# Chapter 51
# Climate Variants of the *MM5* and *REMO* Regional Climate Models

**Thomas Marke, Wolfram Mauser, Andreas Pfeiffer, Günther Zängl, Daniela Jacob, and Swantje Preuschmann**

**Abstract** As global-scale climate scenarios at high spatial detail are not yet available due to existing limitations in computational resources, regional climate models are often applied to allow fine-scale consideration of climate change at the regional scale. This chapter describes the derivation of climate variants from the simulations of the two regional climate models *REMO* and *MM5*, supplementing the climate variants generated by applying predefined climate trends in combination with a statistical climate generator (Chaps. 49 and 50). To overcome limitations arising from the fact that (1) the small-scale climatic variability, primarily in the southern Alpine regions of the study area, cannot be reproduced despite the comparatively high spatial resolution of the regional climate models and (2) systematic deviations between meteorological simulations and observations for the past exist (often referred to as "biases"), a method for refinement (downscaling) and bias correction of RCM data is described that is applied to the RCM data prior to its application as input for DANUBIA. Biases in the applied RCM data are shown exemplarily for simulated precipitation. Moreover the effect of bias correction on simulated discharge is

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illustrated by comparing the discharge duration curve simulated by DANUBIA with and without correction of biases in the RCM data. The climate change signal characterising the climate variants based on scaled and bias-corrected *REMO* and *MM5* data is analysed by considering changes in annual and monthly mean temperature and precipitation as well as spatial patterns and seasonal changes in temperature and precipitation change in the Upper Danube watershed.

**Keywords** Climate variants • Regional climate models • Downscaling • Bias correction • Climate change signal • GLOWA-Danube

## 51.1 Regional Climate Models

Global-scale climate scenarios are being developed at several institutions throughout the world. The climate of the Earth can thereby be calculated using computer modelling on the basis of physical equations. However, despite huge advances in computer technology in recent years, the spatial resolution of the global models is still limited by the existing computational capacities. A direct consequence of this limitation is that many interactive effects that occur between the topography and the atmosphere are still not captured at the resolution of the models; these interactions have particularly great significance in topographically complex terrain like that in the Upper Danube watershed. Therefore, regional climate models are an important tool for more fine-scale consideration of climate changes at the regional scale. With approximately 10–50 km, their spatial resolution is considerably finer than that of global models, such that small-scale topographic features and meteorological processes can be better accounted for.

A model for calculating climate at the regional scale was developed at the Max Planck Institute for Meteorology in Hamburg. The *REMO* regional climate model (Jacob 2001; Jacob et al. 2007) utilises the principle of double nesting to deal with the mismatch in scale from the global to the regional level. This approach first simulates climate with a global model at a coarse spatial resolution of ~180 km and then with the regional model in two additional steps, each at a finer resolution (~40 km, ~10 km); thus, the resulting data from each coarser dataset is entered into a finer calculation as a lateral boundary forcing. *REMO* is used by the Environment Agency Austria (Umweltbundesamt = UBA), among other groups, to calculate possible regional climate changes by the year 2100 for Germany, Austria and Switzerland, at a resolution of $10 \times 10$ km, based on the emission scenarios worked out by the *IPCC*. These data are particularly significant as drivers for DANUBIA, since the spatial resolution is unparalleled to date.

A second model is the *MM5* model, which has already been in place since the beginning of the GLOWA-Danube project (see also Chap. 32). *MM5* also makes use of a multiple-nesting approach. However, only a single nesting step (45 km) is used to translate from the global to the regional scale. The justification for this is that, when using reanalysis data as a lateral driver, quite realistic simulations can

be achieved already with a single nesting in a configuration of *MM5* that is optimised especially for precipitation in the Alpine region for present-day climate (Pfeiffer and Zängl 2010). Moreover, unlike *REMO*, there is also an "online" integration of *MM5* via two-way coupling in the simulation runs of DANUBIA; this would be virtually impossible at finer spatial resolution because of the high computational expense of the meteorological model. The combination of the physical and dynamic refinement of the global simulations through the *MM5* regional climate model and the subsequent statistically based downscaling to 1 km (see paragraph 2) is the best compromise between the technical capabilities and the requirements for high-resolution meteorological model results for DANUBIA.

The means by which regional climate trends can be derived from the results of the *REMO* and *MM5* regional climate models have already been described in Chap. 48. Climate variants can be generated by applying the trends in the development of temperature and precipitation that are inherent in the results of the regional climate models in combination with a statistical climate generator; these variants can be used as input for DANUBIA (see Chaps. 49 and 50).

In addition to the trends derived from the results, the output from the *REMO* and *MM5* regional climate models also contains hourly arrays of the meteorological variables radiation, wind, temperature, atmospheric humidity and precipitation. At least in theory, this output is suitable for use as meteorological drivers for DANUBIA. Two factors limit the direct use of this output from the regional climate models as a driver for DANUBIA:

(a) The small-scale climatic variability, primarily in the southern Alpine region of the study area, cannot be reproduced despite the comparatively high spatial resolution of the regional climate models. While the model scale of DANUBIA is 1 km, *REMO* and *MM5* operate at 10 km and 45 km resolution, respectively. As a result, key details for hydrology, such as valleys and glaciers, are lost in the regional climate models (see Fig. 51.1). This difference in scale must be bridged by a refinement of the spatial resolution (downscaling) of the regional climate simulations.

(b) The accurate quantitative modelling of precipitation, especially in the highly structured topography of the Alpine region, is a huge challenge for climate models; over- or underestimations can arise at the scale of the regional models as a result of a horizontal misalignment of the simulated precipitation events, for example.

