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A) Project Data

Short title:	ReCliS:NG
Full title:	Next Generation Regional Climate Scenarios for the Greater Alpine Region
Programme:	ACRP, 3rd Call
Duration:	18 months
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Cooperating partners (incl. district):	
Key words:	regional climate modelling, dynamical downscaling, RCP scenarios
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Klimafonds-Nr:	K10AC1K00064
Date:	13.11.2013

B) Project overview

1 Executive Summary

Synopsis

The project aimed at the development of two novel regional climate scenarios for the greater Alpine region. These climate scenarios are based on the new "representative concentration pathway" (RCP) emission scenarios that were developed for the upcoming IPCC AR5. The generated climate scenarios extend the ensemble of currently developed regional climate scenarios for the Alpine region (reclip:century) as well as for Europe (EURO-CORDEX).

Abstract

In 2005 the Intergovernmental Panel on Climate Change (IPCC) initiated the development of new emission scenarios, the so-called "representative concentration pathway" (RCP) scenarios. They aim at describing the pathway of emissions and of CO2-equivalent concentrations during the 21st century including mitigation initiatives. For instance, the RCP2.6 (RCP4.6) scenario gives a global warming of 1.8°C (2.8°C) by the end of the 21st century. How climate change in the Alpine region looks like when the 2°C target (RCP2.6) is achieved, was one of the issues investigated in ReCliS:NG. Other objectives, were to extend the ensembles of currently developed regional climate scenarios for Europe (EURO-CORDEX) and the Alpine region (reclip:century) and to analyse the differences between RCP2.6 and RCP4.5 in Austria.

These aims were achieved by conducting two highly resolved (50 km and 12 km grid spacing) climate simulations with the regional climate model COSMO-CLM (CCLM) employing two new RCP scenarios: RCP2.6 and RCP4.5. In addition, the climate simulations were further downscaled (1 km grid spacing) in the Austrian territory by means of a robust empirical/statistical downscaling method (quantile mapping) to provide specialised climate data to the Austrian climate impact community.

The results show that there is considerable benefit in reaching the 2°C target. The temperature increase is more moderate in the RCP2.6 scenario than in RCP4.5. The precipitation parameters (including extremes) of the RCP2.6 scenario also show clear benefits. The investigated climate variables show a stabilising behaviour (particularly in summer) until the end of the 21st century in the case of the RCP2.6 scenario, whereas there is progressive increase in RCP4.5. This strongly pronounces the dependency of climate change effects from greenhouse gases and reveals the strength of mitigation.

2 Background and Aims

Most of the existing climate scenarios, both on global and regional scale, are built upon the Special Report on Emission Scenarios (SRES) [Nakicenovic et al., 2000] for the development of future greenhouse gases. On the international level, SRES have excessively been used for instance in PRUDENCE [Christensen and Christensen, 2007] and ENSEMBLES [Hewitt, 2005], both large-scale projects funded by the European Commission. In Austria, SRES scenarios have been used within the project reclip:century (reclip.ait.ac.at) [Loibl et al., 2011], funded by the Austrian Climate Research Programme (ACRP), and its successor reclip:century 2.

Although well established and widely used in climate modelling, the SRES scenarios do not include mitigation and adaptation initiatives. Therefore, in 2005 the Intergovernmental Panel on Climate Change (IPCC) initiated the development of new emission scenarios, the so-called "representative concentration pathway" (RCP) scenarios [Moss et al., 2008]. They aim at describing the pathway of emissions and the progress of CO2-equivalent concentrations during the 21st century that result in the stabilisation at a prescribed CO2-equivalent concentration level in the year 2100. For instance, the RCP2.6 scenario (formerly also often referred to as RCP3.0-PD) gives a global warming of 1.8°C by the end of the 21st century (compared to pre-industrial times) [Strassmann et al., 2009] and therefore meets the “2°C target” of the European Union. These RCP scenarios have already been employed in the latest generation of global climate models (GCMs) and are currently being used in regional climate models (RCMs), like in the Coordinated Regional Downscaling Experiment (CORDEX) [Giorgi et al., 2009] of the World Climate Research Programme (WCRP) and in its European branch (EURO-CORDEX, www.euro-cordex.net).

How climate change in the Alpine region looks like when the EU target is achieved, was one of the research topics in the 3rd call of the ACRP.

In order to follow this call and to contribute to the international (EURO-CORDEX) and national (reclip:century) activities, ReCliS:NG pursued three aims:

1. Extend the ensemble of currently developed regional climate scenarios for Austria and the Alpine region (reclip:century) in order to enable relevant climate change impact research.

2. Analyse the regional climate implications of the globally formulated “2°C target” for Austria and the Alpine region opposed to less ambitious mitigation targets.

3. Contribute to EURO-CORDEX by providing non-standard simulations.

These aims were achieved by conducting two highly resolved (50 km and 12 km grid spacing) climate simulations with the European regional climate model COSMO-CLM (CCLM) employing two new RCP scenarios: one in-line with the “2°C target” (RCP2.6) and one less ambitious scenario (RCP4.5), for Europe and the Alpine region. This was done in such a way that the requirements of both, the EURO-CORDEX and the reclip:century activities, were fulfilled. In addition, the climate simulations were further downscaled by means of quantile mapping (a robust empirical/statistical downscaling method) to a grid with 1 km grid spacing covering the Austrian territory to provide specialised climate data to the Austrian climate impact community.

The results show that from the Alpine region's point of view there is considerable benefit in reaching the global “2°C target”. The temperature increase is more moderate in the RCP2.6 scenario than in RCP4.5. The precipitation parameters (including extremes) of the RCP2.6 scenario also show clear benefits. The investigated climate variables (temperature, precipitation, extremes, consecutive dry days) show a stabilising or declining behaviour (particularly in summer) until the end of the 21st century in the case of the RCP2.6 scenario, whereas there is progressive increase in RCP4.5. This strongly pronounces the dependency of climate change effects from greenhouse gases throughout the century and reveals the strength of mitigation.

The project pointed out the advantages of dynamical (RCMs) and empirical/statistical downscaling methods, but also their limitations and shortcomings. If robust conclusion about climate change effects from numerical modelling approaches on very small spatial (convection-resolving/permitting) and temporal (sub-daily) scales in complex terrain are of interest, both methodological approaches need to be improved. In addition, proper observational-based reference datasets need to be available.

3 Content and results of the project

Initial situation / motivation for the project

Significant advances have been made over the past decade in modelling the climate system. These advances were made on both, the global and the regional scale as well as on the processes that are included in the models. The models improved our knowledge of the past climate, of current climatic conditions and the interactions of radiate active gases, and of future climate as a result of interactions. Regional climate models (RCMs) have been improved and used with ever finer resolution. While a decade ago, a horizontal resolution of 25 km to 50 km was state-of-the-art (e.g., in projects like PRUDENCE [Christensen and Christensen, 2007] and ENSEMBLES [Hewitt, 2005]), RCM simulations of today more and more feature a horizontal resolution of 10 km (e.g., reclip:century [Loibl et al., 2011]). The project CORDEX (wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html) coordinates endeavours around the globe to produce regional climate simulations at horizontal resolutions ranging from 50 km to 10 km.

Most of the existing climate scenarios, both on the global and the regional scale, build on the SRES scenarios [Nakicenovic et al., 2000]. However, these scenarios lack of a factual link to reality. Instead, they represent different demographic, social, economic, technological and environmental developments. They do not include mitigation and adaptation initiatives. On the other hand the United Nations Framework Convention on Climate Change (UNFCCC) already formulated an objective “to achieve stabilization of greenhouse gas concentrations in the atmosphere that would prevent dangerous anthropogenic interference with the climate system” [UN, 1992] back in 1992. It further already refers to a rough timeline by suggesting that “such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.”

Based on that convention in 1996, the European Council adopted a climate target reading “the Council believes that the global average temperature should not exceed 2°C above pre-industrial level and that therefore concentration levels lower than 550 ppm CO2 should guide global limitation and reduction efforts.” This so-called “EU-target” has been reaffirmed by the EU on a number of occasions, for example by the Council of the Ministers for the Environment in the European Union in 2004 [EU Council, 2004], 2007 [EU Council, 2007] and the latest one in 2010 [EU Council, 2010]. This eventually resulted in the EU’s commitment to cut its CO2 emissions by 20% of the 1990 level until 2020.

Austria in recent years saw a number of projects focusing on the Alpine region using high resolution RCMs, amongst others reclip:more, reclip:century and reclip:century 2. While reclip:more delivered first thoroughly validated datasets of a past and a future decade, reclip:century aimed at transient climate scenarios from the 1960s to the 2040s. This period was further extended until 2100 in its successor, reclip:century 2. In these projects, valuable model related findings have been made regarding parameterizations and sensitivity, apart from the climate change results and the related uncertainties which were their primary aim. However, all the climate scenarios produced in these projects are based on SRES emission scenarios mentioned above. None of these scenarios include additional climate initiatives, and as such they do not consider mitigation initiatives as postulated by the UNFCCC or the emission targets of the Kyoto protocol.

The shortcomings of SRES have also been recognised by the Intergovernmental Panel on Climate Change (IPCC), which initiated the development of new emission scenarios in 2005. The new scenarios should enable the parallel development of climate scenarios on the one hand and socio-economic scenarios on the other hand. The result of this process are the so-called “representative concentration pathway” (RCP) scenarios [Moss et al. 2008]. They aim at describing the necessary progress of CO2-equivalent concentrations and resulting emissions in the atmosphere in order to reach stabilization at a certain CO2-equivalent level in the year 2100. This CO2-

equivalent level is expressed as a certain level of radiative forcing (RF). There are four of these RCP scenarios: RCP2.6 (initially also often referred to as RCP3-PD; [van Vuuren et al., 2007]), RCP4.5 [Clarke et al., 2007; Wise et al., 2009], RCP6.0 [Fujino et al., 2006; Hijioka et al., 2008], and RCP8.5 [Riahi et al., 2007], meaning a RF of +2.6 W/m2, +4.5 W/m2, +6.0 W/m2 and +8.5 W/m2, respectively, in 2100 compared to the pre-industrial era. Such RFs result in a certain degree of climate warming. The actual climate warming depends on the climate sensitivity of the individual GCMs driven with these scenarios, but a general idea of the implicated warming is given in Strassmann et al. [2009]. According to their findings the RCP2.6 (3-PD) scenario gives a warming of 1.8°C by the end of the 21st century and therefore meets the EU target. The RCP4.5 scenario, which will be the IPCC AR5 "standard" scenario (similar to the SRES-A1B scenario in IPCC AR4) gives a warming of 2.8°C.

Two international initiatives are of special interest in combination with the proposed project: CMIP5 and CORDEX. The fifth "Coupled Model Intercomparison Project" (cmip-pcmdi.llnl.gov/cmip5) aims at coordinating the efforts of the global climate modelling community to establish a vast series of long term climate scenarios with different RFs, i.e., different representative concentration pathways. CORDEX, the "Coordinated Regional Downscaling Experiment" [Giorgi et al., 2009], basically does the same, but – as its name suggests – on the regional basis. CORDEX prescribes minimum requirements with respect to domain size and horizontal resolution. The 12 regions defined in CORDEX are spread across the globe and each participating institution is free to choose how many and which domains to simulate. However, CORDEX also encourages each participant to prioritise Africa besides their "home" domain. This is done mainly because Africa will be the focus region in the upcoming Fifth Assessment Report of the IPCC (AR5).

Description of the work packages and mile stones

In order to reach the goals of the project, the work flow was organized in three scientific and one administrative work packages (WPs):

WP1 – Acquisition and preparation of suitable boundary data

This work package aimed at providing the LBCs for the simulations performed in WP2. Therefore it was needed to download and pre-process ERA-Interim as well as GCM data in a way that CCLM can handle it. ERA-Interim input data was provided by ECMWF and was downloaded from its archive by means of WEGC's account at ECMWF, data of the GCM (HadGEM2-ES) was downloaded from the portal of the Earth System Grid Federation (ESGF, pcmdi9.llnl.gov).

WP2 – Simulation of hindcast, control and scenario climate

This WP was responsible for all the simulations defined in Table 1: one hindcast (downscaling of the recent history with the reanalysis dataset from WP1) and two control and scenario simulations (downscaling of recent history as well as the future using GCM data). For this task two programs were needed: INT2LM (a pre-processor) and CCLM (the regional climate model). The first one horizontally and vertically interpolated the lateral boundary data gained from WP1 to the resolution of the regional climate model CCLM, which then was used to simulate the given periods.

WP3 – Postprocessing and evaluation of model results

Here, two main tasks have been performed: (1) Do a basic evaluation of the model results and link them to the existing climate scenarios for the GAR. (2) Apply quantile mapping onto the model results obtained in WP2 in order to support climate change impact research with highly resolved (1 km grid spacing) data affected by a minimum of model errors. In the first task, the model results were evaluated with regard to the standard statistical moments (mean bias and standard deviation). Also, analyses of extreme events in these new regional climate scenarios were performed in WP3, and links to the results of existing climate scenarios for the Greater Alpine Region were made (some results are shown below, details can be found in the Annex).

WP4 – Project management and outreach

WP4 mainly contained the administrative parts of the project work: manage the work done in the three "production" work packages (WP1, WP2, WP3), assure timely achievement of project milestones and results and provide the results to the climate research community as well as to the public (see Annex for details).

Evaluation of the hindcast

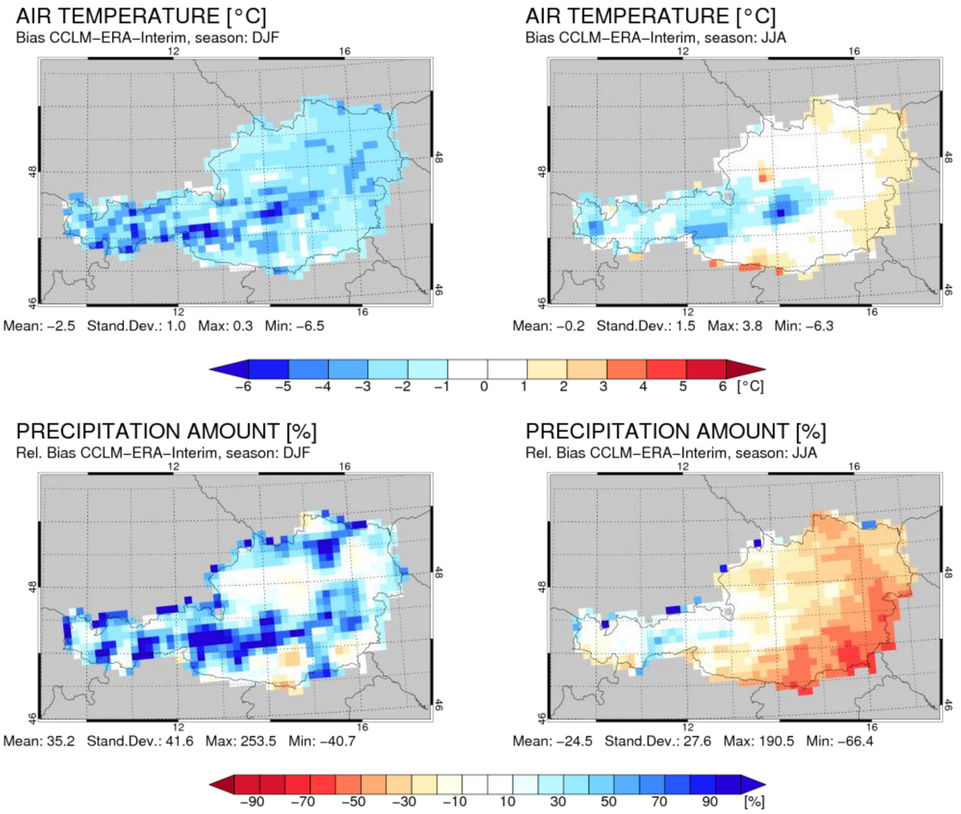

Figure 1: Seasonal mean biases of temperature (upper row) and precipitation (lower row) of the hindcast (period 1991 to 2005) in Austria. Left column: winter (DJF), right column: summer (JJA).

