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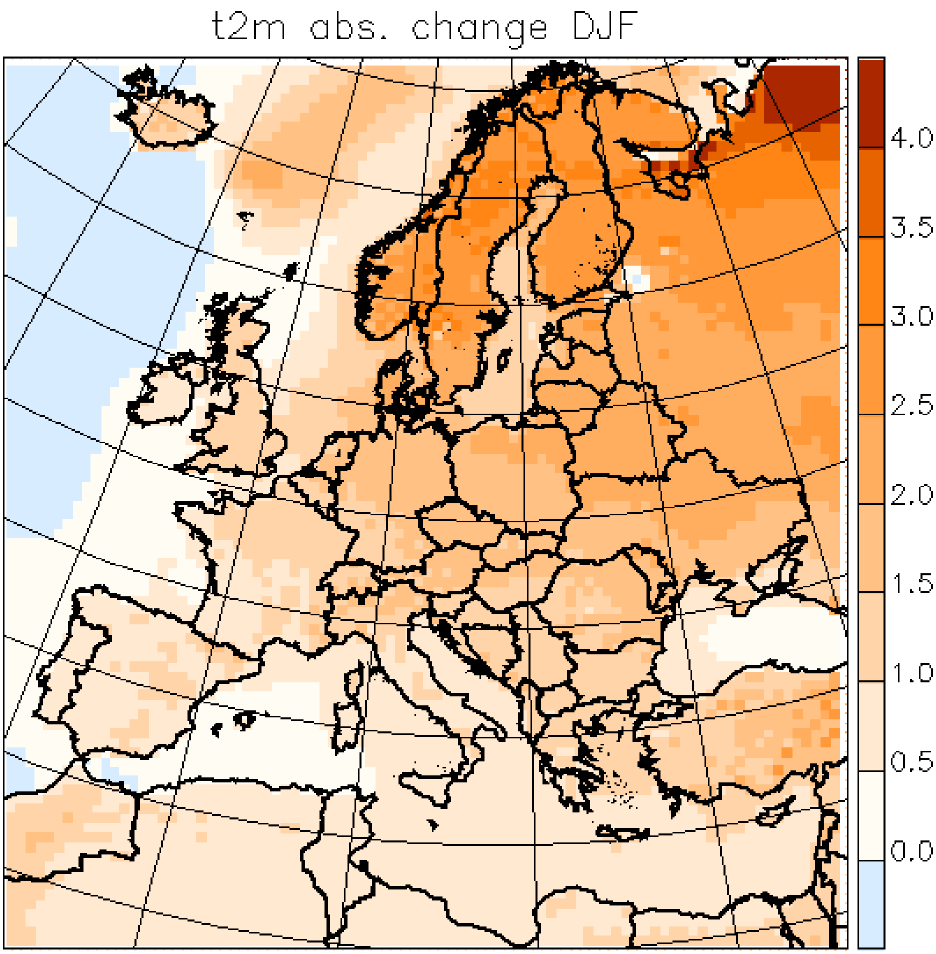
Regional climate change in Denmark according to a global 2-degree-warming scenario

Ole Bøssing Christensen



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Abstract

A regional downscaling of a global climate model simulation corresponding to 2 degrees warming relative to pre-industrial times is presented. Results of mean fields and extremes indices are presented and compared to similar SRES A2 and B2 results.

Background

The European Union has decided to work towards limiting the anthropogenic global warming to 2 degrees with respect to the pre-industrial average. This is an ambitious goal that requires research into ways of limiting the global emissions of greenhouse gases. However, even the details of climate change in such an emission scenario are not known yet. Most numerical simulations with state-of-the-art global models use a small subset of the IPCC SRES (Nakićenović *et al.*, 2000) emission scenarios; consequences of scenarios for stabilization of greenhouse gas concentrations have mostly been simulated with simpler models (IPCC, 2001). In the new round of IPCC simulations for the upcoming 4th assessment report, also several simulations of greenhouse gas stabilization scenarios have been performed with general circulation models (GCMs).

But greenhouse gas stabilization is not the same as temperature stabilization. In order to construct a scenario for the EU goal, simplified assumptions have to be used, since no consistent scenario resulting in this global heating is available; this is the case not the least because an emission scenario can only be translated into a heating through a climate sensitivity, which must be calculated using a coupled global model and which therefore has an appreciable uncertainty, hence the scenario will become model dependent.

For a project defined by the Danish Ministry of the Environment, there has been a need for estimates of local climate change for Denmark and surrounding waters in a scenario consistent with the EU goal. The DMI used the ECHAM5/MPI-OM coupled GCM (Roeckner *et al.,* 2006; Jungclaus *et al.*, 2006) for simulating a transient climate development consistent with the SRES A1B emission scenario. In order to obtain a simulation consistent with the EU goals, the state of this simulation in the year 2020 was copied, and greenhouse gas concentrations were fixed at the 2020 values for a simulation stretching until the year 2100. It was estimated from simple arguments that this would lead to a global temperature change between the periods 1961-1990 and 2071-2100 of around 1.4 degrees, equivalent to a heating of 2 degrees since pre-industrial times, and hence it was estimated that this scenario could give an idea of climate change associated with the EU goals. This global simulation is described in May (2006).

Since the purpose was to obtain regional and local information, the output of the global model was downscaled from T63 (150km resolution) to 50km resolution over Europe with the regional climate model (RCM) HIRHAM. The periods 1961-1990 (control) and 2071-2100 (scenario) were simulated, and the changes between these two periods will be described below. The simulation and scenario will be labelled EU2C. Comparisons are made with simulations according to the SRES A2 and B2 emission scenarios (labelled A2 and B2) as simulated with the same HIRHAM model in the European PRUDENCE project (Christensen *et al.*, 2006). The global model delivering boundary conditions for these simulations was the HadAM3H high-resolution atmospheric GCM of the Hadley Centre (Buonomo et al., 2006). Sea surface temperatures for the control simulation with HadAM3H were observed, and anomalies were added in order to calculate time slices corresponding to the A2 and B2 scenarios for 2071-2100 by adding anomalies calculated with the coupled global model HadCM3, also of the Hadley Centre; see details in Christensen and Christensen (2006). The resolution of these simulations are the same as for the EU2C experiment; the integration area is slightly rotated, which is the reason for plots below of A2 and B2 results do not fit the map exactly.

