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Projected climate change in Fennoscandia — and its relation to ensemble spread and global trends

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Abstract. The need for information about climate change is constantly increasing. This information is usually based on climate model data — data that often have systematic biases. Furthermore, there are questions about how climate model ensembles are affected by the choice of models and emission scenarios. Here, we aim to give a description of climate change in Sweden and neighbouring countries, as well as a discussion on how local climate change relates to global warming. We present climate change projections based on bias adjusted Euro-CORDEX (Coordinated Regional Downscaling Experiment) regional climate model data centred over Sweden. Global warming results in higher temperature, more warm days and fewer cold days in Sweden. The regional climate models capture the signal of the driving global models. The choice of emission scenario has minimal effect on the calculation of mean climate change at a global warming level of 2 degrees. This implies that it would be safe to mix emission scenarios in calculations of global warming levels, as long as mean values are concerned. Moreover, the differences in local and global warming rates seem to decrease with time, suggesting that climate change in Sweden may currently be at its fastest.

1 Introduction

The current strong global warming calls for climate adaptation in all parts of society. Adaptation measures must be based on informed decisions to be cost efficient and to avoid maladaptation (IPCC, 2022). Thus, the need for improved climate data to support decision making and adaptation is ever increasing. Since all parts of society are affected by climate change, it is crucial to have a well-founded description of it—especially given the significant economic investments that will be based on climate projections. By 'a good description,' we mean an ensemble that is both accurate and representative, and, not least, large enough to enable the assessment of the significance and robustness of simulated climate change. Additionally, a general understanding of ensembles is necessary. It is important to know how an ensemble's characteristics are shaped by the models and scenarios that compose it.

Unless strong reductions in emissions of greenhouse gases are implemented, global warming will within the 21st century likely reach +2 °C compared to pre-industrial values (Forster et al., 2024). The temperature response in Europe is correlated

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to, but also larger, than the global temperature change (IPCC, 2021). Since 1850-1900 the global temperature increase of 1.3°C is translated to a warming of 2.3°C in Europe and 3.3°C in the Arctic (C3S, 2024).

Climate modelling is computationally expensive which means that global models (GCMs) are usually run on relatively coarse horizontal resolutions (typically 100 - 300 km). On the other hand, regional models (RCMs) can be run at higher resolution (typically 5-20 km) since they cover a smaller part of the globe. Therefore, RCMs can provide new information despite being governed by the driving GCM (e.g. Vautard et al., 2020; Strandberg & Lind, 2020). Topographical features, such as coastlines or mountains, are better described with higher model resolution. Furthermore, RCM simulations give more details and a better representation of physical processes (e.g. Olsson et al., 2015; Prein et al., 2015; Rummukainen, 2016; Lind et al., 2020).

CORDEX (Coordinated Regional Downscaling Experiment, Jacob et al., 2024) provides the best available RCM ensemble for Europe on a high resolution. A key advantage of using climate model ensembles, like the CORDEX ensemble, is that they allow for a wider set of statistical tests and uncertainty estimations. By relying on only one or very few model simulations there is no way to assess the robustness of the results or to quantify uncertainty. Furthermore, one simulation is not enough to estimate model sensitivity to emissions of greenhouse gases, or natural variability (e.g. Christensen and Kjellström, 2020; 2021).

Here we present a dynamically downscaled ensemble of climate projections for Sweden. Compared to a previous version (Kjellström et al., 2016) improvements include, higher horizontal resolution in the RCMs, bias adjustment of the results, more ensemble members and more indicators developed in dialogue with users to meet their needs. The dataset is an important tool for illustrating various aspects of climate change and is used for studies on climate change impacts and for work on climate change adaptation and for informing decision makers in Sweden. Rather than relying solely on standard climatological variables, inclusion of climate indicators in the assessment enables insights regarding impacts that are more directly relevant to society. These indicators should support climate adaptation, by serving as decision support and informing the general public.

Since these data cover Fennoscandia and the Baltic States, they may also be applicable to surrounding countries. They are based on RCP (Representative Concentration Pathways) scenarios and CMIP5 (Coupled Model Intercomparison Project Phase 5; Taylor et al., 2022) global models. The Swedish climate service relies on these data, and at least until a CMIP6-based downscaled ensemble becomes available, they will continue to be used. This paper serves as a general overview of projected climate change in Sweden, but also discusses how ensembles are constructed; how they depend on the choices of global and regional climate models as well as emission scenarios and how the presented local changes relate to global trends.

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2 Methods

2.1 Euro-CORDEX ensemble

The presented data describing simulated present and future climates are based on the Euro-CORDEX ensemble covering Europe with a grid spacing of 0.11°, which approximately equals 12.5×12.5 km grid spacing (Jacob et al., 2014). Within CORDEX several global climate models (GCMs) are used to force a number of regional climate models (RCMs). Every six hours the RCMs read data from the GCMs on the boundary of their model domains. The boundary conditions include temperature, pressure, humidity and wind at several vertical levels as well as sea surface temperature and sea ice conditions. The Euro-CORDEX RCMs used here are forced by a subset of GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012). The RCMs were evaluated using observations and were judged to generally perform well in the historical climate of the late 20th century (Vautard et al., 2021). Projections for the 21st century from the RCMs have previously been assessed for Europe by Coppola et al. (2021). The simulations and their combinations of GCMs, RCMs and RCPs are listed in Table 1.

Table 1 The simulations used in this study and the GCMs, RCMs and RCPs that they consist of. Members that are part of an ensemble consistent across all RCPs are marked with an '*'.

