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Bias-adjustment of maximum and minimum temperatures for Norway

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Summary: An ensemble of ten EURO-CORDEX GCM/RCM simulations of maximum and minimum temperature, each run under two alternative emission scenarios (RCP4.5 and RCP8.5), were bias-adjusted using an empirical quantile delta mapping method which can preserve the temperature change signals. These high-resolution (1 x 1 km) climate data sets cover the period 1971–2100 and provide an important data source for different types of climate impact studies at national and local scales.

Keywords: Gridded data, EURO-CORDEX, maximum and minimum temperature, bias-correction/bias-adjustment, empirical quantile delta mapping method, SeNorge data, Norway

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Preface

This report gives a brief description of the post-processing methods used to derive high-resolution (1 x 1 km) maximum and minimum temperature projections and to adjust these data for systematic biases inherited from the climate models. These data sets represent an important data source for climate impact studies where such information is required at national and local scales, and thereby also contribute to NVE's climate change adaptation plan.

Oslo, December 2019

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Summary

There is an increasing need for gridded data at higher spatial and temporal resolution as the focus of climate change impact research has shifted from global to regional and local scales. However, the outputs of regional climate models still suffer from systematic biases that often impede the direct use of such results in climate impact studies. In addition, impact models often require data of higher spatial resolution than regional climate models normally can provide. This necessitates post-processing procedures that give plausible results at an appropriate scale for use in local impact studies.

In this report, an empirical quantile mapping method (EQM) was used to bias-correct the maximum (Tmax) and minimum (Tmin) temperature simulations based on an ensemble of ten EURO-CORDEX regional climate models. These model data with a resolution of approximately 12.5 x 12.5 km were first re-gridded to a 1 x 1 km scale using a nearest neighbour method. SeNorge gridded data were then used as the observed data for the bias-correction procedure. A transfer function based on the empirical cumulative distribution functions (ECDFs) for both observed and modelled variables in the control period was applied to correct values from the climate models, quantile by quantile. Calendar-month and grid-cell-specific transfer functions were derived. To bias-adjust future projections with the two emission scenarios (RCP4.5 and RCP8.5), an empirical quantile delta mapping method (EQDM) was applied. For each quantile, the temperature changes between the uncorrected modelled ECDF in both control and projection periods were estimated. These changes are superimposed on the bias-corrected data from the control period, quantile by quantile. To ensure physical consistency, i.e. that Tmax > Tmin, the diurnal temperature range (DTR) was first calculated. Bias-correction and bias-adjustment methods were used on Tmax and DTR separately. Tmin was then derived by subtracting DTR from Tmax. The results show that the procedure preserves the temperature change signals well while also adjusting the systematic biases.

These bias-adjusted maximum and minimum temperature data sets cover the period 1971–2100 and represent an important data source for different types of impact studies at national and local scales. They have been used as forcing data for an improved version of the HBV precipitation-runoff model to produce better evapotranspiration estimates, and to assess projected changes in frost-change days (zero-degree crossings) for Norway.

1 Introduction

Climate change has already had observable effects on the hydrologic cycle and consequently on water resources in Norway. When modelling climate change impacts, simulations of meteorological variables such as maximum and minimum air temperatures, precipitation amount and solar radiation are often required as inputs to various impact models. Evapotranspiration, as a key variable for hydrologic, climatic and agricultural studies, cannot be properly measured in many situations and its estimation is often relied on the application of mathematical models. Studies have shown that the Penman-Monteith formula, which combines the energy balance with the mass transfer equation, is the most accurate method to estimate evapotranspiration under different climatic conditions and is now a widely used approach (e.g. Allen *et al.*, 1998). An improved version of the distributed HBV precipitation-runoff model has recently adopted the Penman-Monteith approach to better estimate projections of evapotranspiration and runoff under a future climate (Huang *et al.*, 2019). As a result, the hydrological model now requires daily maximum and minimum temperatures as forcing data in addition to other meteorological variables.

The number of days where the soil temperature crosses 0 °C (also called frost-change days) is an important indicator for several user groups. The applications cover many sectors ranging from agriculture and reindeer herding (e.g. Rigby and Porporato, 2008; Eira *et al.*, 2018; Vyse *et al.*, 2019) to transport and construction (e.g. Gustafson, 1983; French *et al.*, 2010). However, the statistics of the freeze-thaw phenomenon, essentially a surface feature, are difficult to determine. Maximum and minimum air temperatures (Tmax and Tmin) are therefore often used as proxies to estimate the occurrence of soil freeze-thaw cycles. Following Kerguillec (2015) and Hershfield (1974), a frost-change day occurs if the air temperature crosses the freezing point during a calendar day (i.e. Tmax > 0 and Tmin < 0). A better understanding of potential changes in freeze-thaw cycling under climate change can improve adaptive measures including crop selection and infrastructure maintenance management. A prerequisite for achieving this is that such maximum and minimum temperature data from climate projections are available for analyses.