For evaluation purposes the reference dataset was aggregated from its high resolution (1 km grid spacing) to the resolution of the CCLM output (12 km grid spacing) in advance. Since the hindcast was driven by ERA-Interim, reflecting real weather conditions, the derived biases show the performance of CCLM. At a glance, CCLM shows negative temperature biases over Austria throughout the annual cycle: the seasonal biases are ranging from -2.4°C (in winter) to 0.2°C (in summer) (cf. Figure 1). In addition, these biases are roughly correlated with surface altitude: they increase in magnitude in the inner Alps. Precipitation biases look quite different: there is an overestimation of about +35% in winter and spring, which is also roughly correlated to the surface altitude, but there is also an underestimation in summer especially in the Alpine forelands and in the basins of Graz and

Klagenfurt of about -50% (cf. Figure 1). Nonetheless, these are usual biases of state-of-the-art RCMs as they have also been experienced in reclip:century. But the biases are way too large for a direct application of the model results in climate impact models. Therefore, correction methods need to be applied in advance as it done in ReCliS:NG.

Effect of quantile mapping

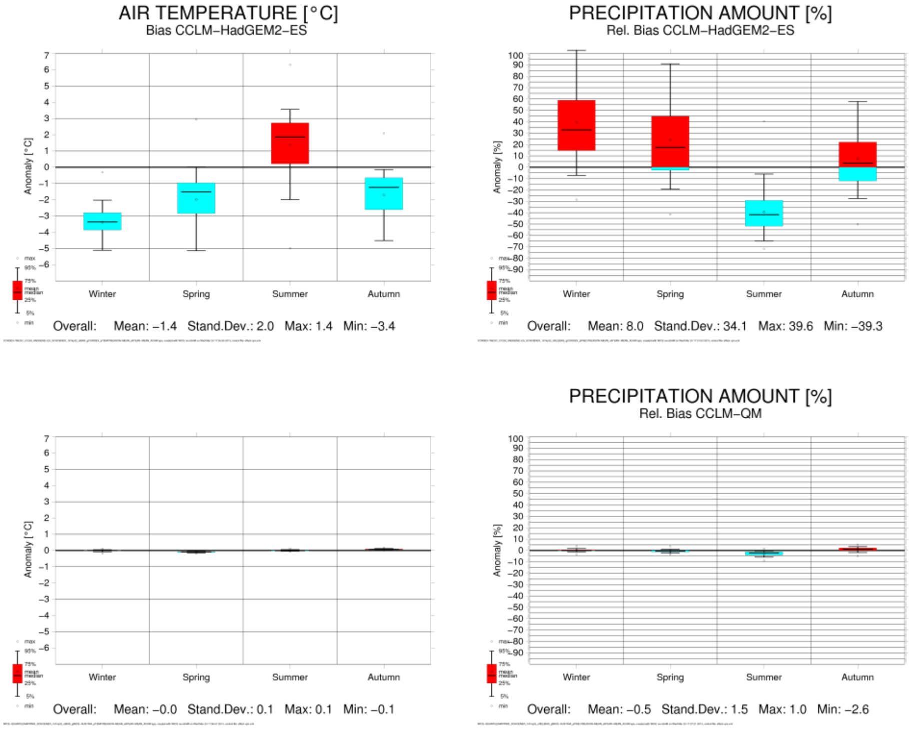

Figure 2: Effect of quantile mapping. Seasonal temperature (left column) and precipitation (right column) biases of the GCM-driven control run (upper row) are drastically reduced by the quantile mapping method (lower row) (period 1974 to 2005).

When an RCM is driven by a GCM, the model output usually is also affected by model errors stemming from the GCM. In ReCliS:NG, this leads to an increase of the biases, compared to the ERA-Interim-driven hindcast: the negative temperature biases in winter become more negative (-3.4°C on average), the small positive biases in summer become more positive (+1.4°C on average) (cf. Figure 2). This is also the case for precipitation: the overestimation in winter is increased to about -40% on average and the underestimation in summer is also stronger pronounced (cf. Figure 2). Due to the application of quantile mapping, these deficiencies have been improved to at least one magnitude (cf. Figure 2).

Model errors that are linear or can be expressed in terms of constant offsets may be cancelled due to the calculation of climate change signals (i.e. differences between future climate and reference period). However, if non-linear variables are concerned (like threshold values), significant errors may be induced and misleading climate scenarios may be derived. This strongly emphasises the application of a proper correction method, like QM, that removes the biases and preserves the climatological (statistical) properties (not shown).

(Corrected) Climate change effects in Austria

The results displayed in this subsection are based on the error corrected model put. Since the observation data for the error correction is limited to daily mean temperature and daily sums of precipitation, the results are also limited to parameters which are based on these two meteorological quantities. The parameters under investigation are:

- daily mean temperature
- daily mean precipitation
- Maximum precipitation during one day
  This parameter investigates the one-day peak precipitation amount. It is attributed to local, short-term heavy precipitation events, like thunderstorms.
- Maximum precipitation during a period of three consecutive days
  describes events that are related to large scale synoptic events, i.e., front passages.
- Maximum precipitation during a period of five consecutive days
  describes events that are related to long-lasting large scale synoptic events.
- Number of days with precipitation sums of more than 30 mm
  investigates the frequency of occurrence of heavy precipitation events and hence it gives evidence whether or not extreme precipitation events will occur more often in the future.
- Consecutive dry days
  gives a first estimate on whether or not drought events will become more intense in future.

In order to analyse the climate change signals we averages of 30 years are calculated. The reference time period is 1971 to 2000. Then there is a mid-century scenario period ranging from 2021 to 2050, and finally there is the late-century scenario period ranging from 2069 to 2098. The “correct” period would be the more common period 2071 to 2100, but due to problems with the driving HadGEM2-ES data the analysed time frame is the most advanced possible. For a more detailed explanation, see below.

<u>Daily mean temperature</u>

The RCP2.6 scenario is intended to reach the global 2°C target which means not to exceed a global climate warming of 2°C (compared to pre-industrial times) until the year 2100. For Austria this means a temperature increase of 1.2°C until mid-century in winter and 2.5°C in summer (Figure 3) and 1.5°C in spring and 2.2°C in autumn (see Annex). The geographical distribution is very heterogeneous: mountainous regions experience a much higher temperature increase than the lowlands, especially in summer: high altitude regions in the West of Austria experience a temperature increase of up to 3.9°C, while temperature in the basins in the South and Southeast increase by just about 2.0°C (Figure 3). In the late-century period the overall temperature increase is not stronger pronounced than in the mid-century period, but there is a shift from the warm seasons to the cold ones: temperature is increased by 2.1°C in winter and by 1.9°C in autumn (Figure 3). The geographical distribution of the temperature increase roughly stays the same.

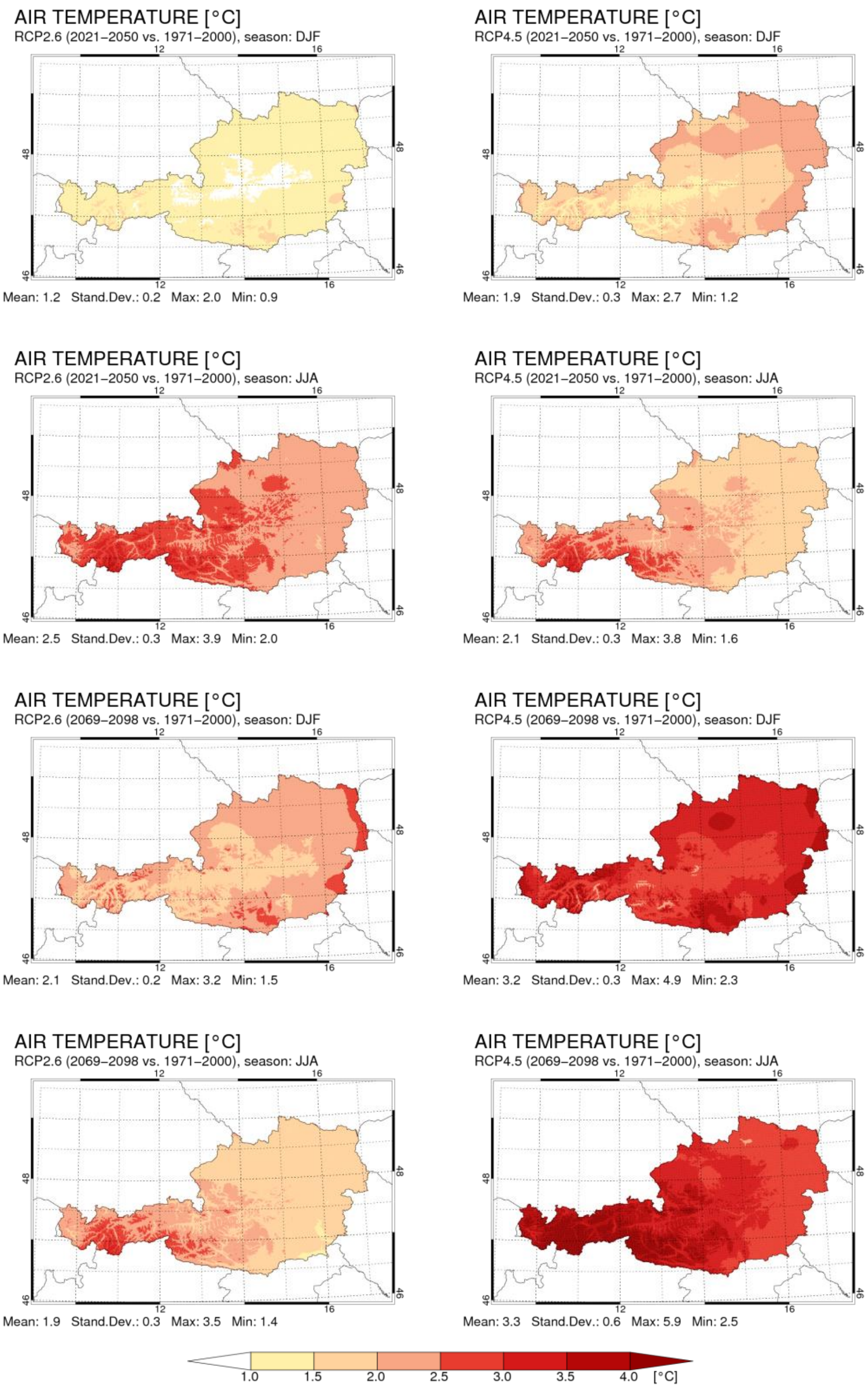

Figure 3: Comparison of changes in seasonal mean temperature between mid-century (period 2021 to 2050) and late-century (period 2069 to 2098) with respect to the reference period (1971 to 2000). Left column: RCP2.6, right column: RCP4.5. Rows refer to winter (DJF) and summer (JJA) seasons of mid-century and late-century periods.

Until mid-century the temperature increase in the RCP4.5 scenario behaves quite similar to the RCP2.6 scenario, they are just slightly stronger: 1.9°C in winter and 2.1°C in summer (Figure 3), and 1.4°C in spring and 1.9°C in autumn (see Annex). Also the altitude dependency is similar to the RCP2.6 scenario. However, in the late-century period, the temperature increase in much stronger pronounced: 3.2°C in winter and 3.3°C in summer (Figure 3), 2.1°C in spring and 3.6°C in autumn (see Annex). Highest seasonal temperature increases of up to 6.4°C (see Annex) are experienced in mountainous regions in autumn. Again, the altitude dependency of the temperature increase remains.

Daily precipitation

The climate change signal for precipitation varies strongly from one season to the other. In the mid-century period in RCP2.6 there are changes of +8.1% in winter and -26.7% in summer (Figure 4) over whole Austria. There is also an increase in spring and a decrease in autumn, but to a smaller extent (see Annex). Towards the end of the 21st century the general picture of an increase in precipitation during winter and spring and a decrease of precipitation during summer and autumn persists, but the magnitude is dampened: the Austrian mean change of precipitation reads +2.4% in winter and -14.4% in summer.

The RCP4.5 scenario also shows this annual cycle in the precipitation changes, but with a constantly strong magnitude throughout the century. The precipitation changes read +21.5% in winter and -22.0% in summer in the mid-century period, and +18.4% in winter and -26.4% in summer at the end of the century (Figure 4).

Extremes in precipitation

The number of days with heavy precipitation (>30 mm/d) show a similar behaviour as the seasonal mean precipitation: they increase in winter and decrease in summer. Also the correlation to the RCP scenario remains: changes in the RCP2.6 scenario are strongest in the mid-century period (+0.2 d in winter; -0.4 d in summer; see Figure 5) and are dampened at the end for the century (+0.1 d in winter; -0.2 d in summer; see Figure 5), while in the RCP4.5 scenario are constantly high throughout the century (+0.4 d in winter; -0.4 d in summer; see Figure 5). However, the spatial distribution of the changes are much more dense in their location: they are located upstream of the mountains (e.g. to the Northern and Southern Prealps; see Figure 5). Here, the changes may reach their maxima of +2.4 d in winter and -3.1 d in summer.

Changes in daily maximum precipitation deviates from the changes of seasonal mean precipitation. Strong reductions occur in summer and autumn, but relative increases are strongest pronounced in spring instead of winter. Also the geographic distribution differs: the summer-time decreases are much more localised. The RCP2.6 scenario shows an Austrian averaged increase of +16.9% in spring and localised decreases up to -33.2% in summer (Figure 6) in the mid-century period. In the late-century period, the increase becomes stronger (+20.0% in spring, Figure X) while the summer-time decrease is balanced by localised increases. The RCP4.5 shows the same behaviour and also nearly the same numbers (Figure 6). This indicates there is evidence for progressively increasing thunderstorms in spring (and also in winter, see Annex) throughout the century, regardless of the emission scenario.