Driving GCM		RCM	Scenario			
GCM	No.		RCP2.6	RCP4.5	RCP8.5	
CNRM-CERFACS-CNRM-CM5	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		CNRM-ALADIN63	x	x	x	*
		DMI-HIRHAM5			X	
		GERICS-REMO2015	X		X	
		IPSL-WRF381P			X	
		KNMI-RACMO22E	X	X	X	*
ICHEC-EC-EARTH	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		DMI-HIRHAM5			X	
		KNMI-RACMO22E		X	X	
		SMHI-RCA4			X	
	r3i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		DMI-HIRHAM5	X	X	X	*
		KNMI-RACMO22E			X	

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		SMHI-RCA4			X	
	r12i1p1	CLMcom-CCLM4-8-17	X	X	X	*
		CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		DMI-HIRHAM5			X	
		ICTP-RegCM4-6			X	
		GERICS-REMO2015	X	X	X	*
		KNMI-RACMO22E	X	X	X	*
		MOHC-HadREM3-GA7-05	X		X	
		SMHI-RCA	X	X	X	*
		IPSL-WRF381P			X	
IPSL-IPSL-CM5A-MR	r1i1p1	DMI-HIRHAM5			X	
		GERICS-REMO2015			X	
		KNMI-RACMO22E			X	
		SMHI-RCA4		X	X	
		IPSL-INERIS-WRF331P		X	X	
MIROC-MIROC5	r1i1p1	CLMcom-CCLM4-8-17	X		X	
		GERICS-REMO2015	X		X	
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17		X	X	
		CLMcom-ETH-COSMO-crCLIM			X	
		CNRM-ALADIN63			X	
		DMI-HIRHAM5	X	X	X	*
		GERICS-REMO2015	X	X	X	*
		ICTP-RegCM4-6	X		X	
		KNMI-RACMO22E	X	X	X	*
		MOHC-HadREM3-GA7-05	X		X	
		SMHI-RCA4	X	X	X	*
		IPSL-WRF381P			X	
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	X	X	X	*

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		CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		CNRM-ALADIN63			X	
		DMI-HIRHAM5			X	
		MPI-CSC-REMO2009	X	X	X	*
		ICTP-RegCM4-6	X		X	
		KNMI-RACMO22E	X		X	
		MOHC-HadREM3-GA7-05			X	
		SMHI-RCA4	X	X	X	*
		IPSL-WRF381P			X	
	r2i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		MPI-CSC-REMO2009	X	X	X	*
		SMHI-RCA4			X	
NCC-NorESM1-M	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1			X	
		CNRM-ALADIN63			X	
		DMI-HIRHAM5		X	X	
		GERICS-REMO2015	X	X	X	*
		ICTP-RegCM4-6	X		X	
		KNMI-RACMO22E	X		X	
		MOHC-HadREM3-GA7-05			X	
		SMHI-RCA4	X	X	X	*
		IPSL-WRF381P			X	

2.2 Bias adjustment

To minimise systematic errors the Euro-CORDEX ensemble was bias adjusted using the method “Multi-scale Bias Adjustment” available in Midas (Berg et al., 2022). Midas is based on quantile mapping ‘day-of-year’ adjustments (Themeßl et al 2011; Wilcke et al., 2013). As reference data the SMHI gridded climatology data set was used (SMHIGridClim, Andersson et al., 2021). SMHIGridClim covers Fennoscandia and the Baltic states (region A in Fig 1), which means that the bias adjusted ensemble covers a smaller domain centred over Sweden, instead of the entire European domain.

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2.3 Calculation of indicators

To assess climate change, a set of climate indicators are calculated using the software package Climix1. A number of indicators were identified, building on the work of Kjellström et al (2016), and together with the Swedish County Administrative Boards and other governmental agencies, that can describe relevant changes in climate. The indicators used in this study are listed in Table 2.

Table 2 Definitions and short names of indicators.

Indicator	Name	Definition	Unit
Average temperature	tas	The daily average temperatures over a season or year	°C
Minimum temperature	tasmin	The daily minimum temperatures averaged over a season or year	°C
Maximum temperature	tasmax	The daily maximum temperatures averaged over a season or year	°C
Frost days	fd	Number of days over a season or year with daily minimum temperature < 0°C	days
Summer days	su	Number of days over a season or year with daily maximum temperature above 20°C	days
Consecutive summer days	csu	Longest period with consecutive days with daily maximum temperature above 20°C	days
Days with zero crossings	nzero	Number of days over a season or year with daily maximum temperature above 0°C and daily minimum temperature below 0°C	days
Precipitation	pr	Average precipitation amount over a season or year	mm/mon
Days with heavy precipitation	r10mm	Number of days over a season or year with precipitation amount of more than 10 mm	days
Dry days	dd	Number of days with precipitation less than 1 mm	days

2.4 Selection and analyses of sub-ensembles

To investigate the robustness of the ensembles and how the simulated climate is affected by the choice of emissions scenario, and global and regional models, we look at all combinations of GCMs and RCMs that simulated all of the scenarios RCP2.6,

[1] https://climix.readthedocs.io/

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RCP4.5 and RCP8.5 (indicated with '*' in Table 1) to get a consistent ensemble. From these 17 combinations of GCMs and RCMs we construct sub-ensembles where all members use the same RCP, GCM or RCM. By doing these divisions, we can at a specific GWL study the relative importance of the choice of RCP, GCM and RCM.

As an example, in the family of GCM ensembles all members in a sub-ensemble are forced with the same GCM. According to Table 1 this means that the sub-ensemble based on the GCM IPSL-CM5A-MR will consist of the RCMs that downscale IPSL-CM5A-MR; which are: DMI-HIRHAM5, GERICS-REMO2015, KNMI-RACMO22E, SMHI-RCA4 and IPSL-INERIS-WRF331P. In the same way the sub-ensemble based on the GCM MIROC-MIROC5 consists of the RCMs CLMcom-CCLM4-8-17 and GERICS-REMO2015 since they are the RCMs used to downscale MIROC5.

In the family of RCM ensembles, all members in a sub-ensemble are using the same RCM. This means that the sub-ensemble based on the RCM SMHI-RCA4 consists of simulations when SMHI-RCA4 is used to downscale the GCMs ICHEC-EC-EARTH, IPSL-IPSL-CM5A-MR, MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR and NCC-NorESM1-M. In the same way the sub-ensemble based on ICTP-RegCM4-6 when this RCM is used to downscale the GCMs ICHEC-EC-EARTH, MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR and NCC-NorESM1-M.

We are here looking at GWL2, which is reached in both RCP4.5 and RCP8.5, but not in RCP2.6. Seven GCMs are in different ways combined with seven different RCMs. This means that we have 2 RCP-based, 7 GCM-based and 7 RCM-based sub-ensembles. In order to determine if any of the model combinations is significantly different from the others we perform two statistical tests, with the null hypothesis that any given two ensembles have the same average. We use a one-way ANOVA (Analysis of variance, Press, 1972) test, which tests whether two or more groups have the same average or not. If the number of groups is equal to 2, which is the case when we compare RCP-based ensembles, a one-way ANOVA is the same as a student's t-test. The ANOVA test does not specify which sub-ensemble is different from the others, if any. To find the different sub-ensemble(s) a post-hoc test is used, the so-called Tukey's honestly significant difference (Tukey, 1949). It is performed after a successful ANOVA test and compares all sub-ensembles pair-wise with a studentised q distribution. The tests are done for a region in northern Sweden and a region in southern Sweden (regions C and D in figure 1). The domain and time averaged data for each member together form an ensemble. A significance level with a family-wise error of 99 % is used. The analyses were made for tas, csu, tasmin, tasmax, pr, dd, cdd, su, r20mm and nzero.

