Optimal Strategies to Retain Water and Nutrients

D3.1: Climate scenarios for integrated modelling

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Project Consortium

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Summary

The objective of OPTAINs task 3.2 was to provide bias-corrected regional climate model (RCM) simulation data for all case studies as input to the OPTAIN modelling approaches. For this purpose, we used a common climate database - RCM simulations from the EURO-CORDEX project and the Representative Concentration Pathway (RCP) scenarios 2.6, 4.5 and 8.5. Bias correction was done using ERA5-Land reanalysis data with non-parametric empirical quantile mapping. Moreover, for the field scale modelling the interpolation of gridded bias-corrected climate model simulations to the location of the modelling sites was made using universal kriging.

This deliverable D3.1 of the OPTAIN project reports about the procedure of creating the bias-corrected RCM simulation data and provides all necessary background information.

The report starts with an introduction, followed by a description of the materials and method, where the process of preparing bias-corrected RCM simulation data is explained in six subchapters, namely: (1) required variables, (2) selection of reference data for bias correction, (3) selection of domains, (4) selection of EURO-CORDEX RCM simulations, (5) bias correction and interpolation of climate simulations and (6) evaluation and analysis. Finally, the last chapter presents an analysis of the results of the bias-correction procedure and the ensemble of RCM simulations. Together with this report, the dataset on climate scenarios for integrated modelling of the OPTAIN case studies was made publicly accessible on ZENODO: [DOI LINK] as a part of the OPTAIN project repository: [ZENODO Community LINK].

Table of Contents

Abbreviations

WP	Work Package
CS	Case Study
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
Tmean	Mean temperature
Tmin	Minimum temperature
Tmax	Maximum temperature
prec	Precipitation
solarRad	Solar radiation
windSpeed	Wind speed at 2 m
relHum	Relative humidity

1. Introduction

The objective of OPTAINs task 3.2 was to provide bias-corrected regional climate model (RCM) simulation data for all case studies as an input to the OPTAIN modelling approaches.

In the last 20 years, several projects have been carried out dealing with regional climate modeling over Europe: PRUDENCE (Christensen and Christensen, 2007), ENSEMBLES (Johns et al., 2011), and the most recent one CORDEX (Giorgi and Gutowski, 2015). Within the CORDEX project, Europe acts as one of the areas (EURO-CORDEX) (Jacob et al., 2014). EURO-CORDEX involves 30 research groups with ten regional climate models, using 12 different global models, which where basis for the Fifth Climate Change Report of the Intergovernmental Panel on Climate Change (Pachauri et al., 2014). Simulations are available in 50 km and 12 km resolutions for four different climate scenarios. These differ in particular in greenhouse gas concentration (Representative Concentrations Pathways - RCPs), which are marked according to the radiation contribution at the end of the 21st century (van Vuuren et al., 2011).

Future climate data is a major source of uncertainty of model-based assessment's output. This uncertainty may arise from different sources, e.g. in the climate model structure or in the forcing data (i.e. the applied scenario). The level of uncertainty can be explored by using a multi-model ensemble approach, which is a standard technique for improving forecasts on different timescales (Klein-Tank et al., 2009) and considering different scenarios. Furthermore, raw climate model outputs have systematic errors compared to observational data. These can be removed by applying different bias correction methods, e.g. quantile mapping, which is one of the most popular bias correction methods (e.g. Enayati et al., 2021).

2. Materials and methods

The process of preparing bias-corrected RCM simulation data can be divided in six steps as shown in Fig. 1 and further described in following subchapters.

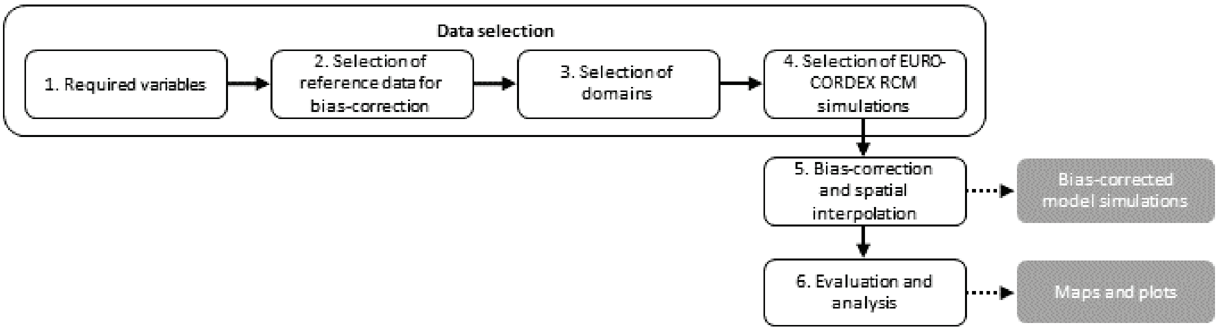

Figure 1: Schematic view of the process of preparing bias-corrected RCM simulation data.

2.1. Data selection

2.1.1. Required variables

As a preparatory step for the creation of OPTAINs climate scenario data, a list of variables needed for OPTAINs modelling approaches was prepared. Together with the project partners from work package 4 (WP4; Integrated assessment of NSWRM) the following variables have been selected:

- Mean air temperature at 2 m (Tmean)
- Minimum air temperature at 2 m (Tmin)
- Maximum air temperature at 2 m (Tmax)
- Precipitation (prec)
- Solar radiation (solarRad)
- Wind speed at 2 m (windSpeed)
- Relative humidity at 2 m (relHum)

2.1.2. Selection of reference data for bias correction

For bias correction and further downscaling of the EURO-CORDEX RCM simulations we originally aimed to use gridded observations from national agencies or the high-resolution surface reanalysis MESAN (Landelius et al. 2016). We thus asked the case study (CS) leaders to fill a template about the availability of gridded observational data and national climate model simulations. The overview of available data showed that it was not reasonable to use existing national datasets due to the following reasons:

- Gridded observational data was not available in all countries nor for all required variables.
- The climate simulations are not gridded in some countries or some variables are missing.
- In several countries there are no simulations for the RCP2.6 scenario.
- The number of RCMs used varies widely across countries, and moreover different models are used, and not all simulations are bias-corrected.
- In one country there are even no high-resolution simulations available at all.

A detailed analysis of the availability of gridded observational data and national climate model simulations for the OPTAIN case studies is available in Annex 1.

Additionally to the decision not to use available gridded observational data, MESAN reanalysis was no longer available (and it was originally prepared only for a limited number of requested variables). Therefore other European wide reanalysis datasets, such as UERRA-LAND (2019), ERA5-Land (2021) and CERRA-Land (2019) (shown in Table 1) were considered to be used as reference data. The focus was on datasets, which have most of the required variables available. CERRA-Land was not available at the time of selection (middle of 2020) and UERRA-Land does not include Tmin and Tmax. As an estimation of these two variables based on 6-hourly Tmean bears to much uncertainty, we decided to use ERA5-Land.

Table 1: Different reanalysis datasets which can be used as reference data.

Dataset name	Resolution	Time step	Variables which can be calculated/estimated
UERRA-Land (MESCAN-SURFEX)	0.05°	6 hours	all except Tmin and Tmax
ERA5-Land	0.1°	1 hour	all
CERRA-Land	0.05°	1 hour (most of variables)	all

Although the spatial resolution is 0.1° (MESAN: 0.05°), we decided that the interpolation does not provide any additional information and is not needed for the catchment scale modelling. This decision was based on the analyses on examples of interpolated precipitation for three case studies (Germany, Poland, Italy) and three different resolutions (0.1°, 0.05° and 0.025°) (carried out by WP4 team members). Nevertheless, the interpolation is needed for the field scale modelling, independently of the resolution.

2.1.3. Selection of domains

The selection of domains was done based on catchments (15 in 12 countries) and pilot fields (23 locations in 6 countries) located in the case study regions. The locations of 8 pilot fields are outside of catchments, 5 of them in Switzerland and 3 of them in Norway. When selecting the domains, we also took into account that a) the minimum size of domain is 0.5°x0.5° due to further interpolation of the gridded data to pilot field locations (and minimum number of points needed for that) and b) catchments and pilot fields are at least 0.1° from the domain border in both directions. Based on the mentioned criteria 18 rectangular domains were selected. All the information about the domains and their connection with case studies and pilot field locations is shown in Table 2.

Table 2: Case studies and domains.

case study	country	name	biogeographic region	domain	domain location (min and max. Longitude, min and max latitude)	pilotFieldNumber	pilot field location (longitude, latitude)
1	DEU	Schoeps	Continental	01	50.95 51.45 14.55 15.05		
2	CHE	Petite Glane	Continental	02	46.35 47.05 6.55 7.15	2	46.816667 6.95
				02_1	46.75 47.25 7.25 7.75	1	46.983333 7.466667
				02_34	47.35 47.85 8.35	3 4	47.433333 8.516667 47.683333 8.616667
				02_5	46.15 46.65 5.95 6.45	5	46.4 6.233333
3a	HUN	Csorsza	Pannonian	03a	46.65 47.15 17.45 17.95	1 2 3 4	46.92649 17.68246 46.9166 17.68976 46.91283 17.69754 46.91283 17.69723
3b	HUN	Felso Valicka	Pannonian	03b	46.45 46.95 16.65 17.15		
4	POL	Upper Zglowiaczka	Con./Pan.	04	52.35 52.85 18.45 18.95	1	52.597469 18.728617
5	SVN	Pesnica	Continental	05	46.35 46.85 15.35 15.85		
6	HUN/SVN	Kebele/Kobiljski	Continental	06	46.45 46.95 16.15 16.65		
7	BEL	La Wimbe	Continental	07	49.85 50.35 4.75 5.25		
8	LTU	Dotnuvele	Boreal	08	55.15 55.75 23.55 24.05	1 2	55.522057 23.799235 55.42233194 23.82580339
9	ITA	Cherio	Continental	09	45.45 45.95 9.65 10.15		
10	NOR	Krogstad	Boreal	10	59.45 59.95 10.75 11.25	1 2 3 4 5 6 7 8	59.71949 10.83576 59.6833306 10.8833298 59.6833306 10.8833298 59.665 10.9475 59.665 10.9475 59.841012 10.903597 59.757631 11.072031 59.539623 10.856447
11	HUN	Tetves	Continental	11	46.45 46.95 17.55 18.05	1 2	46.658333 17.75583 46.656944 17.75833
12	CZE	Cechticky	Continental	12	49.35 49.85 14.75 15.25	1	49.616837 15.078266
13	LVA	Dviete	Boreal	13	55.85 56.35 25.85 26.45		
14	SWE	Ingvastaan Lehstaan	Boreal	14	59.75 60.25 17.55 18.05		

2.1.4. Selection of EURO-CORDEX RCM simulations

The first step of this procedure was to identify which RCM simulations have all required variables available on a daily timescale and for which of them simulations for RCPs: 2.6, 4.5 and 8.5 are available. At the time of selection (middle of 2020) 14 RCM simulations met both criteria.

To reduce the number of needed simulations by the catchment and field scale models (the models have to be run for each RCM simulation for all three different RCPs), we decided with WP4 to limit the number of RCM simulations to up to 6.

The selection process was done by comparing ERA5-Land reanalysis and CORDEX historical data interpolated on ERA5-Land grid for mean temperature and precipitation for the period 1981-2005. First, we calculated the sum of the monthly absolute difference for mean temperature (Tmean) and the sum of the monthly absolute difference in ratio for precipitation (prec) for each RCM and each domain separately. Then we sorted the RCM simulation by means of the mentioned statistics and eliminated 6 RCMs (3 for each variable) with the worst performance.

Of the left 8 RCM simulations we subjectively selected 6 (shown in table 3) based on above mentioned statistics and taking into account equal representation of RCMs and GCMs.

Table 3: Selected RCM simulations

Model number	Driving Model (GCM)	Ensemble	RCM
1	EC-EARTH	r12i1p1	CCLM4-8-17
2	EC-EARTH	r3i1p1	HIRHAM5
3	HadGEM2-ES	r1i1p1	HIRHAM5
4	HadGEM2-ES	r1i1p1	RACMO22E
5	HadGEM2-ES	r1i1p1	RCA4
6	MPI-ESM-LR	r2i1p1	REMO2009

2.2. Bias correction and interpolation of climate simulations

For bias-correction the reference data (ERA5-Land) and RCM simulations (EURO-CORDEX) have to be on the same grid and need to have the same units. Thus, before bias correction procedure, we interpolated EURO-CORDEX RCM simulations to ERA5-Land grid. Furthermore, we calculated values for missing days (some of the RCMs use a 360 day calendar), calculated derived variables and converted units.