Bias-adjusted climate projections including daily precipitation sum and mean temperature for Norway at a 1 x 1 km resolution have been available from the Norwegian Centre for Climate Services (NCCS) since 2017. Due to requests from the scientific and user communities, it was decided that NCCS would also provide bias-adjusted projections of maximum and minimum temperatures (Hanssen-Bauer *et al.*, 2017b). A previously published NVE report 'Gridded 1 x 1 km climate and hydrological projections for Norway' (Wong *et al.*, 2016) gives a brief overview of the necessity for applying bias-correction and bias-adjustment procedures to different climate variables before they can be used as input data for local climate impact studies. Those arguments including model biases due to imperfect models are also valid in this study since the climate projections for Norway, in general, have shown that simulated temperatures are too cold. The limitations and drawbacks of the post-processing methods have also been previously discussed.

The bias-correction procedure used in this report also includes a downscaling component, which involves transforming the climate patterns simulated at a coarse grid resolution to the finer spatial resolution of interest. The term *bias-correction* refers to eliminating systematic biases in simulated values relative to observed ones, which, in principle, reflect the 'true values'. This procedure is typically used to correct simulated data for a period in which observations are available, in this case, the control period. For the future projection periods, since observations are not available, we can only adjust the values based on the correction established for the control period and the original climate change signals. We, therefore, use the term *bias-adjustment* to distinguish the procedure used for future periods with the 'bias-correction' used for the control period. This report provides a brief description of the methods used for adjusting simulated daily maximum and minimum air temperatures derived from the climate model data.

2 Data

2.1 EURO-CORDEX climate projections

Table 1 lists the ten GCM/RCM runs from which daily maximum and minimum air temperature values were obtained for the period 1971 to 2100. These model outputs have a spatial horizontal resolution of approximately 12.5 x 12.5 km.

The selected models are based on the EURO-CORDEX ensemble which has been used in the study 'Climate in Norway 2100' (Hanssen-Bauer et al., 2017a). Similarly, two emission scenarios, RCP4.5 and RCP8.5, were adopted (van Vuuren et al., 2011). RCP4.5 represents a medium emission scenario in which the greenhouse gases steadily increase until 2040 and then begin to decrease. RCP8.5, on the other hand, refers to a future with continuously increasing greenhouse gases throughout the 21st century. The control period used in this study is 1971–2005, whilst 2006–2100 is designated as the projection period.

2.2 'SeNorge' data sets

In-situ observations of maximum and minimum air temperatures from a climate station network were interpolated to derive gridded data sets of 1 km resolution covering the mainland of Norway. For further details of the interpolation procedure, see Mohr (2008). These data sets, referred to as SeNorge (version 1.1) data sets, were used as the observational data for adjusting the biases in the climate model data.

3 Method

The uncorrected outputs of climate models, daily maximum and minimum air temperatures (Tmax and Tmin), were first re-gridded to a 1 x 1 km grid using a nearest neighbour method. This is a rather conservative approach and ensures that the areal means of the fine-scale grid cells match the corresponding RCM grid cell outputs. The SeNorge Tmax and Tmin data sets from the control period were treated as 'observed' data. All the observed data were checked for consistency to ensure that Tmax > Tmin. Since we bias-adjust Tmax and Tmin separately, there is no guarantee that the adjusted data also will be physically consistent, i.e. that Tmax > Tmin. To avoid physically unrealistic correction/adjustment results, we follow the method proposed by Thrasher *et al.* (2012). In this method, the diurnal temperature range (DTR) is first calculated as the difference between daily Tmax and Tmin. Bias-correction and bias-adjustment algorithms are then performed on Tmax and DTR independently such that Tmin can then be derived by subtracting DTR from Tmax.

Global climate model	Ensemble member	Regional climate model	Time period	Institution
CNRM-CERFACS-CM5	r1i1p1	CCLM4-8-17	1971–2100	Climate Limited-area Modelling Community
CNRM-CERFACS-CM5	r1i1p1	RCA4	1971–2100	Swedish Meteorological and Hydrological Institute
ICHEC-EC-EARTH	r12i1p1	CCLM4-8-17	1971–2100	Climate Limited-area Modelling Community
ICHEC-EC-EARTH	r3i1p1	HIRHAM5	1971–2100	Danish Meteorological Institute
ICHEC-EC-EARTH	r1i1p1	RACMO22E	1971–2100	Royal Netherlands Meteorological Institute
ICHEC-EC-EARTH	r12i1p1	RCA4	1971–2100	Swedish Meteorological and Hydrological Institute
MOHC-HadGEM2-ES	r12i1p1	RCA4	1971–2100	Swedish Meteorological and Hydrological Institute
IPSL-CM5A-MR	r1i1p1	RCA4	1971–2100	Swedish Meteorological and Hydrological Institute
MPI-ESM-LR	r1i1p1	CCLM4-8-17	1971–2100	Climate Limited-area Modelling Community
MPI-ESM-LR	r1i1p1	RCA4	1971–2100	Swedish Meteorological and Hydrological Institute

Table 1. Overview of GCM/RCM combinations used in this report.