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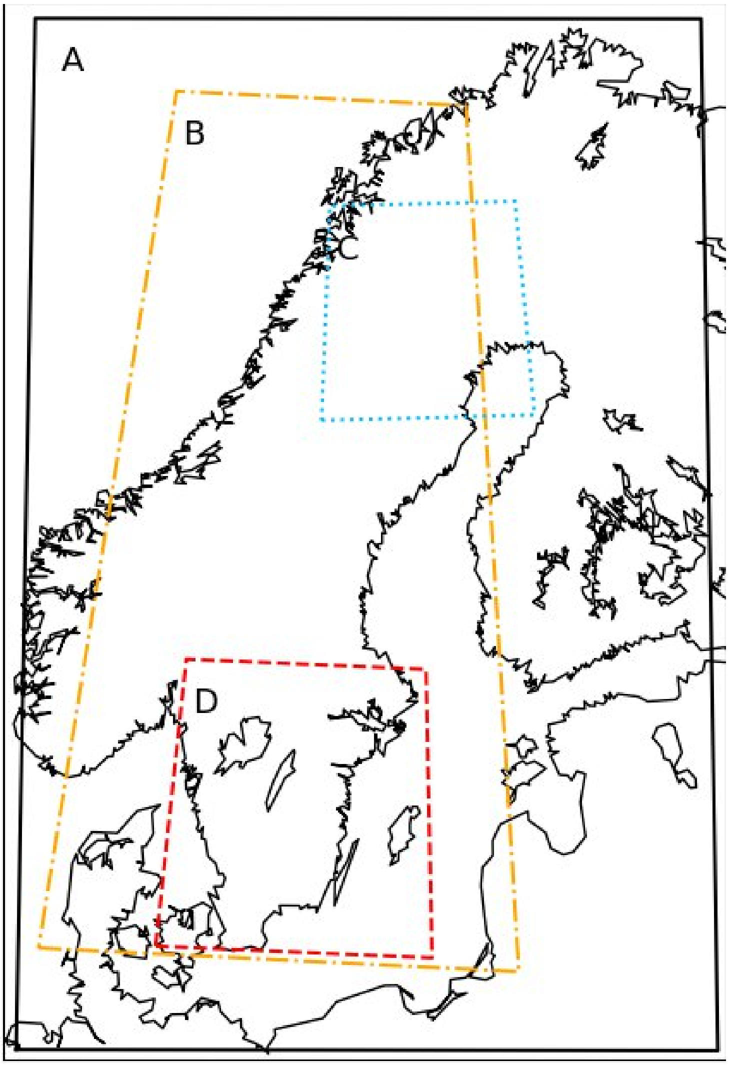

Fig 1: Maps of regions used in analyses in this paper. A) Fennoscandian region (black, full line) is the full model domain, B) Scandinavia (dash dotted orange line), C) northern Sweden ((dotted blue line), D) southern Sweden (dashed red line).

3 Results and discussion

120 Here, we start by describing average changes over the full ensemble before looking into the ensemble spread.

3.1 Projected change in temperature

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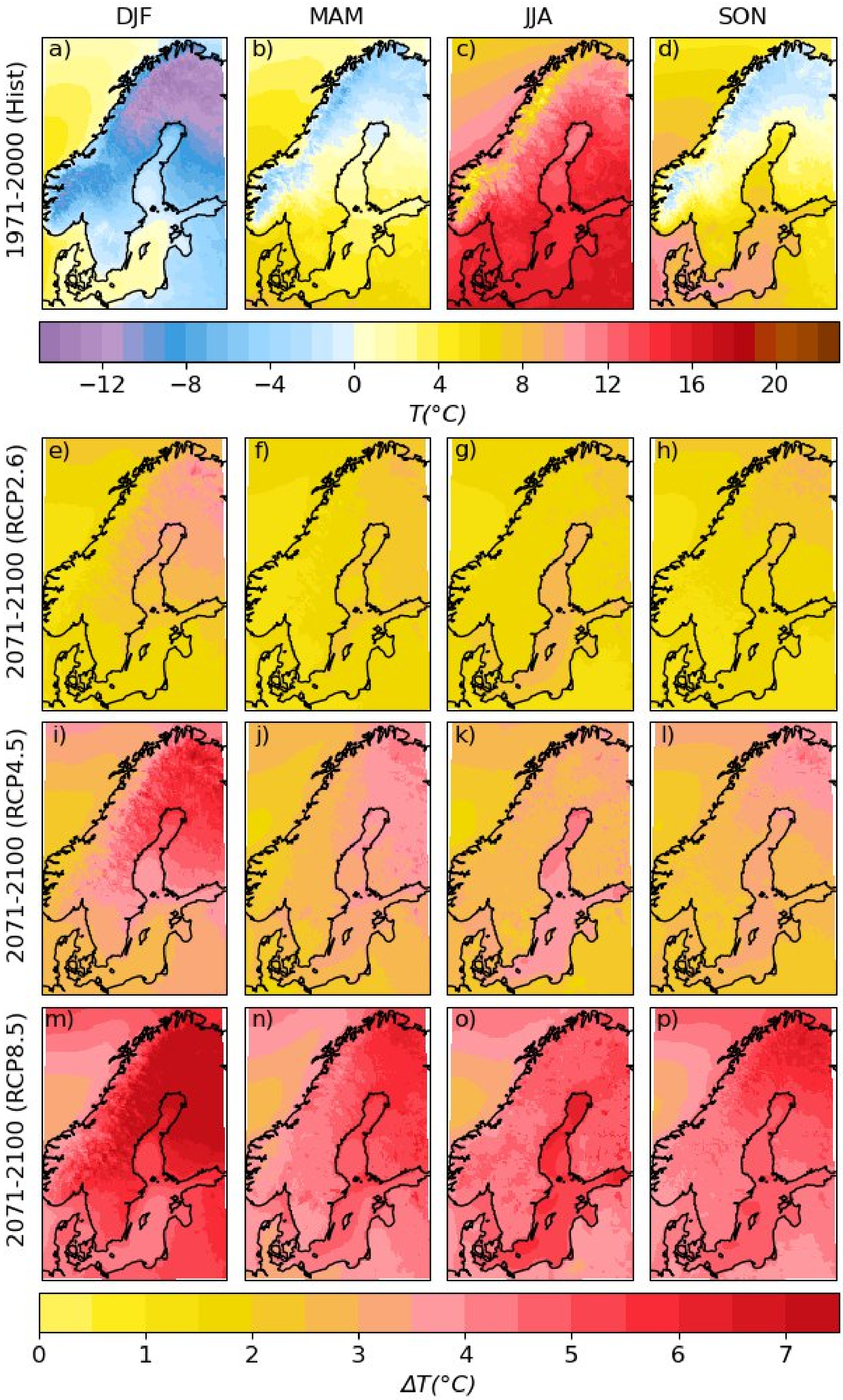