Experimental setup

The HIRHAM model applied in this study is an updated version of HIRHAM4 (Christensen et al. 1996). The dynamical part of the model is based on the hydrostatic limited area weather forecast model HIRLAM, documented by Machenhauer (1988) and Källén (1996). Prognostic equations exist for the horizontal wind components, temperature, specific humidity, liquid water content and surface pressure. HIRHAM4 uses the physical parameterisation package of the general circulation model ECHAM4, developed by Roeckner et al. (1996). These parameterisations include radiation, land surface processes, sea surface sea-ice processes, planetary boundary layer, gravity wave drag, cumulus convection and stratiform clouds. The treatment of precipitation processes includes a newly introduced low precipitation threshold that reduces so-called drizzling, and only when convection is absent. This modification has improved the annual cycle of the mean precipitation in general (see e.g. Hagemann et al. 2001), but also more specifically precipitation frequencies over Denmark (Christensen et al. 2001a). Land surface parameterisations uses five prognostic temperature layers and one bucket moisture layer. Runoff is calculated within the Arno scheme (Dümenil and Todini, 1992). Moreover, the updated model utilises high resolution datasets of land surface characteristics (e.g. Hagemann et al. 1999; Christensen et al. 2001b).

The adopted computational grid is a rotated regular latitude/longitude grid (110x115 grid points) with the rotated South Pole at (18°E, 39.25°S), a resolution of 0.44° (about 50 km) and 19 vertical levels in hybrid sigma-p coordinates. The area encloses Europe and the North Atlantic. The outermost 10 points constitute a relaxation zone towards the boundaries, so the maps shown presently only contain the 90x95 grid of non-relaxed points.

In the present experiment, two 30-year long time-slices corresponding to 1961-1990 and 2071-2100, respectively, were downscaled with HIRHAM from a transient coupled GCM simulation with the ECHAM5/MPI-OM model (Roeckner et al., 2006; Jungclaus *et al.*, 2006) performed at the DMI in a resolution of T63. This simulation followed observed greenhouse gas and aerosol forcing 1860-1990, then followed the SRES A1B scenario until 2020, and finally for 2021-2100 kept the 2020 concentrations of greenhouse gases and let aerosol concentrations slowly decline (May, 2006).

Results

Mean European climate change

Figs 1 and 2 show the mean difference in air temperature between the two 30-year periods for winter and summer, respectively, according to the EU2C experiment. An examination of these reveals a modest warming with very different geographical distribution. In winter, the largest heating of around 2-3 degrees is found over Scandinavia and northern Russia. The North Atlantic is mostly below 1 degree of heating and even shows cooling in some areas. Southern Europe heats around 1 degree. In summer it is Southern Europe that shows the largest heating, around 2-2.5 degrees, whereas Northern Europe warms around 1-1.5 degrees. The Atlantic heats mostly less than 1 degrees, and any cooling is less than a few tenths of a degree.

The general patterns of winter warming taking place in the coldest regions, and summer heating in Europe being largest in the south, is found in all global climate change simulations (IPCC, 2001). The amplitude of the climate change for the current EU2C scenario is lower than for the SRES scenarios considered here, as should be expected. The signal-to-noise ratio is relatively small. Some regions can show a net cooling in some seasons; however, this is not statistically significant.

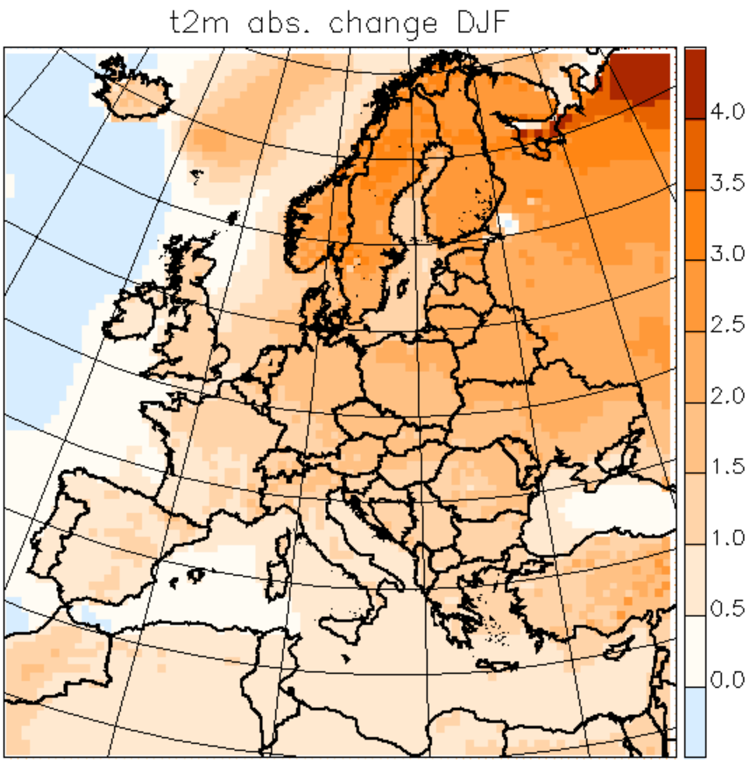

Figure 1 Mean temperature change for the winter season, EU2C. (Unit: ºC)

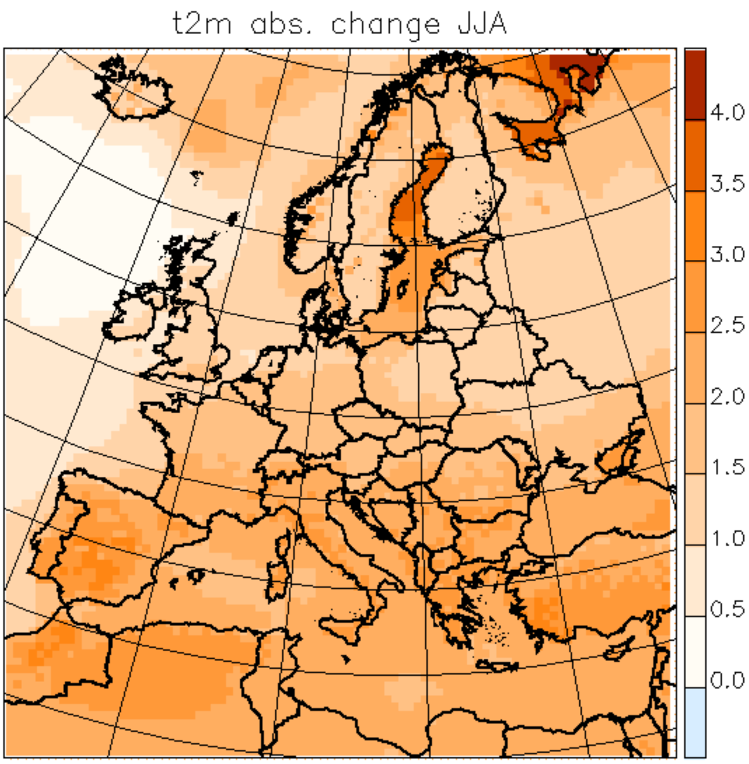

Figure 2 Mean temperature change for the summer season, EU2C (Unit: °C)

For precipitation, Figs 3 and 4 show the relative change in per cent for the winter and summer seasons. Here the bad signal-to-noise ratio is even more striking than for the case of temperature. However, there is a tendency in both seasons of an increase in the mean precipitation in the north-eastern part of the area and a decrease in southern Europe. For Denmark a slight increase is seen in winter precipitation and a slight decrease in summer precipitation in this simulation. But it should be emphasised that precipitation change is a noisy field and conclusions should be drawn with caution especially for a small area like Denmark. Precipitation changes over Denmark are not statistically significant in the EU2C scenario by itself. Since, however, the changes are similar for the other simulations studied below, there is good reason to assign some value to the results anyway.

