Chapter 3

Future Climate of the European Alps

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1. Introduction

The global climate is currently warming and this trend is expected to continue towards an even warmer world, associated partly with drastic shifts in precipitation regimes (IPCC 2007). While the global temperature has roughly been warming by 0.6°C (±0.2°C) during the 20th century (IPCC 2001), the land masses have had a higher temperature increase during the same period, and some areas such as the Alps showed an exceptionally high warming trend, with increases reaching 1.7°C in some regions (Rebetez 2006, Rebetez & Reinhard 2008). Here, we report on the current state of the art in climate model projections for the Alps, with an outlook to the soon available 5th IPCC assessment report.

It is a challenging task to project how the climate might look like in 50-100 years, a duration that is relevant for forest management. Climatologists use a range of models that generate possible climate futures. Each model and each simulation run is considered a representation of how the climate development during the 21st century might look like. For forest management and decision-making, we have to accept that no exact forecast is possible. Rather, we have to base our planning on the projected trends including their uncertainty. At a global scale, the periodic reports by the Intergovernmental Panel on Climate Change (IPCC) summarize the state of the art of how scientists foresee the development of the future climate and the associated impacts on ecosystems, economy and society. Now, the 5th assessment report is approaching, and some comparisons to the last two reports are already possible. The 3rd Assessment Report (IPCC 2001) had assumed that the global climate might be warming by 1.4-5.9°C, with no probabilities given for different increases, and with extreme scenarios projecting even far higher temperature increases. The 4th assessment report (IPCC 2007) provided overall a more narrow range of the likely future of the global climate stating that temperatures will probably be between 2.0 and 4.5°C warmer than in the 1961-1990 period (with a likelihood of 66%), and it also said that temperature increases by more than 4.5°C are not excluded (see Rogelj et al. 2012). In summary, the most likely temperature increase by 2100 was said to be 3.0°C. First indications from global climate modelling studies for the 5th IPCC assessment report project an increase of 2.4-4.9°C as medians from three different scenarios of radiative forcing (following different emission scenarios that are similar to those used in earlier reports). A fourth scenario is added that assumes a more rigorous and rapid reduction of greenhouse gases than was ever used before, predicting a median temperature increase of only 1.1°C during the 21st Century. Overall, the model simulations for the 5th IPCC assessment report expect that the likelihood of having global temperature increase exceeding 4.9°C is 14%, thus also likely, but that the most likely warming scenario at the global scale is still 3.0°C. Thus, in general, the newest scenarios do project similar warming trends as we have seen in the 4th IPCC assessment report, although some scenarios point to somewhat higher warming trends than were calculated for the 4th report.

The global climate is simulated using so-called general circulation models (GCM), which project the climate future on physics-based processes and first-principles. For regional applications, such model outputs are not very useful, as the spatial resolution of GCMs is very coarse, usually in the range of 1°-2.5° Lat/Lon per model cell. For regions such as the Alps only very few cells are modelled and no variation in terrain elevation is considered. In order to obtain more realistic climate projections at a regional to local scale, two types of downscaling are often combined. First, so-called regional climate models (RCM) are applied to certain larger regions of the World (such as e.g. all or parts of Europe). These models contain the same mechanisms as the GCMs, are fed by GCM output, and then simulate the climate evolution within the study region by using the input of the GCMs from outside of the study region. The output of these models is thus very similar, providing a range of climate variables at high temporal and moderate spatial resolution, ranging typically between 15-50km per cell. This is a much better spatial representation of the climate in regions and the output is somewhat sensitive to mountains, their variation in elevation, and their effects on the climate system, though often the output is still too coarse for management and decision-making. Therefore, a statistics-based downscaling procedure is further applied (Gyalistras et al. 1994, Pielke & Wilby 2012, Meier et al. 2012) in order to scale the output from RCMs to finer spatial resolution ranging from e.g. 100m to 1km, which can be considered well-suited for management applications.

For the MANFRED project, we have used five different RCMs driven by four different GCMs resulting in six GCM/RCM combinations in order to study the impact of likely climate changes on forest species and ecosystems. Table 1 gives an overview of the models used, which originate mostly from the ENSEMBLES EU project, using GCM runs that were calculated for the 4th IPCC assessment report (IPCC 2007).