3.1 Empirical quantile mapping (EQM)

For correcting the model outputs in the control period, an empirical quantile mapping method (EQM) was used (Gudmundsson *et al.*, 2012). EQM utilizes the empirical cumulative distribution functions (ECDFs) for both observed and modelled variables. A transfer function matching the modelled ECDF with the observed ECDF is constructed based only on data from the control period (Figure 1). The ECDFs are approximated using lookup tables with entries obtained by spline interpolation between empirical quantiles of observed and modelled data. The bias-correction was carried out on monthly basis for each individual grid cell. The R package ‘qmap’ version 1.0-4 (Gudmundsson, 2016) was applied to bias-correct all the climate model data for the control period for Tmax and DTR respectively.

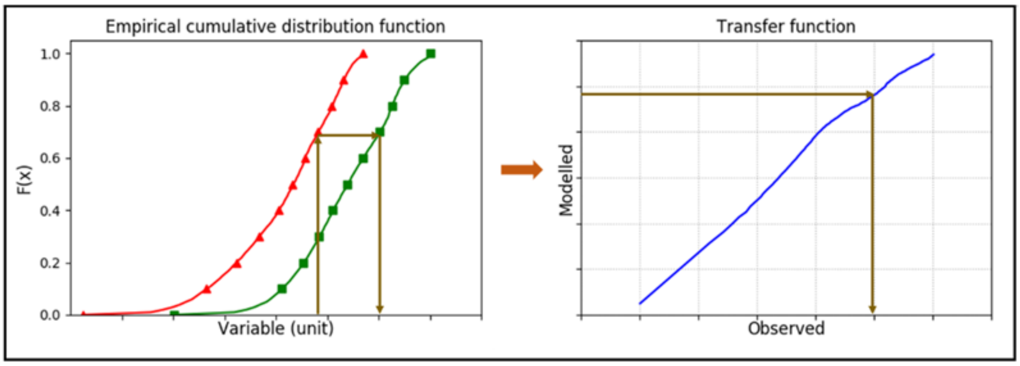

Figure 1. Method for deriving a transfer function based on an empirical cumulative distribution function (ECDF). The red and green lines on the left denote the ECDF of modelled and observed time series respectively. The blue line on the right represents the derived transfer function.

3.2 Empirical quantile delta mapping (EQDM)

For bias-adjusting the future projections, we first examine the changes between the uncorrected modelled ECDF in both control and projection periods, quantile by quantile. These changes in the different quantiles are transferred and superimposed on the corresponding quantiles of bias-corrected data from the control period (Cannon *et al.*, 2015). The bias-adjusted future projections can then be derived on a monthly and individual grid cell basis.

Let $\Delta T_q^{original}$ be the original temperature change signal for percentile q, between the control and projection periods:

$$\Delta T_q^{original} = T_q^{prj} - T_q^{ctrl}$$

where T_q^{prj} and T_q^{ctrl} are equal to the q percentile of ECDF of the uncorrected temperature data from a climate model in the projection and control periods respectively.

The bias-adjusted temperature for percentile q in the projection period $\hat{T}_q^{prj}$ is:

$$\hat{T}_q^{prj} = \Delta T_q^{original} + \hat{T}_q^{ctrl}$$

where $\hat{T}_q^{ctrl}$ refers to the q percentile bias-corrected temperature data using the EQM method in the control period.

Figure 2 illustrates how the future projections for maximum temperature data are adjusted so that the temperature change signals in the various quantiles are better preserved. Again, Tmax and DTR are adjusted separately. After the adjustments, Tmin is recovered by subtracting DTR from Tmax.