The bias correction was made with the R package qmap (Gudmundsson, 2016) for the period 1981–2100; the reference period for estimating bias was the 30-year period 1981–2010. Based on an article by the author of the package (Gudmundsson et al., 2012), in which he compared different methods, we decided to use the method of nonparametric quantile mapping using empirical quantiles with linear extrapolation. We performed the bias correction for each variable separately and for each model cell independently of the others. The general procedure was as follows: We compared the distribution of model data and reference data in the reference period and estimated the differences in the quantiles of this distribution. The estimated differences are used as future model corrections for the selected quantile. Corrections were calculated for each day of the year using a moving window. We opted for a 31-day time window and 100 classes of quantiles. For precipitation we used wet days correction as well.

For the field scale modelling the interpolation of gridded bias-corrected RCM simulations to the location was made using universal kriging (similar or same to kriging with external drift and regression-kriging). Here, the R packages automap (Hiemstra et al., 2009) and gstat (Pebesma, 2004) have been used with the (external) variables x, y, x^2, y^2, x*y, z, where x is latitude, y is longitude, and z is elevation. Elevation was derived from Digital Elevation Model Shuttle Radar Topography Mission (SRTM, 2020; ORNL DAAC, 2017). If it was not possible to make an interpolation due to an error in the interpolation process using the above-mentioned variables, the number of variables was reduced to x, y, x*y, z and if there was still an error to x, y, z.

2.3. Evaluation and analysis

The evaluation of the bias-corrected climate model simulations consists of two parts, the analysis of i) the bias correction procedure and ii) the ensemble of climate simulations.

For the analysis of the bias-correction procedure we calculated climatology for the reference period 1981-2010 for ERA-5 Land reanalysis, and raw and bias-corrected EURO-CORDEX RCM model simulation for each domain and variable.

For the analysis of the ensemble of climate simulations we calculated changes for three 30-years projection periods (1st: 2011-2040, 2nd: 2041-2070, 3rd: 2071-2100) against the reference period 1981-2010 for each RCM model simulation. Then we constructed an ensemble, where the ensemble members were RCM model simulations, and calculated the ensemble spread (minimum, median and maximum values). Changes were estimated at the annual level and at the level of meteorological seasons. The seasons were defined as the following quarters: spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February). The coherence of the climate ensemble was estimated with an indicator called the “reliability of the change” (Bertalanič et al., 2018), which tells us whether the ensemble members show similar changes. The indicator is presented in four levels (very high, high, low, no change) and based on the statistical reliability of the calculated changes. For each ensemble member and each projection period we calculated a Mann-Whitney-Wilcox test with 10% level of significance using the R function wilcox.test (package stats; Rdocumentation, 2020) and joined it with the sign (direction) of the calculated change as shown in Fig. 2. ‘Very high’ level means that changes in a certain direction are very likely to be expected and ‘high’ means that changes are likely to be expected. ‘Low’ level reliability of the climate ensemble means that the ensemble members show statistically significant changes in different directions, thus the change in both directions is equally probable. ‘No change’ means changes are statistically insignificant.

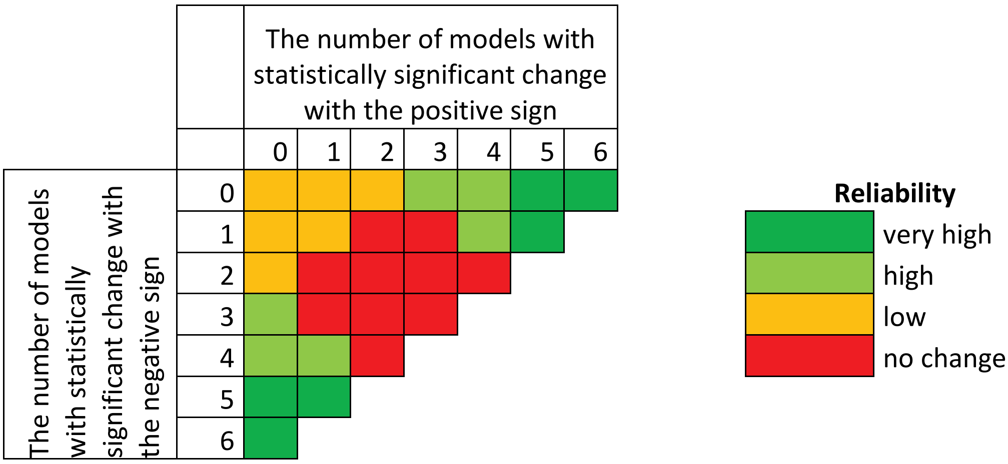

Figure 2. Matrix illustrating the principle of the reliability rating of the change.

3. Results

3.1. Dataset of bias corrected RCM simulations

Bias-corrected RCM simulations have been prepared for the period 1981-2099/2100 for 6 different models and 3 different RCPs (2.6, 4.5 and 8.5). Gridded data is available on 0.1° grid in NetCDF format, point data are in csv format. The files are separated by variables, RCPs and models.

All data are available online for the OPTAIN consortium in the project internal cloud: [LINK] (password protected). A README file is available online and in Annex 2 of this deliverable. A publicly available version of the dataset is accessible on ZENODO: [DOI LINK] as a part of OPTAIN project repository: [ZENODO Community LINK].

3.2. Dataset evaluation and analysis

3.2.1. Analysis of the bias-correction procedure

The analysis of the bias-correction procedure was done by the visual analysis of different maps and plots, namely maps of climatology for 1981-2010 (for all models and difference against ERA5-Land; e.g. Fig. 10 in Annex 3) and domain-averaged: a) timelines and boxplots of yearly means (e.g. Fig. 11 and Fig. 12 in Annex 3), and b) boxplots of daily data (e.g. Fig. 13 in Annex 3). The results of the analysis did not show any outliers or anything exceptional.

3.2.2. Analysis of the ensemble of RCM simulations

The analysis of the ensemble of climate simulations projections contained:

a) maps with the median change of the ensemble (e.g. Fig 14 in Annex 4), the spread of the ensemble (min, median and max change; e.g. Fig. 15 in Annex 4), the median change and reliability of the ensemble (e.g. Fig. 16 in Annex 4), and

b) the domain-averaged timeline with the spread of the ensemble (e.g. Fig. 17 in Annex 4), the spread of the ensemble (e.g. Fig. 18 and Fig. 19 in Annex 4), the median change and reliability of the ensemble (e.g. Fig. 20 in Annex 4),

prepared for all 7 variables and 18 domains separately. Furthermore, to be able to compare different domains and biogeographic regions with each other, the analysis contained:

c) the domain-averaged timeline of the median change of the ensemble (e.g. Fig. 21 in Annex 4), the spread of the ensemble (e.g. Fig. 22 in Annex 4), the median change (Fig. 3 – Fig. 9) and the median of the ensemble by months (e.g. Fig 23 in Annex 4).

All the maps and plots are prepared for seasons and year, except the spread of the ensemble by months (e.g. Fig. 19 and Fig. 23 in Annex 4).

From the analysis of the ensemble of RCM simulations we see that the reliability of the mean temperature changes is high or very high (Fig. 3). The range of the median annual change of the mean temperature in the first period (2011-2040) is not very large, ranging from 0.8°C for the RCP2.6 scenario to 1.2°C for RCP8.5. The variability among domains is mainly 0.1°C or up to 0.3°C. Most seasonal changes are higher in winter and autumn than for the whole year and lower in spring and summer, but all are in the range of 0.5°C to 1.3°C. For the second period (2041-2070), projected annual changes range from 0.9°C (RCP2.6) to 2.8°C (RCP8.5), again being slightly higher for winter and autumn, and slightly lower for spring and summer. For the third period (2071-2100), the changes are even more pronounced and widely scattered among scenarios, from 1 to 4.4°C. Mainly, only the projected changes for spring are lower and similar or slightly higher for the other seasons.

The projections for minimum (Fig. 4) and maximum (Fig. 5) temperatures are very similar and also highly reliable. Only seven (out of 540) results for maximum temperature are not reliable, all for the 1st period. The range of projections for minimum annual temperature change is from 0.8°C (1st period, RCP2.6) to 4.6°C (3rd period, RCP8.5), and for maximum annual temperature change from 0.7°C to 4.4°C, respectively. For minimum temperature, winter changes are usually slightly higher than annual changes, and in some cases summer and autumn changes are also higher. For maximum temperature, seasonal changes are slightly higher than annual changes in many cases, except for spring, where this is rarely the case.

For temperatures, the projected increase is mainly highest in the Boreal region and lowest in Continental region.

The projections of precipitation changes (Fig. 6) are less reliable. High or very high reliability is observed in most cases for winter, less so for the annual scale, and mainly only for the RCP8.5 scenario for spring. Annual changes in the 1st period range from 4% (RCP2.6) to 10% (RCP8.5) increase, in the 2nd period from 4% to 11%, and in the 3rd period from 6% to 19% (both RCP8.5, different domains). The range of winter precipitation increase is from 8% to 38%, with much higher changes in the 3rd period than in the first two. The range of changes in spring for the RCP8.5 is from 9% to 27%. In general, on the annual scale the increase of precipitation is projected to be higher in Boreal region.

For solar radiation (Fig. 7), the projections are reliable mainly for the changes in winter for RCP4.5 and RCP8.5, especially for Pannonian region, for spring for RCP8.5, and for annual changes only for some domains, especially for Boreal region. Projected medians show a decrease of up to 4% on an annual scale and for spring, higher (up to 7%) only for spring in the 3rd period for RCP8.5. A decrease of up to 6% is projected for winter, and up to 12% only in the case of the 3rd period for RCP8.5.

The vast majority of the predicted changes are not reliable for wind speed (Fig. 8) and relative humidity (Fig. 9), and thus must be disregarded, or at least used with all caution and comments about reliability. The rare reliable changes in wind speed range from -6.1% to -1.1%, and changes in relative humidity range from -2.7% to 2.2%.

All the maps and plots are available online for the OPTAIN consortium in the project internal cloud: [LINK] (password protected). A README file is online and in Annex 5.

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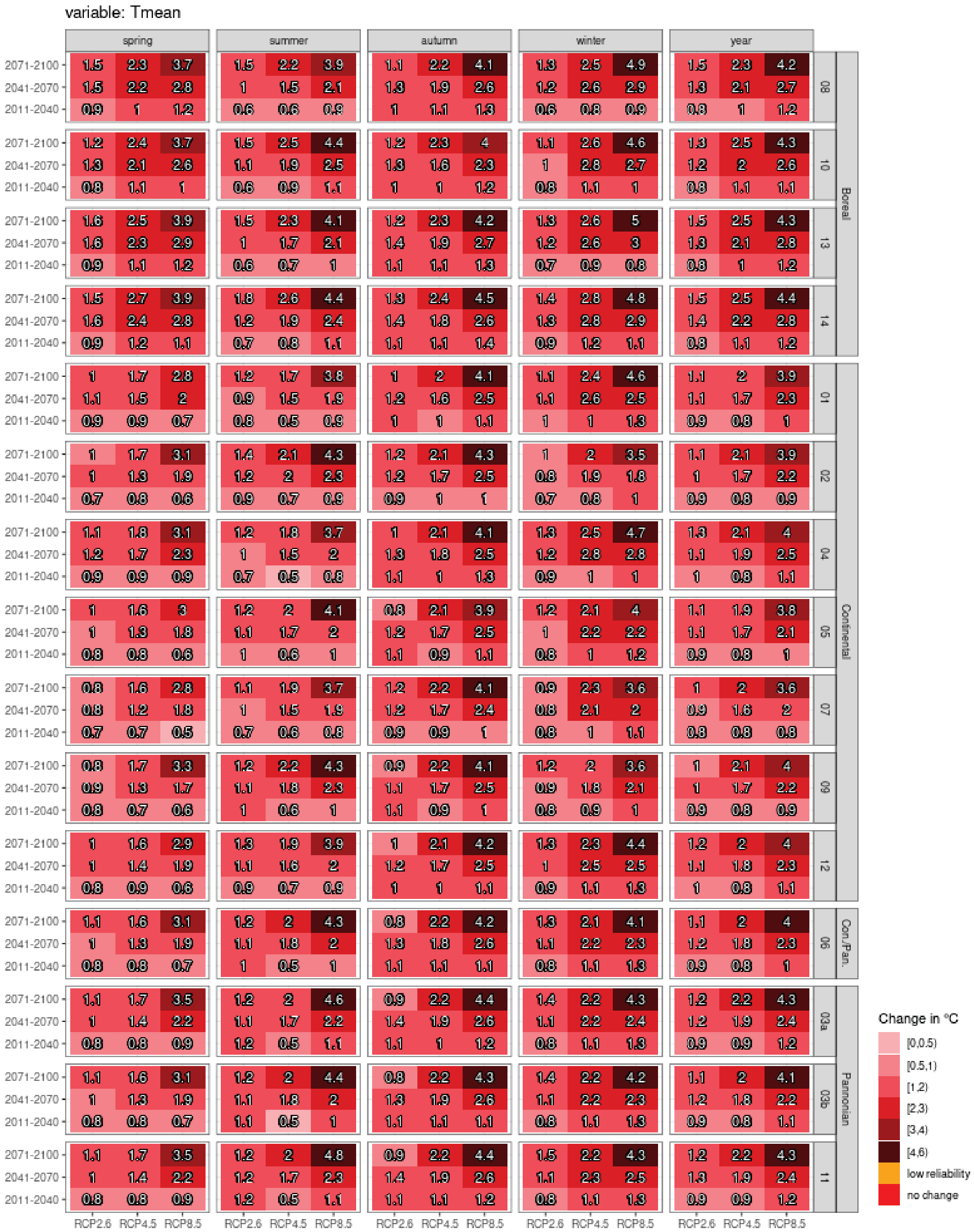