We downscaled basic RCM variables such as monthly temperature and precipitation to finer spatial resolution for the six models, typically to 1km or 100m cell size. The method used can be called the "anomaly-approach", where we scaled the deviation (also called anomaly) of the future compared to the current climate from coarser to finer resolution. This is an efficient method, since anomalies do not depend much on altitudinal lapse rates. Once downscaled, the

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Model RCM/GCM Scenario:	A1Fi	A1B	A2	B1	B2
CLM/ECHAM5, run by MPI	–	x	x	x	–
RACMO2/ECHAM5, run by KNMI	–	x	–	–	–
HADRN3/HadCM3, run by HC	–	x	–	–	–
HIRHAM3/Arpège, run by DMI	–	x	–	–	–
RCA30/CCSM3, run by SMHI	–	x	x	–	x
RCA30/ECHAM5, run by SMHI	–	x	x	x	–

Table 1. Climate models used to assess the impact of climate change on forest ecosystems and tree species ranges in the MANFRED project. RCM models are labeled in bold face, while the GCMs used to feed the RCMs are typed in normal font.

anomalies are added to an existing high-resolution climate map such as those available from Worldclim (Hijmans et al. 2005) or from national mapping campaigns (e.g. Zimmermann & Kienast 1999). The most important step here was to generate anomalies appropriately. First, we needed to identify the reference period of the high-resolution climate maps. Worldclim is mapping e.g. average monthly values of the 1950-2000 period. Next, we generated the monthly climate anomalies for given periods in the future at the RCM output resolution. To calculate the anomaly of each projected future climate month of any RCM relative to the current climate, we used the simulated time series outputs for the period of 1950-2000 from each RCM. By this, we avoided projecting the modeled bias in RCMs should the recent past deviate from climate station measurements. We were only interested in projecting the relative differences between simulated recent past and simulated futures. Once anomalies were generated, we interpolated these anomalies to the high resolution of existing climate maps such as Worldclim and added them to these maps to project the future climate changes to the representations of the existing climate.

The development of climate anomalies was done by first averaging the monthly time series of minimum (*Tmin*), average (*Tave*), maximum (*Tmax*) temperature and precipitation (*Prcp*) over the period of 1951-2000 for each RCM run used, since these represent the same base period of Worldclim maps. Second, we then used monthly RCM outputs to calculate monthly anomalies relative to the 1950-2000 period means per month. We developed these monthly anomalies by: (a) subtracting current from future temperatures, and (b) dividing future by current climate for precipitation. The latter results in ratios of change, which avoids negative precipitation values that could else result after downscaling if the difference method (a) is used. All climate anomalies were first calculated at the spatial resolution of the RCM output, and were then scaled to an intermediate resolution of 1km by bilinear interpolation (and in a second interpolation step to 100m if necessary). All scaling analyses as described above were performed using "cdo"[1] and other tools applied to NetCDF data files. Figure 1 illustrates the projected climate change trend from the six used RCM simulations by the example of annual and seasonal (summer and winter half) means, and by the uncertainty in projected summer climates.