Changes in three-daily maxima of precipitation show a progressive increase in spring (Figure 7) and winter (see Annex) throughout the century, regardless of the emission scenario: in the mid-century this spring increase amounts +17.5% (+19.7%) and in the late-century period it amounts +20.8% (+24.9%) in the RCP2.6 (RCP4.5) (Figure 7) and covers the Eastern Alps and forelands. In summer, the three-daily maxima of precipitation experience a stagnant decrease from -8.3% during the mid-century period to -0.7% in RCP2.6, while it is kept nearly constant in RCP4.5 (-5.5% in mid-century and -5.4% in late-century period, Figure 7) and it is more localised over the alpine forelands. The same behaviour is shown by the five-daily maxima of precipitation, but with a slightly stronger pronunciation.

This gives evidence for distinctive changes in different types of precipitation extremes: there is a coherent progressive increase of large-scale precipitation extremes and thunderstorms in spring and winter throughout the century (regardless of the emission scenario), but in summer, thunderstorms decrease in the mid-century and fully recover by end of the century. In addition, large-scale precipitation extremes in summer depend on the emission scenario: they decrease in the mid-century period, but partly recover in the RCP2.6 scenario.

Consecutive dry days:

Regarding the consecutive dry days, i.e., days with less than 1 mm of daily precipitation, we found an interesting result. For the mid-century period, from 2021 to 2050, the scenario with higher emissions RCP4.5 gives an increase of 19.7% (averaged over the whole country) in summer, whereas RCP2.6 shows an increase of 35.4% (Figure 8). In the late-century period, 2069 to 2098, the signal is inversed: RCP2.6 gives an increase of 16.1% in summer compared to the period 1971 to 2000, RCP4.5 shows an increase of 25.2% (Figure 8). Hence, there is an improved increase of consecutive dry days in the RCP2.6 until the mid-century period, but which declines until the end of the century. In RCP4.5, the increase is progressive and higher than in RCP2.6 at the end of the century. This declining or stabilising behaviour in summer of the RCP2.6 in the late-century period have also been observed for the other parameters.

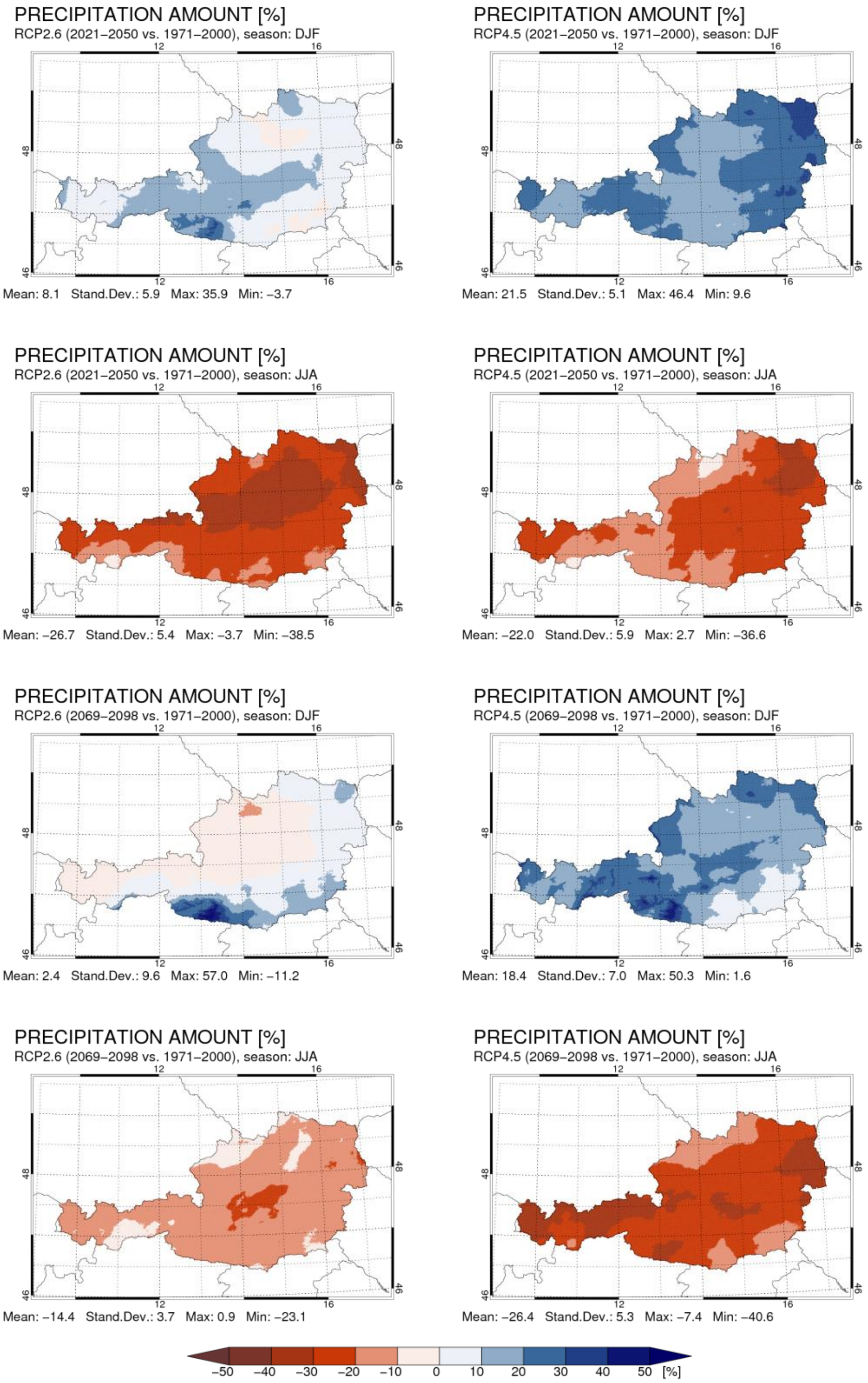

Figure 4: Comparison of changes in seasonal precipitation between mid-century (period 2021 to 2050) and late-century (period 2069 to 2098) with respect to the reference period (1971 to 2000). Left column: RCP2.6, right column: RCP4.5. Rows refer to winter (DJF) and summer (JJA) seasons of mid-century and late-century periods.

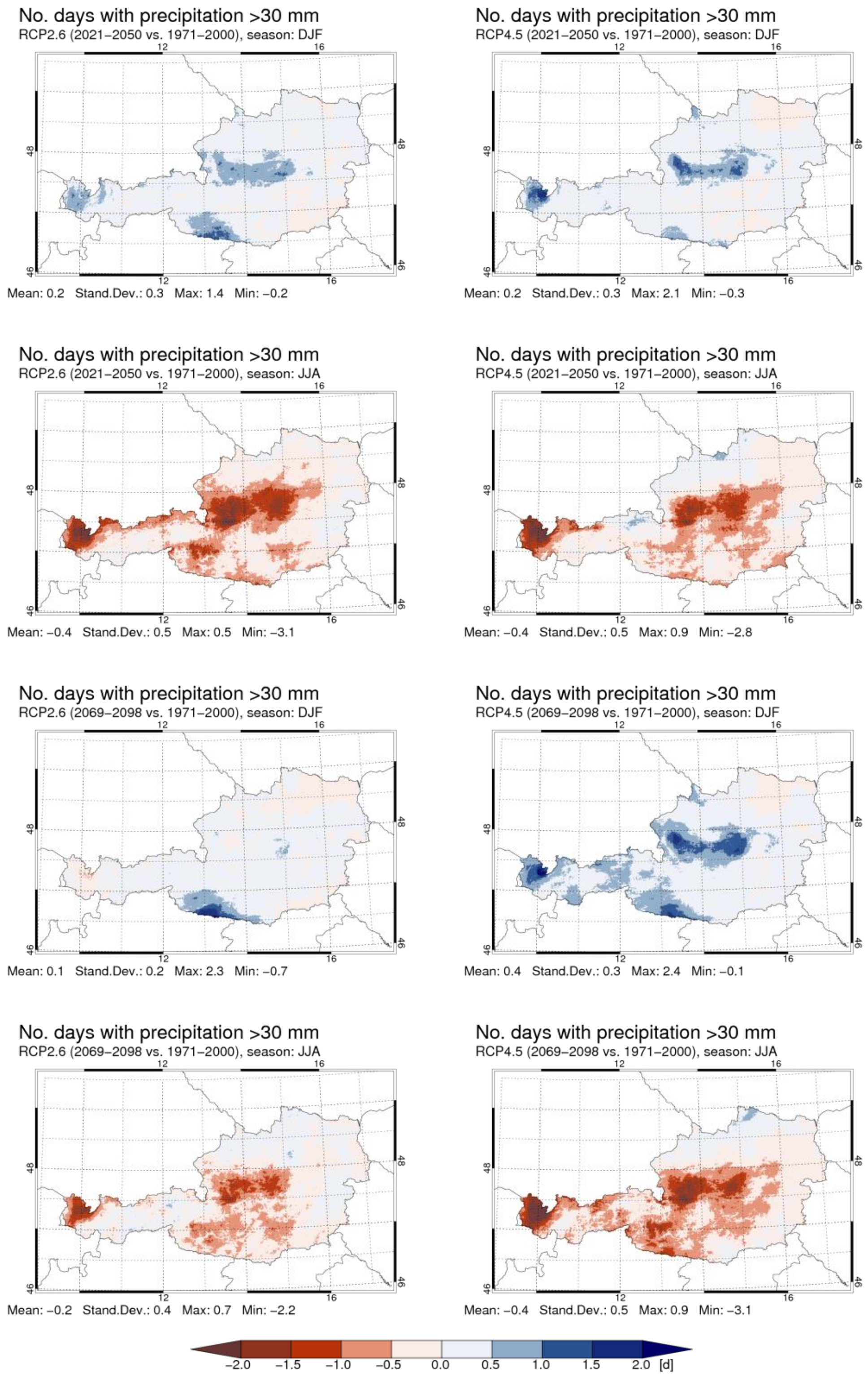

Figure 5: Comparison of seasonal changes of number of days with >30 mm precipitation between mid-century (period 2021 to 2050) and late-century (period 2069 to 2098) with respect to the reference period (1971 to 2000). Left column: RCP2.6, right column: RCP4.5. Rows refer to winter (DJF) and summer (JJA) seasons of mid-century and late-century periods.

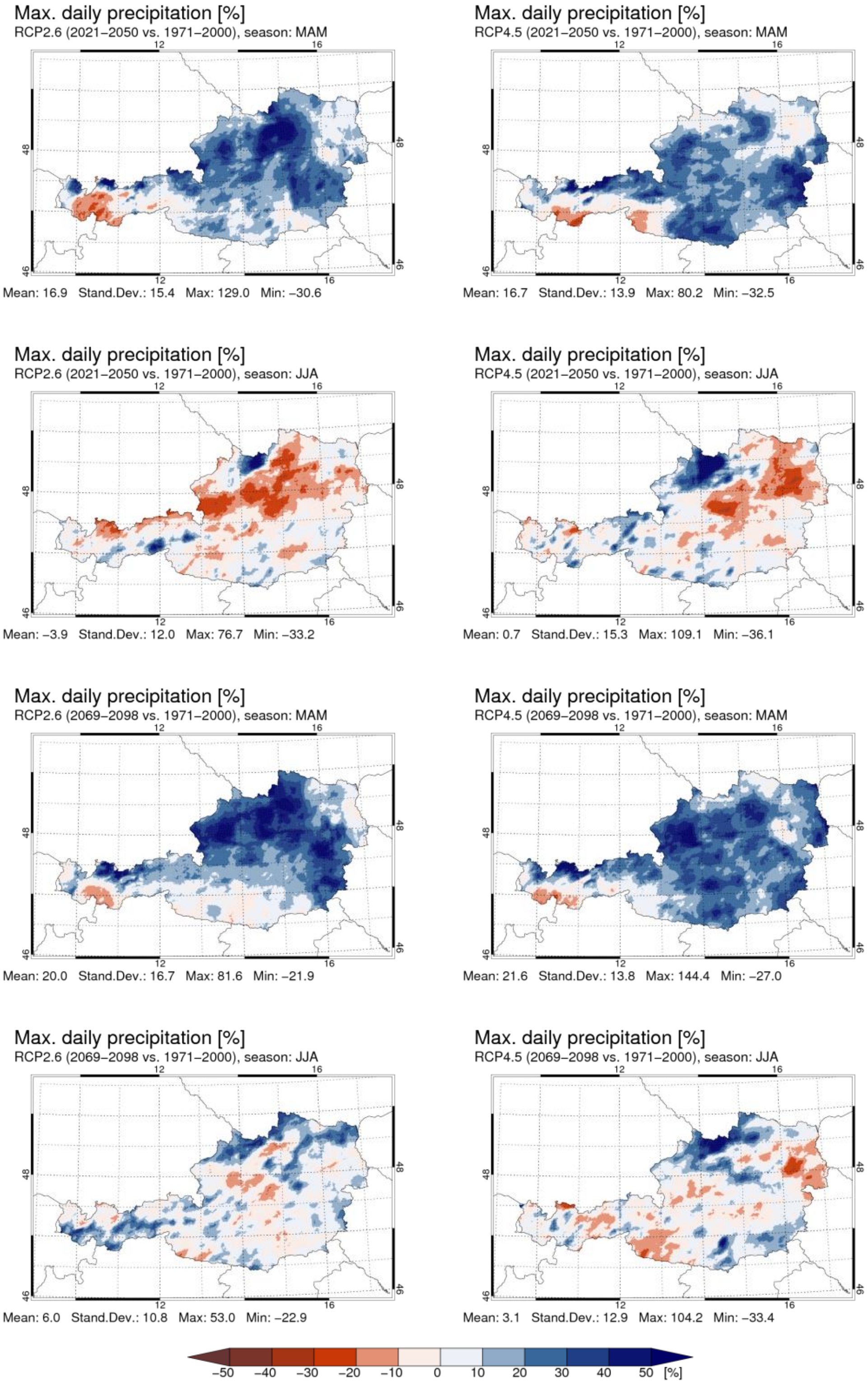

Figure 6: Comparison of seasonal changes of daily maximum precipitation between mid-century (period 2021 to 2050) and late-century (period 2069 to 2098) with respect to the reference period (1971 to 2000). Left column: RCP2.6, right column: RCP4.5. Rows refer to spring (MAM) and summer (JJA) seasons of mid-century and late-century periods.