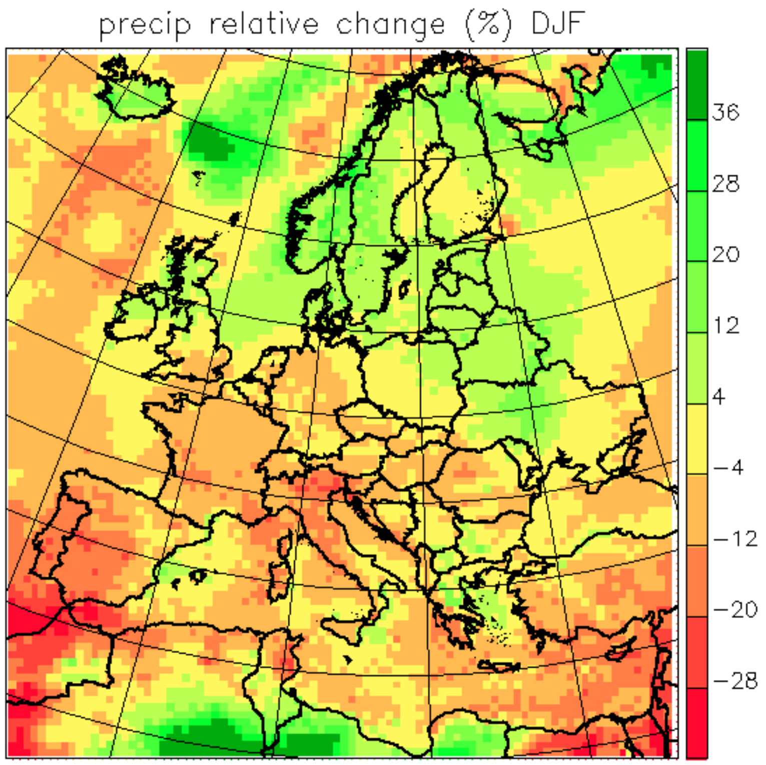

Figure 3 Relative change in mean precipitation for the winter season, EU2C (Unit: %)

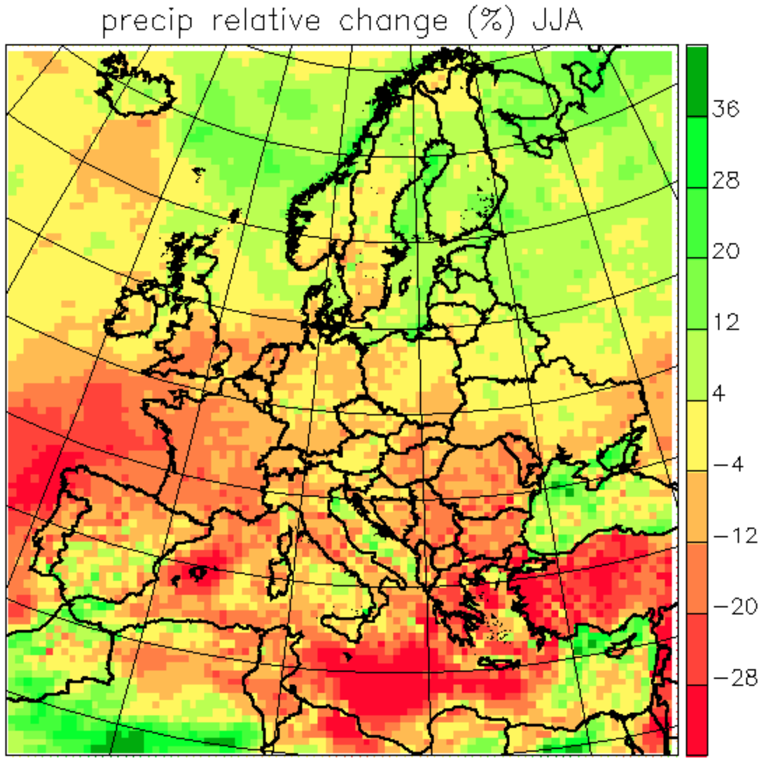

Figure 4 Relative change in mean precipitation for the summer season, EU2C (Unit: %)

Comparison with other simulations

Some climate change signals have quite robust features, where the patterns roughly scale with the general magnitude of the imposed forcing. Other fields exhibit a lot more noise and are hard to predict by simple scaling. We show examples of both cases presently.

Temperature change for the 3 winter months are shown for the A2 and the B2 HIRHAM PRUDENCE simulations in Fig. 5 and can be directly compared to Fig. 1 for EU2C. All simulations show an approximate agreement in the result that the largest heating is taking place in the north-eastern part of the integration area, whereas the North Atlantic Ocean has either a small heating or even a slight cooling in the case of the weakest forcing. The change in global annual mean temperature between the two periods 1961-1990 and 2071-2100 is 3.09ºC in the A2 simulation and 2.28ºC in the B2 simulation as compared to the 1.4 ºC change in the EU2C simulation, reflecting the magnitude of the forcing from greenhouse gasses and aerosols used in these three simulations.

In order to check the scalability of the European temperature change fields, the lower row of Fig. 5 shows the climate change normalized to the EU2C scenario, *i.e.*, simply scaled with the respective average global warming. Both absolute magnitude and warming patterns are similar for the 3 cases; there is, however, a tendency for smaller heating in Scandinavia and a slightly lower oceanic heating for the A2 and B2 experiments that are driven by the HC global model.