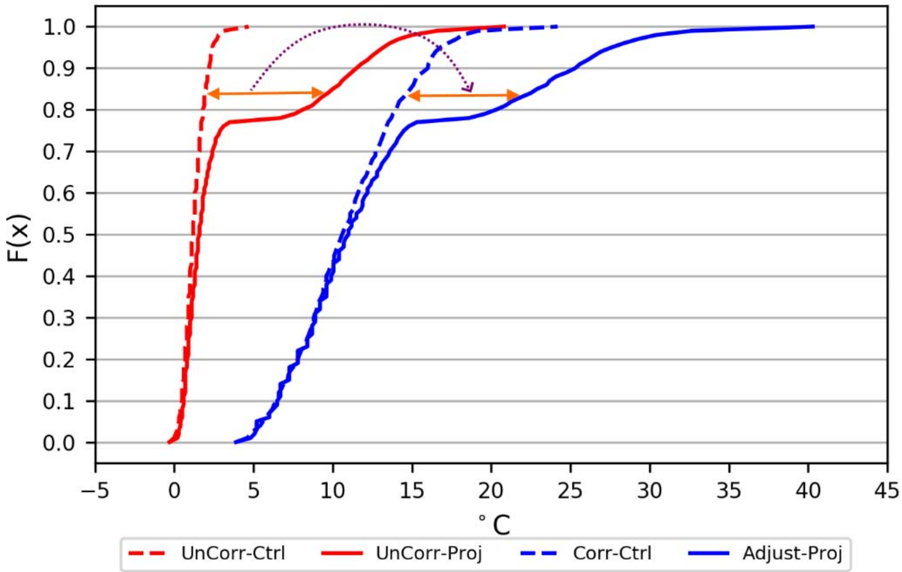

Figure 2. Synthetic example of bias-adjustment of maximum temperature (Tmax) projections. The dashed red line refers to the empirical cumulative distribution function (ECDF) of the uncorrected Tmax from a climate model for the control period while the solid red line represents the ECDF of the uncorrected Tmax for the projection period. Similarly, the dashed blue line denotes the ECDF of bias-corrected Tmax for the control period using the EQM method. The solid blue line indicates the derived, bias-adjusted, Tmax for the projection period. It is based on the temperature difference for a given quantile between the ECDFs of the uncorrected modelled Tmax from the control and projection periods.

4 Results and discussion

Figure 3 shows the annual and seasonal mean maximum temperature for Norway in the reference period (1971–2000) based on SeNorge observed data. Similar results for mean minimum temperature are shown in Figure 4. In summer, for most of the country, the mean maximum temperatures are higher than 15 °C. On the other hand, the mean minimum temperatures in winter are below -10 °C.

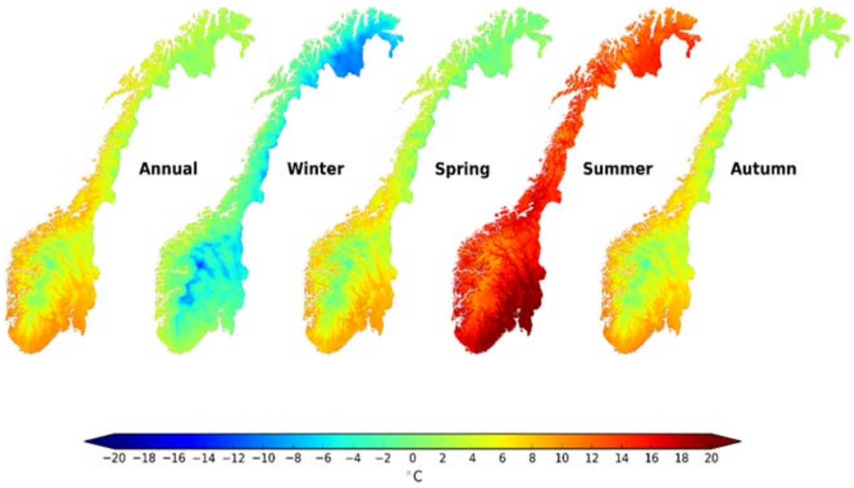

Figure 3. Mean maximum temperatures (annual and seasonal) based on SeNorge observed data for the period 1971–2000.

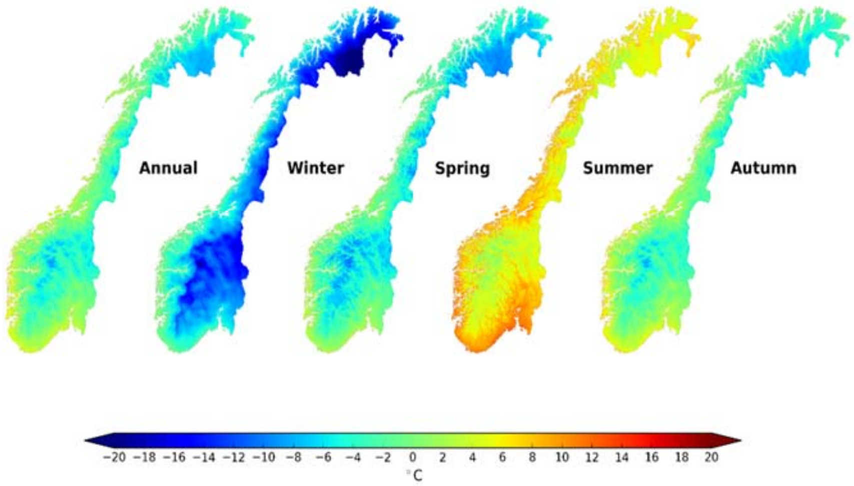

Figure 4. Mean minimum temperatures (annual and seasonal) based on SeNorge observed data for the period 1971–2000.

For the future periods, only the results based on the median change values of the ten projections are presented in this report. Figure 5 and 6 give the median changes in maximum and minimum temperatures when comparing the near future (2031–2060) and the present (1971–2000) climates for RCP4.5 and RCP8.5 respectively. Similarly, Figure 7 and 8 refer to the median changes between the reference period (1971–2000) and the far future period (2071–2100).