Deviations from observed values in precipitation are not necessarily the result of deficiencies in the intrinsic processes described by the regional climate model, but to a large extent can be attributed to the global forcing that is used as input at the boundaries of the model domain (see Chap. 48, Pfeiffer and Zängl 2011). Thus, the comparison of the modelled historical climatology (using the ECHAM5 driver) from *REMO* and *MM5* with a dataset of observational measurements prepared in the context of the GLOWA-Danube project reveals systematic deviations by both models from the measurements. Especially in the winter half of the year, the monthly precipitation in the basin is significantly overestimated by both regional climate models (see Fig. 51.2).
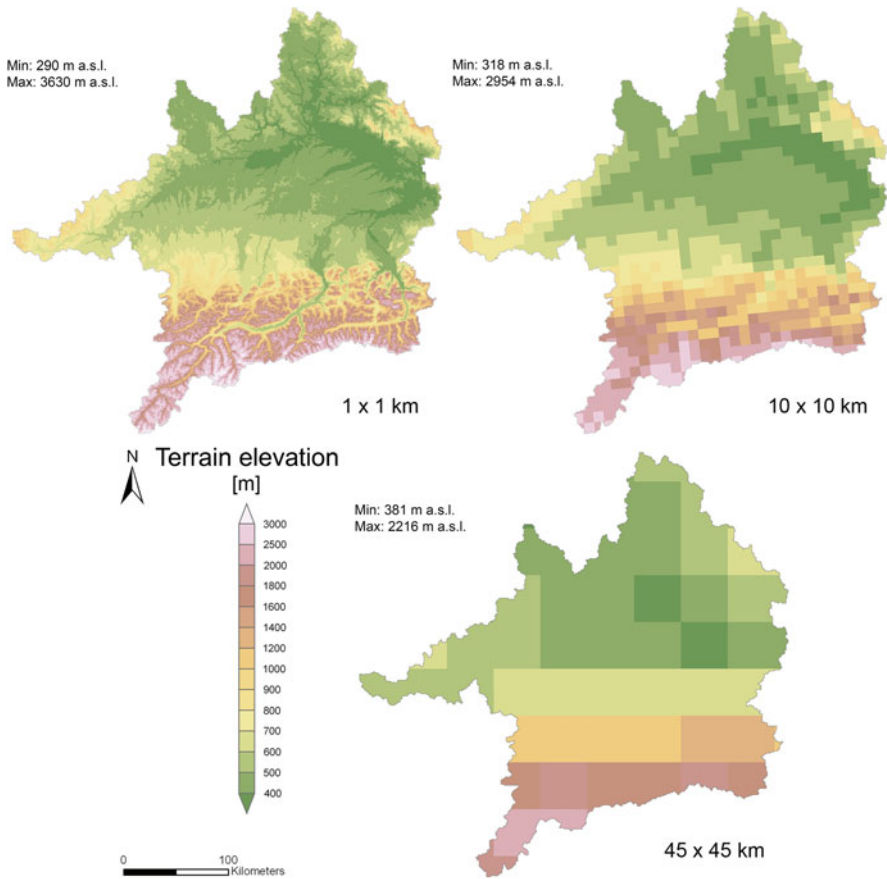
**Fig. 51.1** Terrain elevation in the Upper Danube watershed at the different spatial resolutions of the models DANUBIA (1 km), *REMO* (10 km) and *MM5* (45 km)

If the model results are used directly as inputs for DANUBIA, it would not be possible to realistically reproduce the statistical properties of the measured hydrology. The systematic deviations must be removed by a bias correction, under the assumption that they will continue in the future in the same manner.

The significance of the bias correction for hydrology is clarified in Fig. 51.3. This figure presents the duration curve for discharge at the outlet of the drainage basin at Achleiten that was modelled using the downscaled *MM5* and *REMO* data. As shown in Fig. 51.3, the correction of the subgrid-scale variability in the results of both regional models (see Fig. 51.2) is not sufficient to reproduce the duration curve observed at the outlet of the Upper Danube with DANUBIA.

The overestimation in simulated precipitation in case of both models leads to a significant overestimation of discharge when a bias correction is not performed. The actual trend in the duration curve at the outlet can only be realistically modelled by adding the bias correction in the downscaling process.
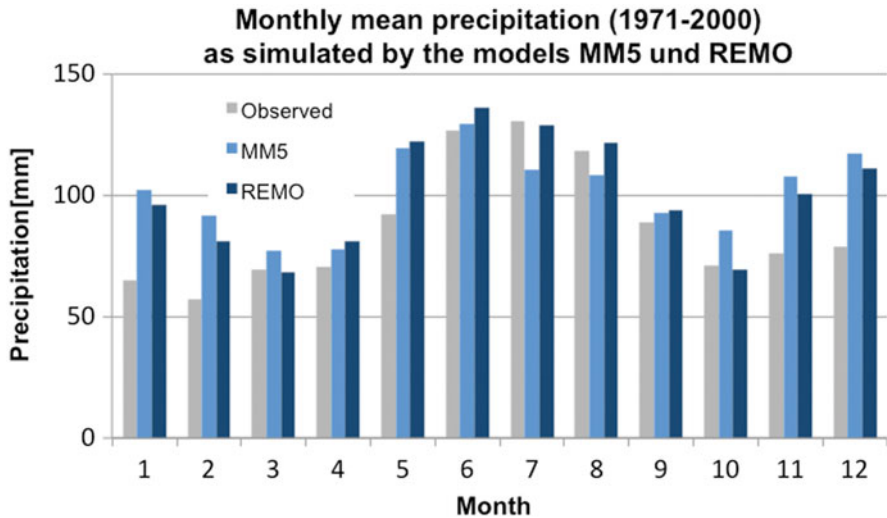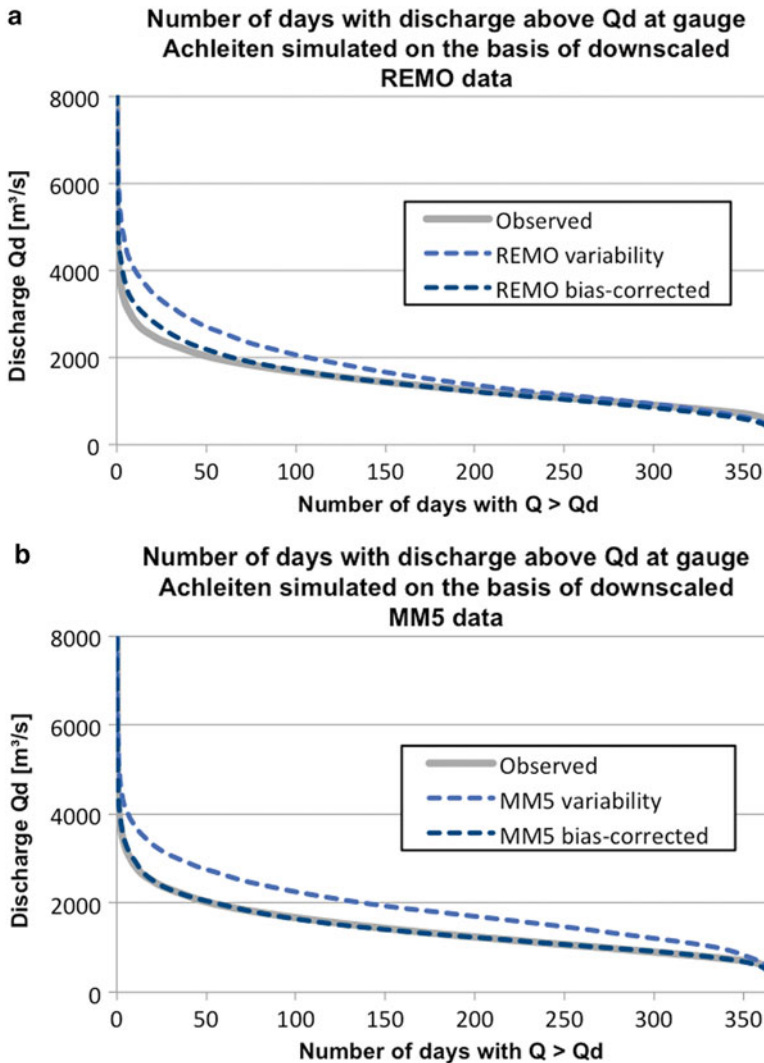
**Fig. 51.2** Mean monthly precipitation in the Upper Danube watershed (1971–2000) according to uncorrected simulations of the models *MM5* and *REMO*