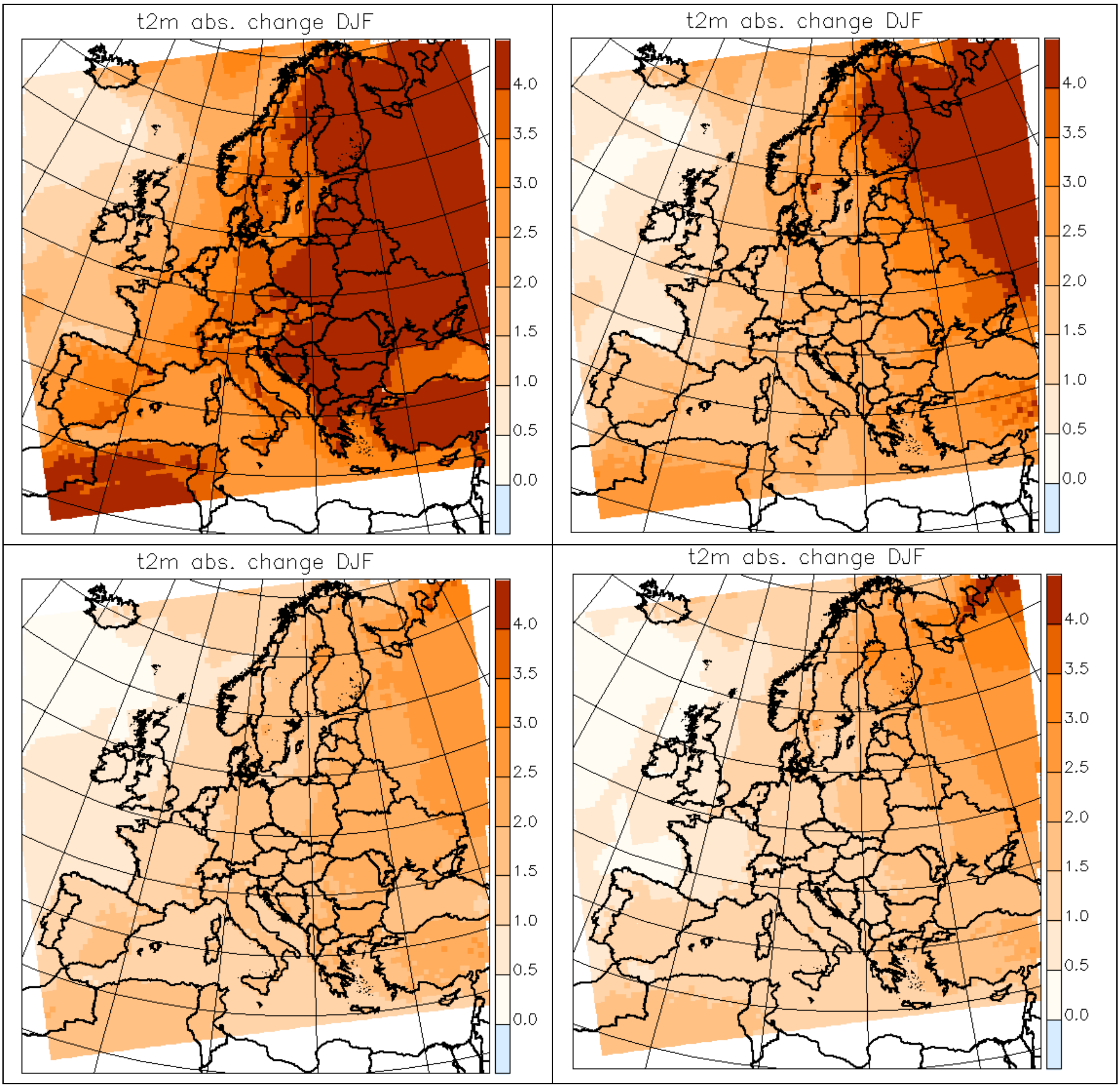

Figure 5 Mean temperature change for the winter season, left panel: A2; right panel: B2. (Unit: ºC). Lowest row: Scaled with global temperature change to the EU2C value.

Different conclusions are drawn in the case of summer precipitation. Relative changes in per cent are shown for A2 and B2 in Fig. 6 as well as for EU2C in Fig. 4. There is some agreement in the generally positive trend in the north and the generally negative trend in the south, but the extent of climate change of a particular sign varies a lot between the EU2C and the other experiments, the EU2C experiment is also considerably less consistent in the negative change in the south. A formal analysis of significance grid point by grid point shows no significant change for precipitation over Denmark in the EU2C experiment. However, the signals from the A2 and B2 are statistically significant over most of the area being investigated. The similarity of result patterns suggests the result of reduction in summer and increase in winter to be generally valid.

Again, the lower row of Fig. 6 shows scaled versions of the A2 and B2 climate change. In the case of summer precipitation it is clear that the EU2C experiment has a noisier signal than the scaled larger-forcing experiments. Furthermore the rather large increase in precipitation over the Baltic Sea is common for the A2 and B2 experiment. It should be emphasised in this connection that the A2 and B2 climate change relates to a common control experiment. It can be seen by a further investigation that the Baltic Sea is not simulated entirely realistically in the control simulation of the coupled model delivering sea surface temperature anomalies to the HadAM3H scenario. This is the probable cause of the large signal for this area in Fig. 6.