Figure 3: The median change and reliability of the change for mean temperature (Tmean), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

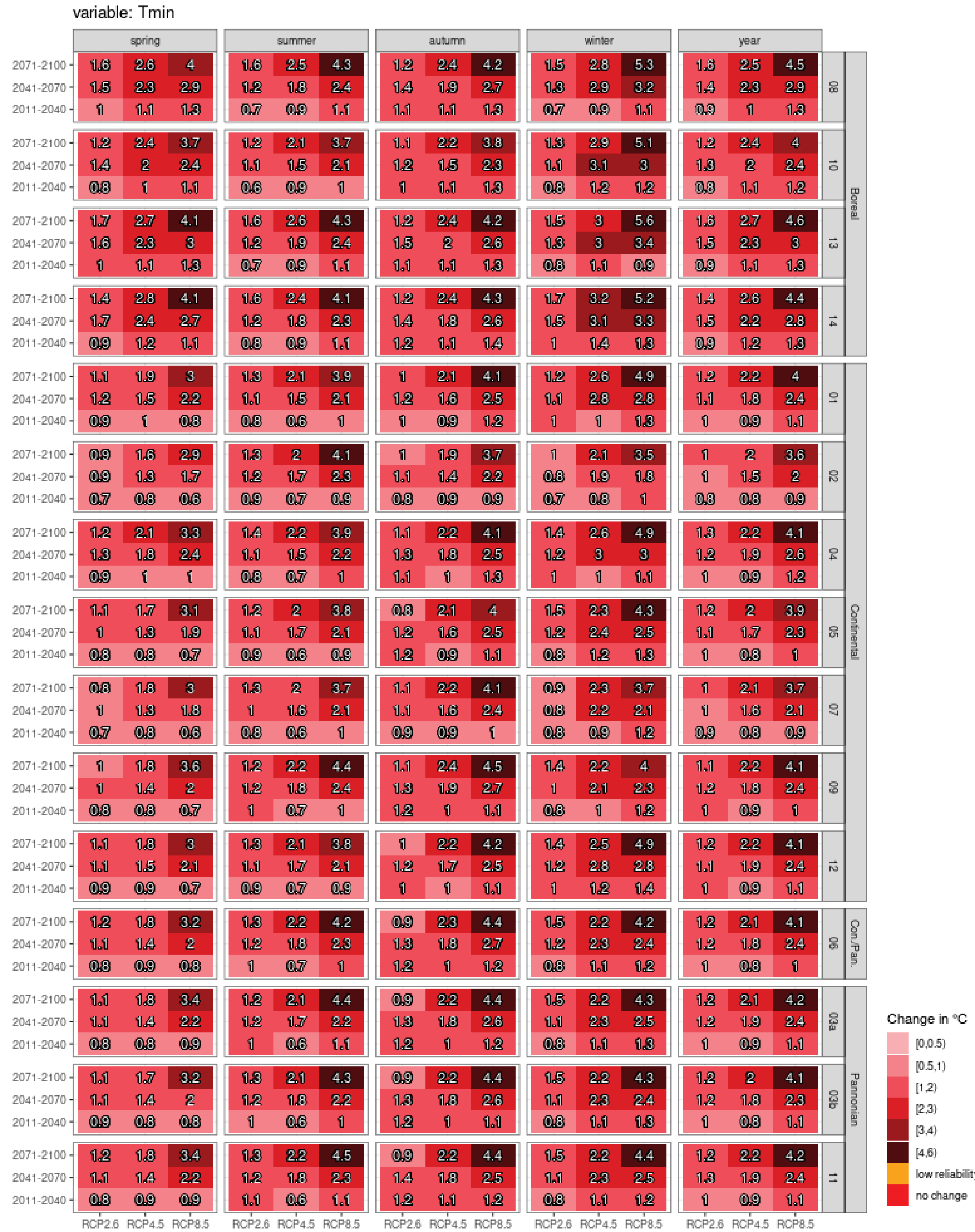

Figure 4: The median change and reliability of the change for minimum temperature (Tmin), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

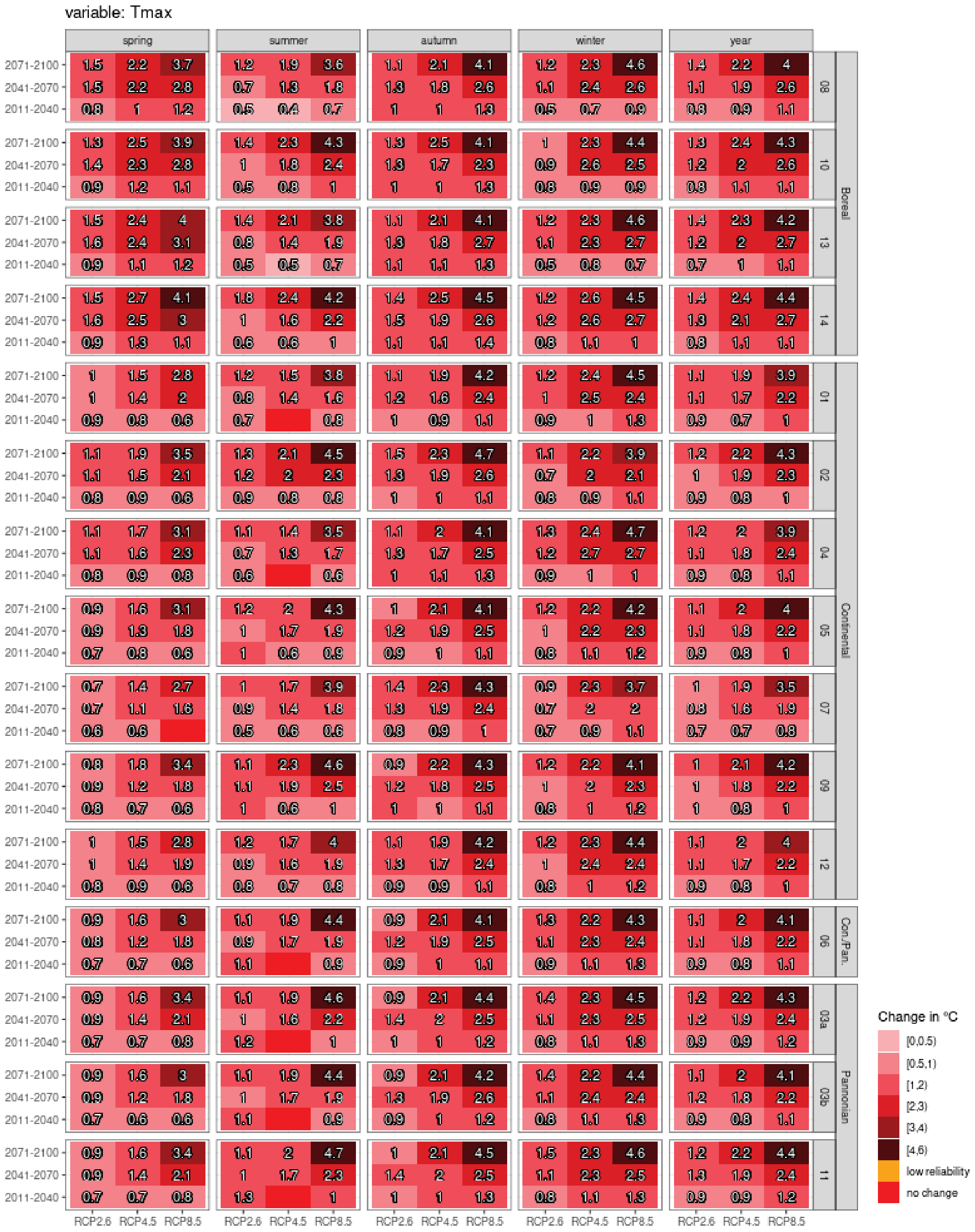

Figure 5: The median change and reliability of the change for maximum temperature (Tmax), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

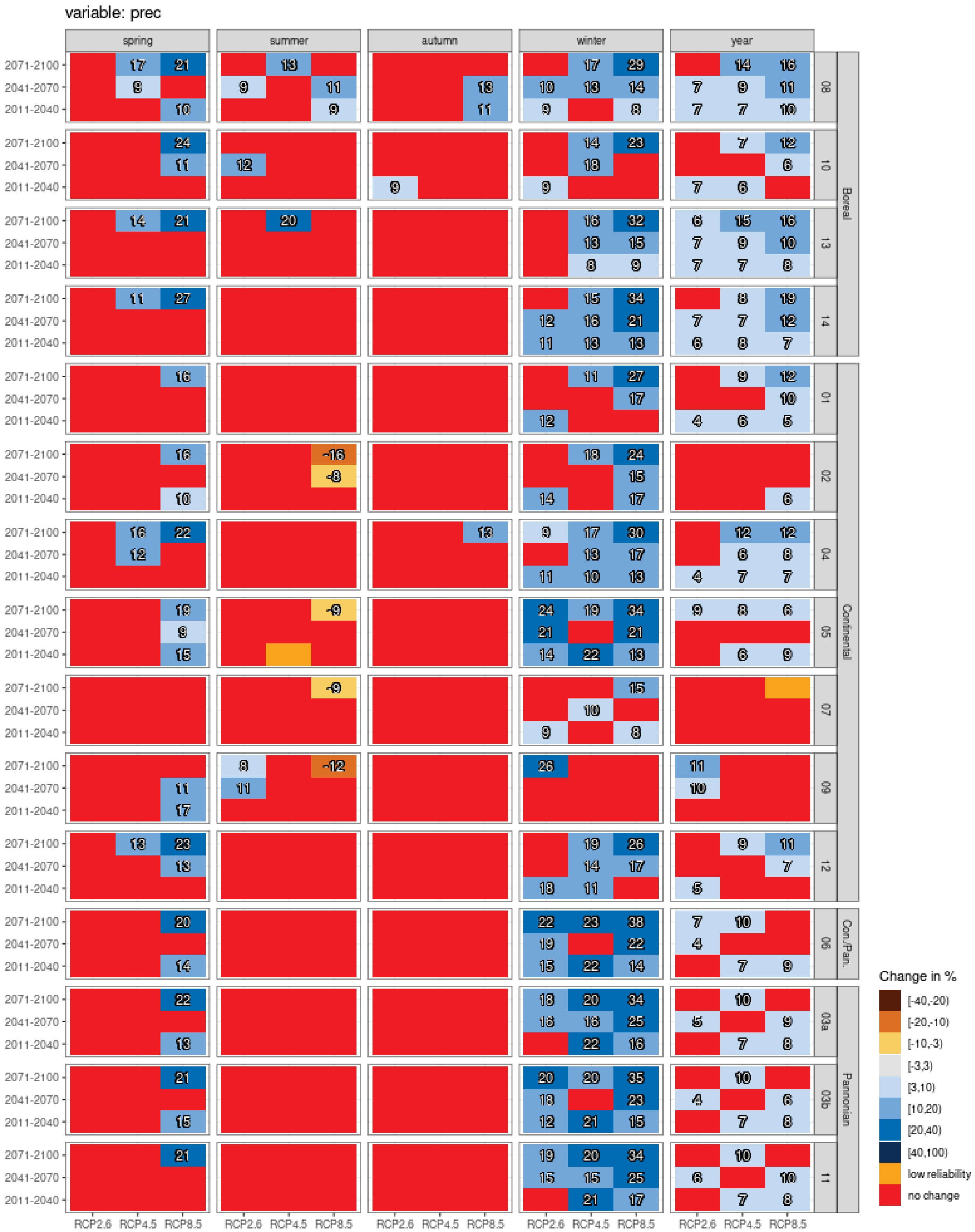

Figure 6: The median change and reliability of the change for precipitation (prec), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