## 51.2 Downscaling and Bias Correction of the Model Results

The downscaling and bias correction of the hourly calculations of *MM5* and *REMO* takes place via the scaling interface SCALMET (Marke 2008; Marke et al. 2011). SCALMET combines various methods for up- and downscaling the meteorological parameter arrays that are used as meteorological drivers for DANUBIA. A statistical scaling method was used for the results presented here. The method is based on Früh et al. (2006) and has been extended by Marke et al. (2011). It utilises monthly scaling functions for downscaling the regional climate simulations to the $1 \times 1$ km resolution required for calculations within DANUBIA (see Fig. 51.4).

In a first step for this method, the subgrid-scale variability of the observed climate within each grid square for each regional climate model is derived from a high-resolution climatology (see Chap. 32). This high-resolution climatology (1 km) is aggregated to the spatial resolution of each respective regional climate model, while preserving the energy and mass, such that the result of the process is an observed climatology at the resolution of *MM5* and *REMO*. The subgrid-scale variability within each climate model pixel is calculated by comparing the dataset that results from the aggregation with the original observational data (1 km) (i.e. for each $1 \times 1$ km pixel within a climate model pixel, the extent to which the high-resolution monthly temperatures are above the mean for a pixel at the resolution of the climate model under consideration is noted).

The first step in the processing corrects only the subgrid-scale variability, but not the deviations between the modelled and observed climatologies; therefore, in a second step, model-specific functions for bias correction are derived from the

**a**

### Number of days with discharge above Qd at gauge Achleiten simulated on the basis of downscaled REMO data



**b**

### Number of days with discharge above Qd at gauge Achleiten simulated on the basis of downscaled MM5 data



**Fig. 51.3** Number of days with discharge above discharge Qd as simulated with DANUBIA for 1972–2000 on the basis of downscaled *MM5* and *REMO* data. Downscaling is carried out (**a**) and (**b**) here stand for the REMO (**a**) and MM5 (**b**) model, not for the different scaling techniques (these are represented by the lines)

observed climatology and the modelled climatology for both models. These functions are derived from the deviations of the coarse climate simulations from the monthly mean of the aggregated observations. The following overall correction ($f_{total}$) derives from the functions for correcting the subgrid-scale variability ($f_{variability}$) and the functions for bias correction ($f_{bias}$):
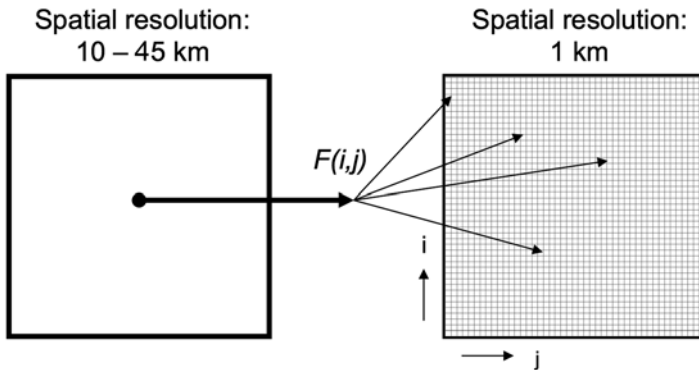
**Fig. 51.4** Schematic illustration of the downscaling process on the basis of statistical downscaling functions

$$f_{total} = f_{variability} * f_{bias}$$

By comparing the observed and modelled climatologies according to this method, there are correction functions for all meteorological parameters for each month in the year. These functions account for both the subgrid-scale variability and the bias at the level of the respective model grid.

In the case of precipitation, the results are spatially distributed correction factors at a spatial resolution of $1 \times 1$ km for each month in the year, which are incorporated into the hourly precipitation arrays of the regional climate models. For other meteorological parameters, such as temperature, the correction can also be done using additive correction values that represent the offset against the simulated values. This method allows the comparison of the modelled data for the present climate with the observed data, such that the downscaled and bias-corrected model climatologies of the past are then identical to the observed climatologies per construct of the scaling procedure.

The respective model-specific scaling functions are then applied to the model results from the future simulations, whereby the desired effect of an observed and statistically based resolution refinement to $1 \times 1$ km is achieved. The maps for this chapter therefore present the results of a combination of dynamic (regional climate models) and statistical (SCALMET) scaling methods. As a result of the correction method used, the data shown should be distinguished from the original climate simulations by the *MM5* and *REMO* models, which were used to derive the regional climate trends in Chap. 48. Hereafter, the model data resulting from the scaling and bias correction are termed climate variants according to the logic of the GLOWA-Danube scenarios presented in Chap. 47, where the terms *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* are used, depending on the underlying model.