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Figure 2: Ensemble mean temperatures (°C) in winter (DJF, first column), spring (MAM, second column), summer (JJA, third column) and autumn (SON, fourth column). First row shows absolute values for 1971-2000. Rows 2 to 4 show anomalies from 1971-2000 to 2071-2100 according to scenarios RCP2.6, RCP4.5 and RCP8.5, respectively.

The mean temperatures (tas) are projected to increase in all seasons and in all emissions scenarios across the whole domain (Fig. 2), consistent with other studies of the European climate (e.g. Coppola et al., 2021; Ranasinghe et al., 2021). This signal is unchanged even in a bias-adjusted ensemble (Gobiet et al., 2015). The annual warming in Sweden to the end of the century is 1-2°C in RCP2.6 and 4-6°C in RCP8.5, with larger differences in the north than in the south. The changes scale in such a way that RCP8.5 in the close future shows similar warming to RCP2.6 in the middle of the century, and RCP8.5 in the middle of the century is similar to RCP4.5 in the end of the century (Strandberg et al., 2024a).

In Fennoscandia, we highlight two climate change patterns for temperature: winter is the season with the fastest warming rate, and the northern parts of the region is warming faster than the southern parts. In RCP2.6 the warming in winter is 1.5-3.5°C from south to north (Fig 2e) and 1.5-2°C in summer (Fig 2g). In RCP8.5, the corresponding numbers are 4.5-8°C in winter (Fig 2m), and 4-5°C in summer (Fig 2o). This means that the warming is larger in winter, but also the difference between north and south.

The temperature change is especially large for the daily minimum temperature (tasmin) (Fig 3a). For example, in RCP4.5 the increase in tasmin is 3-6.5°C, to be compared to an increase in annual tas of 2-4°C. The increase in daily maximum temperature (tasmax) is more similar to tas, 2-3.5°C (Fig 3b). A warmer climate means fewer cold days and more warm days. Accordingly, the number of frost days (fd) is projected to decrease, though relatively uniform across the domain (Fig 3c). RCP4.5 gives a reduction of 40-50 days in most of Fennoscandia and the Baltic countries. The change is somewhat smaller in parts of the Scandinavian mountain chain (decrease in fd with 30-40 days), and larger over the Bothnian Sea and Bothnian Bay (reduction of 65 days or more).

The increase in the number of summer days (su) according to RCP4.5 stretches from zero, or just a few days, in large parts of the mountain chain and over most of the sea in the domain to 20-24 days in southern Sweden and Denmark (Fig 3d). The number of days with zero crossings (nzero) shows a general decrease on the annual scale (Fig 3e). In winter, however, nzero increases in most of the domain, except for Denmark, southern Sweden and the Baltic countries (not shown). In these areas the temperatures will not drop below zero degrees as often, whereas in parts of northern Sweden the increase is as much as around 10 days (roughly corresponding to an increase of 50 %).

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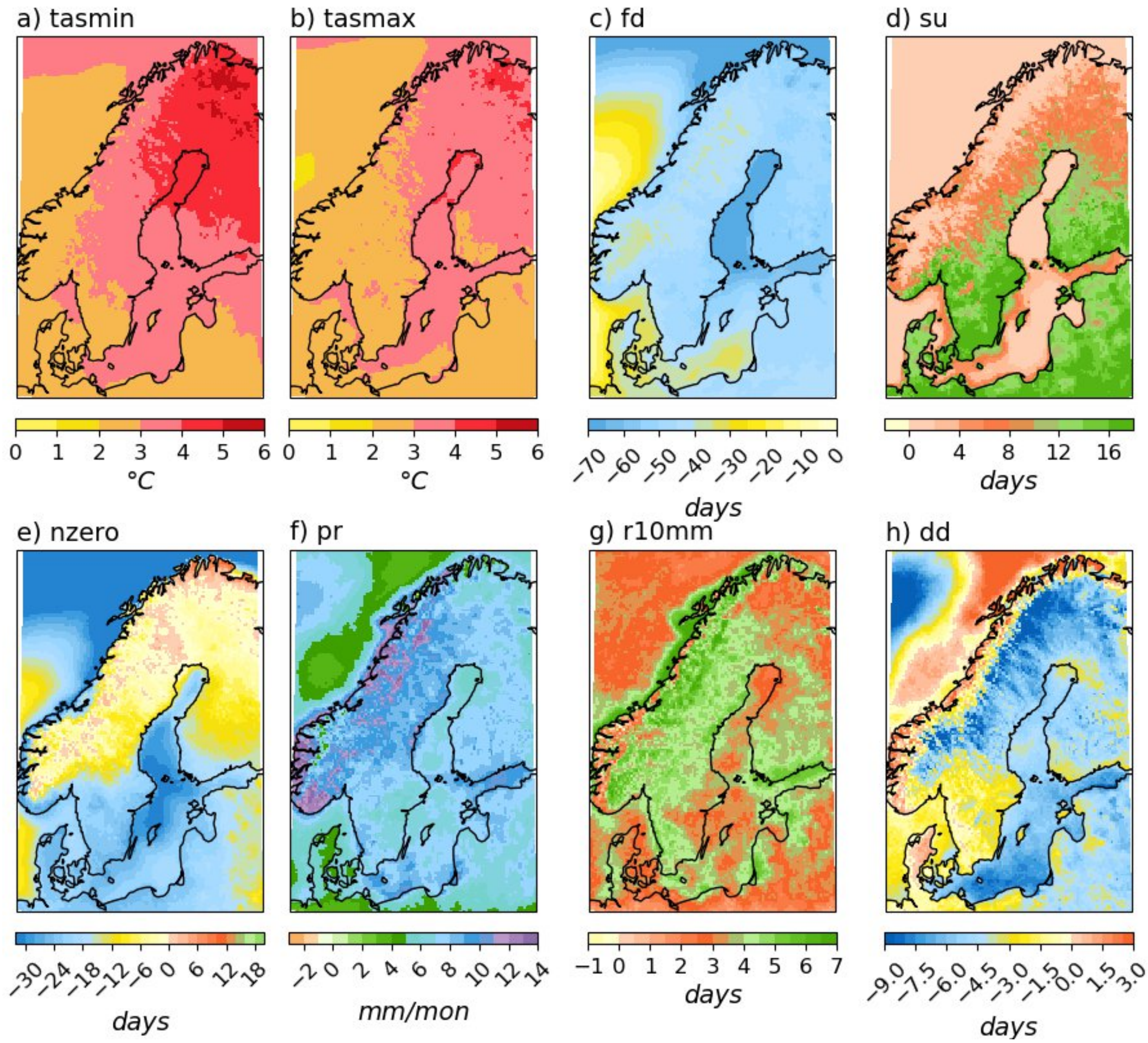