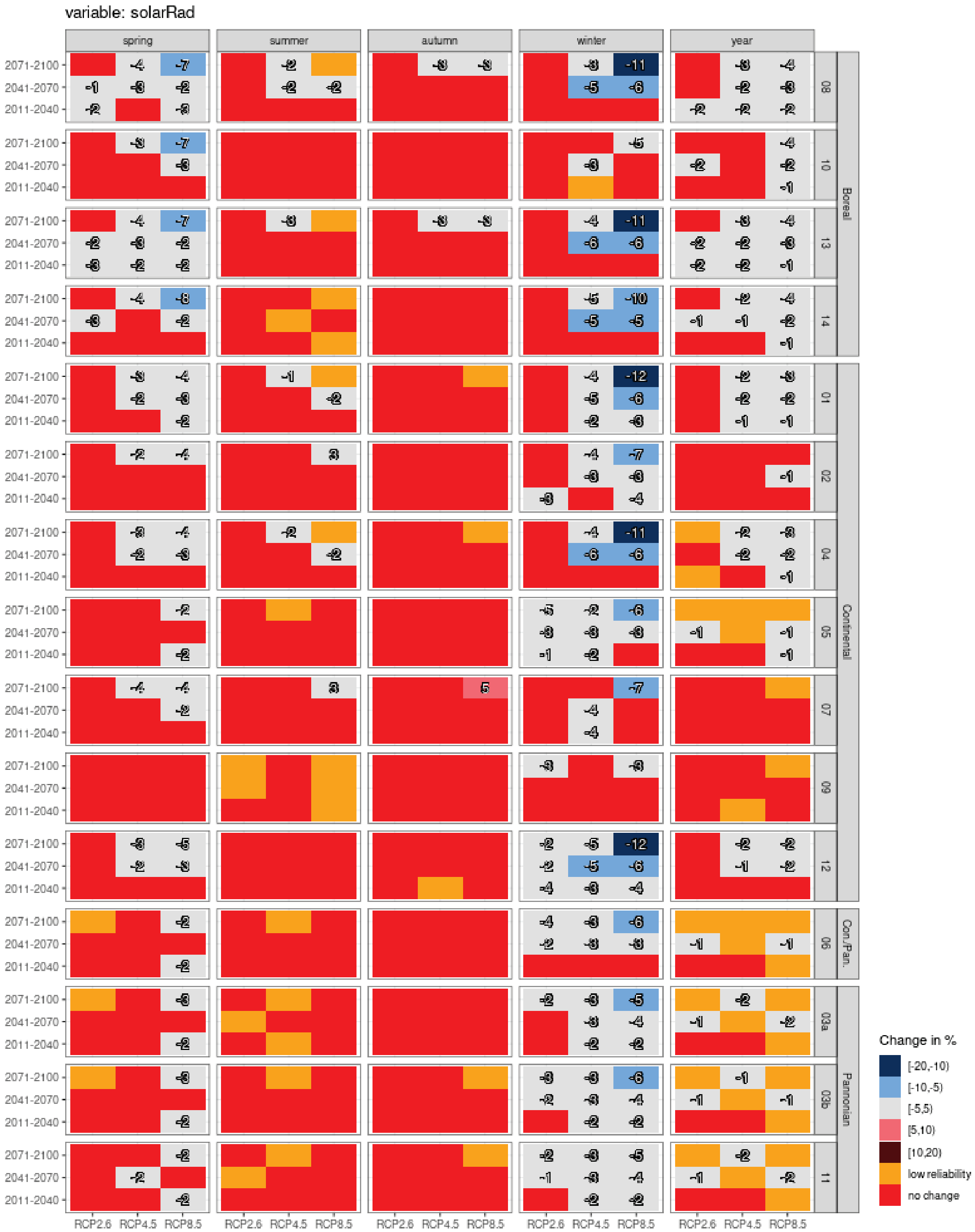

Figure 7: The median change and reliability of the change for solar radiation (solarRad), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

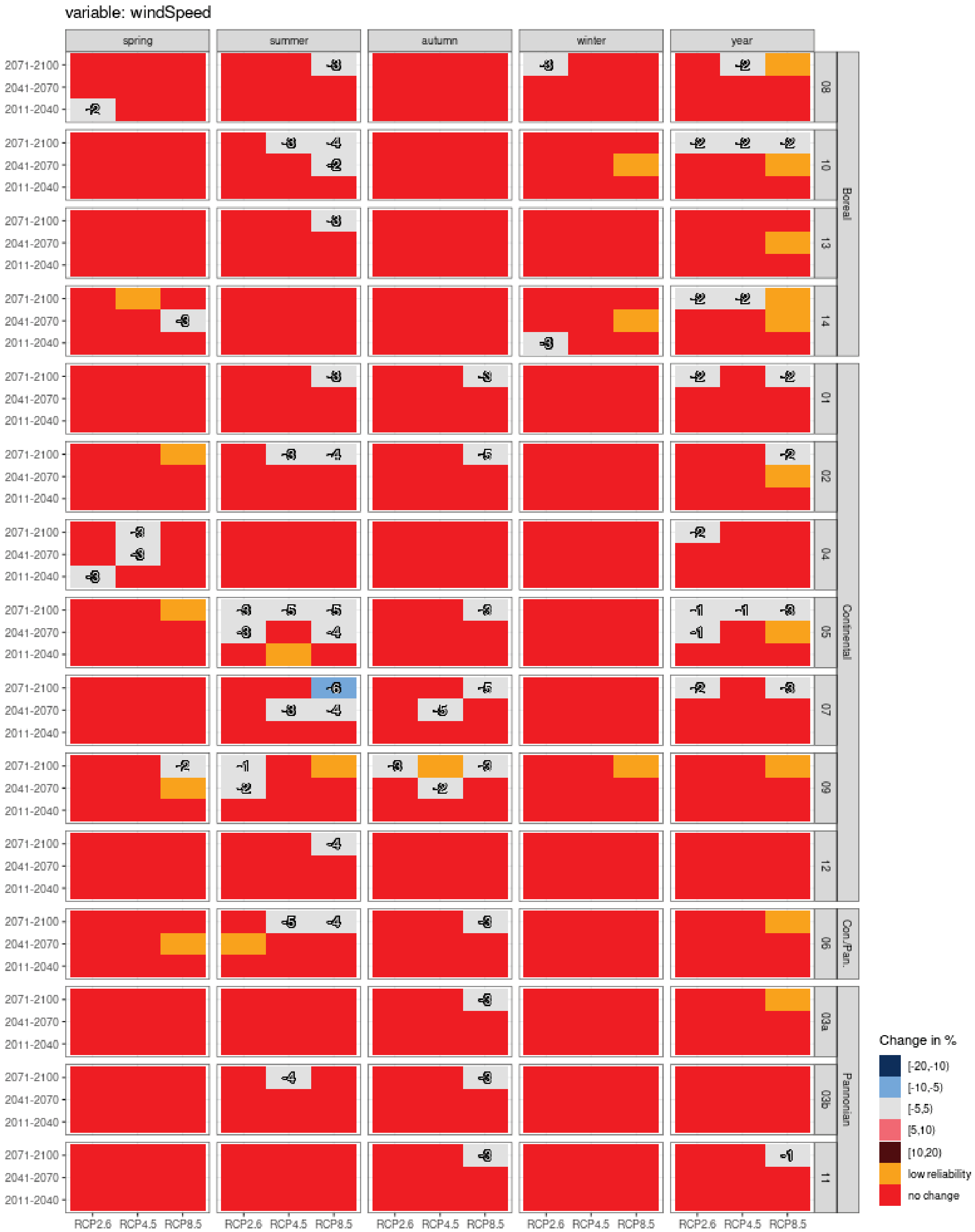

Figure 8: The median change and reliability of the change for wind speed (windSpeed), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

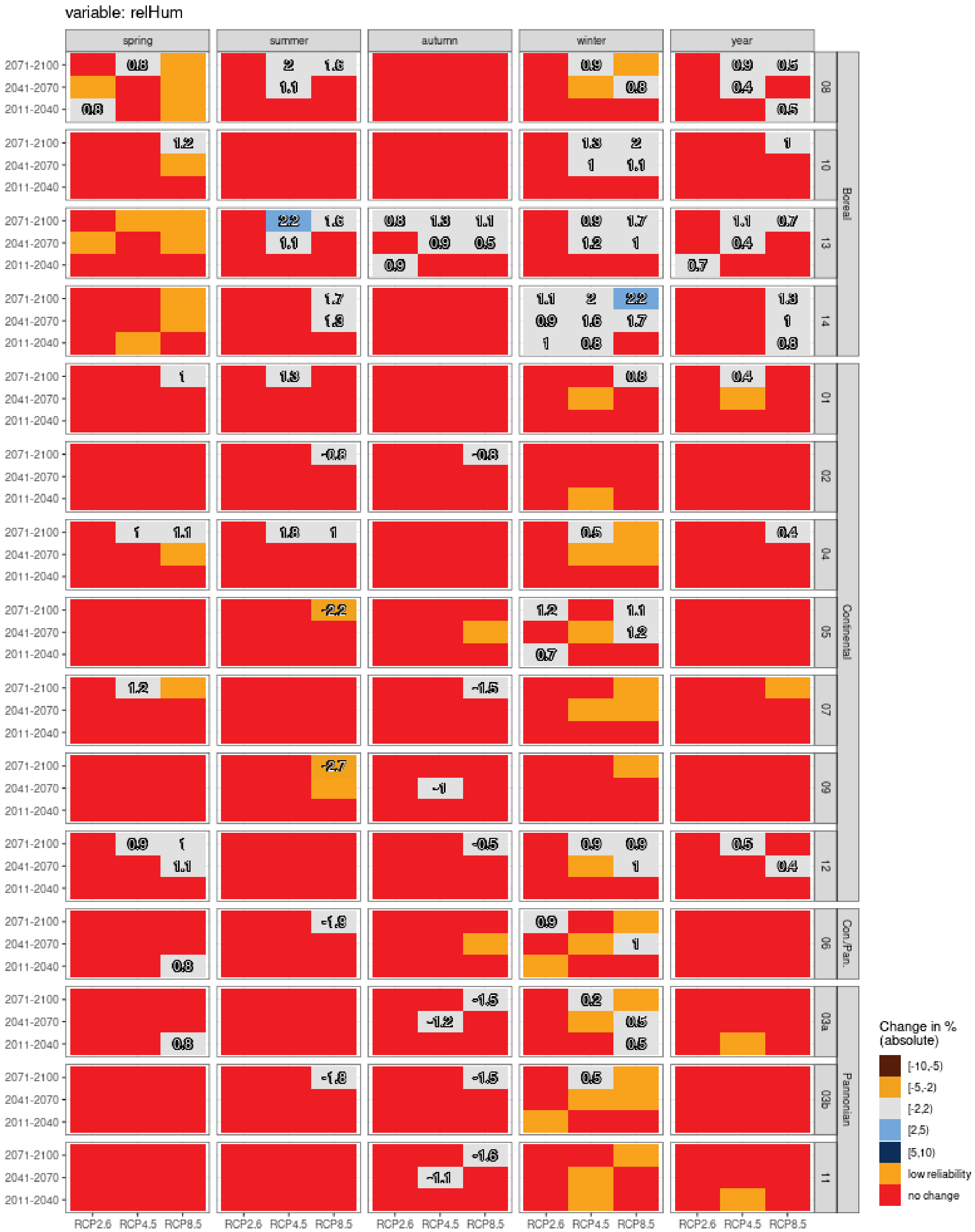

Figure 9: The median change and reliability of the change for relative humidity (relHum), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5. Results are grouped by biogeographical regions of the case studies.

4. Final statement / Outlook

Bias-corrected EURO-CORDEX RCM simulations were prepared for all OPTAIN case studies and are ready to be used for the OPTAIN modelling approaches. Furthermore, we prepared the ERA5-Land reanalysis for all domains and pilot field locations as well, which can be used for the calibration of the models, if local measured meteorological data are not available.

Catchment- and field- scale models have to be run for each RCM model simulation for each scenario for the whole period, including the reference. The changes in the future climate should be calculated as a difference from the reference period separately for each run.

Although the data were analysed, it is still possible that there are some bugs left in the data that might be found later on. If this will be detected, it is possible to prepare corrected versions of outputs in a reasonable time due to the automated process.