Generally, all the changes in temperature (both maximum and minimum) are positive, indicating that an increase in temperature in the future is expected. However, the changes in the minimum temperatures, both annual and seasonal, are significantly larger than the changes in the maximum temperatures. For RCP8.5, the positive changes are also greater than for RCP4.5.

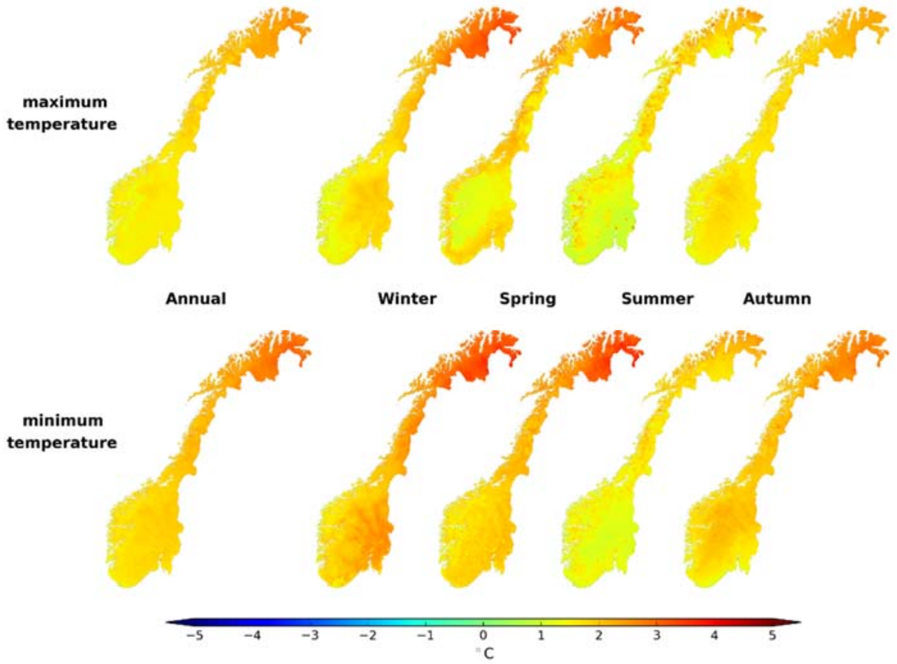

Figure 5. Median changes in annual and seasonal maximum temperatures (upper panel) and minimum temperatures (lower panel) based on 10 RCM runs for RCP4.5. The changes are estimated between the reference period (1971–2000) and the projection period (2031–2060).

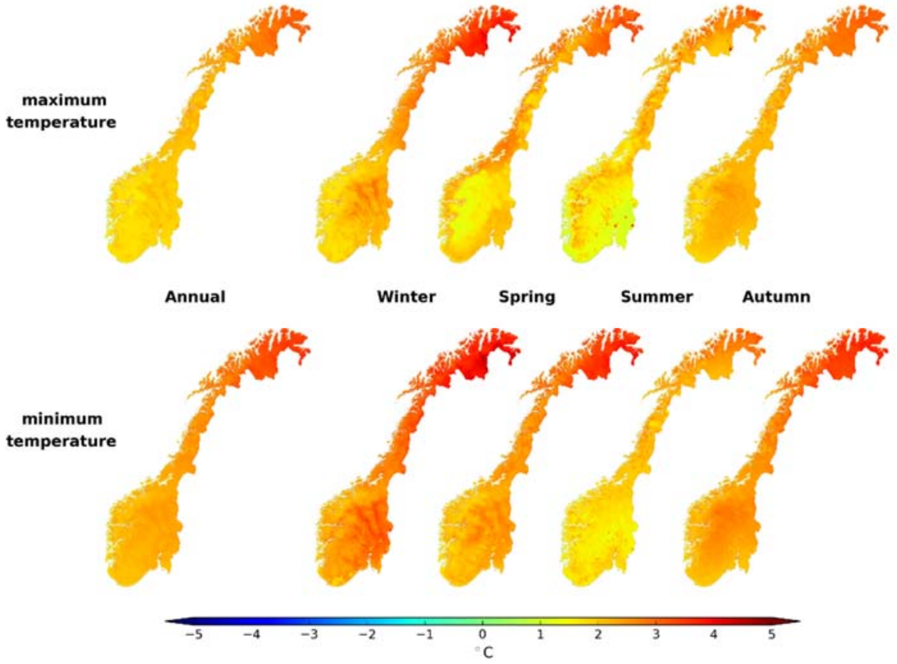

Figure 6. Median changes in annual and seasonal maximum temperatures (upper panel) and minimum temperatures (lower panel) based on 10 RCM runs for RCP8.5. The changes are estimated between the reference period (1971–2000) and the projection period (2031–2060).