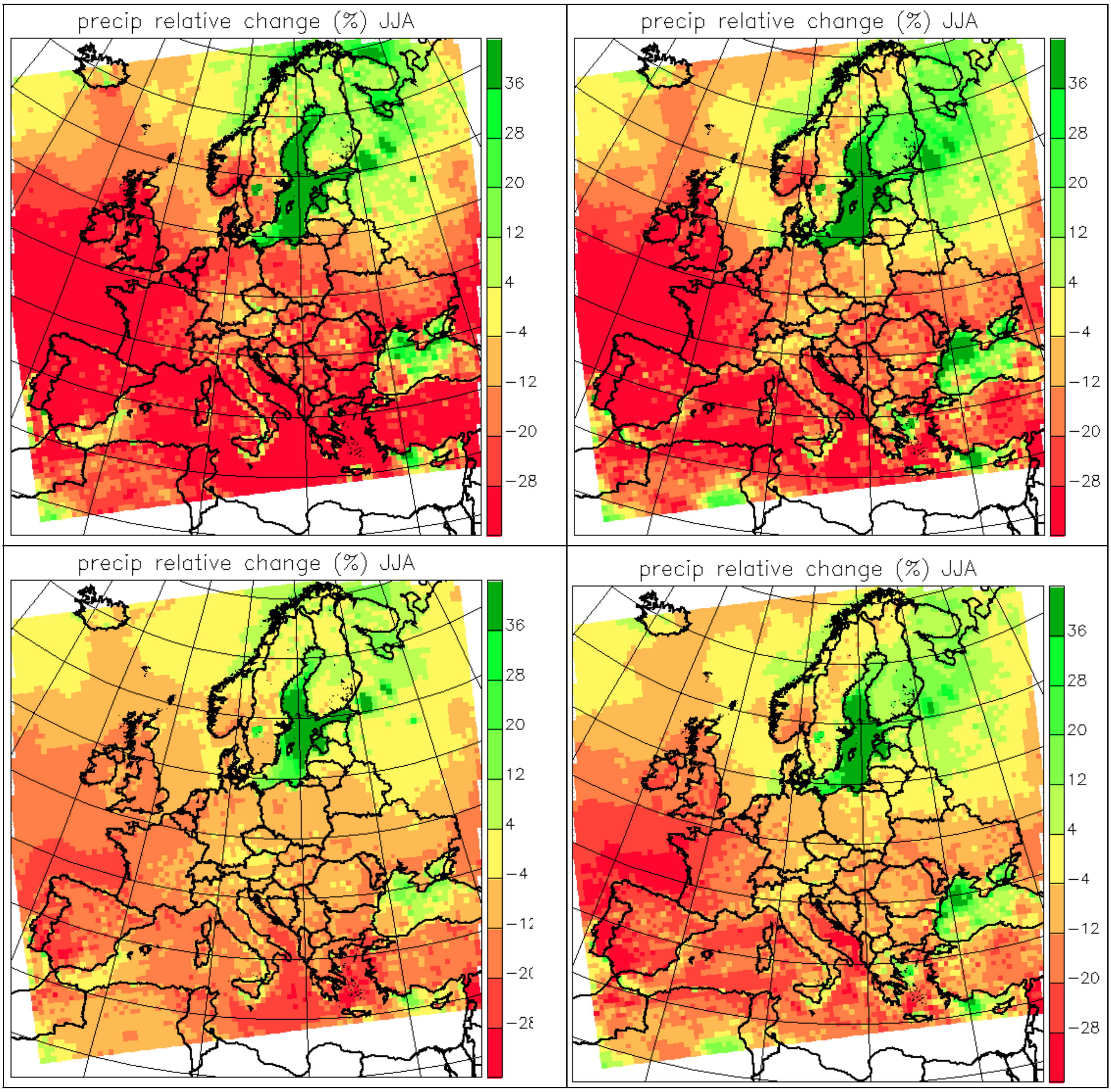

Figure 6 Relative change in mean precipitation for the summer season, left panel: A2; right panel: B2 (Unit: %). Lower row: Scaled with global temperature change to the EU2C value.

Extremes Indices

In order to analyse further the possible impacts of the EU2C scenario on Danish society, several extremes indices (Frich et al., 2002) based on daily model output have been calculated. Four of these will be presented here: Change in number of frost days, where a frost day is a day with minimum temperature below 0°C; change in growing season length, where the growing season goes from the first 6-day consecutive period with average temperature above 5°C to the first 6-day consecutive period with average temperature below 5°C; change in the annual number of heavy precipitation days, i.e. days with more than 10mm of precipitation; the change in heat wave length defined as the annual maximum of the number of consecutive days with average temperature more than 5 degrees over the control climate value for the period; and finally the change in the longest dry period for a typical year, with precipitation lower than 1mm. In all cases we will compare with the two Hadley-driven simulations corresponding to SRES scenario A2 and B2, respectively.

The number of frost days (Fig. 7) decreases in all cases, generally with a larger amplitude over land and over the relatively shallow Baltic Sea, whereas changes are zero for the North Sea, since there are no frost days in the model over open sea. The pattern shows the largest reduction in absolute numbers over the northern part of the area plotted, probably because it has more frost days to begin with. In fact, only around half the frost days are left in Denmark in the A2 simulation. Comparing the 3 simulations by examining the lower row of Fig. 7, we see that the absolute magnitude of the change is roughly as should be expected from the simple scaling argument. The A2 and B2 experiments have local maximum changes in Eastern Europe, consistent with the more zonal winter temperature gradient in these simulations than in EU2C.