Figure 3: Climate change anomalies between 1971-2000 and 2071-2100 according to scenario RCP4.5. The maps show ensemble means of a) daily minimum temperature (tasmin, °C), b) daily maximum temperature (tasmax, °C), c) number of frost days (fd, days), d) number of summer days (su, days), e) number of days with zero crossings (nzero, days), f) mean precipitation (pr, mm mon-1), g) number of days with heavy precipitation (r10mm, days) and h) dry days (dd, days). See table 1 for definitions of the indicators.

3.2 Projected change in precipitation

The annual average precipitation shows a general increase in the future (Fig 3f). According to RCP4.5 the increase in annual average daily precipitation is 5-10 mm mon-1 in large parts of the domain, the increase along the Norwegian west coast is up

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to 15 mm mon-1. In RCP2.6 the increase is smaller, 2-6 mm mon-1 (fig. S1), and in RCP8.5 larger, 8-15 mm mon-1 (fig S3). For most of the domain, the increase is larger in winter and smaller in summer compared to the annual change (not shown). Denmark and southern Sweden show changes in summer precipitation close to zero. On the annual scale all models agree on the sign of change in most of the domain and all RCPs. The signal is least robust in RCP2.6 since the change is smaller there, and since precipitation has generally large variability. The number of days with heavy precipitation (r10mm) is projected to increase with 3-5 in most of the domain (to be compared with 10-12 days in the reference period) (Fig 3g). The change is smaller in RCP2.6 (up to +2 days increase) and larger in RCP8.5 (+4-8 days) (Figs S1g & S2g). The number of dry days is projected to decrease with 1-8 days (Fig 3h). The signal is not robust, half of the ensemble members give increasing number of dry days, and half of the members decreasing.

3.3 RCMs compared to GCMs and the larger CMIP ensemble

Even though the Euro-CORDEX ensemble consists of several simulations using different GCM-RCM combinations, it may not represent the full potential spread of the climate change signal. To investigate how well the Euro-CORDEX RCMs capture the variability within the greater CMIP5 ensemble the average changes in temperature and precipitation over the Fennoscandian domain (region A in Fig 1) are calculated. Figure 4 shows that the ensemble spread in the CMIP5 ensembles is larger than in the Euro-CORDEX ensemble. This could not entirely be explained by differences in ensemble sizes. See for example the numbers for RCP8.5 in Fig. 4c, where the GCM and RCM show large differences in spread although the ensembles are of comparable sizes. On the other hand, the 67 members are only forced by 7 unique GCMs, which is much less than the 25 unique GCMs in the full CMIP5 ensemble. When looking at an ensemble just consisting of the 9 GMCs (including different realisations) used to force the RCMs the spread is much smaller. Kjellström et al (2018) also show that the spread between the driving GCMs were larger than the spread between RCMs, although the RCM ensemble had more members. Especially, the distance between the minimum and maximum larger. The ensemble means, however, are quite similar. In general the two ensembles agree on the large scale differences, and the choice of emissions scenario is of greater importance than the construction of the ensemble. The result is the same even when looking at smaller regions in northern and southern Sweden (e.g. regions C and D in Fig 1). A conclusion is that the Euro-CORDEX ensemble well captures the mean climate change signal, but that the spread is limited compared to the CMIP5 ensemble.

