**50°N - 50°S, 180°W - 180°E**	https://www.chc.ucsb.edu/data/chirps
ERA5 (C3S, 2017)	**sfcWind (calc. from u and v), hurs (calc. from mean temperature and dew point temperature)**	**0.28°**	**global**	https://cds.climate.copernicus.eu/cdsapp#!/home
SARAH-2 (Pfeifroth et al, 2017)	**rsds**	**0.05°**	**65°N - 65°S, 65°W - 65°E**	https://doi.org/10.5676/EUM_SAF_CM/SARAH/V002

3.2.6. CHELSA: New global observational data

Since the start of the ClimaProof project, a new global observational dataset is available that may be noteworthy for future bias correction efforts in the project area. The dataset CHELSA (Climatologies at high resolution for the earth's land surface areas) provides global observational data for the period 1979 – 2016 at 30 arcsec resolution. The data is available on a daily basis and includes the variables Daily Mean Precipitation (pr, kg m-2 s-1), Daily Mean Surface Downwelling Shortwave Radiation (rsds, W m-2), Daily Mean Near-Surface Air Temperature (tas, K), Daily Maximum Near Surface Air Temperature (tasmax, K) and Daily Minimum Near Surface Air Temperature (tasmin, K). The data is freely available and can be downloaded here:

https://chelsa-climate.org/downloads/

(State: May 2022)

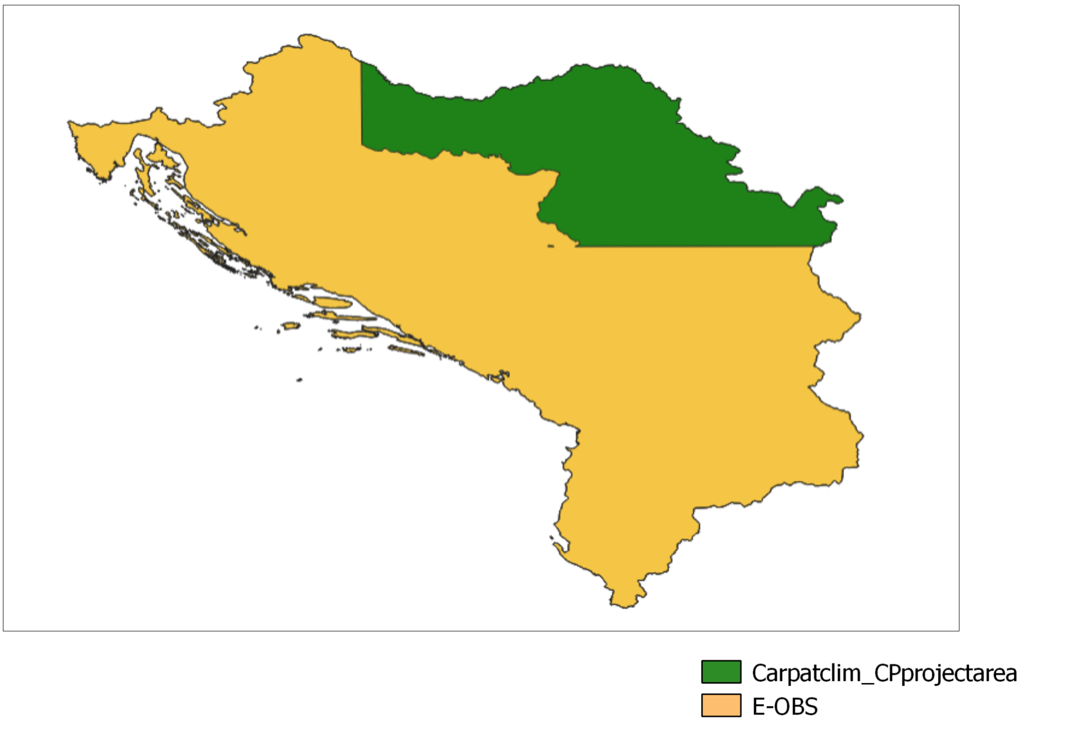

Figure 7: Observational data used for bias correction of temperature ©BOKU-Met, created with QGIS, datasource: DIVA-GIS, Carpatclim