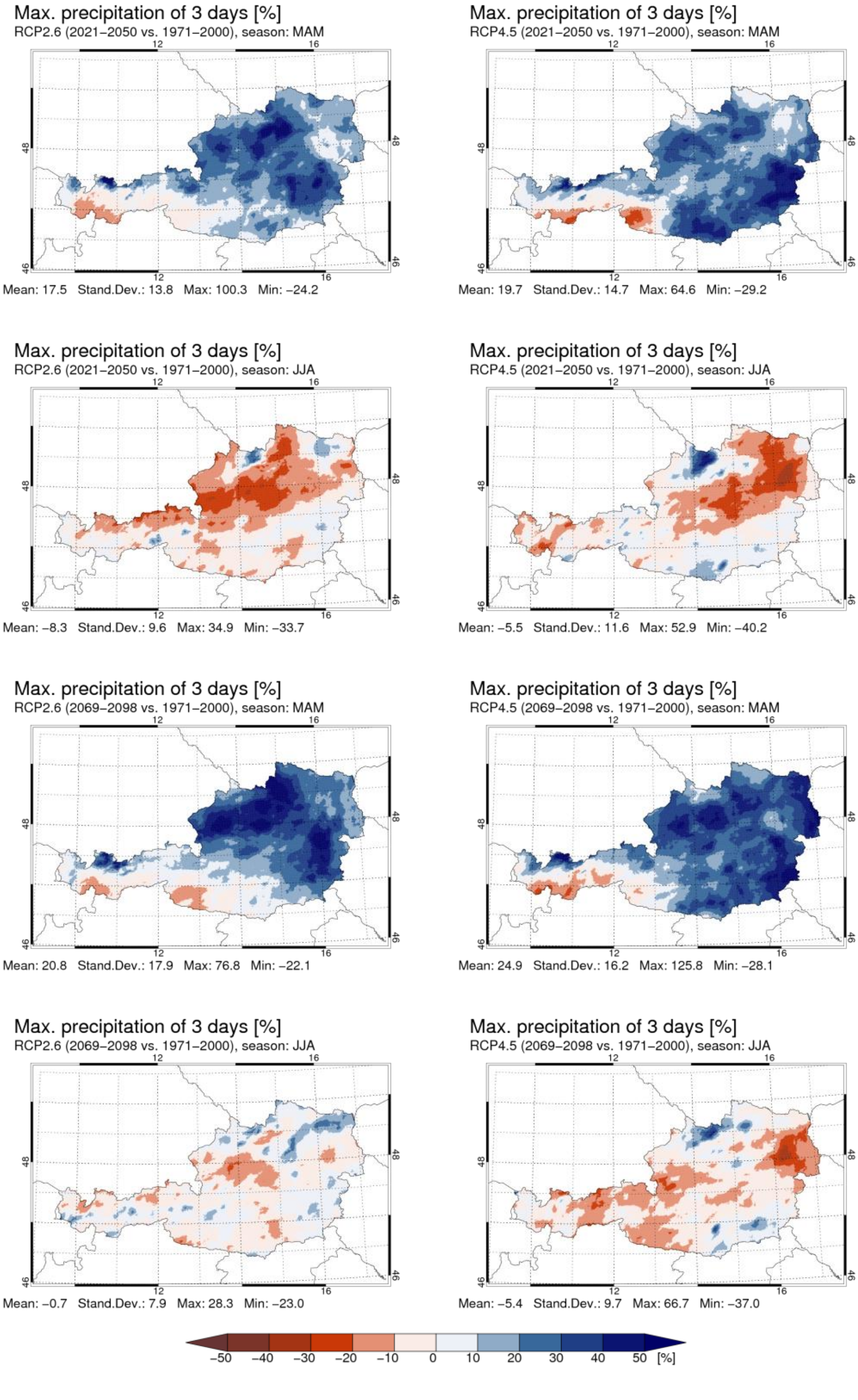

Figure 7: Comparison of seasonal changes of maximum precipitation over three days between mid-century (period 2021 to 2050) and late-century (period 2069 to 2098) with respect to the reference period (1971 to 2000). Left column: RCP2.6, right column: RCP4.5. Rows refer to spring (MAM) and summer (JJA) seasons of mid-century and late-century periods.

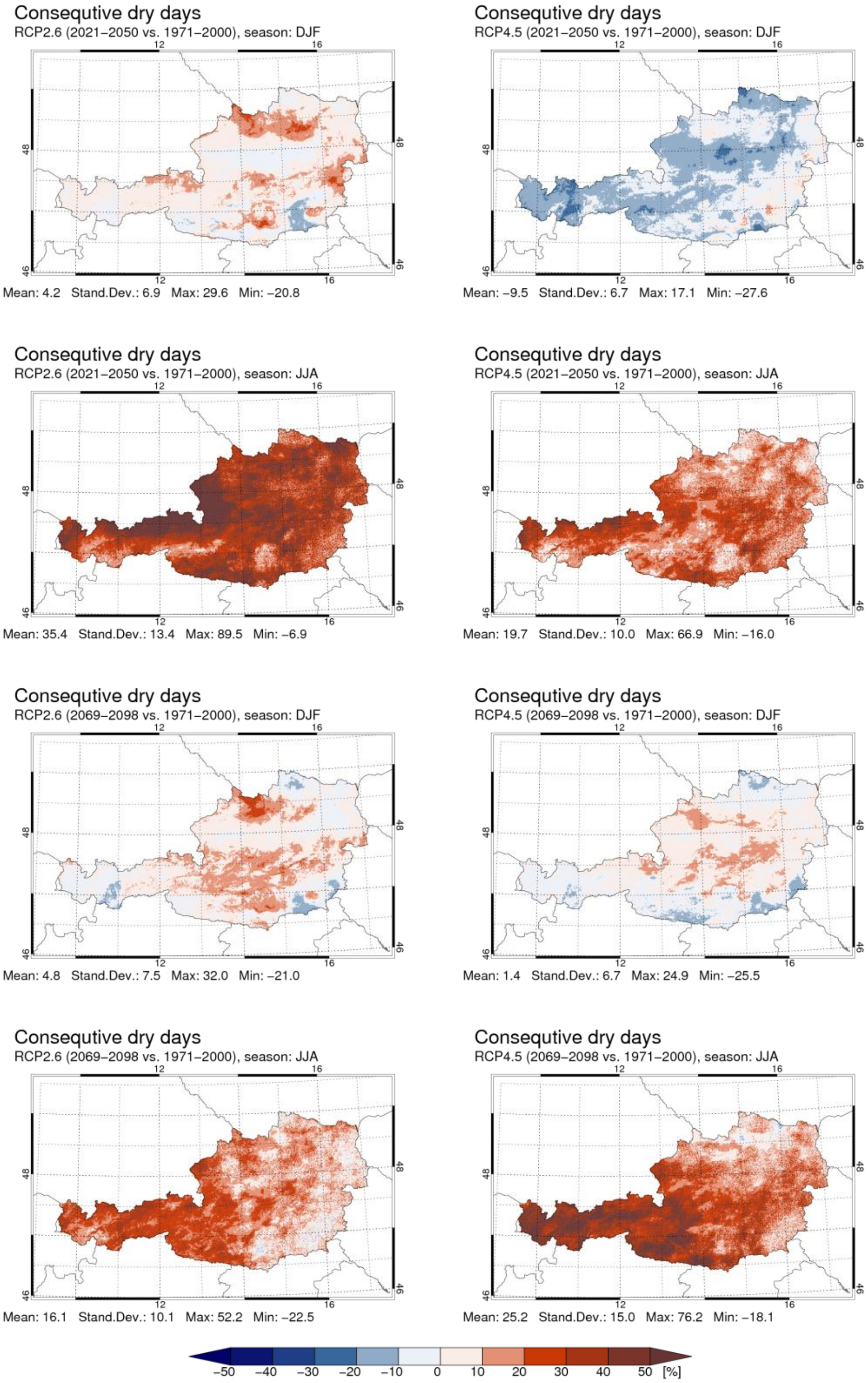

Figure 8: Comparison of seasonal changes of consecutive dry days between mid-century (period 2021 to 2050) and late-century (period 2069 to 2098) with respect to the reference period (1971 to 2000). Left column: RCP2.6, right column: RCP4.5. Rows refer to winter (DJF) and summer (JJA) seasons of mid-century and late-century periods.

Difficulties encountered during the project

The main issue that came up during the project was the availability of the HadGEM2-ES data for the RCP2.6 simulation. Initially, it was said that the data would be available for download by December 2011. That would have fitted perfectly into the time schedule of the project. However, as time passed by the date was shifted to end of February 2012. That was when we had to extend the project period for 3 months. Eventually, it was mid of May when the boundary data finally could be downloaded. Since everything else was prepared the simulation then could be initiated instantaneously. And thanks to the HPC environment in Jülich, the simulation finished just in time for the postprocessing to be started.

Another problem affecting the project was the availability of suitable observation data in order to perform the statistical downscaling / error correction not only for daily mean temperature and daily precipitation sums, but also, e.g., for minimum and maximum temperature, as it was planned in the proposal. However, the status quo of useful long-term observation datasets is still limited to daily data. Of course, climate indices based on threshold values such as summer days or ice days could have been generated on direct model output, but since this would lead to large errors [Themeßl et al., 2011], we skipped this analysis and calculated climate change effects on extreme events in terms of maximum precipitation for one day and for a period of three consecutive days, daily precipitation sums of more than 30 mm, and consecutive dry days, which are also very rewarding for the climate impact community according to the results of a questionnaire that was sent out within the ACRP project KlimDatZ (project number A963747) [Themeßl et al., 2011a].

One problem that could not be solved until the end of the project was the availability of the boundary data for the year 2100. HadGEM2 data ends on 1st December, 2099. This has two implications: 1) we could not simulate the year 2100 at all, and 2) since we look at full years we settled on the end year 2098 in the analysis.

4 Conclusions and recommendations

Empirical/statistical downscaling methods have successfully been employed. The project clearly shows up, how dynamical and statistical methods may be combined to concentrate their strengths and compensate their weaknesses. Model errors stemming from the RCM as well as from the GCM have been eliminated as far as the conceptual limitations allow.

Climate change effects have been derived from corrected model output. From the selected climate modelling approach, underlying its limitations (one GCM, one RCM, one empirical/statistical downscaling method), the following conclusions can be drawn:

- Temperature increase is forced by the scenario: it is bounded to 1.9°C (annual average) in the RCP2.6 scenario, while it reaches 3.1°C (annual average) in the late-century period in the RCP4.5 scenario.

- Temperature increase in correlated to surface altitude: mountainous regions are more affected by climate change than others, especially in summer and autumn.

- Precipitation changes show a strong annual cycle: there are increases in winter and spring, but decreases in summer and autumn. In the RCP2.6 scenario the precipitation changes in the mid-century are stronger than in the late-century and reach +8.1% in winter and -26.7% in summer. In the RCP4.5 scenario the precipitation changes are constantly strong throughout the century and amount approx. +20% in winter and more than -22.0% in summer.

- Changes in days with more than 30 mm precipitation roughly follows the changes in mean precipitation, but are much more localised upstream to the Prealps (up to +2.4 d in winter and -3.1 d in summer). Emphasising the role of orography in climate change.

- There is evidence for a progressive increase of thunderstorms in spring and winter of approx. 20% until the end of the century, regardless of emission scenario, while a decrease in summer-time thunderstorms is limited to the mid-century period (afterwards, they reach their level of the reference period).

- There is evidence for distinctive changes in different types of precipitation extremes. A coherent progressive increase of large-scale precipitation extremes and thunderstorms in spring and winter throughout the century may occur regardless of the emission scenario, while large-scale precipitation extremes in summer depend on the emission scenario: they decrease in the mid-century period, but partly recover in the RCP2.6 scenario.

- All parameters show a stabilising or declining behaviour in summer until the end of the 21st century in the case of the RCP2.6 scenario, whereas there is progressive increase in RCP4.5. This strongly pronounces the dependency of climate change effects from greenhouse gases.

The results laid out above show quite impressively the benefit of hitting the RCP 2.6 curve. The more moderate temperature and precipitation (including extremes) changes should be an incentive, strong enough by itself.

C) Projektdetails

5 Methods

Dynamical downscaling – regional climate model. The simulations were carried out using the regional climate model COSMO-CLM (CCLM; www.clm-community.eu). COSMO-CLM is a community model of the European regional climate research community. The setup of the model heavily relied on experiences gained in projects reclip:century as well as NHCM-1, a basic research project, funded by the Austrian Science Fund (FWF) and led by Andreas Gobiet.

Domains. The simulation domains were similar to the ones used in reclip:century. The coarser resolved simulation covering Europe as a whole was only slightly extended to be compliant with the CORDEX region for Europe. A list of simulations performed in the project is given in Table 1.

Driving Data. RCMs need so called lateral boundary conditions (LBCs) which are provided by GCMs or re-analysis datasets (e.g., ERA-Interim). The CCLM needs the parameters air temperature, horizontal wind components, surface air pressure, specific humidity, cloud ice and cloud water content, surface snow amount and soil temperature and humidity. This data had to be pre-processed so that CCLM can handle and process it.

As the driving global model we settled on HadGEM2-ES [Collins et al, 2008]. The decision was based on the simple fact of short term availability. Besides HadGEM2-ES also the GCMs ECHAM6/MPI-OM as well as EC-EARTH were in range, but both had to cope with serious problems which delayed their availability. Additionally a hindcast simulation, i.e., a simulation of the past climate, was conducted for evaluation purposes. This hindcast simulation used the re-analysis dataset of the European Centre for Medium Range Weather Forecasts (ECMWF), the ERA-Interim [Simmons et al., 2007] dataset. Though starting in 1989 it is also permanently updated so that a 22 years long simulation until the end of the year 2010 had been possible. With regard to CORDEX ERA-Interim simulations for at least the period 1989 to 2005 are required.

Climate scenarios. The two anticipated regional climate simulations are based on the next generation scenarios, the RCP scenarios. Two of these RCPs were simulated: The first RCP scenario conducted in the proposed project was the RCP4.5 scenario [Clarke et al., 2007]. It shows a similar emission pathway as the SRES A1B scenario [Nakicenovic et al., 2000]. It stabilises at a RF of roughly +4.5 W/m2 after the year 2100 without overshooting this peak value during the 21st century. The RF roughly corresponds to a greenhouse gas concentration of 650 ppm CO2-equivalent and a global warming of about 2.8°C compared to preindustrial times. It is further the main RCP scenario for all GCMs (it is one of two core scenarios of the CMIP5 experimental design) as well as the RCM community. The second RCP scenario in ReCliS:NG was the RCP2.6 scenario [van Vuuren et al., 2007]. It initially also was referred to as RCP 3.0-PD, where PD stands for "peak and decline" which nicely sums up the emissions pathway of this scenario: it is assumed that the CO2 emissions peak around 2020 with a corresponding RF value of about +3.0 W/m2 and decline afterwards to reach a RF of +2.6 W/m2 in 2100. This cumulates to a global warming of about 1.8°C in 2100 compared to preindustrial times.

Resources. All simulations were carried out at the Jülich Supercomputing Centre (JSC), Germany. On this high performance cluster (HPC) the reclip:century simulations of the Wegener Center for Climate and Global Change

(WEGC) have already been conducted. In the course of these simulations this HPC has proven to be ideally suited for climate simulations of this magnitude.