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6. Appendix

6.1. Annex 1: Gridded observational data and climate model simulations available in the case studies

6.1.1. Gridded observational data

Gridded observational data (Table 4) are available in most of the countries, except for Italy, Lithuania and Latvia, where only station data is available. In addition, there is no data on relative humidity in Switzerland, on mean temperature and solar radiation in Poland, on relative humidity, solar radiation and wind speed in Slovenia, and on relative humidity and solar radiation in Norway. There is only data on mean temperature and precipitation in Sweden.

The time periods of gridded observation data vary considerably, starting with 1951 (Poland), 1961 (Germany, Switzerland, Czech Republic), 1971 (Hungary, Norway) or 1981 (Slovenia, Belgium).

The data is mainly available in NetCDF or ascii format, with spatial resolutions ranging from 0.5x0.5 km to 5x5 km. For Sweden the availability is not known, for others the data is available online or on request, but not always free of charge.

6.1.2. Climate model simulations

The differences between countries regarding the available climate model simulation data (Table 5), proposed to be used in case studies, are even more pronounced. First of all, in Sweden there are no simulation data with a higher resolution than 50x50 km. In Italy projections are made for stations (not gridded), and in Latvia there are no daily data. In the other countries, again mainly data on mean temperature (not in Poland and Lithuania), maximum and minimum temperature and precipitation are available. In Germany, Switzerland, Belgium and the Czech Republic there are also simulations of relative humidity, wind speed and solar radiation. Only in Slovenia and Belgium projections for potential evapotranspiration are made. Their spatial resolution is also very different, ranging from 0.5x0.5 km to 12x12 km.

Most climate model simulations are produced up to the end of the century, but the reference periods vary from country to country. The RCP4.5 scenario is used in all countries, whereas the RCP2.6 scenario is used in six countries, the RCP6 scenario in only one, and the RCP8.5 scenario in all but one. The countries use different models and even a very different number of models, from 1 to 31. The simulations are bias-corrected in six countries. The format of the data is mainly NetCDF or ascii, with the exception of Germany. Again, the data are available online or on request, but not always free of charge.

Table 4: An overview of gridded observational data availability based on information provided by CS leaders.

Country	Tmean	Tmin	Tmax	prec	relHum	solarRad	windSpeed	period	format	resolution	URL
Hungary	yes	yes	yes	yes	yes	yes*	yes*	1971-2020 or *2001-2020	ascii	0.1°	link or link
Italy	no	no	no	no	no	no	no	NA	NA	NA	NA
Germany	yes	yes	yes	yes	yes	yes	yes	1961-2020	ascii	1x1km	link
Switzerland	yes	yes	yes	yes	no	yes	yes	1961-2021, 1991-2021-> cloud	NetCDF, GeoTIFF, ASCII	1x1,2x2 or 5x5km	on request
Poland	no	yes	yes	yes	yes	no	yes	1951–2019	NetCDF, geotiff	2x2km	link
Slovenia	yes	yes	yes	yes	no	no	no	1981-2010	NetCDF	0.125x0.125° 1x1km on request	link
Belgium	yes	yes	yes	yes	yes	yes	yes	1981-2020		5x5km	on request
Lithuania	no	no	no	no	no	no	no	NA	NA	NA	NA
Norway	yes	yes	yes	yes	no	no	no	1971-2020	NetCDF	1x1km	online
Latvia	no	no	no	no	no	no	no	NA	NA	NA	NA
Sweden	yes	no	no	yes	no	no	no	unknown	unknown	4x4km	on request, availability not known
Czech Republic	yes	yes	yes	yes	yes	yes	yes	1961-2020	NetCDF, GeoTIFF, dbf, csv	0.5x0.5km	on request

Table 5: An overview of climate model simulation data availability based on information provided by CS leaders.

Country	Tmean	Tmin	Tmax	prec	relHum	solarRad	windSpeed	time step	period	RCP2.6#	RCP4.5#	RCP8.5#	Bias-corrected	resolution	format	URL
Hungary	yes	yes	yes	yes	no	no	no	daily	1950-2099; 1971-2099 (ELU)	0	3/4	0	optionally	10x10km	NetCDF	HMS (compensation), ELU on request
Italy	yes	yes	yes	yes	yes	yes	no	daily	1983-2099	3G-4R	3G-4R	3G-4R	yes	21 stations	ascii, csv	on request
Germany	yes	yes	yes	yes	yes	yes	yes	daily	1961-2005 (historic), 2006-2100 (scenarios)	7	7	7	no	12x12km	kli	link
Switzerland	yes*	yes*	yes*	yes*	yes	yes	yes	daily	1981-2099	12	25	31	yes	stations or *2x2km	NetCDF, Rdata, csv	on request
Poland	no	yes	yes	yes	no	no	no	daily	1971-2000, 2021-2050, 2071-2100	0	9	9	yes	5x5km	NetCDF	link
Slovenia[1]	yes	yes	yes	yes	no	no	no	daily	1981-2100	2	6	6	yes	0.125x0.125° 1x1km on request	NetCDF	link
Belgium[1]	yes	yes	yes	yes	yes	yes	yes	daily	1950-2005 (historical), 2006-2100 (scenarios)[2]	1	1	3	no	4x4km (model ALARO-0)	NetCDF, ascii	link
Lithuania	no	yes	yes	yes	no	no	no	daily	1988-2100	0	5	5	yes	unknown	NetCDF, ascii	on request
Norway	yes	yes	yes	yes	no	no	no	daily	1971-2100	0	10	10	no	1x1km	NetCDF, BIL, GeoTIFF	link
Latvia	no	no	no	no	no	no	no	per.[3]	1961-2100	0	unknown	unknown	unknown	10x10km	unknown	link
Sweden	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	*50x50km*	unknown	unknown
Czech Republic	yes	yes	yes	yes	yes	yes	yes	daily	2021-2100	unknown	unknown	unknown	yes	0.5x0.5km	NetCDF, GeoTIFFdbf, csv	on request

the number of models used for this scenario; [1]also data on ETp; [2]also: 1976-2005 (historical), 2071-2100(RCP8.5) model COSMO-CLM and 1980-2015 (historical), 2080-2099 (RCP8.5) model MAR; [3]ensembles at a 10 km grid resolution are available for three time periods: 2011-2040; 2041-2070; 2071-2100 - no daily data

6.2. Annex 2: OPTAIN climate simulations - data

The name of the files is *domain-type*.zip, where *type* is gridded (NetCDF) or point (csv). Each zip file contains multiple files, organized in subfolders: CORDEX-BC/*experiment*/*modelNumber*/*variable*.nc (gridded) or CORDEX-BC/*experiment*/*modelNumber*/*variable-pilotFieldNumber*.csv (point) for bias-corrected EURO-CORDEX RCM simulations and ERA5-Land/*variable*.nc (gridded) or ERA-5Land/ *variable-pilotFieldNumber*.csv for ERA5-Land reanalysis, where *experiment* is: rcp26, rcp45 or rcp85.

6.2.1. domain and pilotFieldNumber

domain	pilotFieldNumber	pilot field location (longitude, latitude)	case study number	country	name
01			1	DEU	Schoeps
02	2	46.816667 6.95	2	CHE	Petite Glane
02_1	1	46.983333 7.466667			
02_34	3 4	47.433333 8.516667 47.683333 8.616667			
02_5	5	46.4 6.233333			
03a	1 2 3 4	46.92649 17.68246 46.9166 17.68976 46.91283 17.69754 46.91283 17.69723	3a	HUN	Csorsza
03b			3b	HUN	Felso Valicka
04	1	52.597469 18.728617	4	POL	Upper Zglowiaczka
05			5	SVN	Pesnica
06			6	HUN/SVN	Kebele/Kobiljski
07			7	BEL	La Wimbe
08	1 2	55.522057 23.799235 55.42233194 23.82580339	8	LTU	Dotnuvele
09			9	ITA	Cherio
10	1 2 3 4 5 6 7 8	59.71949 10.83576 59.6833306 10.8833298 59.6833306 10.8833298 59.665 10.9475 59.665 10.9475 59.841012 10.903597 59.757631 11.072031 59.539623 10.856447	10	NOR	Krogstad
11	1 2	46.658333 17.75583 46.656944 17.75833	11	HUN	Tetves

12	1	49.616837 15.078266	12	CZE	Cechticky
13			13	LVA	Dviete
14			14	SWE	Ingvastaan Lehstaan

6.2.2. modelNumber

modelNumber	Driving Model (GCM)	Ensemble	RCM	End date
1	EC-EARTH	r12i1p1	CCLM4-8-17	31.12.2100
2	EC-EARTH	r3i1p1	HIRHAM5	31.12.2100
3	HadGEM2-ES	r1i1p1	HIRHAM5	30.12.2099
4	HadGEM2-ES	r1i1p1	RACMO22E	30.12.2099
5	HadGEM2-ES	r1i1p1	RCA4	30.12.2099
6	MPI-ESM-LR	r2i1p1	REMO2009	31.12.2100

6.2.3. variable

Variable	Name	Unit	Comment
Mean temperature	Tmean	°C	
Min temperature	Tmin	°C	
Max temperature	Tmax	°C	
Precipitation	prec	mm	
Solar radiation	solarRad	MJ/m2	
Wind speed at 2m	windSpeed	m/s	
Relative humidity	relHum	%	
Elevation	elev	m	Only for ERA5-Land

6.2.4. version

Number	Date	Comment
1	2021-08-21	Initial version; point data prepared using nearest-neighbour method
2	2021-10-25	Added hard limits (prec, solarRad, windSpeed, relHum < 0.0000000001 -> 0; relHum > 100 -> 100); point data: a) prepared using universal kriging and b) rounded to 3 decimals
3	2022-02-16	Point data: a) fixed bug (wrong pilotFieldNumber), b) changed values and decimal separators to comma and point; reorganization (only zip files).
4	2022-02-21	Added ERA5-Land for period 2011-2021

6.3. Annex 3: Analysis of bias correction procedure for the example of the Tetves case study (CS 11)

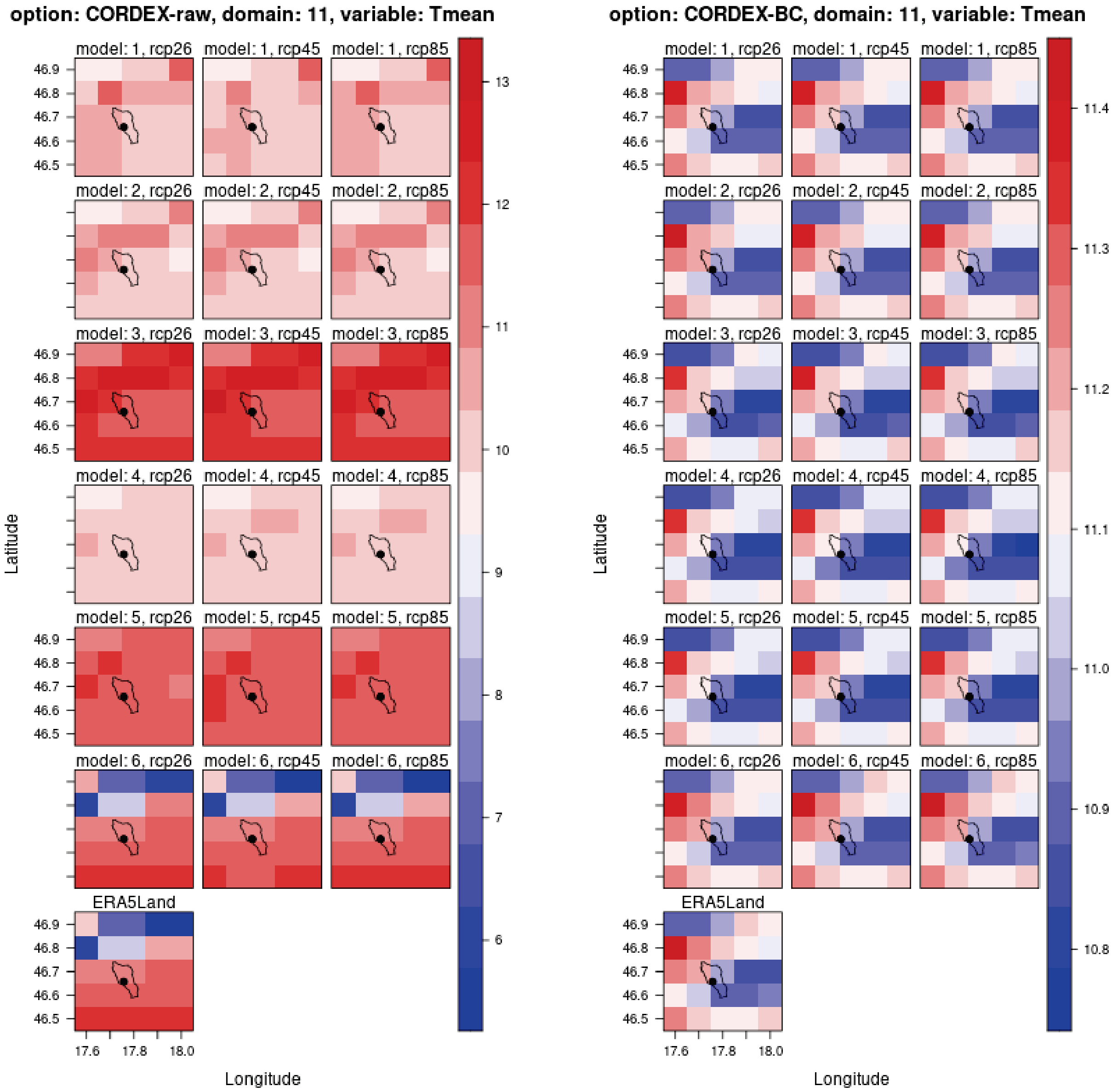


Figure 10. Maps of multi-year average value for mean temperature (Tmean) for raw CORDEX data (left) and for bias-corrected CORDEX data (right) for 6 models for 3 different RCPs for the period 1981-2010 for the Tetves case study (CS 11).