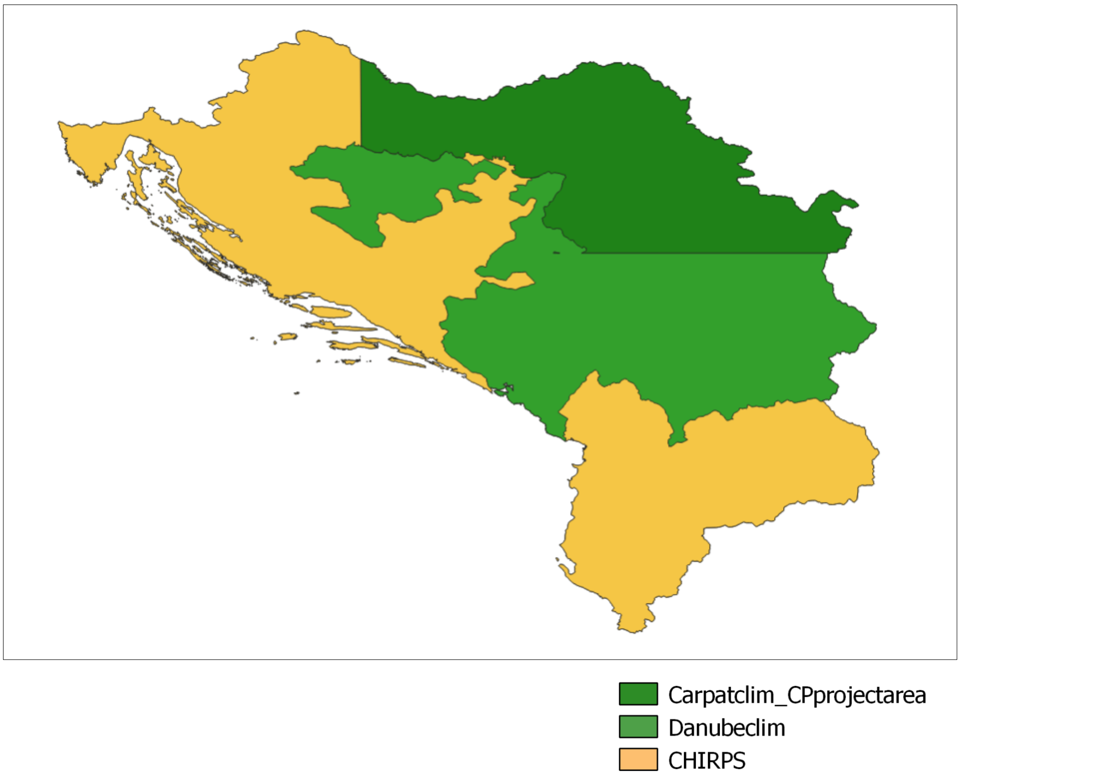

Figure 8: Observational data used for bias correction of precipitation ©BOKU-Met, created with QGIS, datasource: DIVA-GIS, Carpatclim, Danubeclim

4. Methods

4.1. Regridding of model and observational data

To perform bias correction all the model and observational datasets have to be on the same grid. This is necessary, because the correction is applied to every grid point separately. The Carpat/Danubeclim grid with a horizontal resolution of 0.1° was chosen as the common grid. This allows us to use unaltered observational data within the Carpat/Danubeclim domain.

For the observational data outside this domain as well as for the climate models a regridding algorithm has to be applied. The method used for regridding the data to the common grid is based on the Earth System Modelling Framework (ESMF) software **ESMF_RegridWeightGen** (ESMF Reference Manual: https://earthsystemmodeling.org/docs/release/latest/ESMF_usrdoc/). The advantage of this method is that it can handle both rectilinear grids (grids described by one-dimensional latitude and logitude coordinates) as well as curvilinear grids (two-dimensional coordinates) which are used in climate models.