## 51.3    Results

In the following, the simulated climate change in the Upper Danube watershed will be shown for the meteorological variables temperature and precipitation. In Fig. 51.5 (top), the temporal trend in the change in annual mean temperature for the period 1970–2100 is compared to the annual mean temperature for the reference period (1971–2000) after downscaling and bias correction. Since the scaling for temperature takes place using an additive correction term, the temperature change remains unaffected by the scaling. The trend in temperature change shown in Fig. 51.5 (top) therefore corresponds to the temperature change for the unscaled climate model data as shown in Fig. 48.7 in Chap. 48. The *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* climate variants both contain a significant increase in the annual mean temperature. In addition, both climate variants show quite similar trends in temperature change over time, and only at the beginning and the last third of the twenty-first century do they exhibit differing temperature changes, with a difference of approximately 1 °C (see Fig. 51.5 top). The warming calculated for the Upper Danube watershed shows an increase in the annual mean temperature of up to 3 °C by the year 2060. Although there are still years in this period with an annual mean temperature below the average value for the reference period, the annual mean temperature by the end of the twenty-first century for both model simulations is without exception above the mean (up to +5 °C) for the reference period.
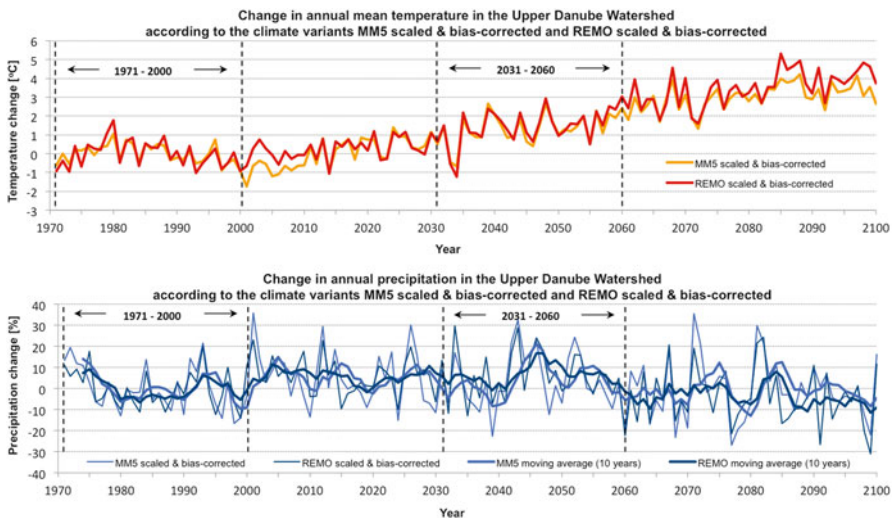


**Fig. 51.5** Climate change signal in simulated temperature and precipitation for the period 1971–2100 according to downscaled and bias-corrected *MM5* (*top*) and *REMO* (*bottom*) simulations

The temporal trend in the relative change in precipitation is shown in Fig. 51.5 (bottom). For the purpose of the visualisation, each 10-year moving average (thick lines) is shown behind the highly variable annual change (thin lines). In contrast to the scaling of temperature, a multiplicative correction term is used in the case of precipitation. The result is that in addition to spatial patterns and absolute values, the change in precipitation is also affected by the scaling. Nonetheless, a comparison between Fig. 51.5 (bottom) and the trend in precipitation in Fig. 48.7 from Chap. 48 shows that the impact of the scaling on the change in precipitation is quite minor and can be ignored compared to the uncertainties in the simulated precipitation trend.

If the *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* climate variants are compared, both reveal a trend in the same direction for the calculated precipitation change. However, it should be noted that the high degree of correspondence can largely be attributed to the common global driver used for the *MM5* and *REMO* model (ECHAM5; see Chap. 48, Fig. 48.6). Even so, the likelihood of the simulated climate change actually occurring is not higher, since the probability of occurrence of the results of the underlying ECHAM run is not known.

Although there is no significant increase or decrease in the annual precipitation for the first half of the twenty-first century, the data from both climate variants deviate more strongly from each other beyond 2060. Although *MM5 downscaled and bias corrected* shows considerable increases of almost 40 %, *REMO downscaled and bias corrected* reveals more pronounced decreases (up to −30 %). The trend in the moving average for the second half of the twenty-first century thus tends to be characterised by more precipitation increases in the case of the *MM5* climate variant, whereas in the case of *REMO* there tend to be more precipitation decreases.

If the linear trend in climate change is calculated across the years 1990–2100, the results are the changes in temperature and precipitation presented in Tables 51.1 and 51.2. In addition to the annual means and linear trends, the spatial pattern and seasonal changes in temperature and precipitation can be important for addressing some issues in climate change research. The climate change signal presented on

**Table 51.1** Linear trend of temperature change in the Upper Danube watershed (1990–2100) in relation to the mean of 1971–2000

| Temperature change 1990–2100 [°C] | | |
|---|---|---|
| Time | *MM5 downscaled and bias corrected* | *REMO downscaled and bias corrected* |
| Winter | +5.2 | +6.7 |
| Spring | +3.2 | +3.7 |
| Summer | +5.8 | +5.3 |
| Autumn | +4.8 | +5.1 |
| Year | +4.7 | +5.2 |

**Table 51.2** Linear trend of precipitation change in the Upper Danube watershed (1990–2100) in relation to the mean of 1971–2000

| Precipitation change 1990–2100 [%] | | |
|---|---|---|
| Time | *MM5 downscaled and bias corrected* | *REMO downscaled and bias corrected* |
| Winter | +8.4 | −1.4 |
| Spring | +14.5 | +10.7 |
| Summer | −29.4 | −32.6 |
| Autumn | −2.7 | −12.6 |
| Year | −6.2 | −12.4 |

Maps 51.3 and 51.4 were calculated as the difference between the downscaled and bias-corrected model calculations for the scenario period 2031–2060 and the historical scaled model results from 1971 to 2000.
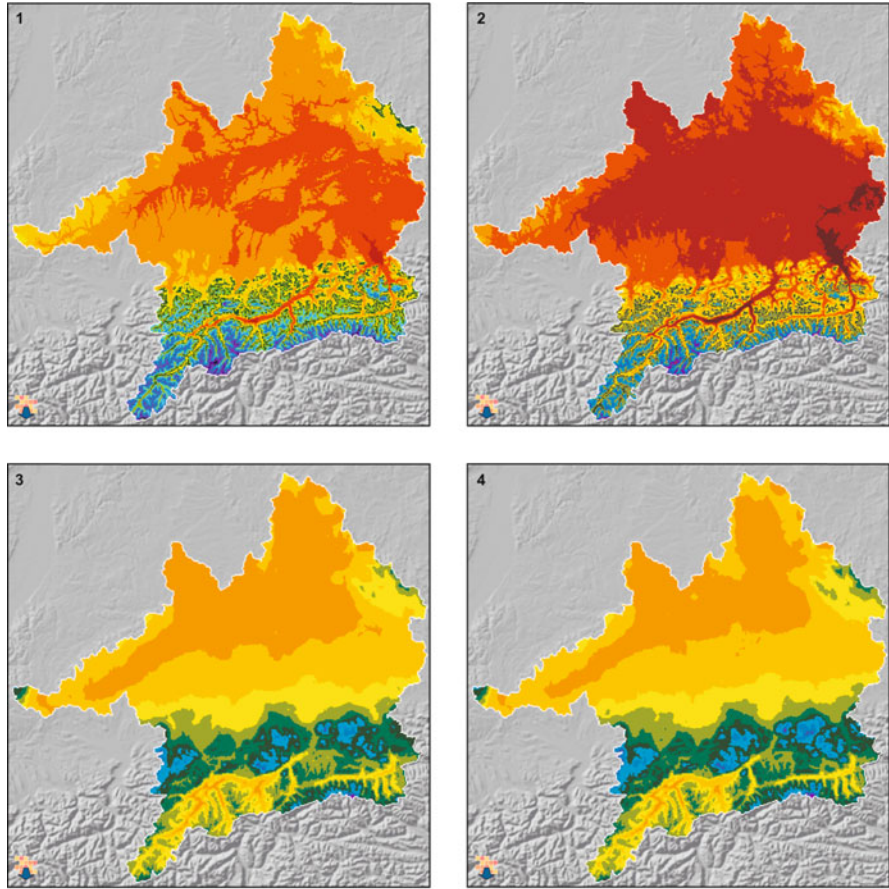
### 51.3.1 Temperature

As shown in Table 51.1, the data from the *REMO downscaled and bias-corrected* climate variant show a stronger increase in temperature for the annual mean compared to the *MM5* climate variant.