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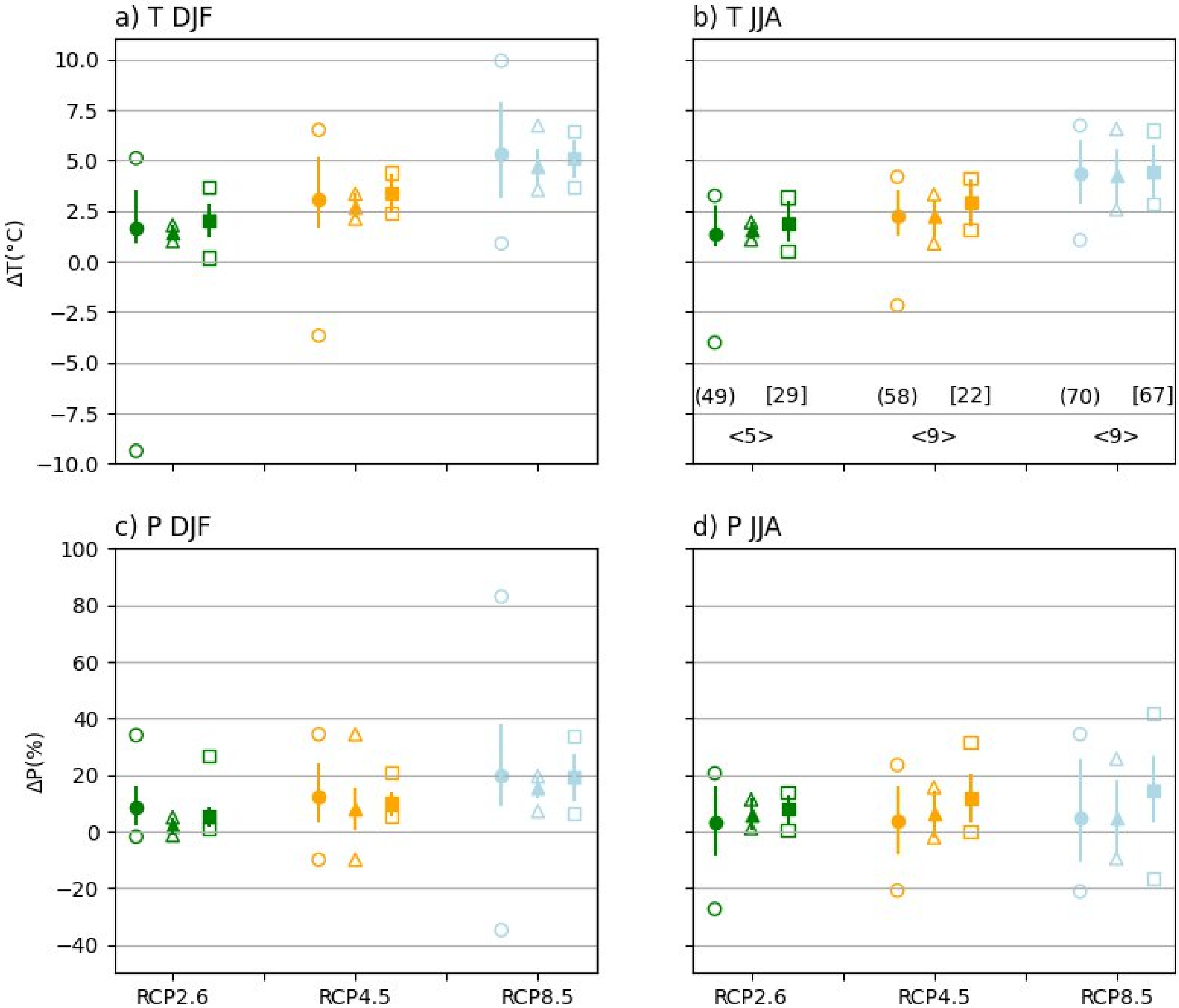

190 **Figure 4: Temperature (°C) (a, b) and precipitation (%) (c, d) anomalies in Fennoscandia 1971 — 2000 to 2071 — 2100 for winter (a, c) and summer (b, d) according to the scenarios RCP2.6 (green), RCP4.5 (yellow) and RCP8.5 (blue). The CMIP5 GCMs are represented by circles, the GCMs used to force the RCMs by triangles and the CORDEX RCMs by squares. The central marker represents the ensemble mean, the line spans between the 10th and 90th percentiles, open markers show ensemble minima and maxima. Panel b) also shows the number of members in the respective ensembles.**

3.4 Importance of GCM, RCM, RCP on GWLs

A way to avoid the discussion on which emission scenario to use and which scenario is the most likely — a discussion that is sometimes heated (Hausfather & Peters, 2020; Schwalm et al., 2020) — is to use global warming levels (GWL). Instead of a fixed period of time in a certain scenario GWLs focus on the period when a particular level of global warming is reached.

For example, GWL2 is the period when +2°C global warming is reached compared to pre-industrial times. This period may occur at different times in different models – instead of consistency in time between the members of the ensemble there is thus a consistency in climate change. In that way, using GWLs is a powerful method since it is possible to mix simulations using different scenarios to create larger ensembles; and since it reduces the uncertainty around the choice of emission scenarios. One example of how to use GWLs for regional data is found in Strandberg et al. (2024b). The mixing of emission scenarios in GWLs can nevertheless be criticised because the trends are different between scenarios (Bärring & Strandberg, 2018). This means that a GWL ensemble is sensitive to how it is constructed with regards to which models and scenarios that are used as input.

The results for sub-ensembles forced by the same GCM (all members of a sub-ensemble is forced with the same GCM, see Methods) are exemplified by tas and csu. Figure 5 shows which sub-ensembles that are significantly different from each other in the case of tas. All sub-ensembles from 1 to 7 are pair-wised compared to see if they are significantly different or not. As an example, a green box at row 5 and column 1 means that sub-ensembles 5 and 1 are significantly different. In winter the average temperature change at GWL2 is +1.5-2.8 °C in the south and +1.7-4.2 °C in the north, depending on the chosen sub-ensemble (Fig. S4). Despite the rather large spread in warming the significant differences between sub-ensembles are not systematic in winter. However, in summer, where the temperature change is +1.0-2.5 °C in the south and 1.3-2.9 °C in the north (fig. S3), there are systematic significant differences between sub-ensembles. The two sub-ensemble with the largest warming, labelled 4 & 7, are significantly different from the other sub-ensembles (green boxes at lines 4 and 7, and columns 4 and 7 in fig 5). This pattern is also, to some extent, seen for csu (Fig 6). In the south, sub-ensemble 7 is significantly different from 5 of the other sub-ensembles; in the north sub-ensemble 4 is significantly different from 5 other.

For precipitation, the difference at GWL2 is small compared to the variability within each sub-ensemble. Only a few pairs of sub-ensembles are significantly different (none in summer in the north), but not in a systematic way (not shown).

The choice of GCM can have a large impact on the ensemble. The difference in simulated change in tas can be up to 2 °C depending on the driving GCM; this does however, transfer into consistent significant differences for only two sub-ensembles.

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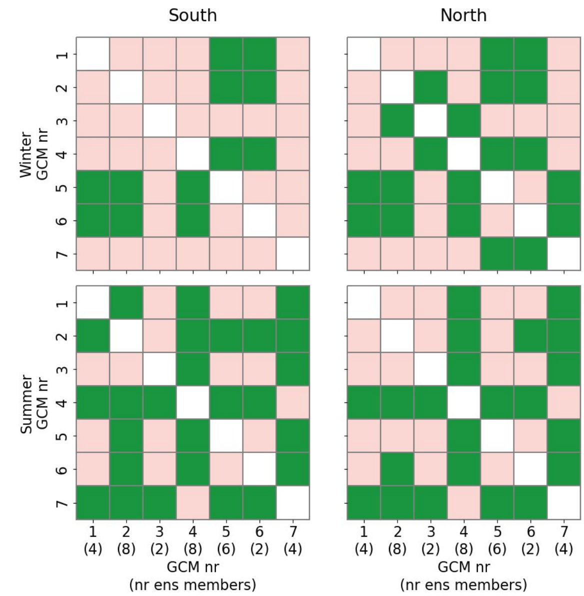

Fig 5: Matrix of significant differences in temperature (tas) between GCM-based sub-ensembles. Green colours indicate significant differences between two sub-ensembles and pink non-significant differences. White colours indicate that an ensemble is compared with itself. Numbers indicate sub-ensemble numbers, with the number of members in parenthesis.