All parameters were regridded using the **"**patch**"** method. This method is the ESMF version of a technique called "patch recovery" commonly used in finite element modelling. It typically results in better approximations to values and derivatives when compared to bilinear interpolation. Patch interpolation works by constructing multiple polynomial patches to represent the data in a source cell. One patch is constructed for each corner of the source cell, and the patch is constructed by doing least squares fit through the data in the cells surrounding the corner. The interpolated value at the destination point is then a weighted average of the values of the patches at that point (ESMF, 2018: Ch. 24.2.2).

4.1.1. Model data

All model data is regridded using the algorithm described above. Furthermore, data points near the coast that are not resolved by the original data due to the coarse resolution are filled using nearest neighbour interpolation. Since bias correction is applied later, no height correction was done for the model data.

4.1.2. Observational data

Radiation (SARAH) and precipitation data (CHIRPS) was upsampled from a higher resolution (0.05°) to the 0.1° grid by grid averaging.

The coarser resolved ERA5 and E-OBS data with a resolution of 0.28° and 0.25° respectively are only used where no other observational data is available. To account for the better resolved topography at the common grid a simple height correction is applied to the data. In order to do so, first residuals *r* are calculated by removing the height dependency from the data:

(1) $$r = Obs - (\gamma \cdot h)$$

with *Obs* being the original gridded observations, γ the vertical gradient and *h* height above sea level. The residuals are then regridded using the algorithm described above. Furthermore, data points near the coast that are not resolved by the original observational dataset due to the coarse resolution are interpolated with nearest neighbour interpolation. Finally, the height dependency is added back to the regridded residuals.

For the E-OBS temperature data the standard vertical temperature gradient (γ = -6.5 K/km) was used.

Relative humidity

Since relative humidity is not available instantaneously from the ERA5 dataset, it must be calculated from mean temperature *T*, dew point temperature T_d. These parameters were first regridded separately. For the temperature data (T, T_d) a 30-year monthly mean vertical gradient is calculated by a linear regression with elevation and then substracted on a monthly basis (see equation 1).

After regridding, the relative humidity *hurs* is calculated as the relation of vapor pressure *e* and saturation vapor e_s pressure

(2) $$hurs = e / e_s \cdot 100$$

using the Magnus approximation (Alduchov and Eskridge, 1996):

(3) $$e(T) = 610.78 \cdot \exp(17.625 \cdot T / (T + 243.04)) \text{ and } \quad e_s = e(T_d)$$

10-m wind speed

The wind components *u* and *v* from the ERA5 dataset are first regridded separately to the common grid without any dependency on elevation. The wind speed is then calculated from the regridded components.

We found that the height dependency from ERA5 wind was not consistent with the Carpatclim data. While in the Carpatclim dataset an increase of wind speed with height is present, the wind decreases with increasing elevation in ERA5. Furthermore, due to the coarser underlying topography in ERA5, the data is much smoother. In order to get a more homogeneous observational dataset for wind speed a height-dependent correction factor is applied to the regridded ERA5 wind speed.

First, the difference of ERA5 and Carpatclim wind speed is computed for the part of the domain that is covered by the Carpatclim data. The correction factor is the slope of the linear regression of the differences with elevation. This correction factor is then applied to the ERA5 wind speed for the whole domain.

It is important to notice, that apart from a basic height dependency, downscaling of the coarse resolved observational datasets (E-OBS and ERA5) to a 0.1° grid does not add additional value to the data.

4.2. Bias correction method

In literature, several methods that remove systematical model biases can be found. A widely used method is quantile mapping (QM) (Piani, Haerter & Coppola, 2010; Themeßl, Gobiet & Leuprecht, 2011). This algorithm adjusts the cumulative density function (CDF) of the model so that it becomes identical with the CDF of the observations. The CDFs can be calculated empirically (non-parametric approach) or a parametric distribution is fitted to the data. In most cases, the non-parametric method was found to outperform the parametric method (Gudmundsson et al., 2012).