Statistical downscaling – error correction. After the simulations were finished the parameters near surface air temperature, and precipitation amount were error corrected. Since even high resolution regional climate models (such as the model applied in ReCLiS:NG) are known to feature considerable errors, particularly regarding precipitation and their extremes (e.g., Suklitsch et al., 2010; Jacob et al. 2007), an empirical-statistical downscaling and error correction method (DECM, Themeßl et al., 2011; Déqué, 2007) is applied. In ReCliS:NG, quantile mapping (QM), which represents a distribution based model output statistics approach (Maraun et al., 2010), was used as the DECM of choice as it already proofed its robustness and superior performance even for non-normally distributed parameters such as daily precipitation (Themeßl et al., 2011; Piani et al., 2009). This error correction approach has considerable advantages to the so-called “delta approach” (Déqué, 2007) which is widely used in climate change impact studies. With the “delta approach” climate scenarios are generated by adding climate change signals (difference between the future and the past) from climate models to observational data. Assuming that the systematic errors in the past and in the future remain unchanged, the errors are cancelled out and the climate change signal becomes bias-free. However, the “delta approach” results in unchanged day-to-day variability since it is inherited from the observations. Furthermore, it assumes a quantity-independent climate model error characteristic of the respective parameter, e.g. similar precipitation errors at low and high intensities, which was disproved by e.g. Themeßl et al. (2011). As the here applied QM procedure builds on daily, intensity dependent correction functions, changes in the variability and thus in the extremes in future can be investigated more accurately which also increases the applicability of this scenario in climate impact research community. Nonetheless, one has to bear in mind that QM affects the climate change signal and relies on the assumption, that the relationship between statistical properties of the model output of the control simulation and the observational data is not affected by climate change. In other words, this relationship is supposed to be stationary. However, even in the worst cases of non-stationarity, QM still clearly improves the biases of the raw RCM output [Wilcke et al., 2013].

Evaluation. The evaluation was done using the Wegener Center Integrated Climate model Evaluation system (WICE). The evaluation covered the standard quantities such as climate change signals for various parameters (e.g., temperature, precipitation) and derived “climate impact parameters” (e.g., consecutive dry days, consecutive wet days, maximum daily and 3-daily precipitation amount). As reference data, a highly-resolved (1 km grid spacing) gridded observation dataset on daily basis for temperature and precipitation, developed during reclip:more from 70 stations by ZAMG [Schöner and Cardoso, 2004], was used.

Table 1: Overview on the simulations performed in the project ReCliS:NG

Driving model	Simulation	Period	Horiz. resolution
HadGEM2-ES	RCP4.5	1955 – 2100	0.44°/0.11°
HadGEM2-ES	RCP2.6	1955 – 2100	0.44°/0.11°
ERA-Interim	Hindcast	1989 – 2010	0.22°/0.11°

6 Work and time scedule

Project ReCliS:NG Gantt Diagram	Timescale																				
	Project month																				
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
WP 1 - Acquisition and preparation of suitable boundary data																					
M1.1 - ERA-Interim data processed and copied in place																					
M1.2 - GCM RCP4.5 data processed and copied in place																					
M1.3 - GCM RCP2.6 data processed and copied in place																					
R1.1 - Preprocessor for CMIP5 data, deliverable to the CLM community																					
WP2 - Simulation of hindcast, control and scenario climate																					
M2.1 - Hindcast (H) simulation completed			H																		
M2.2 - Control (C) and Scenario (S) climate simulation RCP4.5 completed						C			S												
M2.3 - Control (C) and Scenario (S) climate simulation RCP2.6 completed												C						S			
WP3 - Postprocessing and evaluation of model results																					
M3.1 - Error correction of model output finished													4.5						2.6		
M3.2 - Evaluation of model results finished														4.5						2.6	
R3.2 - (Error corrected) Model results available																				all	
WP4 - Project management and outreach																					
M4.1 - Kick-Off meeting																					
M4.2 - Progress meeting																					
R4.1 - Publication and project reports																					

The table above shows the Gantt diagram for project ReCliS:NG in its final state. When compared to the one in the proposal one can see that most milestones and results were achieved in time. As mentioned earlier in the report the availability of the RCP2.6 data was delayed by more than half a year. We therefore applied for a cost neutral extension of the project period for 3 months which was granted. This extension is marked by shades of gray in the table above.

7 Publication and dissemination

Suklitsch, M., A. Gobiet, M. Themeßl, H. Truhetz (2011), ReCliS:NG – Next Generation Regional Climate Scenarios for the Greater Alpine Region (poster), International Conference on the Coordinated Regional Downscaling Experiment (CORDEX), 20–26 March 2011, Trieste, Italy

Suklitsch, M., A. Gobiet, M. Themeßl, H. Truhetz (2011), ReCliS:NG – Eine neue Generation regionaler Klimaszenarien für den erweiterten Alpenraum (oral), Klimafolgenforschung in Österreich: Aktuelle Projekte im Überblick (ACRP-Infotage), 17–18 Mai 2011, Wien, Österreich

Suklitsch, M., H. Truhetz, A. Gobiet (2012), ReCliS:NG – Next Generation Regional Climate Scenarios for the Greater Alpine Region – Concept and First Results (poster), NIC-Symposium, Feb 7 – Feb 8 2012, Jülich Supercomputing Centre (JSC), Jülich, Germany.

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Annex

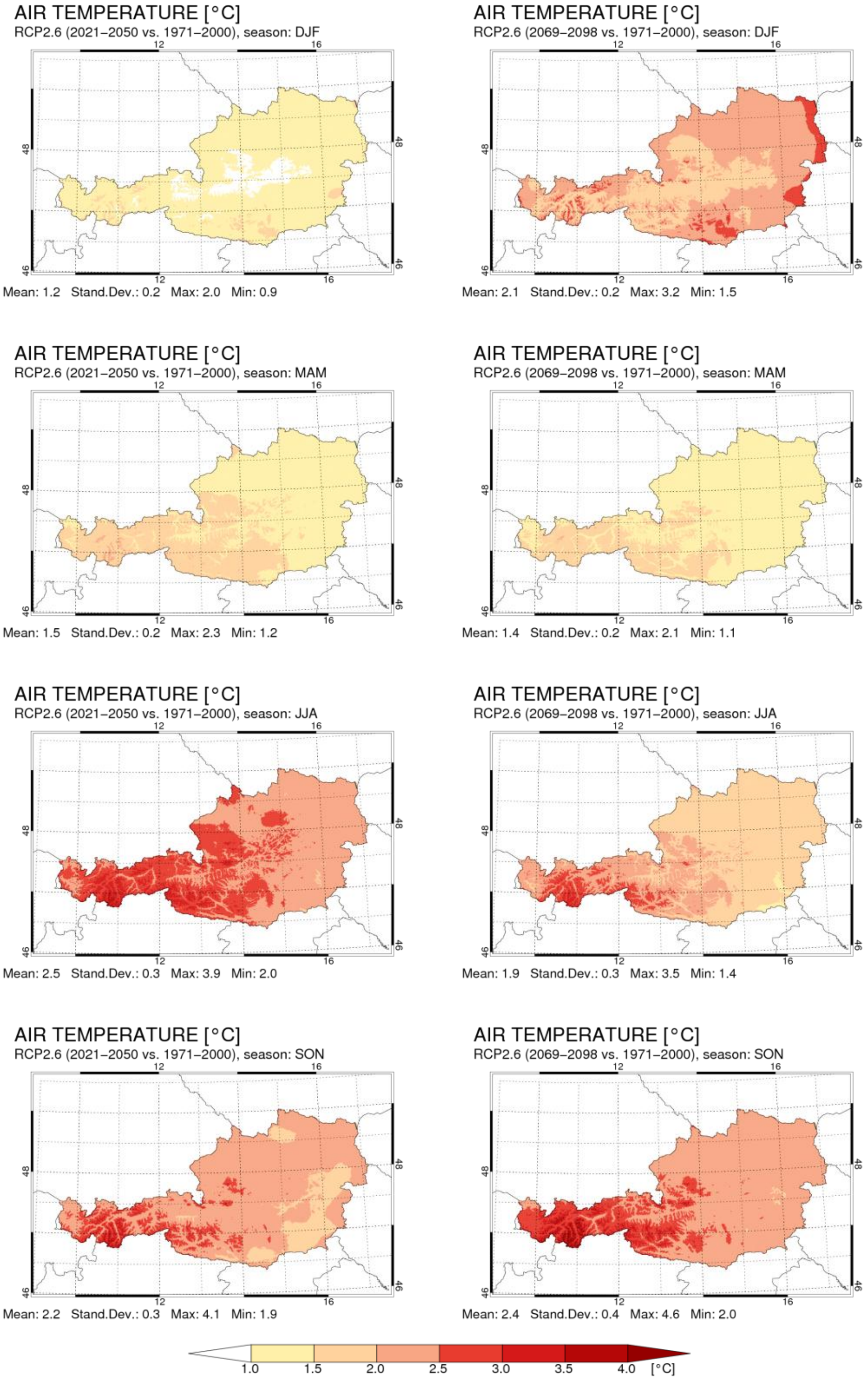

Figure 9: Seasonal changes of temperature in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

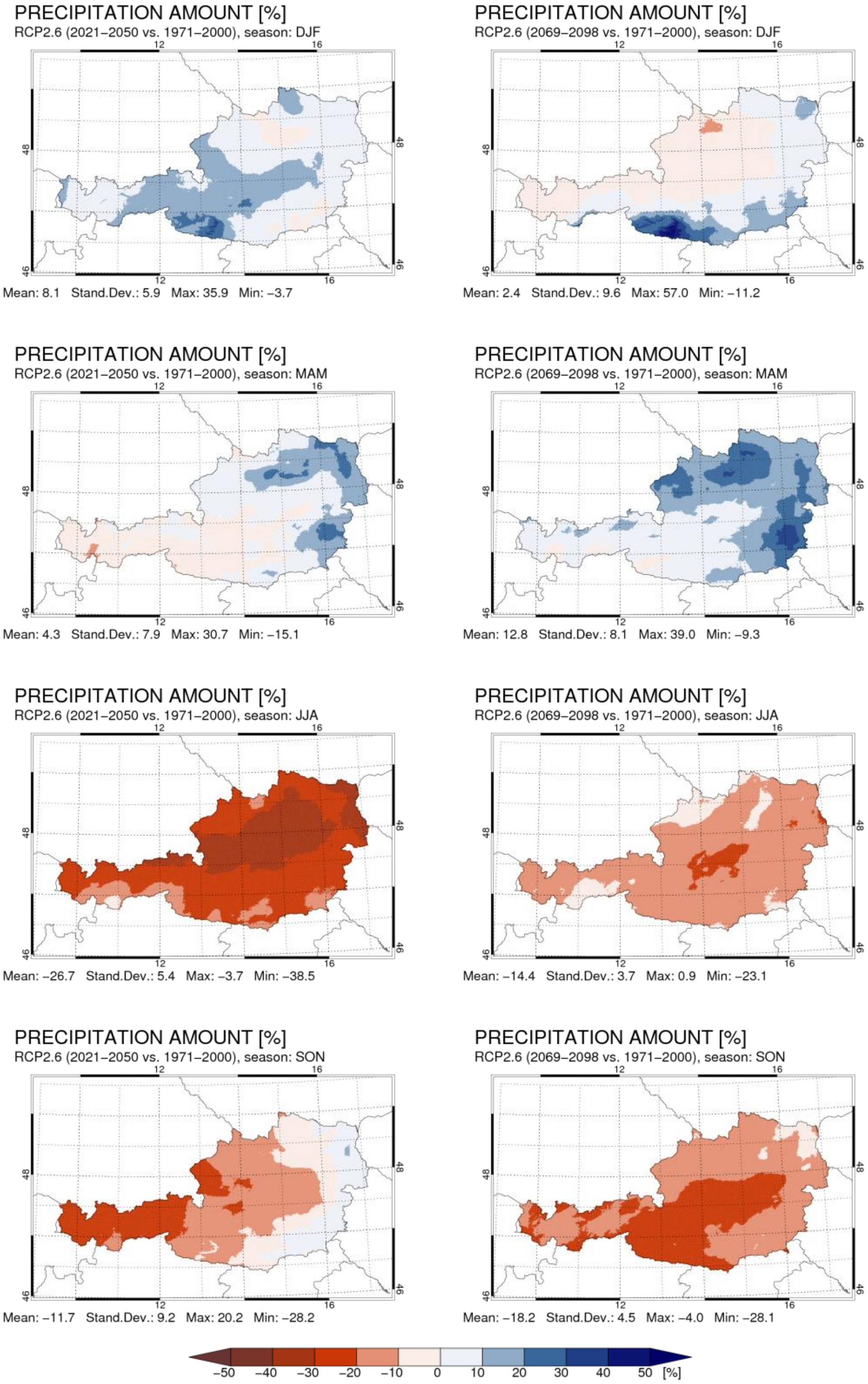

Figure 10: Seasonal changes of precipitation in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