An examination of the linear trends reveals that the seasonal temperature changes for the climate variants show significant differences from each other, especially in winter. Hence, in the last two decades of the twenty-first century, the temperature change in winter derived from the *MM5* data (+5.2 °C) is 1.5 °C less than the increase calculated from the downscaled and bias-corrected *REMO* data.

The annual mean temperatures averaged over the period from 2031 to 2060 for the Upper Danube watershed calculated according to the *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* climate variants are similar, at approximately 1.5 °C higher than the mean for the reference period (see Maps 51.1 and 51.2). However, if only the higher mountainous regions are considered, the most marked warming for the climate variant derived from *MM5* data is approximately 1.6 °C, but for the variant calculated from *REMO* simulations, it is approximately 2.3 °C.
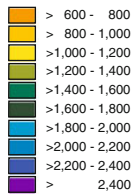
The spatially distributed change signal derived from the *MM5 downscaled and bias-corrected* climate variant is characterised by a rather uniform increase in the temperature change from north to south, but the changes from *REMO downscaled and bias corrected* reveal smaller-scale patterns. This significantly smaller-scale variability in the temperature change compared to the data based on *MM5* can be explained on the basis of the higher spatial resolution of the underlying *REMO* model. Indeed, the scaling of the model results in the case of both models produces subgrid-scale patterns at a spatial resolution of 1 × 1 km (see Maps 51.1 and 51.2),
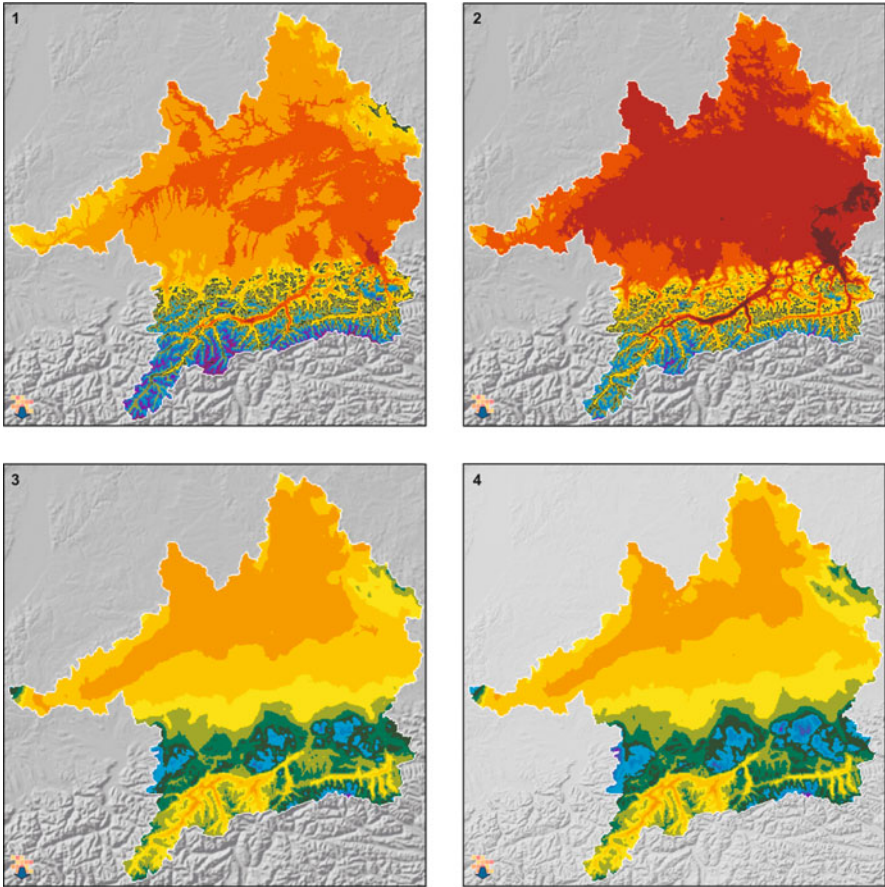
Map 1: Mean air temperature 1971-2000
Map 2: Mean air temperature 2031-2060
in [°C]

Map 3: Mean annual precipitation 1971-2000
Map 4: Mean annual precipitation 2031-2060
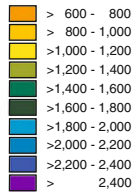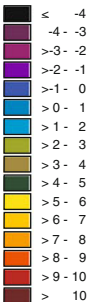in [mm]

0   30   60   90   120 km

| | |
|---|---|
| ≤ -4 | |
| -4 - -3 | |
| >-3 - -2 | |
| >-2 - -1 | |
| >-1 - 0 | |
| > 0 - 1 | |
| > 1 - 2 | |
| > 2 - 3 | |
| > 3 - 4 | |
| > 4 - 5 | |
| > 5 - 6 | |
| > 6 - 7 | |
| > 7 - 8 | |
| > 8 - 9 | |
| > 9 - 10 | |
| > 10 | |

| | |
|---|---|
| > 600 - 800 | |
| > 800 - 1,000 | |
| >1,000 - 1,200 | |
| >1,200 - 1,400 | |
| >1,400 - 1,600 | |
| >1,600 - 1,800 | |
| >1,800 - 2,000 | |
| >2,000 - 2,200 | |
| >2,200 - 2,400 | |
| > 2,400 | |

**Map 51.1** Simulation of air temperature and precipitation with *MM5 downscaled and bias corrected* (global forcing: ECHAM5-MPIOM coupled atmosphere-ocean circulation model; dynamic regionalization: *MM5* regional climate model, calculations by Meteorological Institute, LMU Munich; data for the statistical scaling: DWD, Deutscher Wetterdienst; ZAMG, Zentralanstalt für Meteorologie und Geodynamik)