Recent discussions however highlight, that this form of bias correction could artificially alter the climate change signal originating from the climate models significantly (Themeßl, Gobiet and Heinrich, 2012; Maurer and Pierce, 2014). This alteration is caused by the assumption, that the error correction function calculated for the calibration period can be applied to any period of interest (= stationarity assumption) (Switanek et al., 2017).

More recently, modifications of the standard QM method have been developed, that specifically preserve the projected climate change signal of the raw model. Detrended Quantile Mapping (DQM) which was used by Hempel et al. (2013) preserves the monthly mean trend but still modifies daily trends. Cannon, Sobie and Murdock (2015) extended this work and introduced an algorithm called Quantile Delta Mapping (QDM) which explicitly preserves the trend in all quantiles and does not rely on the stationarity assumption.

A slightly different approach was published by Switanek et al., (2017): Scaled Distribution Mapping (SDM). The method scales observed distributions by raw model projected changes in magnitude, rain-day frequency and likelihood of events (return period). For SDM no assumption of stationarity is made during bias correction since the scaling between model and observations changes as a function of the bias correction period. In contrast to QDM, SDM uses a parametric model, which reduces the error associated with sampling noise (compared to empirical methods) (Switanek et. al., 2017). They further investigated the effect of different bias correcting methods on the raw model climate change signal. Compared to traditional QM, QDM and DQM, SDM causes the least inflation or deflation to the raw projected mean change.

As a result of the literature research **Scaled Distribution Mapping (SDM),** described in detail in the publication of Switanek et al. (2017), was chosen as the method for bias correction within the ClimaProof project. The method was also used for the production of the OKS15 climate scenarios (Leuprecht et al., 2017). Switanek et al. (2017) describes the algorithm for temperature (absolute correction) and precipitation (relative correction), but other parameters can be corrected in a similar manner. 5 gives an overview over the fitted distribution for each parameter as well as the applied correction type (absolute or relative) that was used for bias correction.

Table 5: Parametric distributions and correction type used for Scaled Distribution Mapping.

Parameter	**Fitted Distribution**	**Correction Type**
tasmax, tasmin	**Normal**	**absolute**
pr	**Gamma**	**relative**
rsds	**Gamma**	**relative**
sfcWind	**Weibull**	**relative**
hurs	**Weibull**	**absolute**

Analogous to the paper, SDM was implemented to use 30-year periods with a 10-year sliding window in order to correct the middle 10 years.

4.3. Downscaling to 0.01°

Impact modelling usually requires climate model data as input data at a very high resolution - higher than the 0.1° grid that is provided as a default resolution of the ClimaProof dataset. To meet these needs, the **ClimaProof Downscaling Tool** was developed. It enables the user to further localize the model scenarios as well as the observational data to a horizontal resolution of 0.01° (~1 km).

The approach for downscaling to the 0.01° grid is based on the regridding method described above (ESMF_RegridWeightGen). A more detailed description on the downscaling methods and the tool is provided in section 5.3.

5. Tools

In order to make the most out of the ensemble of bias-corrected climate model scenarios created within the ClimaProof project, three tools have been developed by BOKU-Met to increase usability.

1. The **ClimaProof Model Selection Tool** helps with selecting the right model scenario for specific user needs.

2. The **ICC-OBS Tool** gives the opportunity to further improve and customize model scenario data by including additional station data for a specific area of interest.
3. The **ClimaProof Downscaling Tool** enables the user to easily downscale model and obervational data to higher resolution.

In the following chapter the methods used within the tools are described more in detail. A User Guide with step-by-step instructions how to install and use the tools is provided here:

https://github.com/boku-met/climaproof-docs

5.1. ClimaProof Model Selection Tool

Within the ClimaProof Project an ensemble of 44 climate change scenarios has been developed. To assist with the selection of a specific climate change scenario that fits the needs of the user, the ClimaProof Model Selection Tool has been developed. It compares and visualizes climate change signals of the available models in an interactive and user-friendly way.