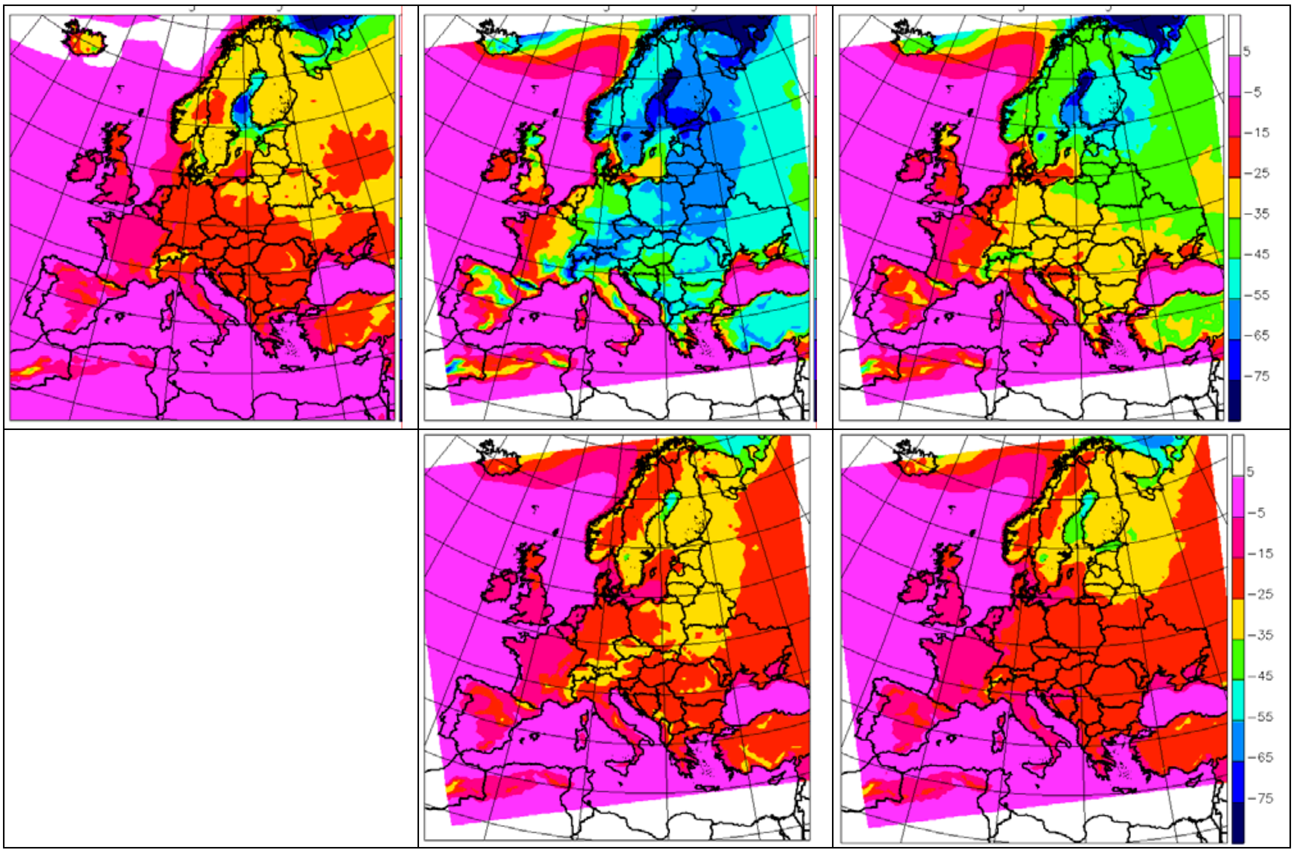

Figure 7 Change in number of frost days. Left panel: EU2C; middle panel: A2; right panel: B2 (unit: Days per year). Lower row: Scaled with global temperature change to the EU2C value.

The growing season length (Fig. 8) over land increases mostly around the Baltic Sea, hence including Denmark in the region with the largest benefits in this respect. The general magnitude of increases follows the choice of scenario as can be seen in the lower panels. In Denmark the growing season has a length of around 7.5 months in the control simulations, and the A2 simulation increases this value by almost 2 months. Generally there seems to be a slightly larger increase in the growing season in coastal areas, possibly because of less temperature variation on the relevant weekly time scale as compared to the continental climate in Eastern Europe.

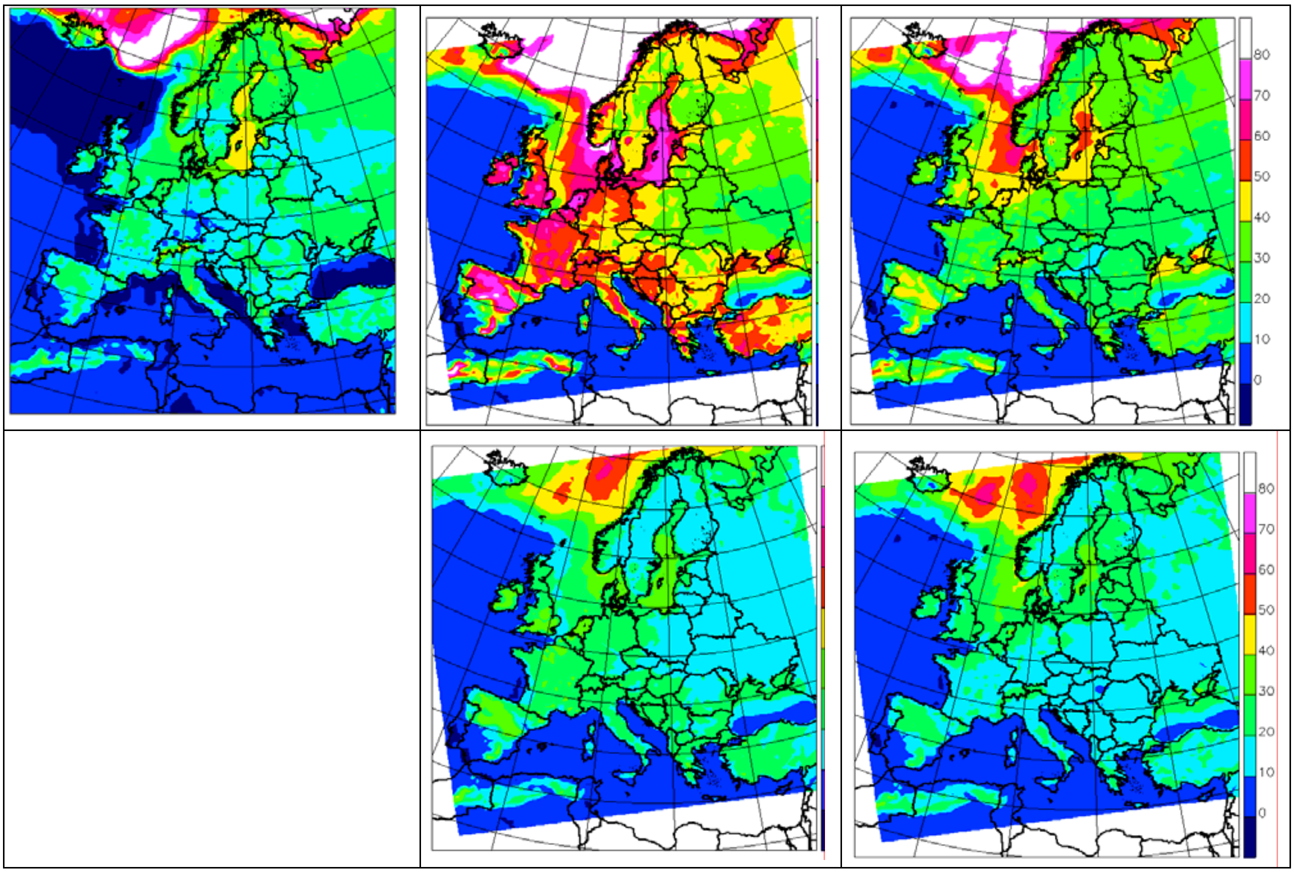

Figure 8 Change in growing season length. Left panel: EU2C; middle panel: A2; right panel: B2 (unit: Days). Lower row: Scaled with global temperature change to the EU2C value.

Precipitation, and to an even higher extent heavy precipitation (Fig. 9), are very noisy fields, where the expected consistency of results, even taken over 30-year periods, is not expected to be very large. Present-day simulated values are around 10-15 days per year for Denmark. The 3 simulations all show slight increases, largest in the north, but with rather noisy spatial distributions. Both A2 and B2 exhibit positive change for most of the area, in contrast to the EU2C result which is very noisy. An estimation of noise and confidence intervals shows that the only large area with significant change is the area with positive change covering the North Sea, Scandinavia and nort-western Russia in the A2 and B2 simulations.