Map 1: Mean air temperature 1971-2000
Map 2: Mean air temperature 2031-2060
in [°C]

Map 3: Mean annual precipitation 1971-2000
Map 4: Mean annual precipitation 2031-2060
in [mm]

0   30   60   90   120 km

| | Map 1/2 [°C] |
|---|---|
| | ≤   -4 |
| | -4 -  -3 |
| | >-3 -  -2 |
| | >-2 -  -1 |
| | >-1 -   0 |
| | > 0 -   1 |
| | > 1 -   2 |
| | > 2 -   3 |
| | > 3 -   4 |
| | > 4 -   5 |
| | > 5 -   6 |
| | > 6 -   7 |
| | > 7 -   8 |
| | > 8 -   9 |
| | > 9 - 10 |
| | >    10 |

| | Map 3/4 [mm] |
|---|---|
| | >  600 -   800 |
| | >  800 - 1,000 |
| | >1,000 - 1,200 |
| | >1,200 - 1,400 |
| | >1,400 - 1,600 |
| | >1,600 - 1,800 |
| | >1,800 - 2,000 |
| | >2,000 - 2,200 |
| | >2,200 - 2,400 |
| | >      2,400 |

**Map 51.2** Simulation of air temperature and precipitation with *REMO downscaled and bias corrected* (global forcing: ECHAM5-MPIOM coupled atmosphere-ocean circulation model; dynamic regionalization: *REMO* regional climate model, calculations by Max Planck Institute for Meteorology (MPI-M), financed by the Federal Environment Agency (UBA); data for the statistical scaling: DWD, Deutscher Wetterdienst; ZAMG, Zentralanstalt für Meteorologie und Geodynamik)
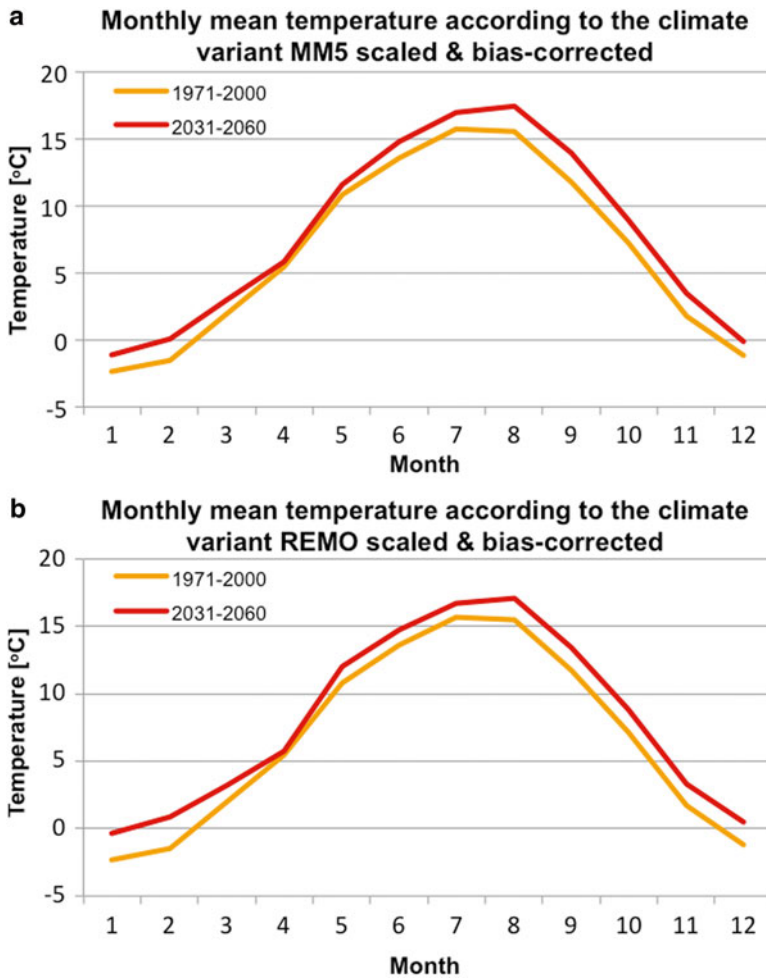
**Fig. 51.6** Mean monthly temperature in the Upper Danube watershed according to downscaled and bias-corrected *MM5* (**a**) and *REMO* (**b**) simulations for the reference (1971–2000) and scenario period (2031–2060)

although the scales of the temperature change signals are dominated by the horizontal resolution for each regional climate model.

Like the trend analysis, there are significant differences in the comparative images for the winter season DJF for both climate variants. While the winter according to *REMO downscaled and bias corrected* represents the season with the highest temperature increase (+2 °C), the increase in winter calculated from the *MM5* data is significantly smaller (+1.3 °C) and is in fact less than the increases in summer (+1.5 °C) and fall (+1.9 °C). These differences can be attributed to the various trends in the individual months (see Fig. 51.6).

As Map 51.4 shows, the data from the *REMO downscaled and bias-corrected* variant reveal a maximum warming in winter and fall, whereas *MM5 downscaled and bias corrected* show the highest temperature increases in summer and fall.

### 51.3.2   Precipitation

In the case of both climate variants, the linear trends for the changes in precipitation in the Upper Danube watershed show a decrease in the annual precipitation by the end on the twenty-first century; however, in the case of the *MM5 downscaled and bias-corrected* climate variant, this decrease is less marked (see Table 51.2).

The trends for the seasonal changes in precipitation derived from the climate variants are generally consistent, especially in summer and spring.

The linear trends based on both climate variants show a considerable decrease in precipitation in summer and a significant increase in precipitation in spring. The future patterns in winter precipitation differ based on the linear trends in both the *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* climate variants. Whereas the linear trend for the *MM5 downscaled and bias-corrected* variant is characterised by an increase in winter precipitation by 8.4 % by the end of the twenty-first century, the winter precipitation in the *REMO downscaled and bias-corrected* variant decreases by 1.4 %.

If the precipitation trends derived from the climate variants are compared to the results from the comparison of the reference and scenario periods, the differences are obvious: while the linear trend in the precipitation change (1990–2100) describes a decrease in the annual precipitation in both models, the comparison of the mean annual precipitation in the scenario period (2031–2060) with the precipitation in the reference period (1971–2000) shows an increase in precipitation in both models (see Maps 51.3 and 51.4). These results highlight the dependency of the climate change signals on the length and position of the period being considered within the modelled time series, as well as the dependency of the results on the method used to study climate change.