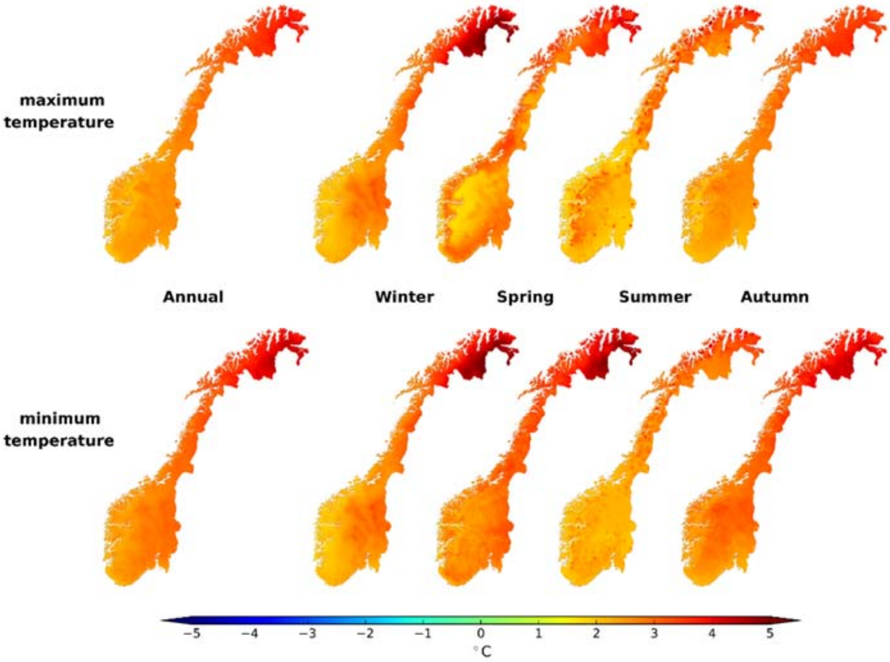

Figure 7. Median changes in annual and seasonal maximum temperatures (upper panel) and minimum temperatures (lower panel) based on 10 RCM runs for RCP4.5. The changes are estimated between the reference period (1971–2000) and the projection period (2071–2100).

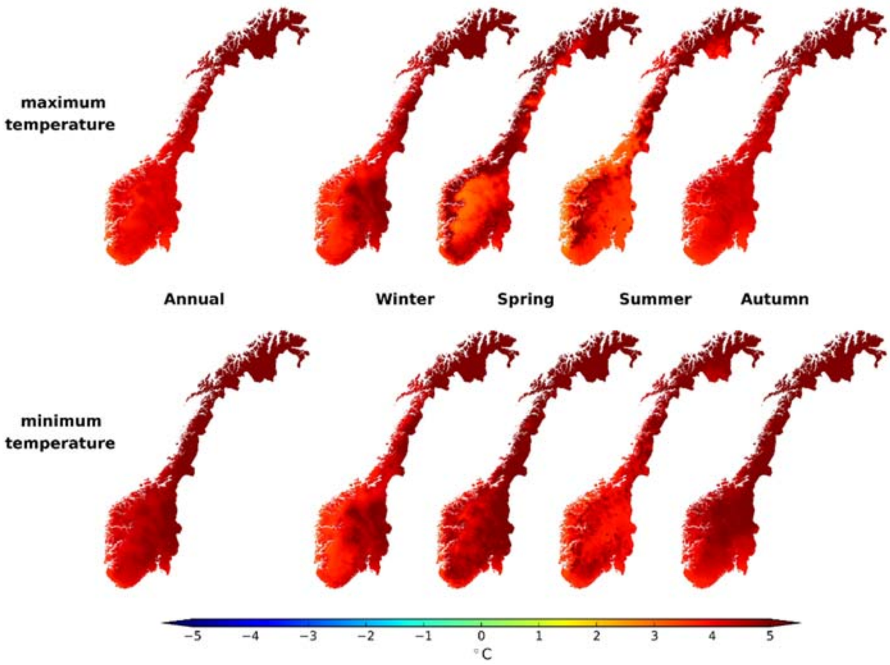

Figure 8. Median changes in annual and seasonal maximum temperatures (upper panel) and minimum temperatures (lower panel) based on 10 RCM runs for RCP8.5. The changes are estimated between the reference period (1971–2000) and the projection period (2071–2100).

To examine whether the original climate change signals have been modified by the bias-adjustment method, the mean annual maximum and minimum temperature changes for the whole of Norway derived from the original climate model outputs and bias-adjusted data are compared. Figure 9 shows the comparison of the ten projections between the periods of 2031–2060 and 1971–2000. The change signals with and without bias-adjustment are very close to each other. This implies that the bias-adjustment method does a fairly good job in preserving the original change signal on an annual basis while also rectifying the systematic biases. However, it is questionable if the method also performs equally well on a grid cell basis.