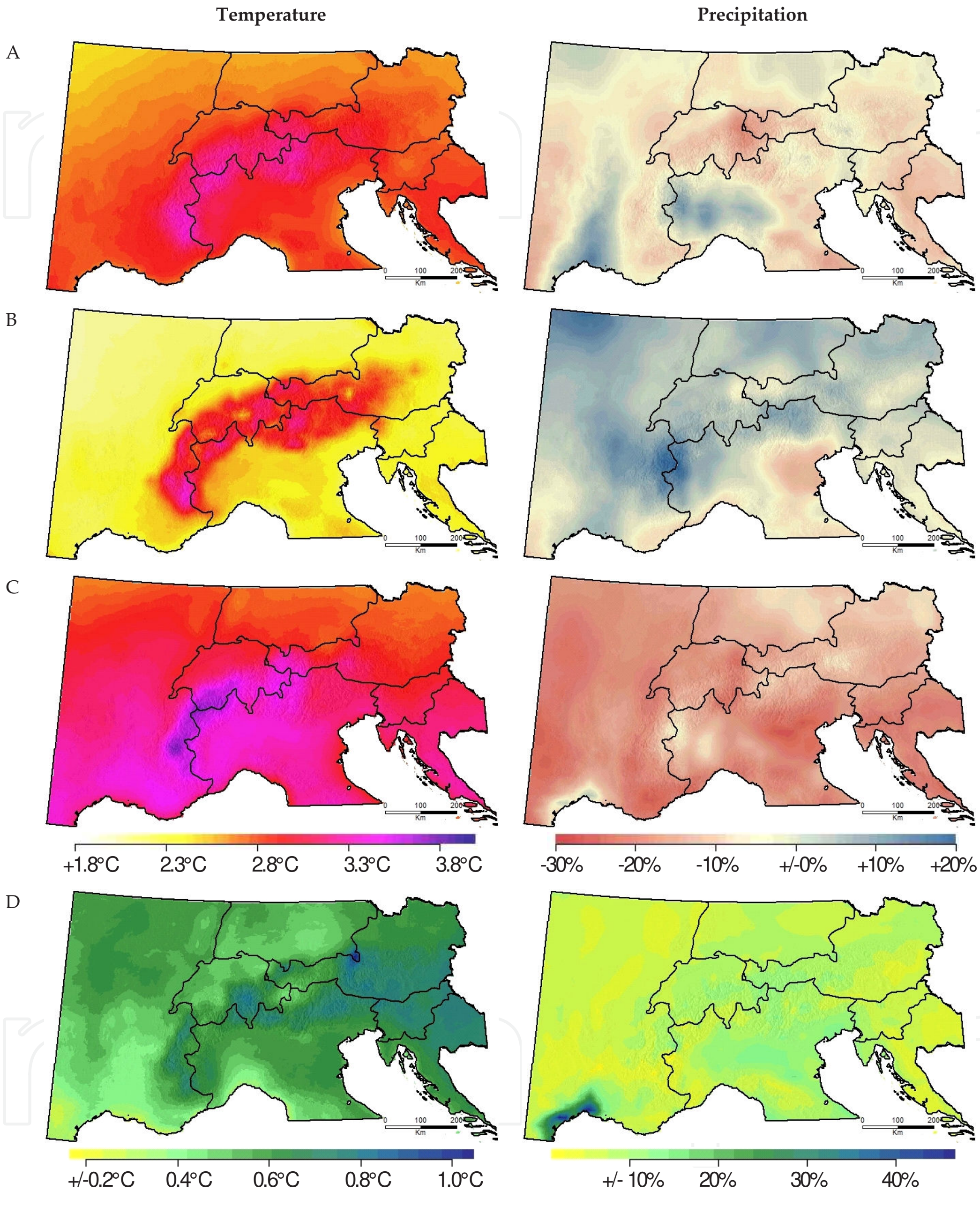

Figure 1. Climate anomalies for the A1B scenario by 2080 (deviations of the 2051-2080 period from the current, i.e. 1950-2000 climate) averaged over the six RCM models used to assess the impact of climate change on forest ecosystems and tree species ranges in the MANFRED project. A: Anomalies for annual temperature and precipitation; B: Anomalies for winter months (October-March): C: Anomalies for summer months (April-September); D: Uncertainties in summer anomalies among all 6 RCM models (calculated as the standard deviation among individual summer anomalies of the six models).

1 Climate Data Operators (https://code.zmaw.de/projects/cdo)

For temperature, we observe a general warming trend in the range of 1.8 to 4.0 °C over the Alps for the annual mean of the 2051-2080 period, with least warming in the winter half, and highest warming in the summer months. The Alps generally face higher warming trends than the surrounding mainland, specifically in the winter months. In summer, the warming is more pronounced in the Western Alps and generally in the South of the Alps, while the northern ranges and lowlands will face a lower warming. Uncertainty among the six models is highest in the higher altitudes of the Alps, and generally increases towards the Eastern part of the Alps.

For precipitation, the annual trend is not very strong, with some regions South of the Alps obtaining a bit more, while most of the regions obtain a bit less precipitation annually. However, the seasonal differences are large. The summer half year is projected to obtain significantly less rainfall, with some regions in the Central Alps obtaining only 70% of the current summer rainfall amounts, and with only small regions in the Southwest and in the East of the Alps obtaining roughly the same amount as today. The winter half is projected to be wetter for most regions, especially the Southwestern Alps, with the Po plain and some Mediterranean regions obtaining less rainfall than today (-20%). The uncertainty among models is highest along the Mediterranean coast in the West, and is also comparably high in the Po plain and at higher elevation in the Alps, while in the plains north of the Alps, the six models show comparably high agreement.