Although the increase in the annual precipitation in the data from the *REMO downscaled and bias-corrected* climate variant, calculated by comparing the periods 1971–2000 and 2031–2060, is somewhat higher in some regions compared to the *MM5 downscaled and bias-corrected* climate variant, the horizontal distribution of the precipitation change signal in both downscaled model results is generally consistent. This distribution is characterised by an increase in precipitation in the region of the Bavarian Forest, but primarily in the north-eastern Alpine region. In contrast, the south-western part of the basin is characterised by a decrease in the annual precipitation. In addition, the seasonal precipitation changes in the Upper Danube watershed are very similar in both climate variants (see Map 51.4(9–16)). Both downscaled model results indicate an increase in the mean regional precipitation for spring (*MM5 downscaled and bias corrected* +27 mm, *REMO downscaled and bias corrected* +32 mm) and fall (*MM5 downscaled and bias corrected* +19 mm, *REMO downscaled and bias corrected* +38 mm), as well as a decrease in precipitation in summer (*MM5 downscaled and bias corrected* −6 mm, *REMO downscaled and bias corrected* −13 mm).
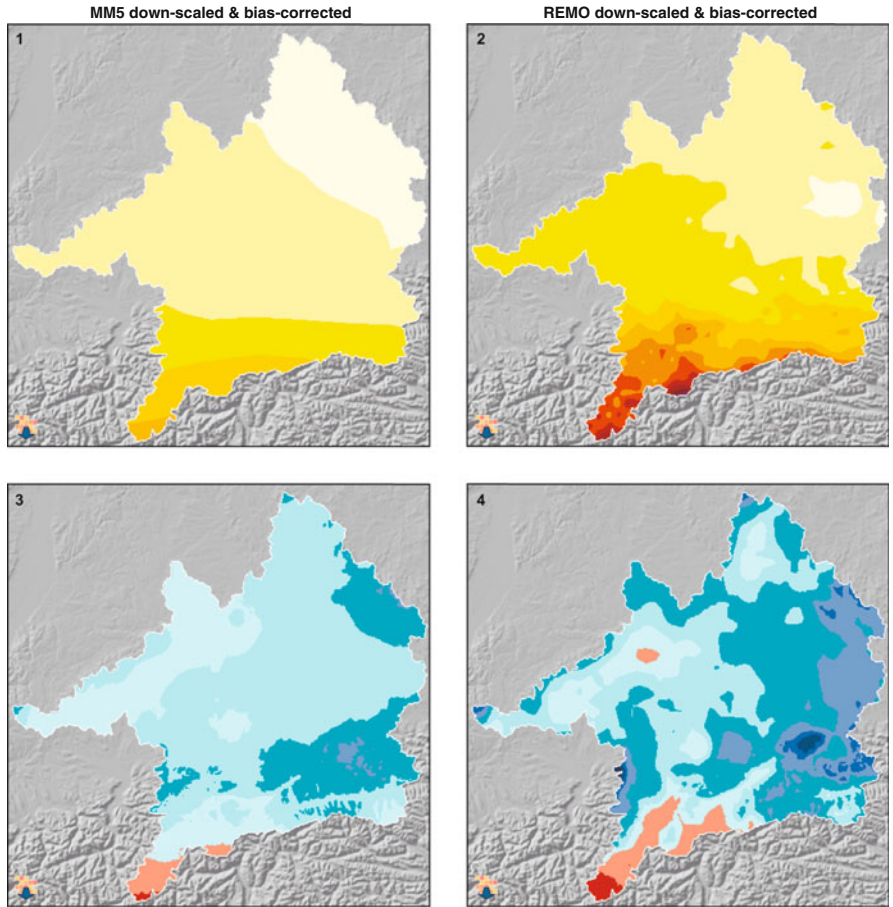
**Map 51.3** Change of air temperature and precipitation between 2031–2060 and 1971–2000 with *MM5* and *REMO*, both downscaled and bias corrected (global forcing: ECHAM5-MPIOM coupled at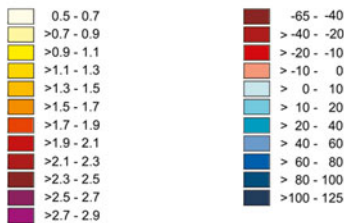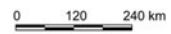mosphere-ocean circulation model; dynamic regionalization: *REMO* regional climate model, calculations by Max Planck Institute for Meteorology (MPI-M), financed by the Federal Environment Agency (UBA); *MM5* regional climate model, calculations by Meteorological Institute, LMU Munich; data for the statistical scaling: DWD, Deutscher Wetterdienst; ZAMG, Zentralanstalt für Meteorologie und Geodynamik)
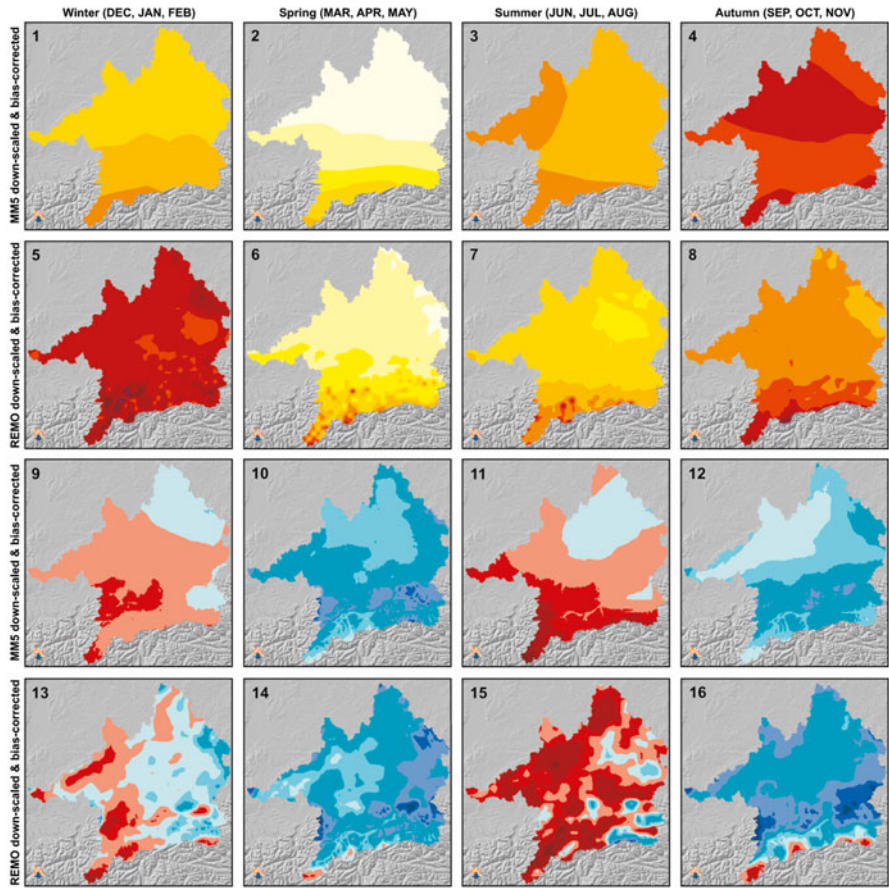
**Map 51.4** Seasonal change of air temperature and precipitation between 2031–2060 and 1971–2000 with *MM5* and *REMO*, both downscaled and bias corrected (global forcing: ECHAM5-MPIOM coupled atmosphere-ocean circulation model; dynamic regionalization: *REMO* regional climate model, calculations by Max Planck Institute for Meteorology (MPI-M), financed by the Federal Environment Agency (UBA); *MM5* regional climate model, calculations by Meteorological Institute, LMU Munich; data for the statistical scaling: DWD, Deutscher Wetterdienst; ZAMG, Zentralanstalt für Meteorologie und Geodynamik)
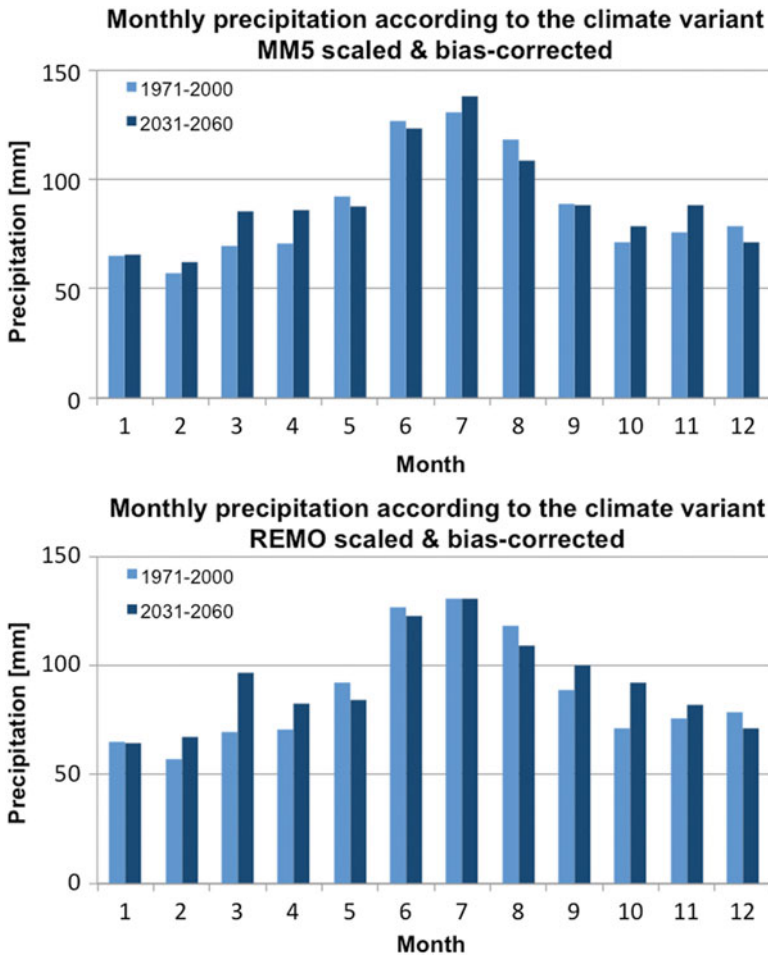
**Fig. 51.7** Mean monthly precipitation in the Upper Danube watershed according to downscaled and bias-corrected *MM5* (*top*) and *REMO* (*bottom*) simulations for the reference (1971–2000) and scenario period (2031–2060)