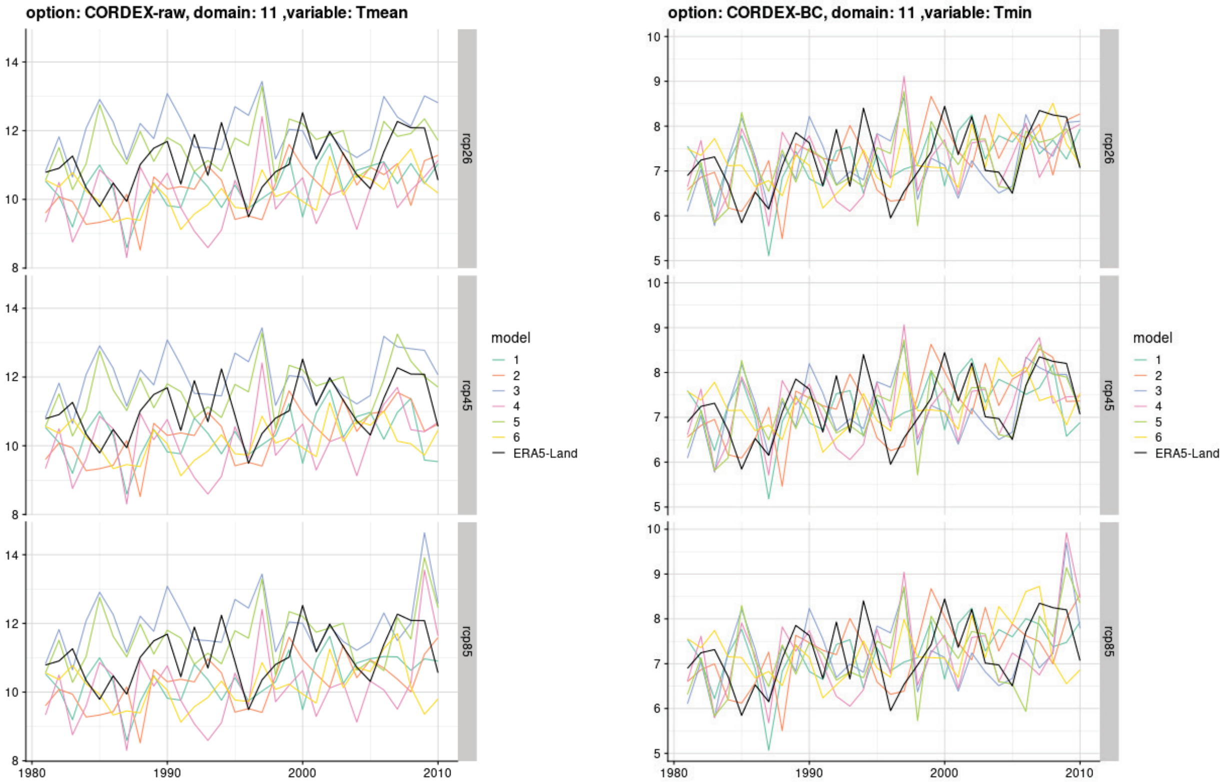


Figure 11. Timelines of average annual values for mean temperature (Tmean) for raw CORDEX data (left) and for bias-corrected CORDEX data (right) for 6 models for 3 different RCPs for the period 1981-2010 for the Tetves case study (CS 11).

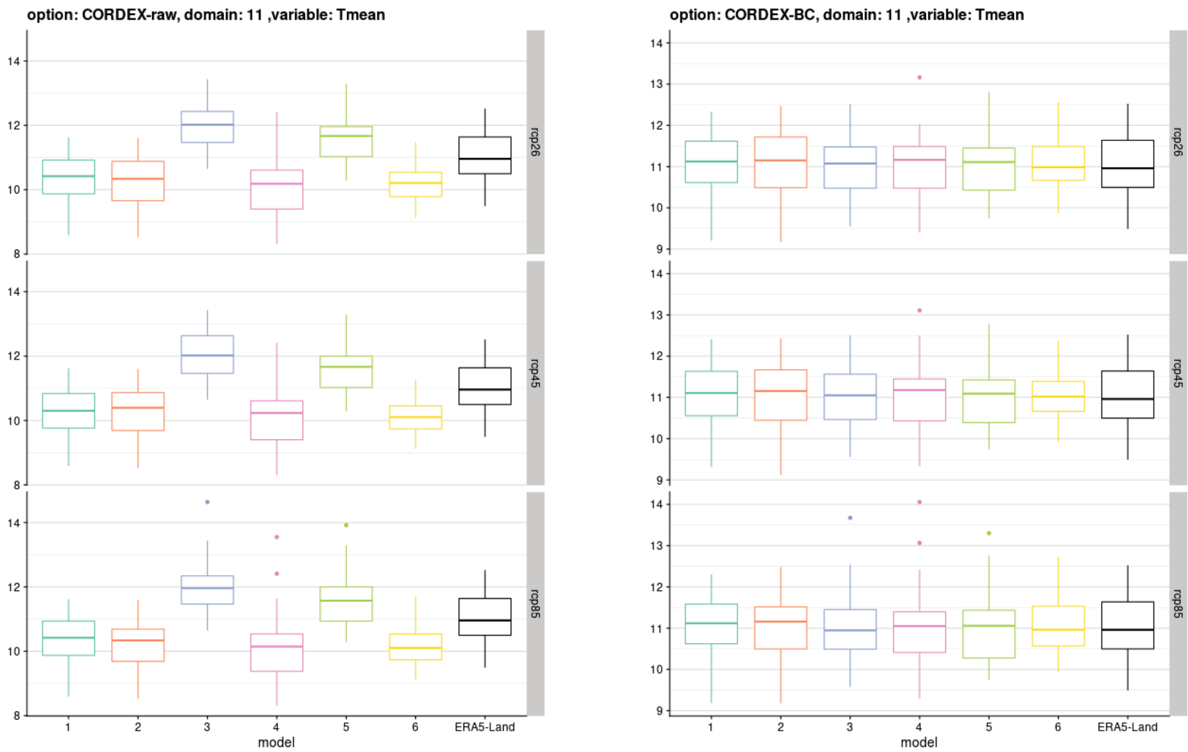


Figure 12: Boxplots of average annual values for mean temperature (Tmean) for raw CORDEX data (left) and for bias-corrected CORDEX data (right) for 6 models for 3 different RCPs for the period 1981-2010 for the Tetves case study (CS 11).

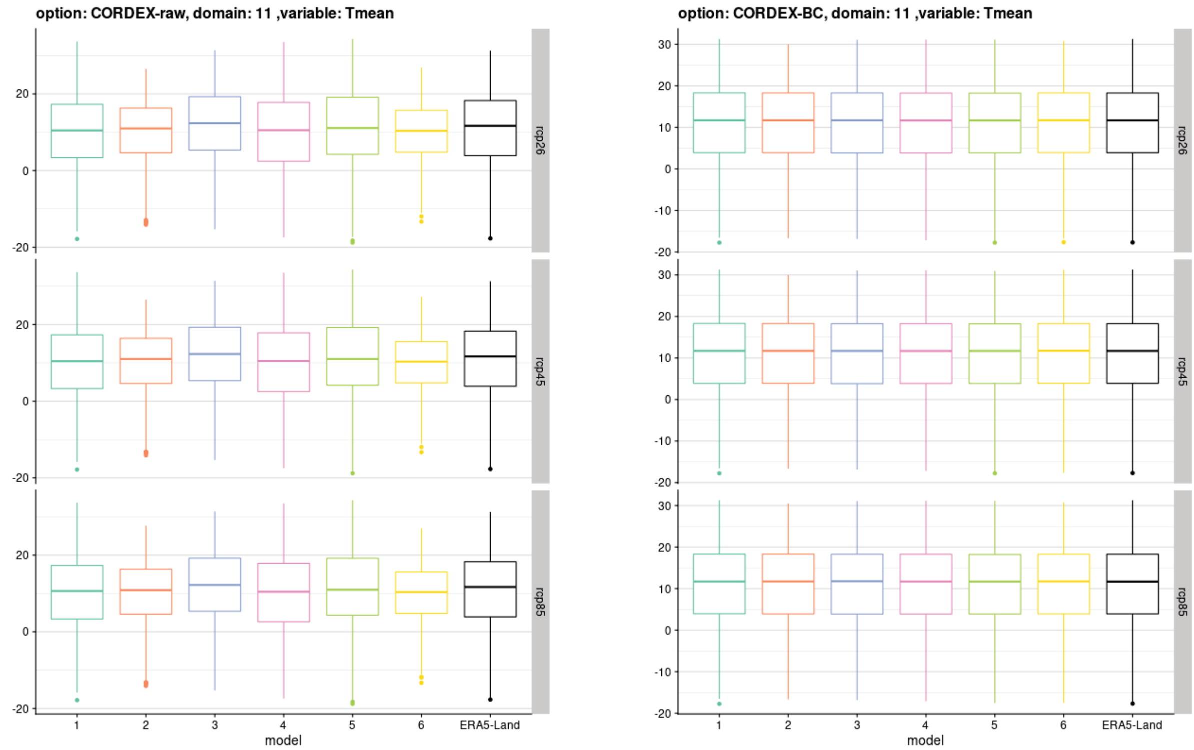


Figure 13. Boxplots of daily values for mean temperature (Tmean) for raw CORDEX data (left) and for bias-corrected CORDEX data (right) for 6 models for 3 different RCPs for the period 1981-2010 for the Tetves case study (CS 11).

6.4. Annex 4: Analysis of the ensemble of RCM simulations

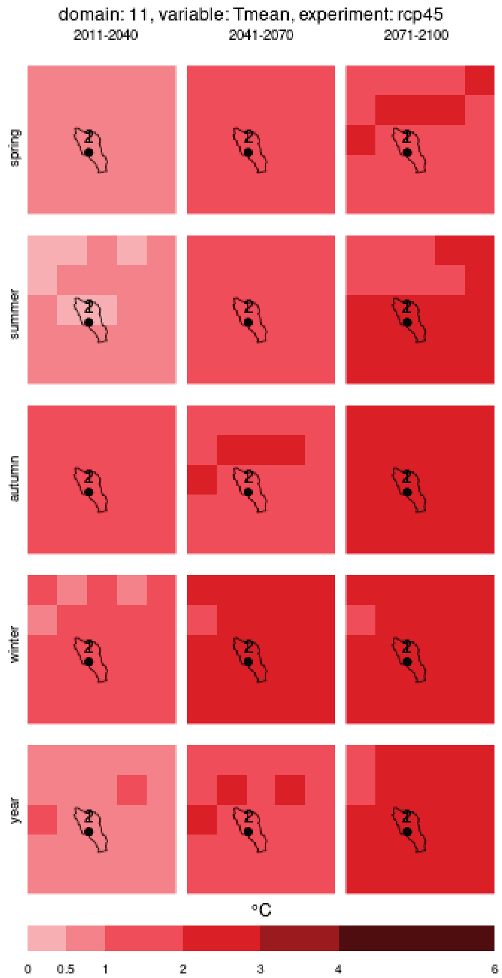


Figure 14. Maps of the median change of the ensemble of climate simulations against the reference period 1981-2010 for mean temperature (Tmean), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP4.5 for the Tetves case study (CS 11).