The projected climate simulated differs quite significantly among the six models (Fig. 2). The HadRM3/HadCM3 model projects the highest (ca. +5° C), while the RCA30/CCSM3 model foresees the lowest (ca. +2.8° C) average summer temperature increase by 2100. With regards to precipitation, the HIRHAM/Arpege model projects the strongest (ca. -30%), while the RCA30/ECHAM5 model foresees the lowest (ca. -5%) reduction in summer precipitation over Europe. The year-to-year climate variability is significantly higher in the HIRHAM/Arpege and in the HadRM3/HadCM3 than in the CLM/ECHAM5 model. These differences indicate uncertainties with regards to climatic extremes we may face and with regards to the degree of climata change we will face in forest management decisions.

We also observe strong spatial variation in projected climate patterns, both among models (Fig. 1d) and throughout the projected time series (Figs. 3 & 4). The HadRM3/HadCM3 model reveals high spatial variation and additionally strong fluctuations around a warming trend until 2100 (Fig. 3), meaning that temperatures cannot be expected to gradually warm up. Early in the 21st century, regions North of the Alps are partly projected to show higher temperature increases than the south of the Alps, while after 2050, the South (and partly the West) of the Alps show clearly higher summer temperature increases. After 2030, 2055 and 2070, clear jumps to higher anomaly levels are observed in this model. The HIRHAM/Arpege model reveals a very high spatial variation and considerable temporal fluctuations in summer precipitation anomalies (Fig.4). This means that despite a general drying trend, some wet years are projected to occur, although with decreasing frequencies. On the other hand, such high fluctuations over time also indicate that very dry years are expected to occur increasingly more frequent. Some regions to the Southwest of the Alps show specifically high temporal fluctuations, with very wet years occuring infrequently.