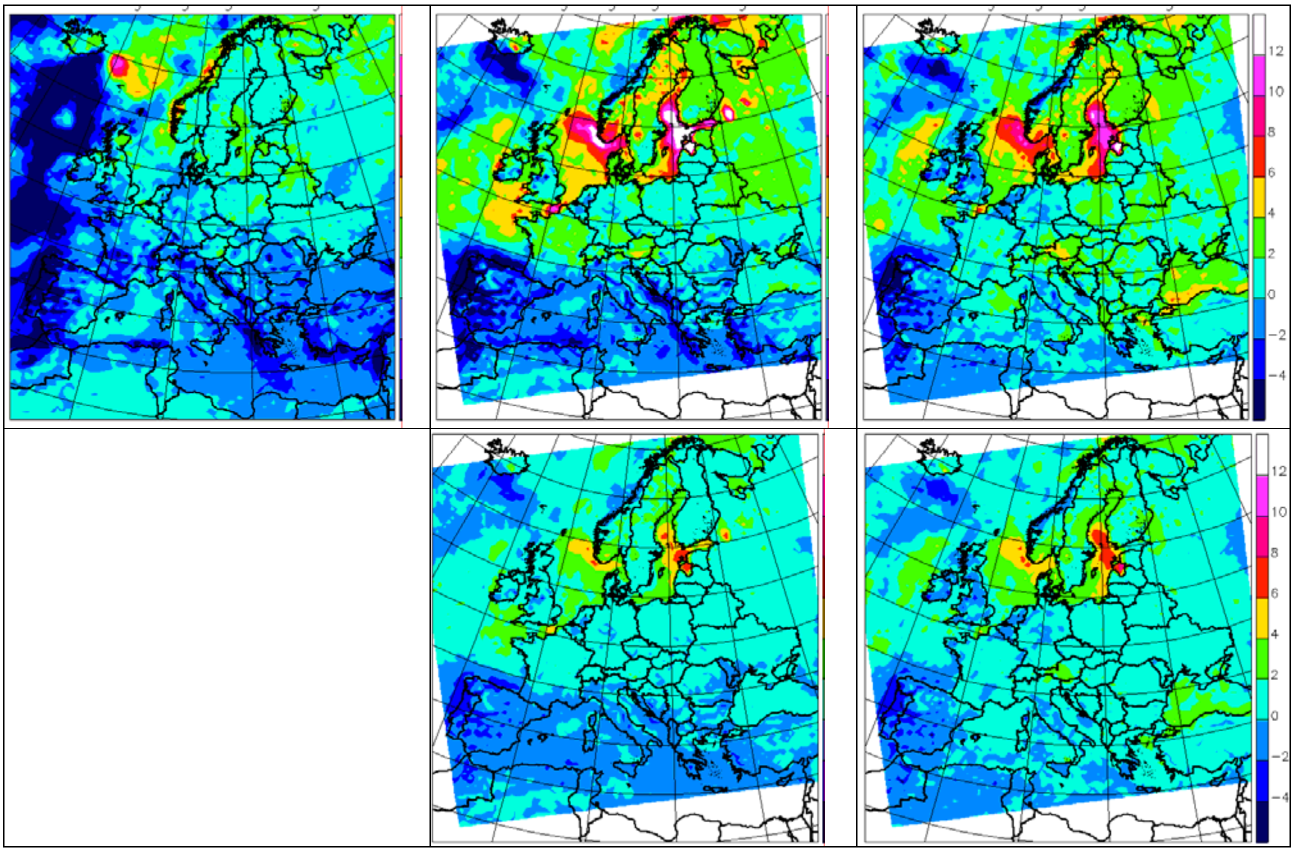

Figure 9 Change in days with heavy rain. Left panel: EU2C; middle panel: A2; right panel: B2 (unit: Days per year). Lower row: Scaled with global temperature change to the EU2C value.

The average annual-maximum heat wave length (Fig. 10) as it is defined here is 4-6 days in Denmark in the control simulation. Please note that the term heat wave in this definition is a misnomer: The definition concerns long lasting exceedances of more than 5 degrees with respect to the average temperature of the season, i.e., there are “heat waves” all year round.

In all the three simulations of the future climate there is a substantial and significant increase in the heat-wave length for virtually the entire land mass. As exceedances of more than 5 degrees with respect to the control temperature increases more than proportionally with the heating, we see increases that are much larger than a factor of 2 in the A2 experiment as compared to the EU2C experiment. As the scaled climate signal increases with the forcing, it is clearly seen that the climate change is more than proportional to the forcing.