The tool is provided free of charge and can be downloaded from the BOKU-Met GitHub repository (https://github.com/boku-met/climaproof-tools).

The climate change signal is calculated by subtracting the climatological mean of the historical period (1981-2010) from the mean of the future period (near, mid or far future) on an annual as well as a seasonal basis. The climate change signal for temperature is an absolute value (in °C). For precipitation and radiation, a relative climate change signal (in %) is calculated by dividing the absolute value by the historical mean.

Within the tool the user can specify:

- region of interest by country or custom area (defined by latitude and longitude)
- emission scenario (RCP 2.6, RCP 4.5 or RCP 8.5)
- season of interest (winter, summer or annual)
- time frame of interest:
- near future (2021-2050)
- mid-century (2036-2065)
- end of century (2070-2099)
- climate variable of interest (individual or combinations of two variables)
    - minimum or maximum temperature
    - precipitation
    - radiation

Based on the selection by the user, the tool creates a visualization of the climate change signals. Additionally, a table shows the climate change signal of the models and the corresponding percentiles for the selected parameters.

5.2. ICC-OBS Tool

Freely available gridded observations on the small scale often do not represent the reality very well and general access to better data or additional station data is difficult or expensive. Local station data, that has the potential to improve the climate model data, is often available to local experts but cannot be distributed freely.

Therefore, BOKU-Met developed an easy-to-handle tool for “Improving bias-corrected Climate Change scenarios with local OBServational data” (ICC-OBS Tool). The tool allows the integration of additional local observations for further improvement of the climate change scenarios developed within the ClimaProof project on sub-regions (e.g. countries, river catchments, …).

The ICC-OBS Tool is provided free of charge and can be downloaded from the BOKU-Met GitHub repository (https://github.com/boku-met/ICC-OBS).

Features of the ICC-OBS Tool are:

- Selection of the area of interest by latitude and longitude,
- Integration of additional observational data (station data) to existing gridded observations (used for bias correction) to improve local observation quality,
- Bias correction (Scaled Distribution Mapping) with improved observational data and saving the new bias-corrected data to a CF-conformal netCDF file,
- Automatic creation of plots for a quick look at the improved data.

The ICC-OBS Tool is programmed in Python and uses netCDF as its default output file format.

As **input** for the tool **climate model data (not bias-corrected)** and **gridded observational data** on the same grid (available via the CCCA data server) as well as **local station data** are needed.

Ideally station data should cover 30 years, but at least 10 years of daily data are recommended as input for the tool, covering the period 1981-2010.

5.2.1. Merging of station data with gridded observations

In order to integrate the station data to the existing observational grid (for the historical period 1981-2010), several steps have to be performed.

First, a simplified 30-year monthly mean linear height gradient is calculated from the gridded observations Γ_g. The height gradient is a mean value over the whole user-specified domain.

The gradient is then used to calculate residuals by removing the height dependency from the gridded observations as well as from the station data:

(4) $$Obs_{res} = Obs - (\Gamma_g \; h)$$

with *h* being the height above sea level. For precipitation no simple height dependency can be calculated and therefore this step is skipped.

The residuals are then interpolated to the location of the stations using linear interpolation. Differences are calculated by substracting the interpolated gridded observations from the station data.

In a next step, the differences are interpolated from the station locations to the grid.

To receive the final merged observational grid, the interpolated differences are added to the residuals of the gridded observations. Finally, the height dependency is added back to the merged gridded data.

Interpolation Methods

For interpolation of the differences between station data and gridded observations to the grid, two different interpolation methods are implemented in the ICC-OBS Tool: Inverse distance weights interpolation (IDW) and ordinary kriging (OK).

Ly et al. (2011) state that ordinary kriging and inverse distance weighting interpolation are considered the best and most robust methods for interpolating daily rainfall especially when using only a limited number of sample points. For kriging the gaussian variogram model was most frequently found to be the best fit.