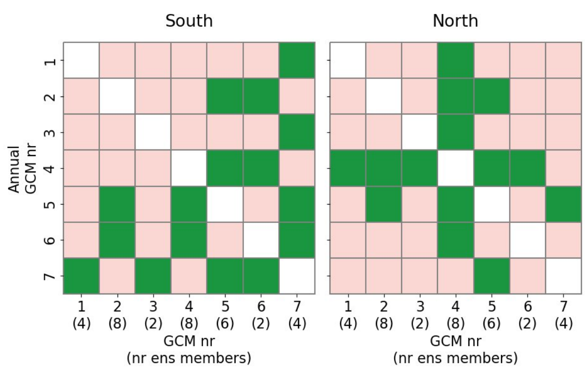

Figure 6: Same as Figure 5 but for annual csu

Then, we instead look at sub-ensembles where the same RCM is used (all members of a sub-ensemble use the same RCM). Figure 7 shows which sub-ensembles that are significantly different from each other with regards to tas. The difference in change is about 1 °C between the sub-ensemble with the smallest and the largest change. Still, sub-ensemble no. 7 is the only sub-ensemble with systematically significant differences; in winter in the northern region and in summer it's different to all, or all but one, of the other ensembles. Sub-ensemble no. 7 is the sub-ensemble with the smallest temperature increase. For csu there are more significant differences in the southern region than in the northern, reflecting the larger variability in csu in the south (Fig 8). There are however, only two sub-ensembles that are significantly different to three other sub-ensembles.

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Again sub-ensembles 4 and 7, with a low number of csu. For precipitation, the difference at GWL2 is small compared to the variability within each sub-ensemble. Only a few pairs of sub-ensembles are significantly different (in winter in the north one), but not in a systematic way (not shown).

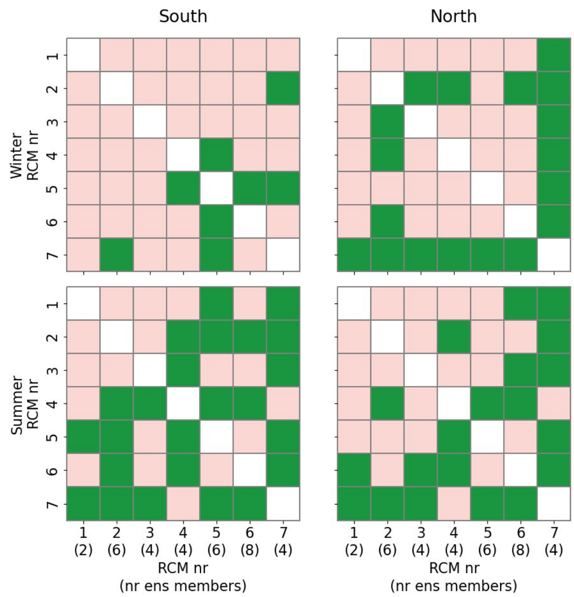

Figure 7 Matrix of significant differences in tas between RCM-based sub-ensembles where green colours indicate significant differences. Numbers indicate sub-ensemble numbers, with the number of members in parenthesis.

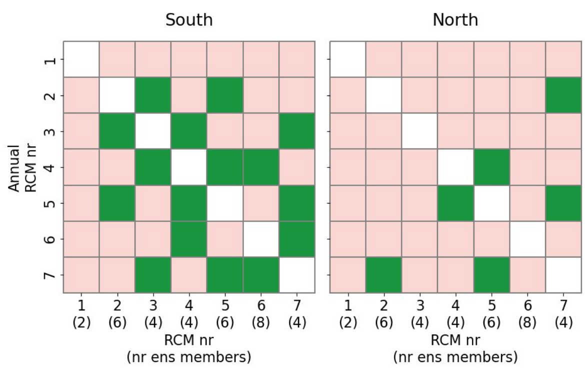

Fig 8 Same as Fig 7, but for annual csu.

As a last step, we look at sub-ensembles using the same RCPs. This analysis answers the question whether it matters which RCP you use to describe a GWL climate. In this case there are only two sub-ensembles to be compared. The differences between the ensembles based on RCP4.5 and RCP8.5 are generally small and not significant (see fig S5 for tas). RCP8.5 give larger anomalies in tas, tasmin and tasmax in summer in all regions. The difference compared to RCP4.5 is around 0.15°C and just below 95 % confidence. The difference in all other indicators are insignificant on a 99 % level.