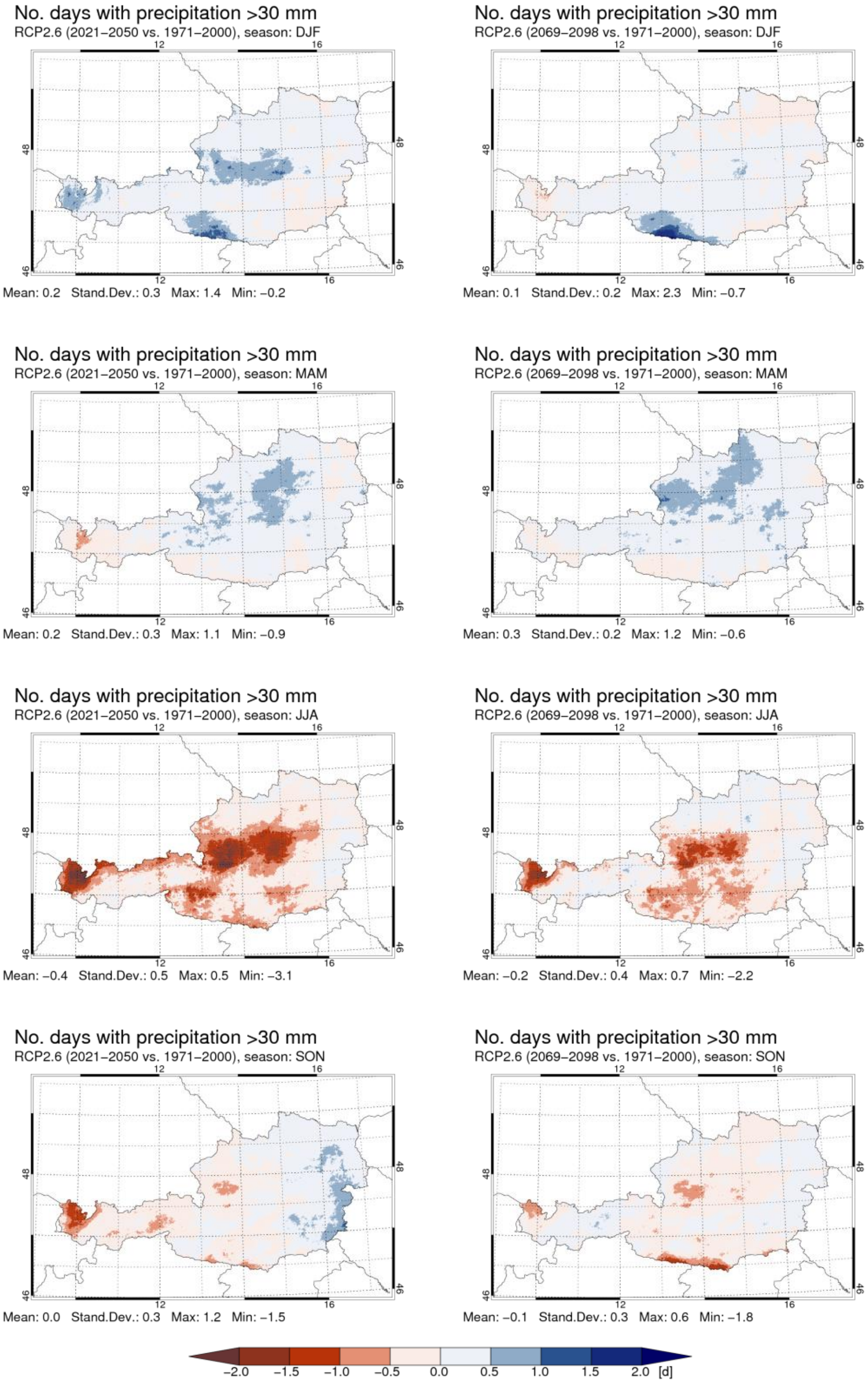

Figure 11: Seasonal changes of days with precipitation sums of more than 30 mm in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

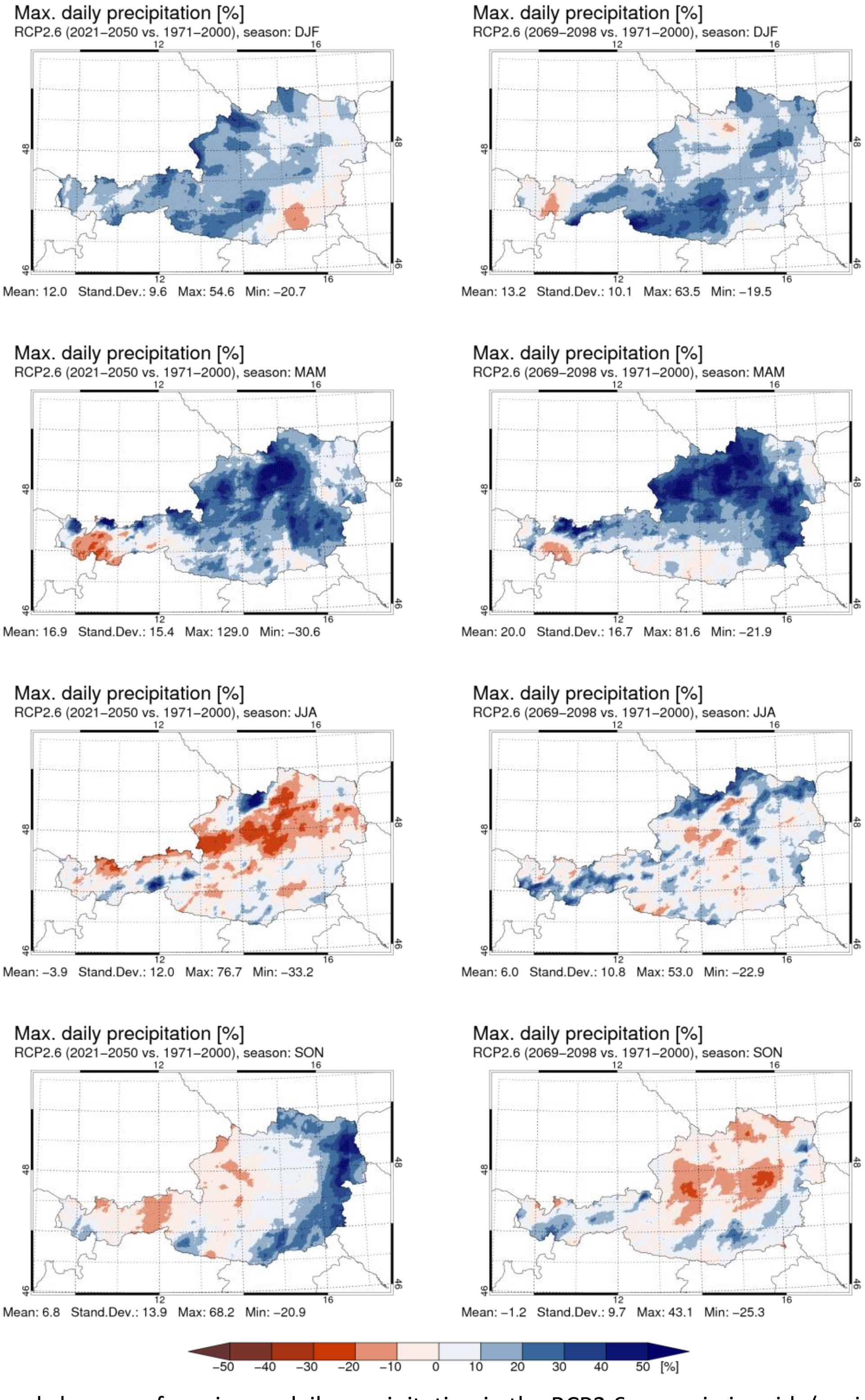

Figure 12: Seasonal changes of maximum daily precipitation in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

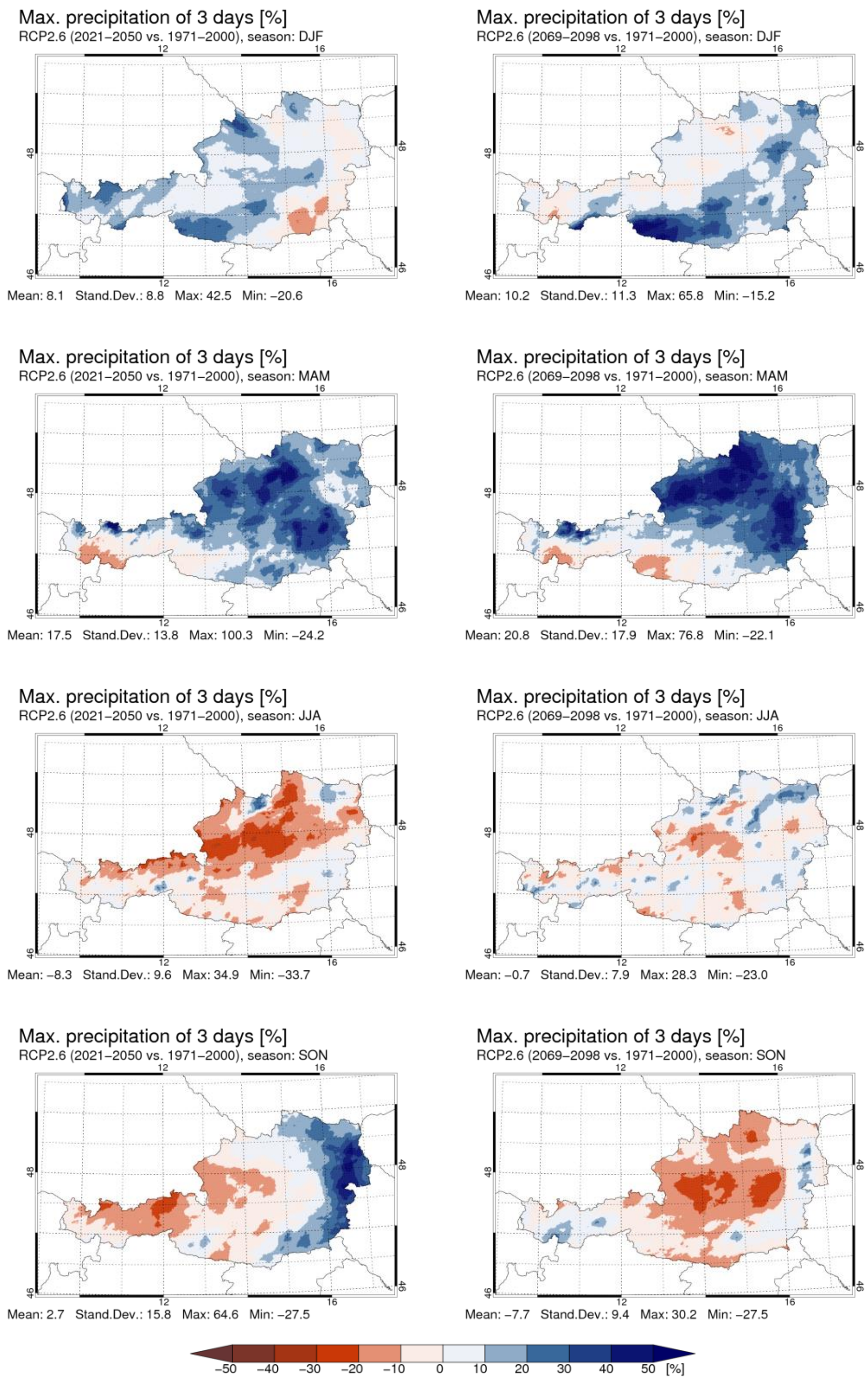

Figure 13: Seasonal changes of maximum precipitation of three days in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

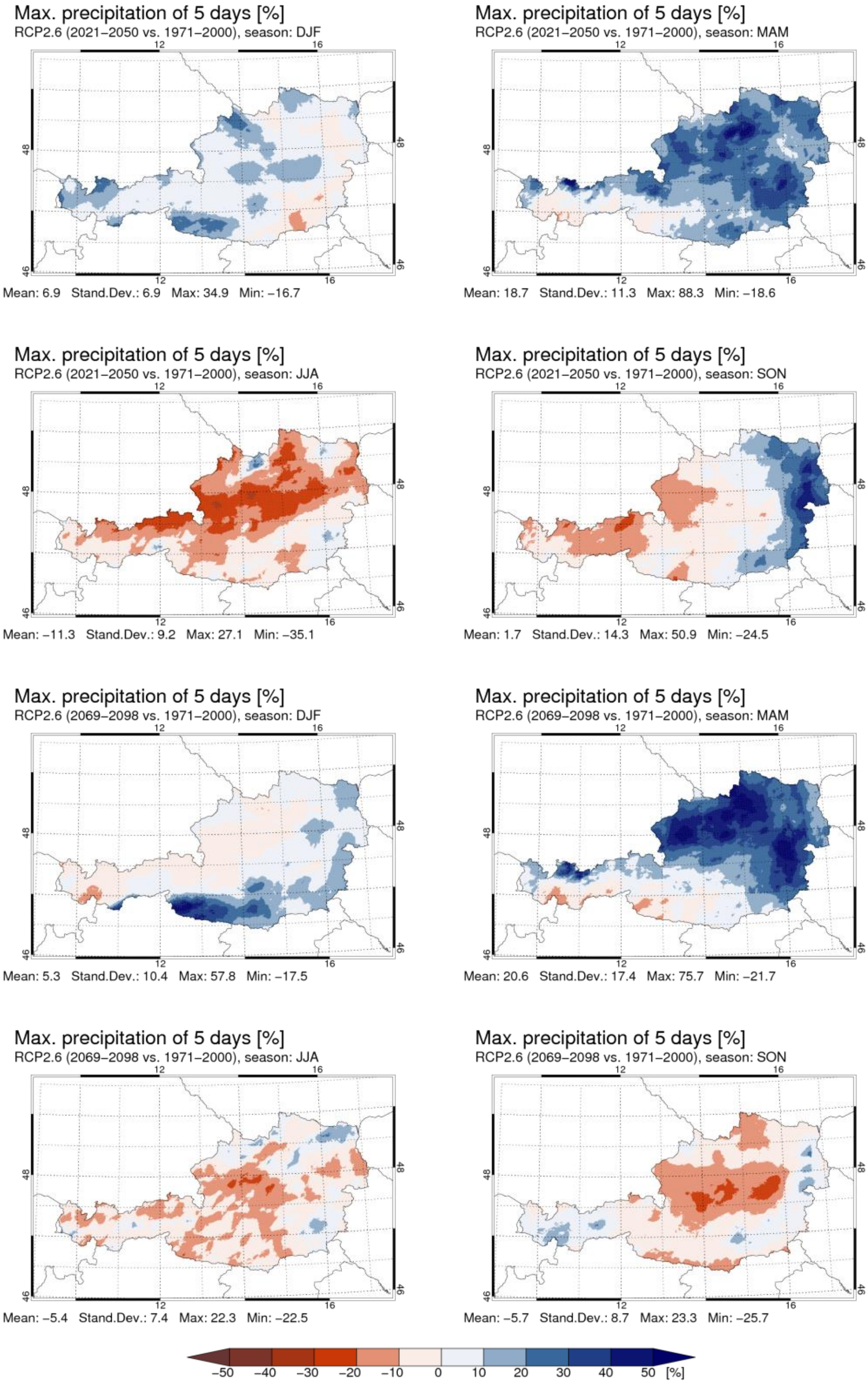

Figure 14: Seasonal changes of maximum precipitation of five days in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