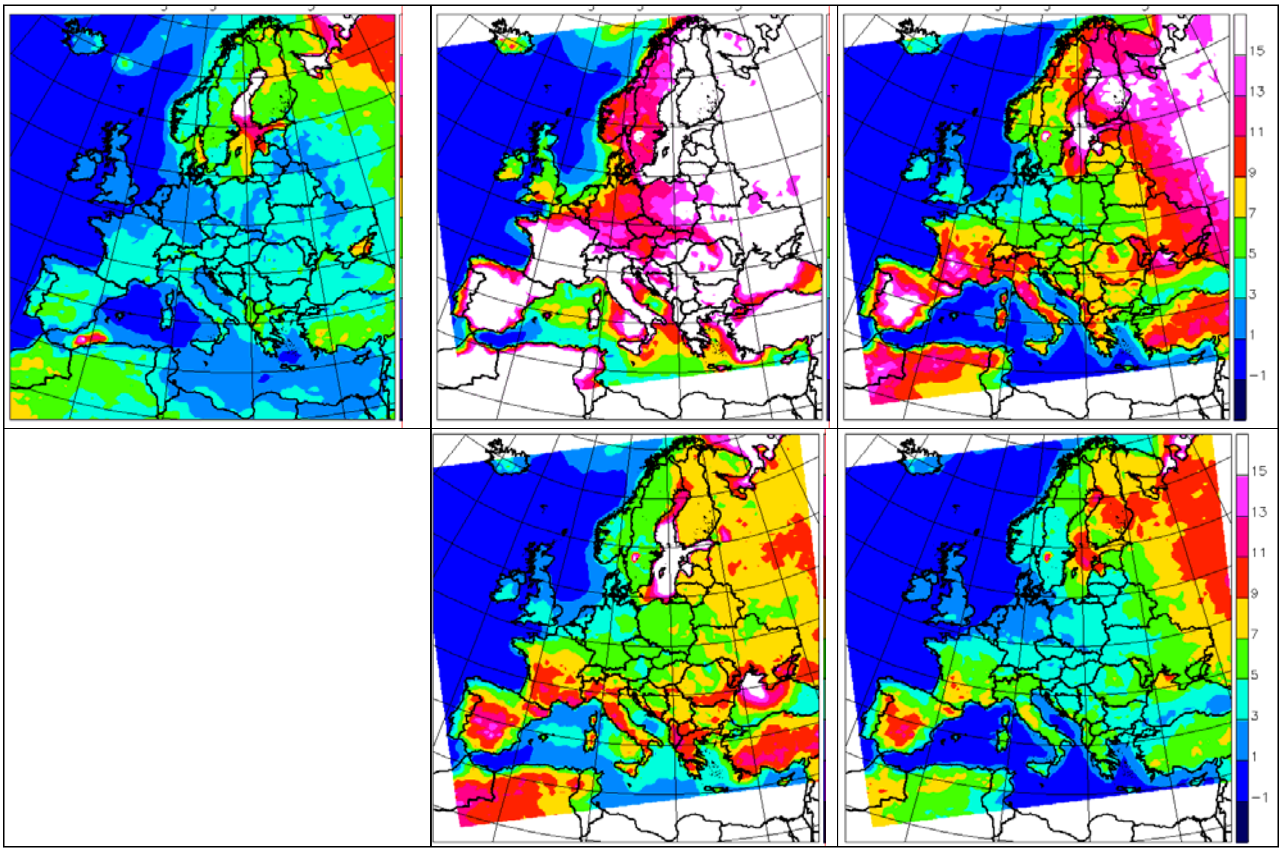

Figure 10 Annual-maximum heat wave length. Left panel: EU2C; middle panel: A2; right panel: B2 (unit: Days). Lower row: Scaled with global temperature change to the EU2C value.

In the northern part of the integration area, the drought index (Fig. 11) does not change very much. But in Southern Europe, where the average precipitation decreases a lot, as does the number of rain days, there are substantial increases. The scaled index is similar for A2 and B2, and the signal looks less noisy than for EU2C. The magnitude of the change is rather similar for all experiments. It should be noted that hardly any of the changes are statistically significant when each grid point and experiment is analysed by itself. Again the similarity of the general pattern of change leads to a subjective credibility of the results in spite of this.

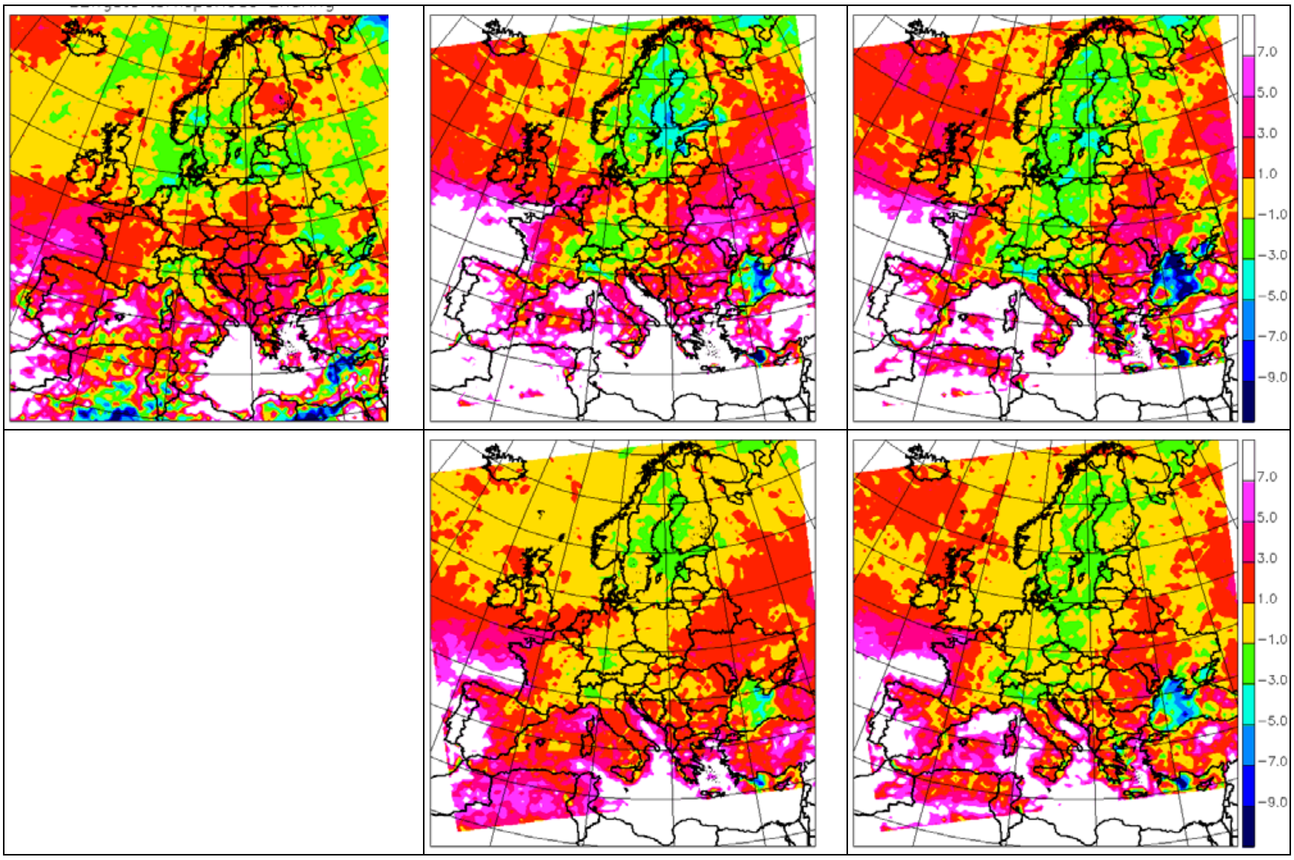

Figure 11 Annual-maximum number of consecutive dry days (< 1mm). Left panel: EU2C; middle panel: A2; right panel: B2). Lower row: Scaled with global temperature change to the EU2C value.

Conclusions

A simulation of future climate with a global climate model resulting in a stabilisation of the global annual mean temperature at the end of the 21st century at a 2ºC increase compared to pre-industrial time has been downscaled for the European and North Atlantic domain using a regional climate model. Results showing changes between the period 1961-1990 and 2071-2100 are compared to similar downscalings of A2 and B2 scenarios.

Temperature and temperature related indices (e.g. length of growing season and heat wave length) show relatively robust patterns of change, and the changes are roughly proportional to the magnitude of the applied forcing –the smallest changes are found in the EU2C simulation and the largest changes in the A2 simulation. However, indices of extremes employing fixed temperature thresholds like the heat wave duration index increase more than proportionally to the global temperature change.

Precipitation and precipitation related indices (e.g. days with heavy rain) are much more noisy fields, and although general tendencies are seen in the three simulations the changes do not necessarily scale with the choice of scenario to the same extent as in the case of temperature. The signal-to-noise ratio is small for these precipitation based fields and many changes are not formally statistically significant –especially in the EU2C simulation where the changes are relatively small. However, similarity of climate change patterns enhance the credibility of these somewhat. A scaling of simulations with larger forcing generally gives less noisy results. It is, however, not necessarily a valid procedure to perform this scaling procedure on more complex fields.

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