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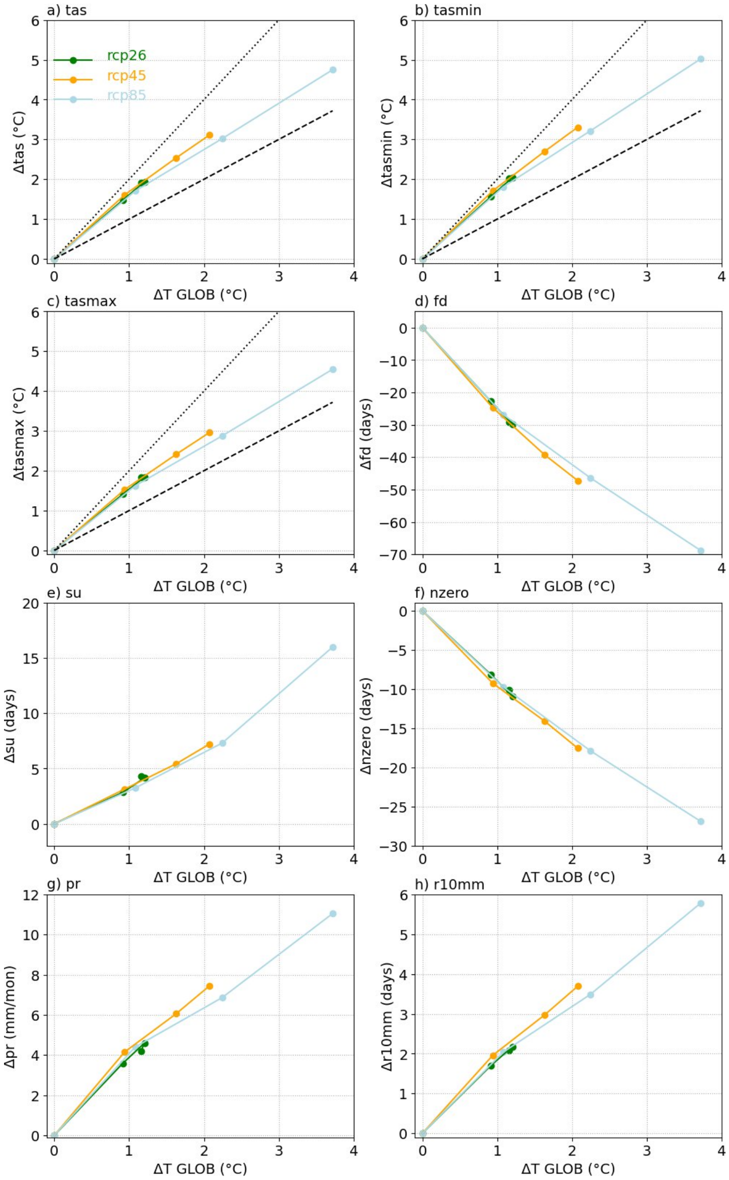

255 **Fig 9: Climate change in in the Fennoscandian domain (region A in Fig 1) relative to the difference in global annual temperature. X-axes show change in global mean annual temperature relative to the period 1971 — 2000, y-axes show a) mean temperature (tas, °C), b) minimum temperature (tasmin, °C), c) maximum temperature (tasmax, °C), d) no. of frost days (fd, days), e) no. of summer days (su, days), f) no. of days with zero crossings (nzero, days) g) precipitation (pr, mm mon-1) h) no. of days with heavy precipitation (r10mm, days). All values are relative to 1971 — 2000. Points represent the periods 1971 — 2000, 2011 — 2040, 2041 — 2070, 2071 — 2100 for emissions scenarios RCP2.6 (green), RCP4.5 (orange) and RCP8.5 (light blue). In panels a-c the one-to-one relationship is shown with a dashed line, and the two-to-one with a dotted line.**

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Inevitably, the characteristics of a climate model ensemble is determined by the simulations that it consists of. Using other models will not give the same results. These differences are however not systematic in any way, and mostly not significant. Even though an ensemble should be constructed with care, the role of the composition should not be exaggerated.

3.5 Global vs. local trends

Climate change is not evenly distributed across the globe. In Scandinavia, like most of Europe, the warming rate was about twice the global mean during the 20th century (Schimanke et al., 2022; WMO, 2023). In this section, we take a look at how local climate change relates to the change in global mean surface temperature (GMST) (fig 9).
The almost two-to-one relationship between global and local temperature is seen for mean, minimum and maximum temperatures in the early parts of the 21st century until the period 2011-2040 (Fig. 9 a-c). Within this period the ratio between regional and global warming is 1.6-1.8. With increasing global warming this relationship is approaching a one-to-one relationship between change in global and local temperatures (i.e. parallel to the dotted lines in Figs 8a-c). In RCP4.5 and RCP8.5 the trend from 2041-2070 to 2071-2100 is roughly one to one (1.1-1.2), suggesting that the faster warming in Scandinavia will slow down as GMST increases. A conclusion of this could be that the ratio between warming in Scandinavia and global warming is at its largest in the beginning of the 21st century.
For indicators representing cold conditions the trend gets flatter in RCP8.5 reflecting that the potential for change decreases. For example: the number of frost days cannot be less than zero. For warm indicators, trend instead gets steeper. The number of summer days is based on a temperature threshold, which means that there is a sudden effect when temperatures exceed the threshold. Consequently, the increase may be limited if the number of days above the threshold is already large.

4 Summary and conclusions

Global warming means for Fennoscandia higher temperature, more warm days and fewer cold days. In southern Sweden the number of summer days is doubled until the end of the century according to RCP4.5. At the same time the number of frost days decreases with 20-50 %. Precipitation increases generally, this shows in increasing mean precipitation, increasing number of days with heavy precipitation and decreasing number of dry days.
The RCM ensemble used here capture, on average, the change pattern from the CMIP5 GCM ensemble. The ensemble spread, however, is larger in the CMIP5 ensemble.
The choice of RCP has minimal significance on the GWL2 ensembles. This implies that it would be safe to mix RCPs in the construction of GWL ensembles in order to increase ensemble size, and that a GWL could be based on only one RCP. It should be noted however, that we only look at mean changes. Trends within a GWL period do indeed depend on the RCP, and this could influence extremes. The largest difference between GWL2 sub-ensembles, regardless of how they are constructed in terms of combining GCMs and RCMs, is seen for temperature-based indices; however, it is difficult to say whether the choice of GCM or RCM contributes most to these variations.

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All studied climate indicators scale somewhat linearly to the change in GMST. For indicators based on temperature thresholds, there may be a shift in trend slope when the temperatures rise above a certain level. Currently the regional temperature change in Sweden is almost twice as large as the global trend. This ratio will decrease as GMST increases, to more and more approach a one-to-one relationship. This suggests that there is a limit to the feedback mechanisms that now accelerates the warming in Sweden. And that the ratio between local and global warming currently may be at its largest. Furthermore, this means that the steady relationship between global and regional warming that is sometimes assumed in weather attribution and regional warming levels may not hold in the future.

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Author contributions

GS – Conceptualization, Methodology, Formal analysis, Visualization, Project administration, Writing – Original Draft; **AT** – Methodology, Formal analysis, Visualization, Writing – Review & Editing; **LB** – Software, Data Curation, Writing – Review & Editing; **EK** – Writing – Review & Editing; **MS** - Data Curation, Writing – Review & Editing; **RW** – Software, Data Curation, Writing – Review & Editing; **GN** – Resources

Data availability

Ensemble means of 30 year periods (absolute values and anomalies) can be viewed and downloaded at:
https://www.smhi.se/en/climate/tools-and-inspiration/climate-change-scenario/climate-change-scenario-tool

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Competing interests

The authors declare that they have no conflict of interest.

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