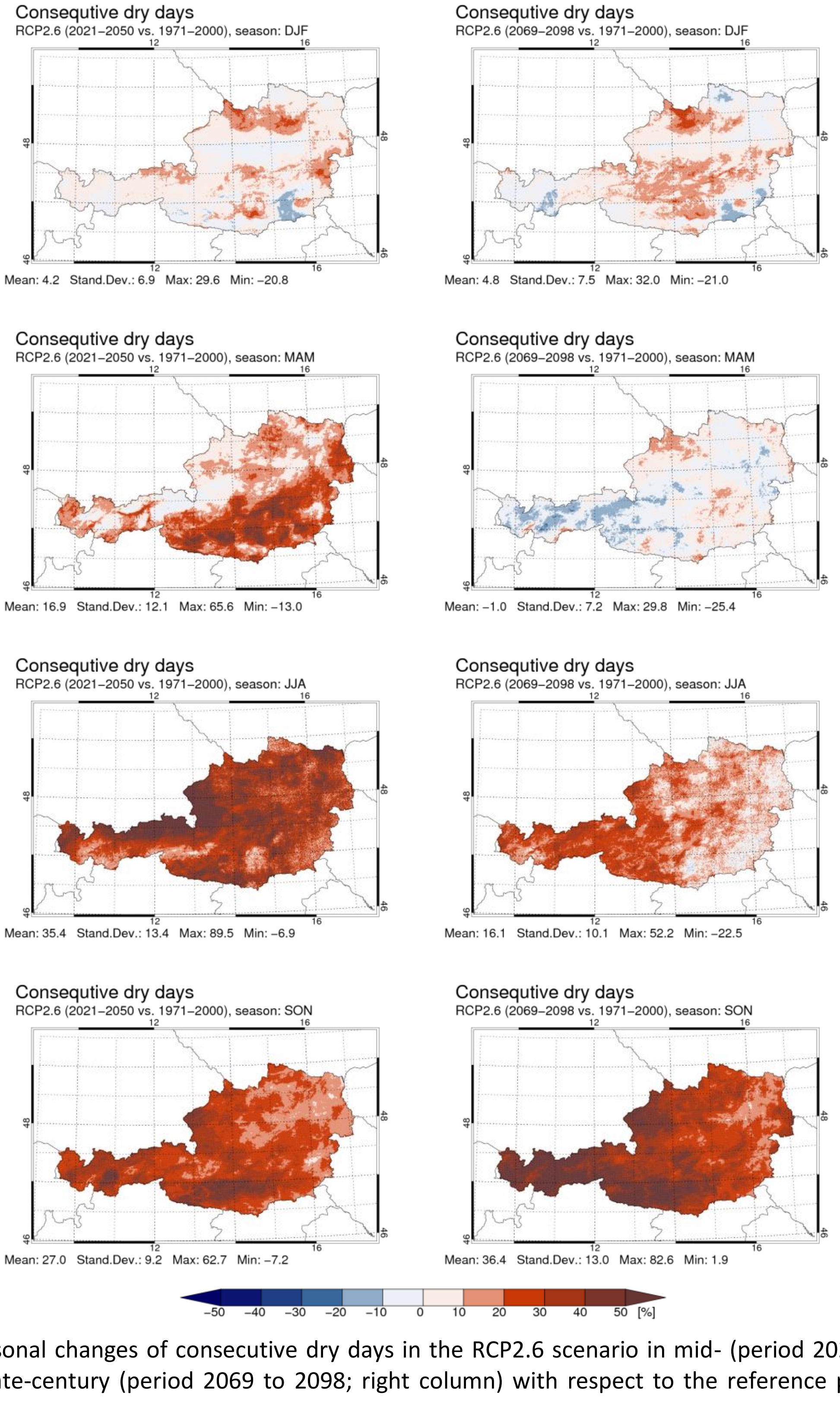

Figure 15: Seasonal changes of consecutive dry days in the RCP2.6 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

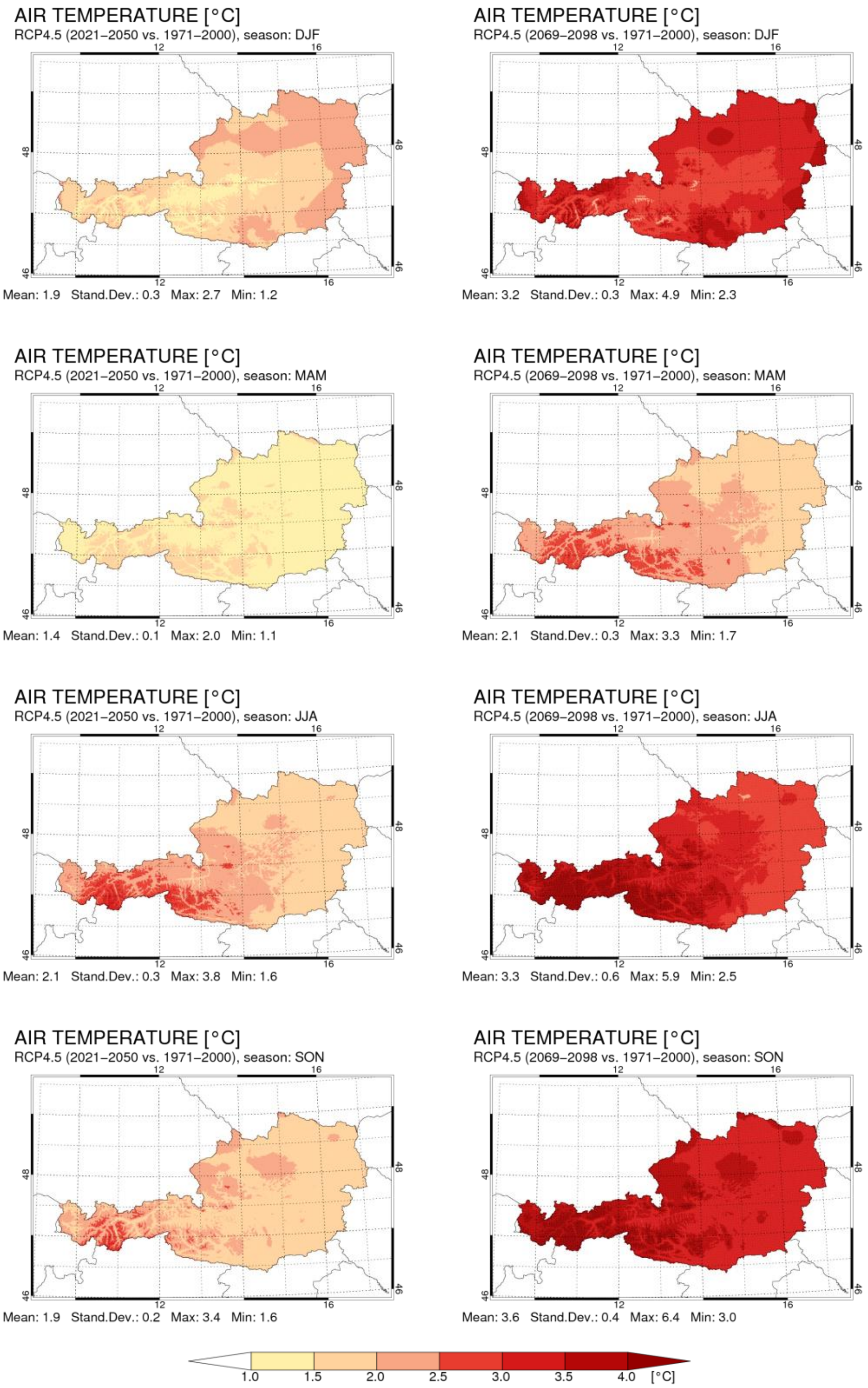

Figure 16: Seasonal changes of temperature in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

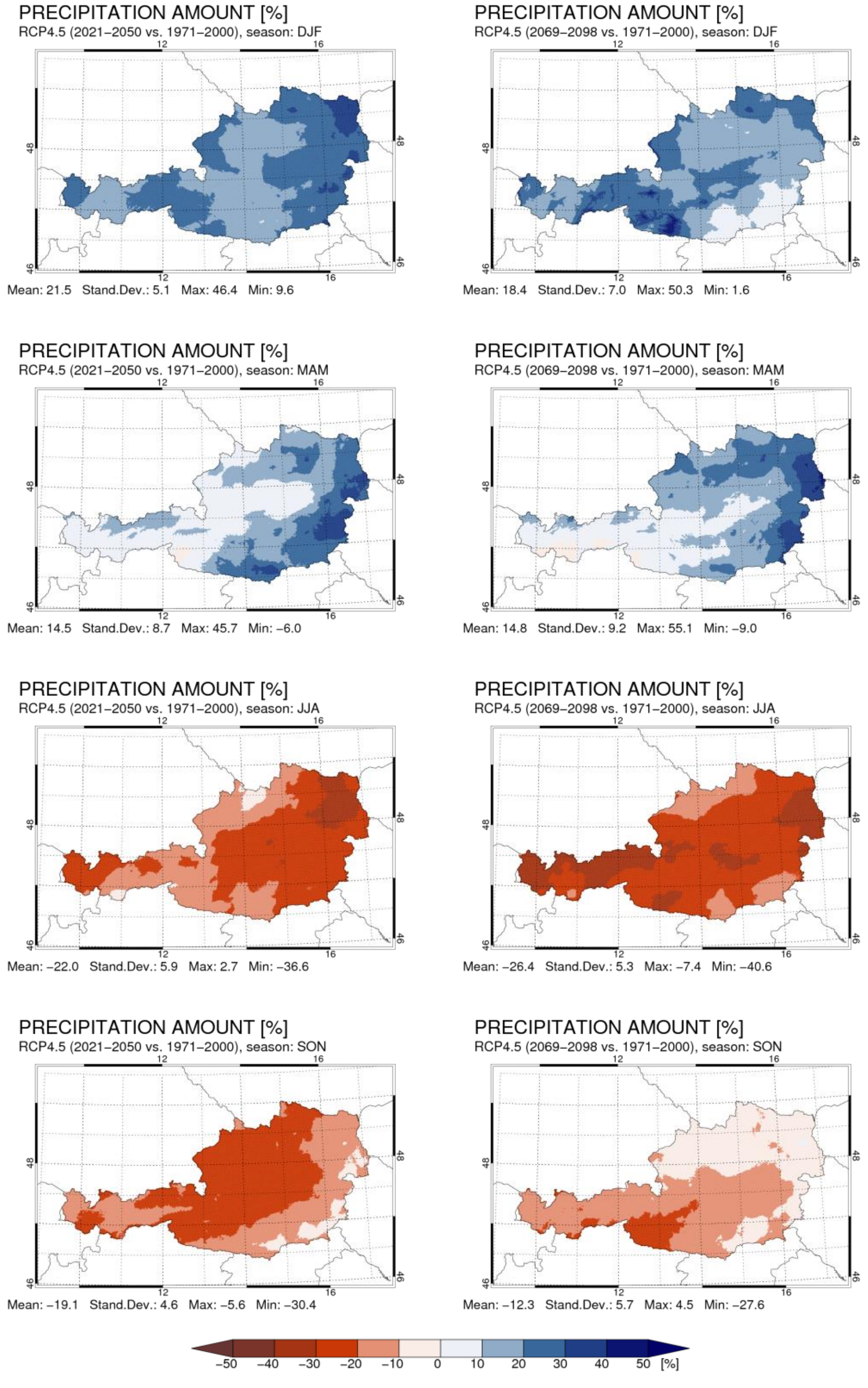

Figure 17: Seasonal changes of precipitation in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

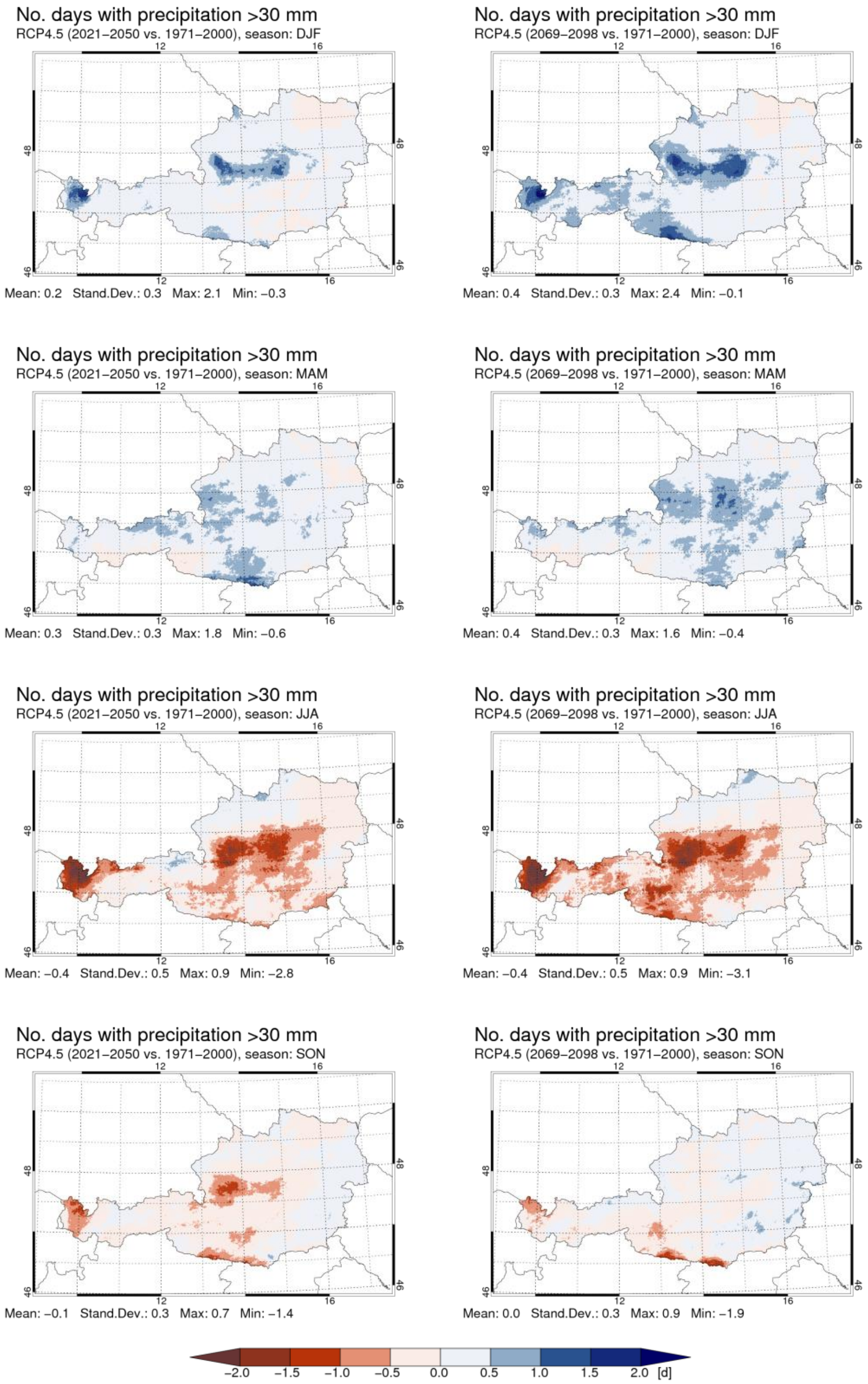

Figure 18: Seasonal changes of days with precipitation sums of more than 30 mm in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