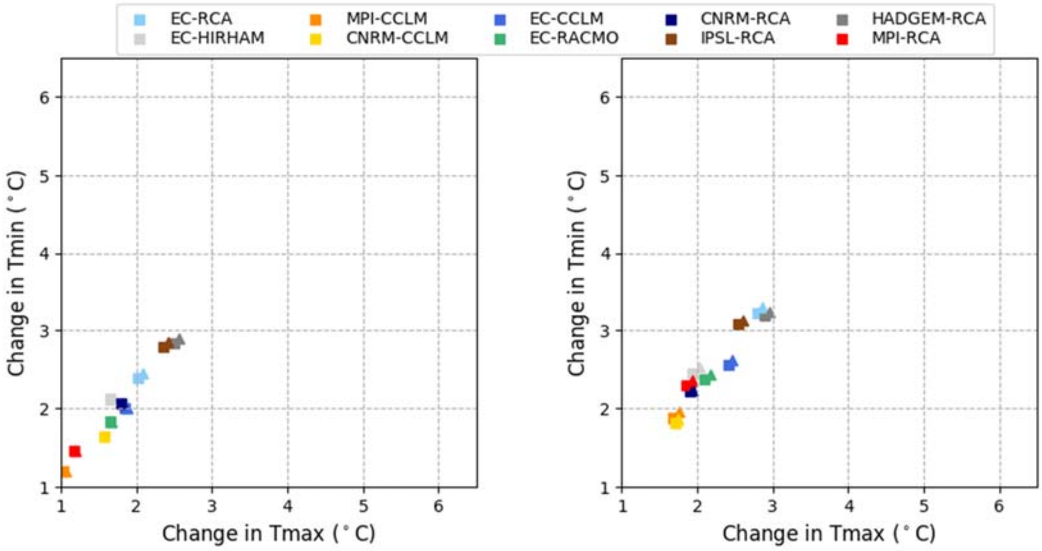

Figure 9. Changes in annual mean maximum and minimum temperatures for Norway between the reference period (1971–2000) and the projection period (2031–2060) for RCP4.5 (left panel) and RCP8.5 (right panel). Triangular marks denote the changes based on the original climate model outputs while changes derived from bias-adjusted data are marked by squares. Each colour represents one of the ten members of EURO-CORDEX ensemble used in this report.

For the far future period (2071–2100), the results are shown in Figure 10. As expected, the mean temperature changes are larger than the near future period. The increase in temperature is, in general, 1 and 2 °C higher than the near future period for RCP4.5 and RCP8.5, respectively. The differences between the change estimates based on data with and without bias-adjustment are rather small, though they are slightly larger than for the near future period, especially for RCP8.5. The discrepancy can mainly be attributed to the mean temperature changes in summer (Figure 11).

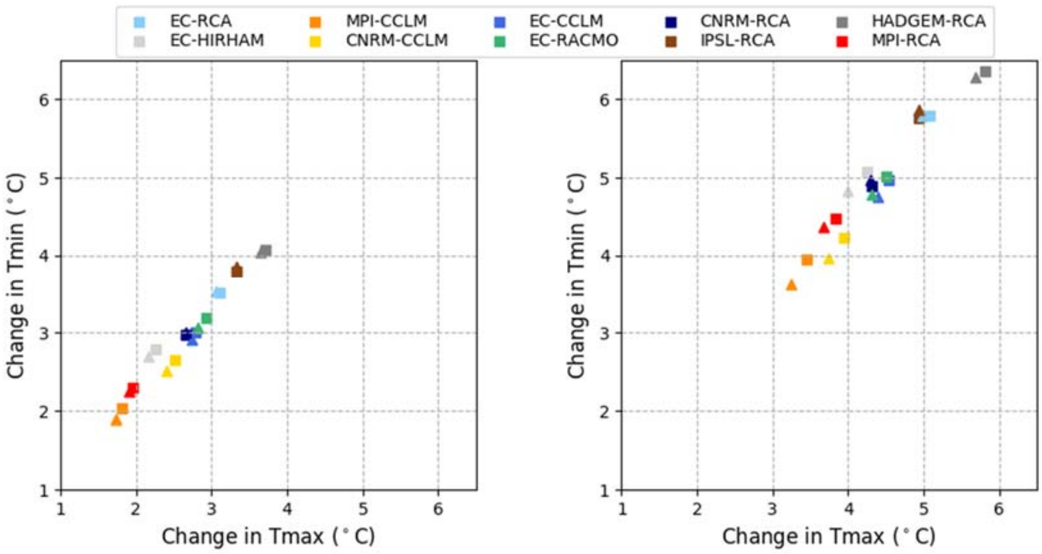

Figure 10. Changes in annual mean maximum and minimum temperatures for Norway between the reference period (1971–2000) and the projection period (2071–2100) for RCP4.5 (left panel) and RCP8.5 (right panel). Triangular marks denote the changes based on the original climate model outputs while changes derived from bias-adjusted data are marked by squares. Each colour represents one of the ten members of EURO-CORDEX ensemble used in this report.