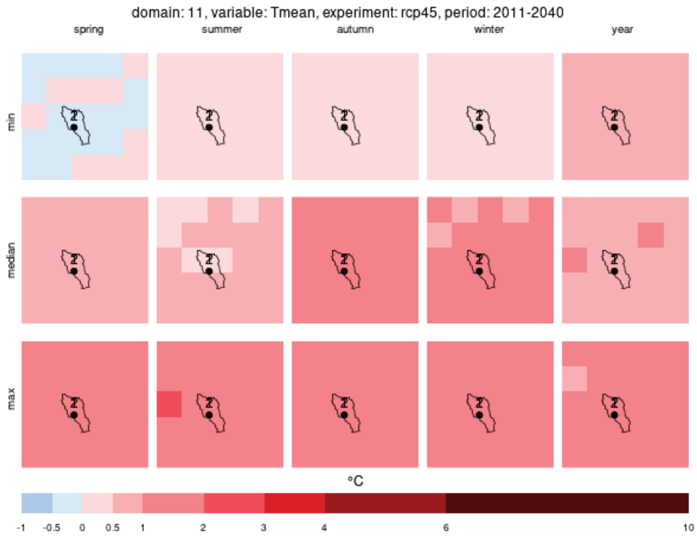
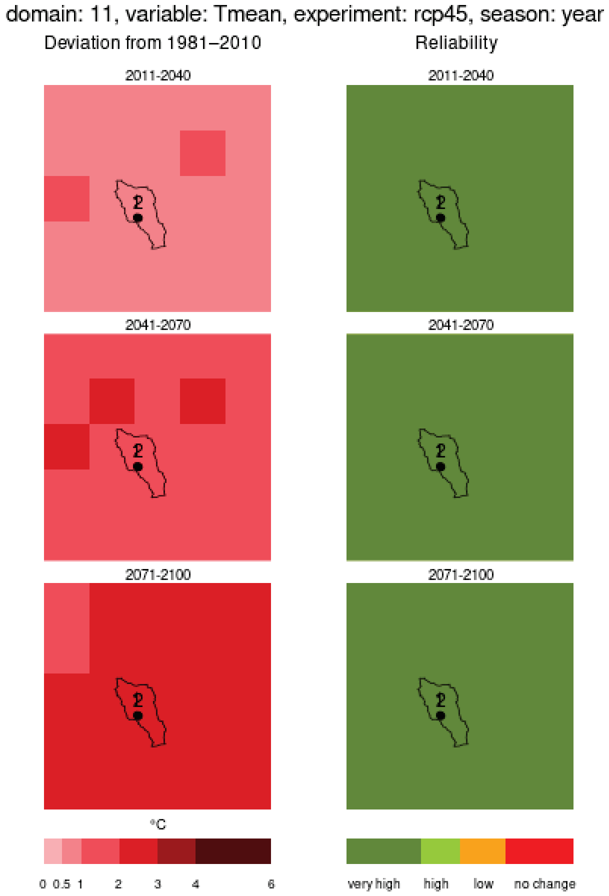


Figure 15. Maps of the spread of the ensemble (median, minimum and maximum change) for mean temperature (Tmean), for all seasons and year, for the period 2011-2040, considering RCP4.5 for the Tetves case study (CS 11).



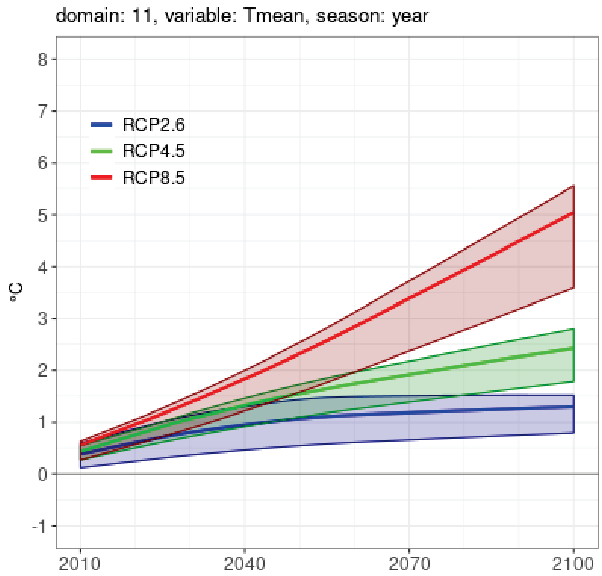


Figure 16. Maps with the median change of the ensemble and reliability of the change for mean temperature (Tmean) for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP4.5 for the Tetves case study (CS 11).

Figure 17. Timelines with the spread of the ensemble (min, max, median change) for mean temperature (Tmean) considering RCP2.6, 4.5 and 8.5 for the Tetves case study (CS 11).

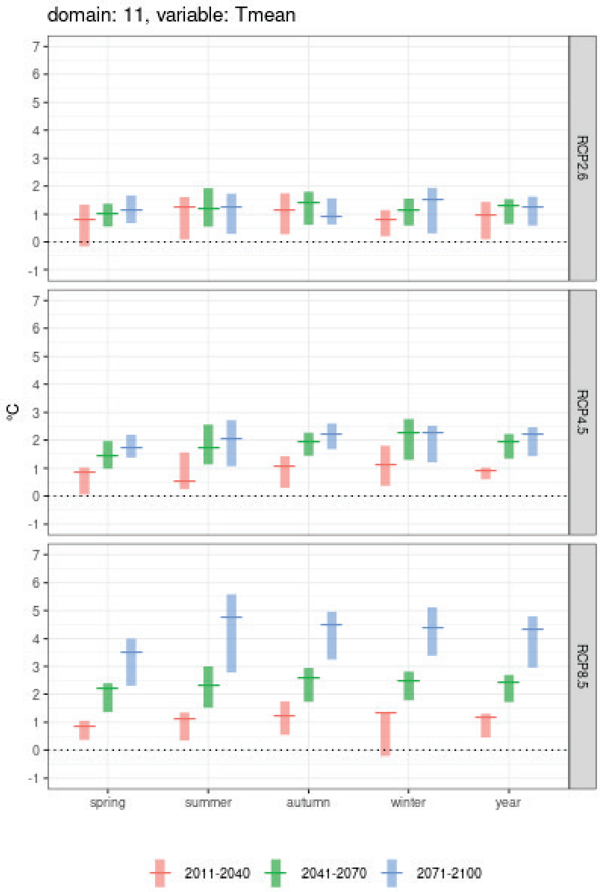


Figure 18. Spreads of the ensemble (min, max, median change) for mean temperature (Tmean), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5 for the Tetves case study (CS 11).

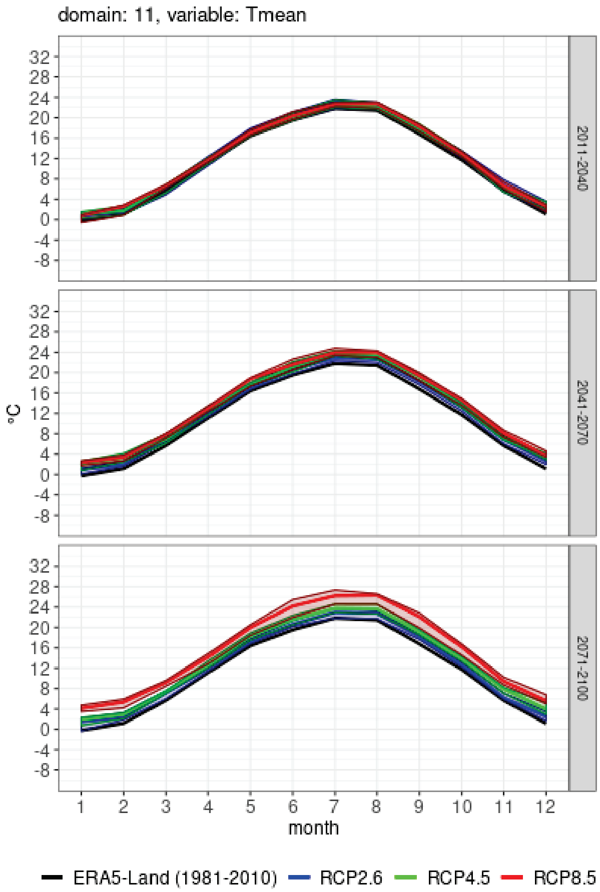


Figure 19. Spreads of the ensemble (min, max, median change) by months for mean temperature (Tmean), for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5 for the Tetves case study (CS 11).

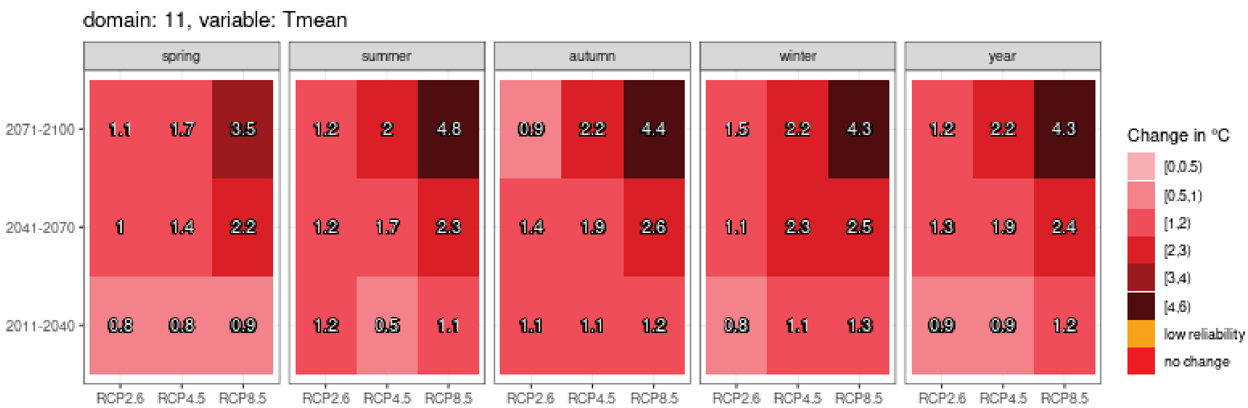


Figure 20. The median change and reliability of the change for mean temperature (Tmean), for all seasons and year, for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5 for the Tetves case study (CS 11).

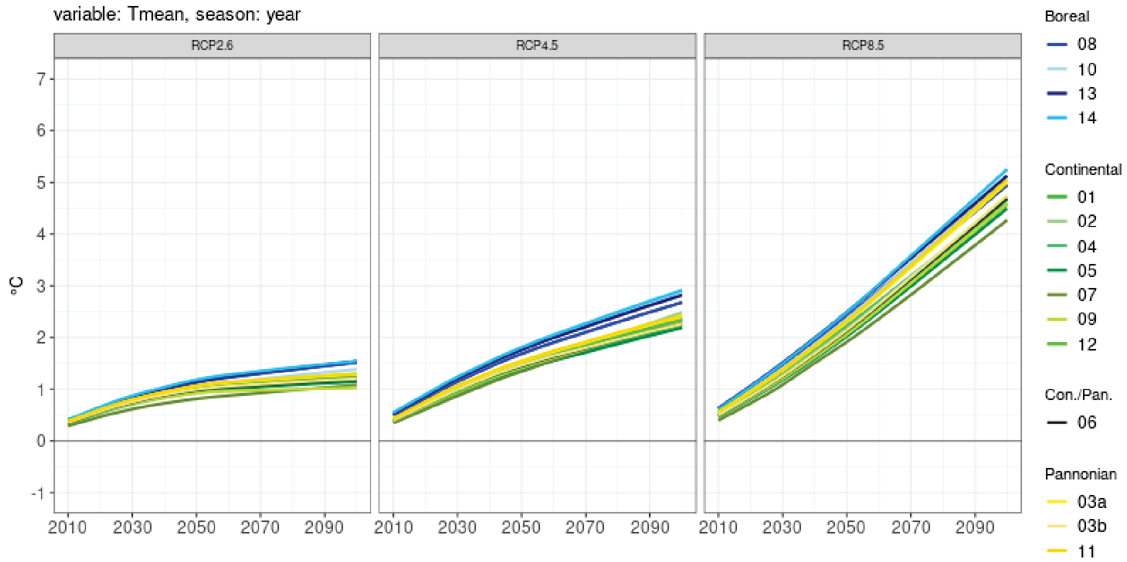


Figure 21. Timelines of the median change of the ensemble, considering RCP2.6, 4.5 and 8.5 for all case studies.