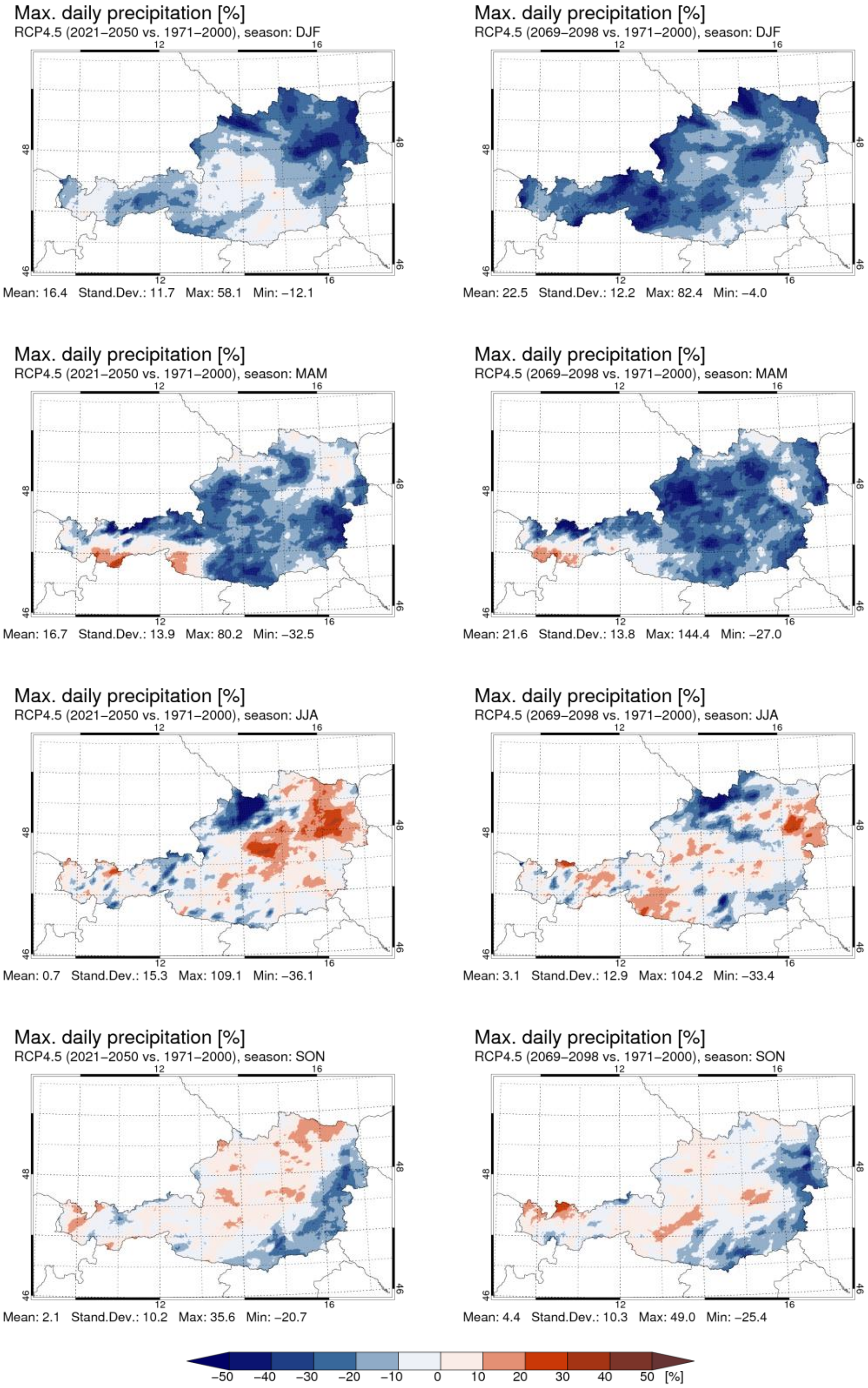

Figure 19: Seasonal changes of maximum daily precipitation in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

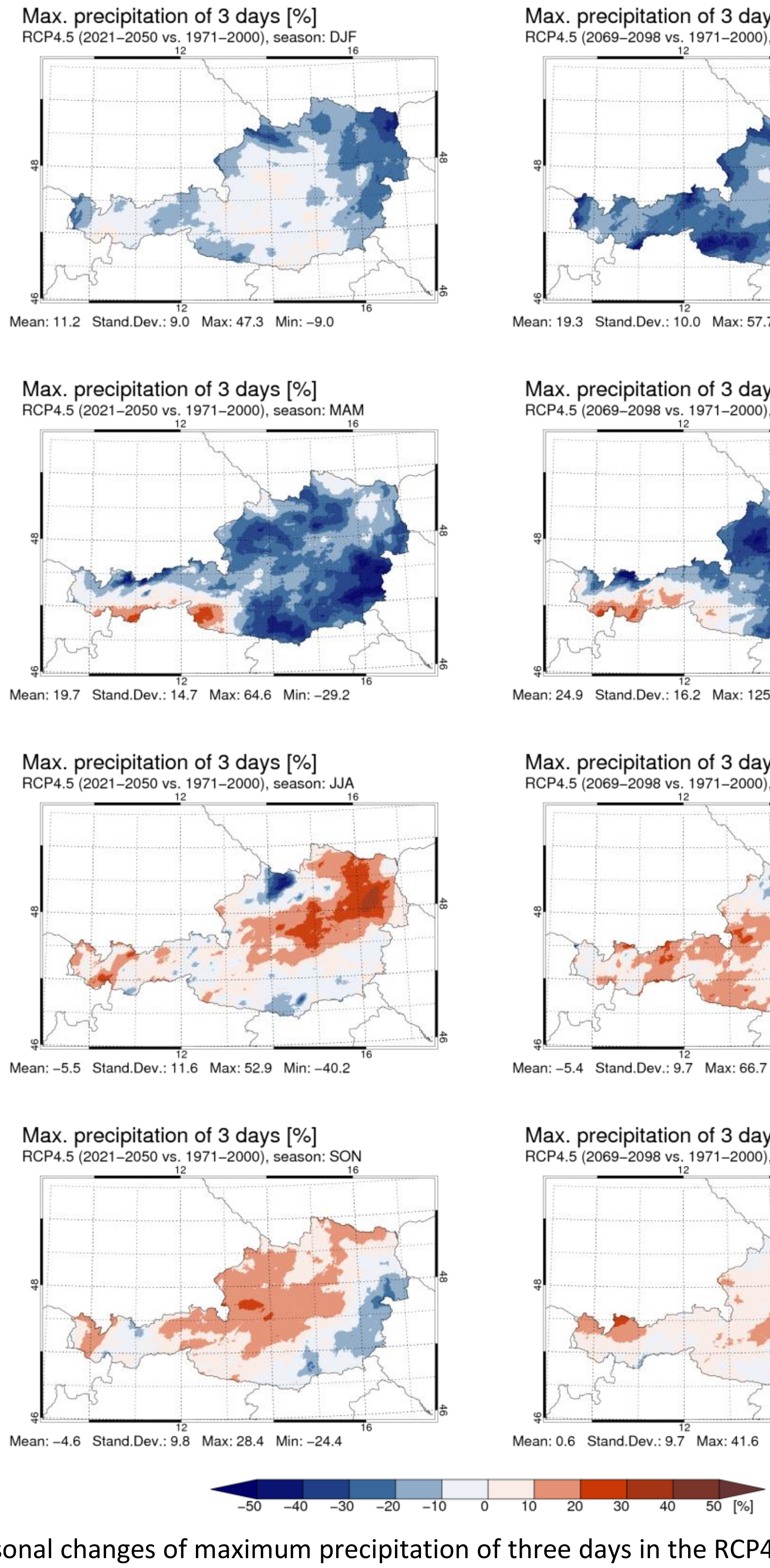

Figure 20: Seasonal changes of maximum precipitation of three days in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

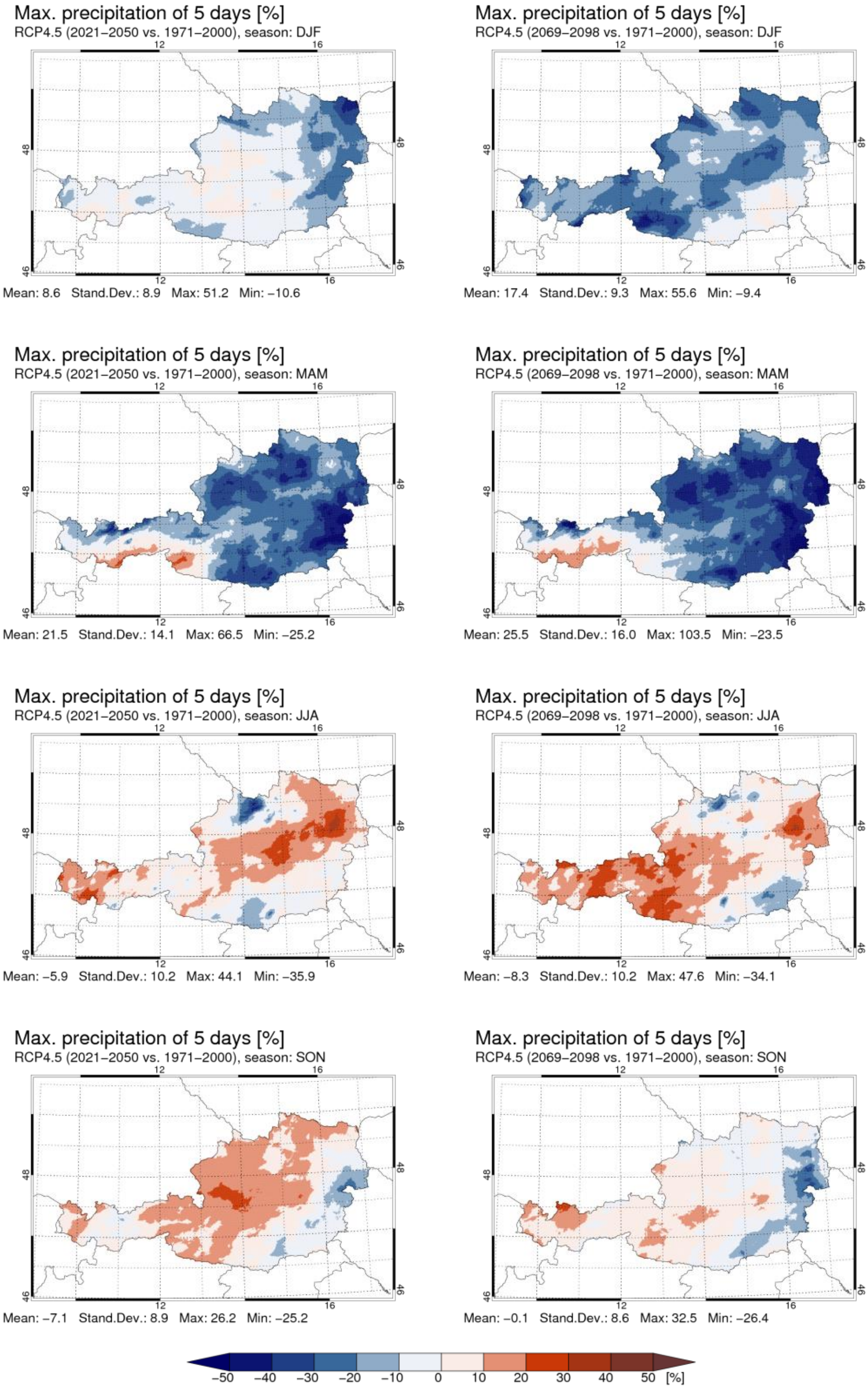

Figure 21: Seasonal changes of maximum precipitation of five days in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).

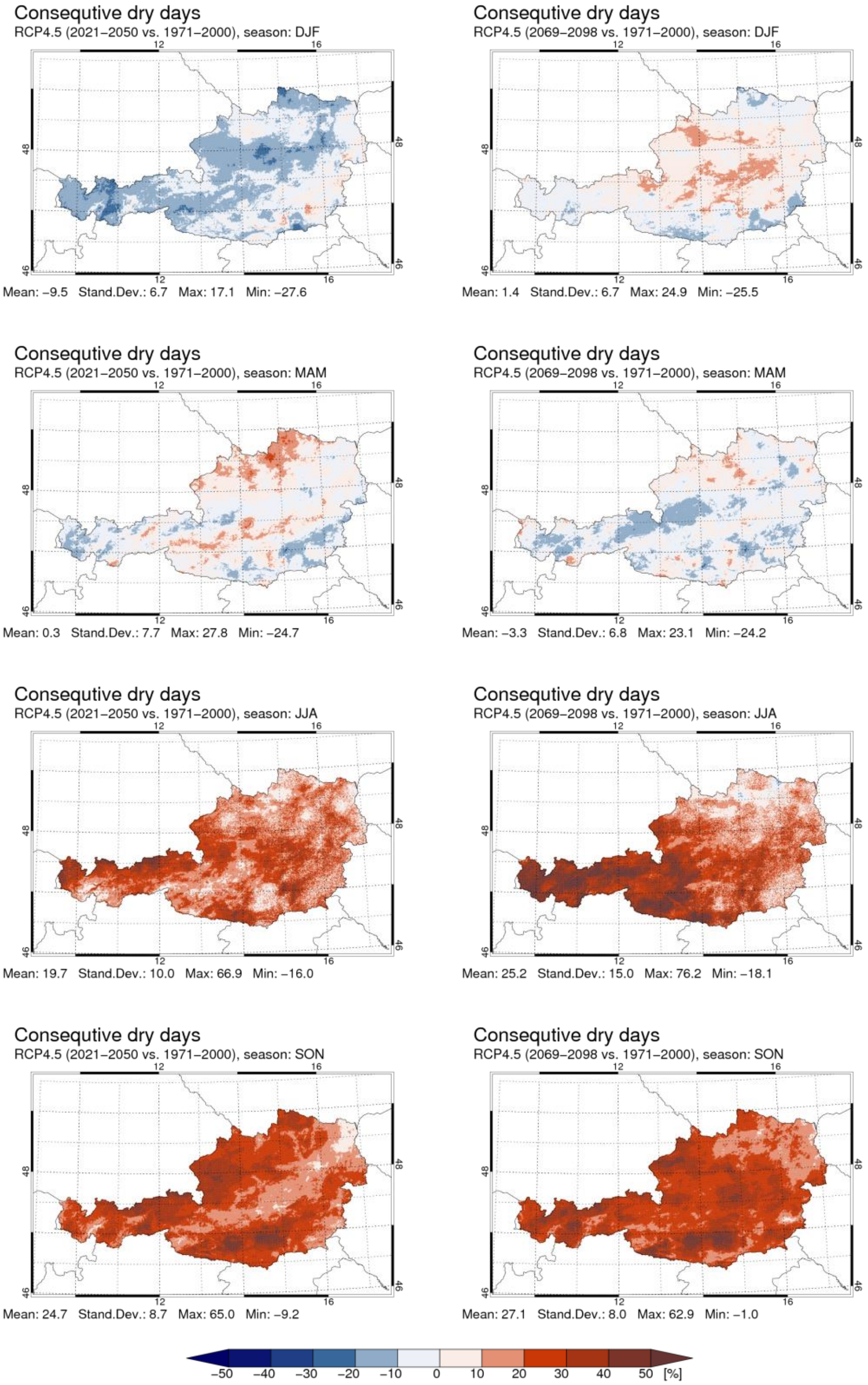

Figure 22: Seasonal changes of consecutive dry days in the RCP4.5 scenario in mid- (period 2021 to 2050; left column) and late-century (period 2069 to 2098; right column) with respect to the reference period (1971 to 2000).