The approach used here, which involves first bias-adjusting Tmax and DTR and then deriving Tmin by subtraction of DTR from Tmax, ensures that the results are physical consistent i.e. that Tmax > Tmin. The inter-variable correlation structure may not, however, be consistent as the variables are adjusted independently of each other. In addition, the method does not change the temporal order of the uncorrected climate model data. Therefore, it does not remove or reduce any temporal biases that might exist in the climate model outputs, such as the mean number of consecutive days with a maximum temperature over 20 °C. A question can also be raised regarding the preservation of the spatial correlation structure found in the observed data, as the method is only applied to one grid cell at a time without considering neighbouring cells. The spatial correlation of the adjusted data therefore resembles the spatial rank correlation of the climate model, which may be rather different from the observed correlation structure.

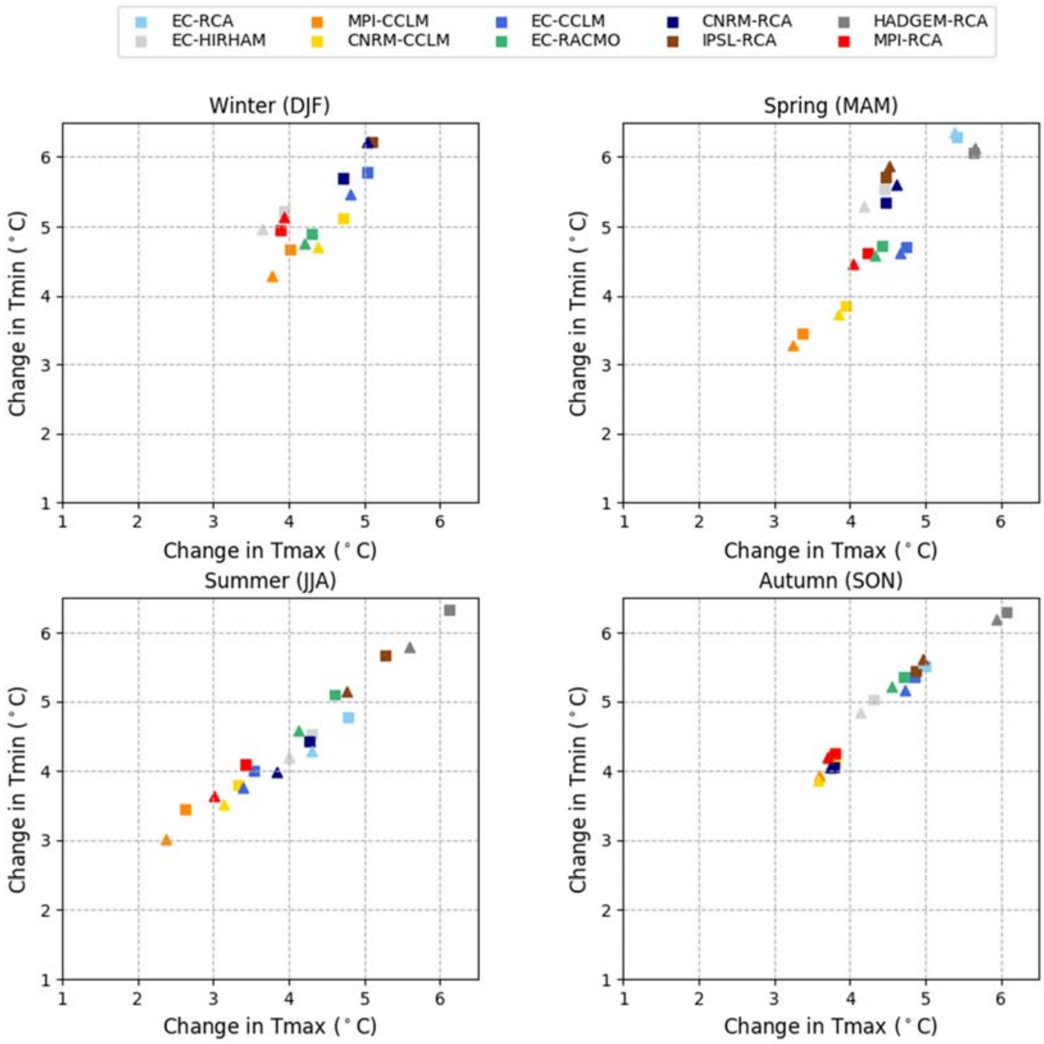

Figure 11. Changes in seasonal mean maximum and minimum temperatures for Norway between the reference period (1971–2000) and the projection period (2071–2100) for RCP8.5. Triangular marks denote the changes based on the original climate model outputs while changes derived from bias-adjusted data are marked by squares. Each colour represents one of the ten members of EURO-CORDEX ensemble used in this report.

Although the bias-adjustment methods applied in this work have their limitations, they nevertheless provided an efficient approach for bias-adjusting climate model outputs which may suffer from various degrees of systematic biases. Climate change signals also seem to be generally preserved after applying the procedures. The bias-adjusted, high-resolution data sets represent an important source of data for impact studies at national and local scales. They are available on the Norwegian Climate Data Store (NCDS) and can be downloaded from the following website: [https://nedlasting.nve.no/klimadata/kss.](https://nedlasting.nve.no/klimadata/kss)

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