In a comparison of the periods 1971–2000 and 2031–2060, the results for the winter show overall a less-marked difference, but opposite trends for both climate models. While the data based on *REMO* reveal an absolute increase in winter precipitation by 2 mm, the results derived from the *MM5* model calculations indicate a decrease in winter of approximately 3 mm.

If the monthly precipitation in the reference and scenario periods for the two models are compared (see Fig. 51.7), it is obvious that the differing precipitation change in winter in general can be attributed to the differing precipitation for the month of February (2031–2060). In addition, Fig. 51.7 reveals that the maximum increase and maximum decrease in both climate variants occur in the same months (March: increase and August: decrease).

## 51.4   Summary

As presented in this chapter, the climate variants, as downscaled and bias-corrected model results of the *MM5* and *REMO* regional climate models, both describe rather similar changes of temperature and precipitation for the periods in question. This is primarily due to the use of the same lateral driver for both models, which comes from the results from the same ECHAM5 simulation (A1B, Member 1).

The comparison of different analysis methods (comparison of the reference and scenario simulations and the trend analyses) and the analysis time periods indicated that the climate change signal is sometimes highly dependent on the method used and the period being considered. Especially in the case of annual and winter precipitation, the various data analyses resulted in different, sometimes even opposite, change signals. There were differences in the simulated changes to precipitation between the models; this fact, in combination with the fact that a difference of approximately 10 % for the precipitation changes in fall and winter arose for both climate variants when different analysis methods were used and when different time periods were considered, indicates the challenges and uncertainties in calculating future precipitation totals.

In the analysis and interpretation of the results, it is important to bear in mind that only a few realisations among a few predefined global climate trends have been considered, and these have then been further refined with *MM5* and *REMO*. As a result, it is not possible to make statements about the range of expected climate changes and the probabilities of occurrence of specific climate patterns based on the present results from the regional climate modelling. Different realisations within the scenarios must be considered in order to more accurately estimate the range of possible climate changes and their effects. The required range of model realisations is unfortunately not yet available to date, not least because of the high computational expense of such simulations.

Nevertheless, the results of the *REMO* and *MM5* simulations do reveal the expected variability of the simulated climate trends. Thus, the linear trends in precipitation from the *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* climate variants for fall and winter indicate a difference of almost 10 percentage points. However, for spring and summer, the trends in precipitation from the model calculations are generally similar, with a difference of only 3 percentage points. The comparison of the trends shows that *MM5* and *REMO* simulate strong deviations in precipitation only for the last 15–30 years, but show quite similar trends for the period from 1970 to around 2070.

The increase in temperature in the Upper Danube watershed is very similarly represented by the *MM5 downscaled and bias-corrected* and *REMO downscaled and bias-corrected* climate variants; the temperature increase in the variant based on *REMO* calculations is generally somewhat larger. In this case as well, the differences in the change in temperature between the two climate variants result from the different calculations of the regional climate models for the last two decades of the twenty-first century.

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