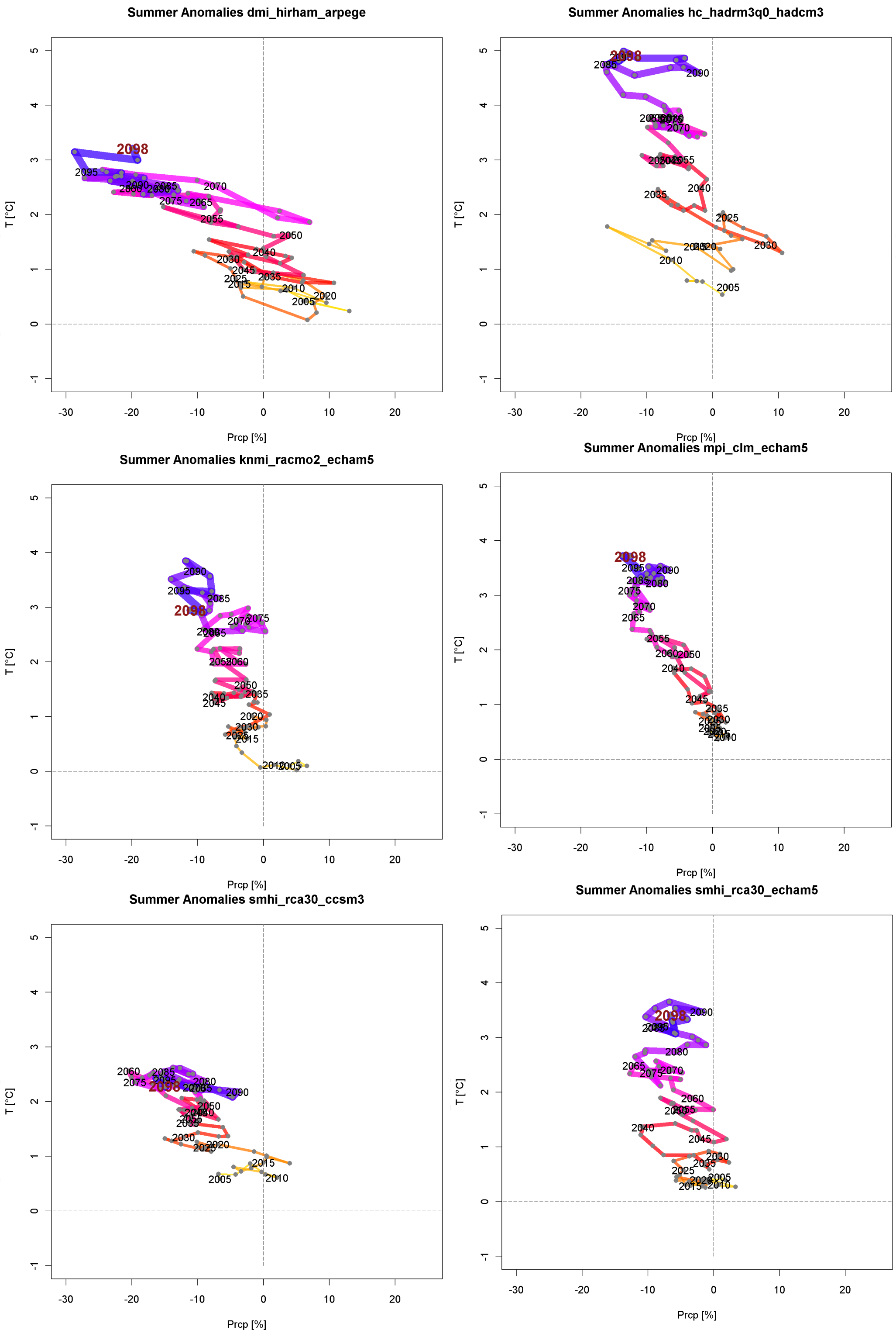

Figure 2. Time series of climate anomalies for the A1B scenario from 2001 until 2100 compared to the current climate (i.e. 1950-2000) over Europe for the six RCM models used in the MANFRED project. For each RCM, the anomalies are mapped as absolute (temperature) and relative (precipitation) values. The lines map the evolution of climate as 5-year averaged anomalies starting in 2005 (2001-2005). Every 5th year is labelled on each graph and grey dots represent the end year of the 5-year running average.

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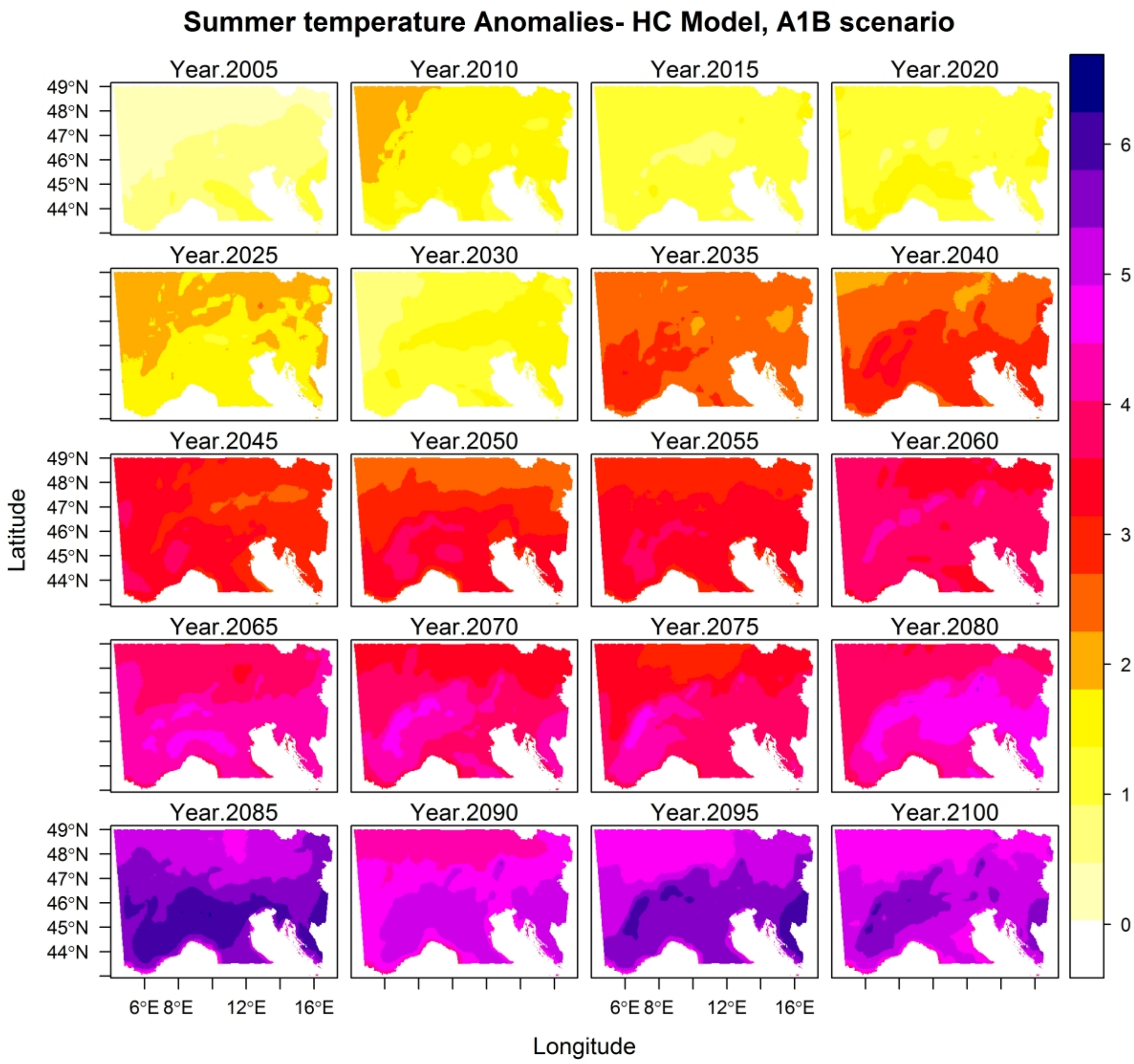