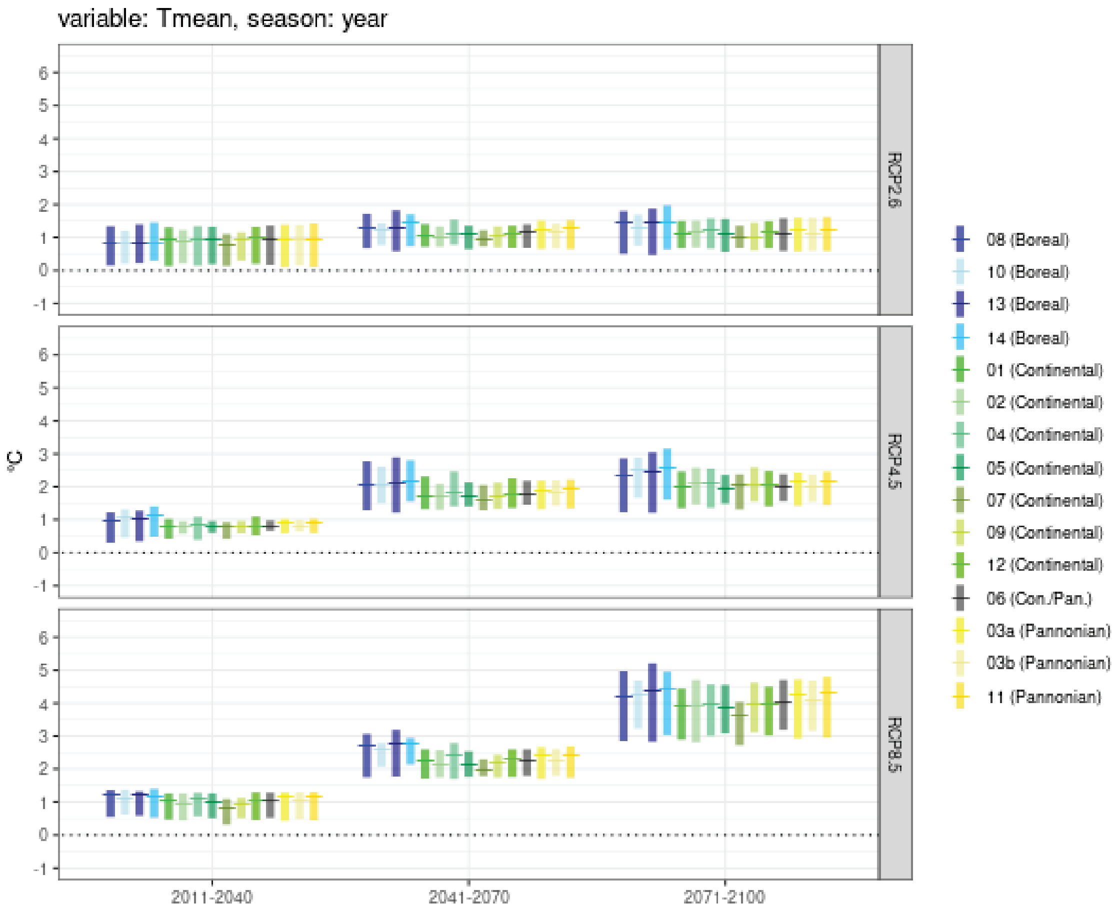


Figure 22. Spreads of the ensemble (min, max, median change) for mean temperature (Tmean), for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5 for all case studies.

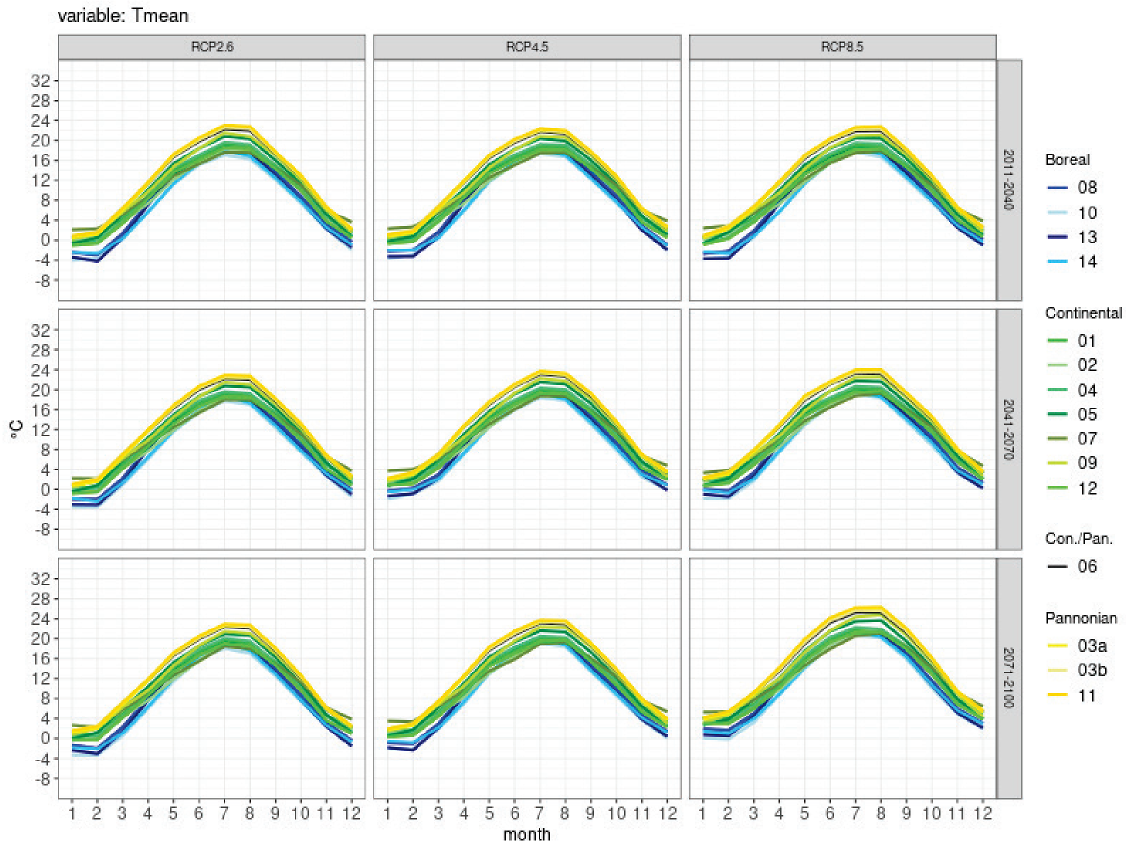


Figure 23. The median of the ensemble by months for mean temperature (Tmean), for periods 2011-2040, 2041-2070 and 2071-2100, considering RCP2.6, 4.5 and 8.5 for all case studies.

6.5. Annex 5. OPTAIN climate simulations – evaluation and analysis data

The name of the files is *domain*.zip. Each zip file contains multiple files, organized in folder and subfolders as shown in following table.

folder	subfolder	Description
1-domains		Domains with elevation (from ERA5-Land), catchments and locations (files: elev.png)
2-bias-correction		Bias correction analysis OPTION: CORDEX-raw/CORDEX-BC EXPERIMENT: rcp26/rcp45/rcp85
	a-maps	Climatology 1981-2010 for all models (files: OPTION-VARIABLE.png) and difference against ERA5-Land (files: diff-OPTION-VARIABLE.png)
	b-domainAverage	Domain averaged (for all models): • Timeline of yearly means (files: OPTION-VARIABLE_timeline.png) • Boxplot of yearly means (files: OPTION-VARIABLE_boxplot.png) • Boxplot of daily data (files: OPTION-VARIABLE_boxplot_daily.png)
3-projections-basic		Projections SEASON: year, MAM (spring), JJA (summer), SON (autumn), DJF (winter) PERIOD: 2011-2040, 2041-2070, 2071-2100
	a-maps	Maps with median of ensemble for all SEASONs (files EXPERIMENT-VARIABLE.png)
	b-maps-spread	Maps with min, median and max of ensemble for all SEASONs (files: EXPERIMENT-VARIABLE-PERIOD.png)
	c-maps-reliability	Maps with median of ensemble and reliability (files: EXPERIMENT-VARIABLE-SEASON.png)

	d-domainAverage-envelopes	Domain-averaged timeline with spread of ensemble for all EXPERIMENTs (files VARIABLE-SEASON.png)
	e-domainAverage-spread	Domain-averaged spread of ensemble (min, max, median) for all EXPERIMENTs and SEASONs (files: VARIABLE.png).
	f-domainAverage-reliability	Domain-averaged reliability and median of ensemble for all EXPERIMENTs and SEASONs (files: VARIABLE.png).
	g-domainAverage-month	Domain-averaged spread of ensemble (min, max, median) for all EXPERIMENTs by months (files: VARIABLE.png).
	h-domainAverage-XLS	Domain-averaged: a) change (min, max, median, reliability) by periods (files: change.xlsx) and b) absolute values (min, max, median) by periods for seasons and year (files: values.xlsx) or months (files: values-month.xlsx).
	i-domainAverage-PDF	Figures from d, e and f (files: domainAverage.pdf).

Furthermore, there is a file allDomains.zip with all domains with catchments. The zip file contains multiple files, organized in folder and subfolders as shown in following table.

folder	subfolder	Description
3-projections-basic		Projections SEASON: year, MAM (spring), JJA (summer), SON (autumn), DJF (winter) PERIOD: 2011-2040, 2041-2070, 2071-2100 EXPERIMENT: rcp26/rcp45/rcp85
	j-domainAverage-timeline-allDomains	Timeline with median of the ensemble for all EXPERIMENTs (files VARIABLE-SEASON.png)
	k-domainAverage-spread-allDomains	Domain-averaged spread of ensemble (min, max, median) for all EXPERIMENTs and SEASONs (files: VARIABLE-PERIOD.png) or for all EXPERIMENTs and PERIODs (files: VARIABLE-SEASON.png).
	l-domainAverage-reliability-allDomains	Domain-averaged reliability and median of ensemble for all EXPERIMENTs and SEASONs (files: VARIABLE.png).

	m-domainAverage-month-allDomains	Domain-averaged median of the ensemble for all EXPERIMENTs by months (files: VARIABLE.png).
	n-domainAverage-XLS-allDomains	Domain-averaged: a) change (min, max, median, reliability) by periods (files: change.xlsx) and b) absolute values (min, max, median) by periods for seasons and year (files: values.xlsx) or months (files: values-month.xlsx).

6.5.1. domain

domain	case study number	country	name
01	1	DEU	Schoeps
02	2	CHE	Petite Glane
02_1			
02_34			
02_5			
03a	3a	HUN	Csorsza
03b	3b	HUN	Felso Valicka
04	4	POL	Upper Zglowiaczka
05	5	SVN	Pesnica
06	6	HUN/SVN	Kebele/Kobiljski
07	7	BEL	La Wimbe
08	8	LTU	Dotnuvele
09	9	ITA	Cherio
10	10	NOR	Krogstad
11	11	HUN	Tetves
12	12	CZE	Cechticky
13	13	LVA	Dviete
14	14	SWE	Ingvastaan Lehstaan

6.5.2. modelNumber

modelNumber	Driving Model (GCM)	Ensemble	RCM	End date
1	EC-EARTH	r12i1p1	CCLM4-8-17	31.12.2100
2	EC-EARTH	r3i1p1	HIRHAM5	31.12.2100
3	HadGEM2-ES	r1i1p1	HIRHAM5	30.12.2099

4	HadGEM2-ES	r1i1p1	RACMO22E	30.12.2099
5	HadGEM2-ES	r1i1p1	RCA4	30.12.2099
6	MPI-ESM-LR	r2i1p1	REMO2009	31.12.2100

6.5.3. Variables

Variable	Name	Unit
Mean temperature	Tmean	°C
Min temperature	Tmin	°C
Max temperature	Tmax	°C
Precipitation	prec	mm
Solar radiation	solarRad	MJ/m2
Wind speed at 2m	windSpeed	m/s
Relative humidity	relHum	%

6.5.4. Versions

Number	Date	Comment
1	2021-12-24	Initial version
2	2022-01-20	Changes to 3-projections-basic: -Reorganization (first maps, then domain average), renamed range to spread, significance to reliability -Fixed bug in e-domainAverage-spread (wrong season names) -Reliability: addded aditional level (very high), changed color table -Additional: f-domainAverage-reliability, g-domainAverage-XLS and h-domainAverage-PDF -Other minor changes for nicer look.
3	2022-02-17	Changes to 3-projections-basic: -Added g-domainAverage-month and thus renamed h- to i- and previous g- to h- -Changed plots for f-, updated i- -Added values (year, season, month) to h- -Additional for all domains together: j-domainAverage-timeline-allDomains, k-domainAverage-spread-allDomains, l-domainAverage-reliability-allDomains, m-domainAverage-month-allDomains and n-domainAverage-XLS-allDomains