Inverse Distance Weights Interpolation (IDW)

The IDW interpolation method is based on the assumption that values at sampled points closer to the point if interest are more relevant than those further away. This method uses a linear combination of values at sampled points (station data) to estimate the values at an unsampled grid point. The sampled points are weighted by an inverse function of the distance from the point of interest to the sampled points (Li and Heap, 2008). The calculation of the weights is based on the method developed by Cressman (1959).

IDW is implemented via the MetPy Python package (https://unidata.github.io/MetPy/latest/index.html) and is the standard interpolation method for all parameters except precipitation. As additional parameters, the user can define the following parameters in the interpolation settings of the ICC-OBS Tool:

Radius of infuence: The radius from the grid center in km, within which observations are considered and weighted. If not changed, it defaults to the average distance between the sampled points.

Minimum neighbours: The minimum number of neighbours (stations) within the defined radius needed to perform IDW interpolation for that grid point. By default it is set to 3 but can be varied from 2-4.

Ordinary Kriging (OK)

For interpolation with kriging, PyKrige (Version 1.4.1), a kriging toolkit for Python, is used within the tool. The documentation of the package can be found here:

https://geostat-framework.readthedocs.io/projects/pykrige/en/latest/contents.html

The ICC-OBS Tool uses an ordinary kriging algorithm with a Gaussian variogram model as the default for interpolation of precipitation. Other available variogram models that can be selected by the user are exponential, spherical and linear.

5.2.2. Notes

- Since the procedure is computationally expensive, the processed area should be as small as possible and only cover an area, where additional data is available.
- **The more stations, the better** the localisation of the observational data. Especially when using kriging, a high number of stations is necessary for a good estimation of the variogram model and hence a reasonable interpolation.
- **Good quality of station data** is important. If the quality of the additional data is low, there won't be any improvement of the final dataset.
- Please check your station data carefully for erroneous values before using it within the tool.
- It is important to use the **uncorrected climate model scenario data as input** for the tool. Performing this bias correction method twice on a dataset can lead to wrong results.
- The tool is still in its beta phase and therefore errors can occur. If you find a bug, please report back to us and we will try to fix it.

5.3. ClimaProof Downscaling Tool

The ClimaProof Downscaling Tool assists with downscaling data for applications that need a higher resolution than the 0.1° provided by default.

Features of the Downscaling Tool are:

- selection of the area of interest by latitude and longitude,
- selection of the data that should be downscaled (gridded observations or model data),
- saving downscaled data as a CF-conformal netCDF file.

The tool is provided free of charge and can be downloaded from the BOKU-Met GitHub repository (https://github.com/boku-met/climaproof-tools).

5.3.1. Interpolation Method

For the interpolation from 0.1° to 0.01° either a bilinear interpolation or the patch algorithm, developed by the Earth System Modelling Framework (ESMF), can be used.

- **Bilinear interpolation** calculates the value for the destination point as a combination of multiple linear interpolations, one for each dimension of the grid.
- **Patch interpolation** works by constructing multiple polynomial patches to represent the data in a source cell.

For more information about the interpolation methods please refer to the ESMF Reference manual:

https://earthsystemmodeling.org/docs/release/latest/ESMF_usrdoc/

Both methods are implemented in the Python package xESMF (Version 0.1.1). A documentation of the package is available under https://xesmf.readthedocs.io/en/latest/index.html

Height dependency

To take into account the more detailed topography at 0.01° a height correction is applied analogous to the correction described in Section **Fehler! Textmarke nicht definiert.** (to all parameters except precipitation).

First, a 30-year monthly mean vertical gradient is calculated from a linear regression with elevation (one mean value for the whole domain selected by the user). This gradient is then subtracted on a monthly basis to calculate residuals. The residuals are then regridded either bilinear or with the patch algorithm - the method can be chosen by the user. Data points near the coast that are not resolved on the coarse grid are interpolated using nearest neighbour interpolation. In a last step the height dependency is added back to the regridded residuals to get the final field.

5.3.2. Notes

The downscaling algorithm is computationally very expensive. Older machines or machines with small memory can run into memory errors. If this happens, try to select a smaller domain or a shorter time period.

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