Figure 3. Spatial time series of absolute (°C) summer (April-September) temperature anomalies for the A1B scenario from 2001 until 2100 compared to the current climate (i.e. 1950-2000) over the Alps for the HadRM3/HadCM3 model used in the MANFRED project. Anomalies represent 5-year averages starting in 2005 for the 2001-2005 period.

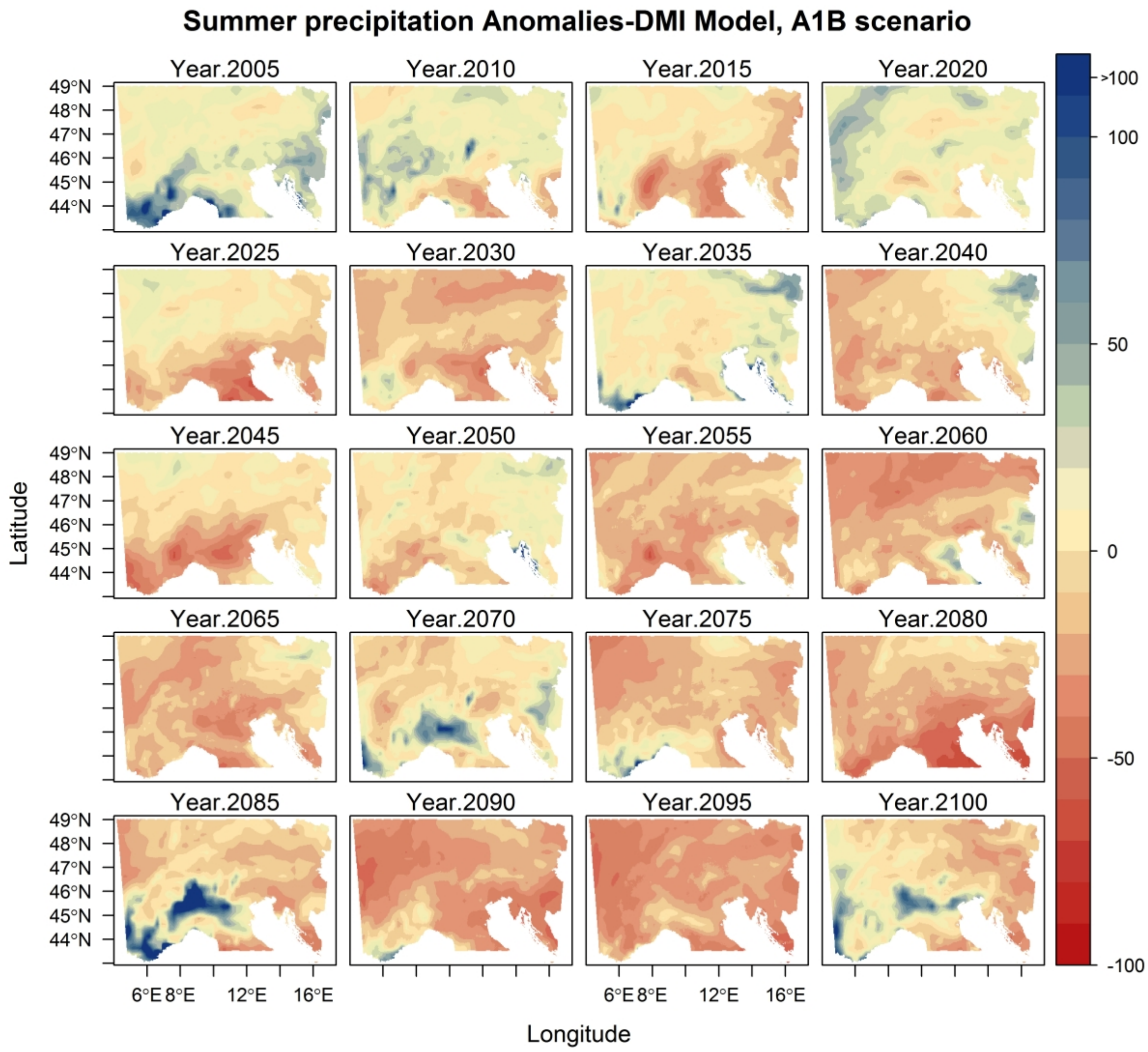

Figure 4. Spatial time series of relative (% change) summer (April-September) precipitation anomalies for the A1B scenario from 2001 until 2100 compared to the current climate (i.e. 1950-2000) over the Alps for the HIRHAM/Arpege model used in the MANFRED project. Anomalies represent 5-year averages starting in 2005 for the 2001-2005 period.

A significant change can also be expected from a change in seasonality (Fig. 5). The CLM model projects a "mediterranization" of the climate, by projecting significantly lower summer precipitations than today, and by simulating increased spring (March, April) and autumn (November) rainfall compared to today, and notably so after ca. 2050.

For forest management this means to be ready for clearly warmer, and at the same time also drier summers, which will have significant effects on some tree species, notably those with lower drought tolerance. This trend is particularly strong in the South of the Alps.

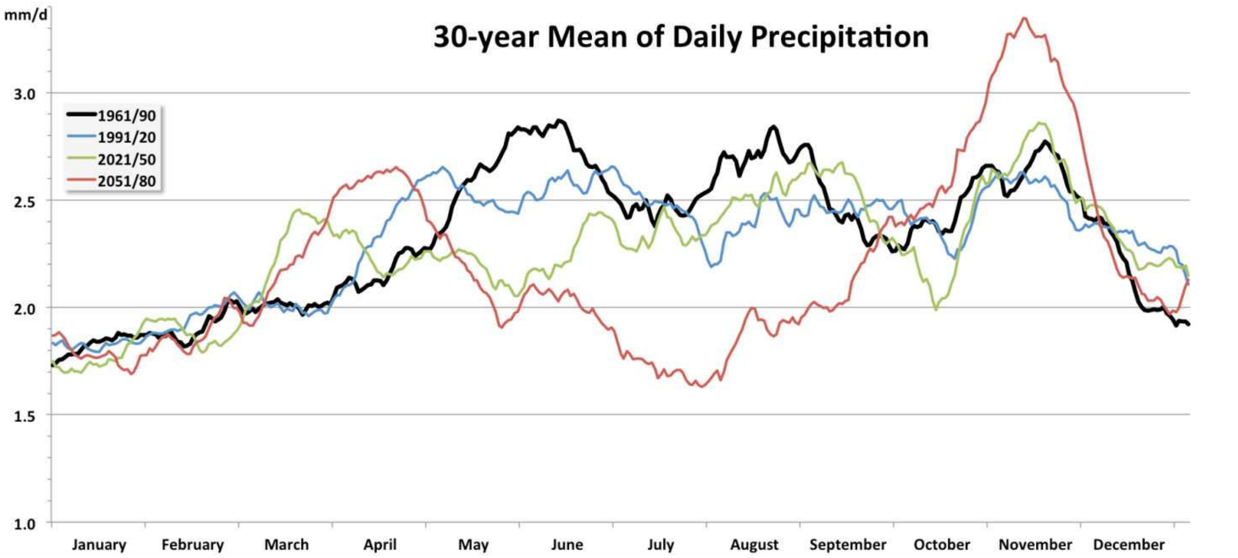

Figure 5. Change in precipitation seasonality across the European Alps as projected by the RCM model CLM that was driven by the ECHAM5 GCM. A trend to drier summer months and somewhat wetter spring (March/April) and autumn (November) months is apparent, specifically visible after 2050, when the RCM simulation projects a strong change to the precipitation regime.

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