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A pragmatic approach for the downscaling and bias correction of regional climate simulations – evaluation in hydrological modeling

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Abstract

The present study investigates a statistical approach for the downscaling of climate simulations focusing on those meteorological parameters most commonly required as input for climate change impact models (temperature, precipitation, air humidity and wind speed), including the option to correct biases in the climate model simulations. The approach is evaluated by the utilization of a hydrometeorological model chain consisting of (i) the regional climate model MM5 (driven by reanalysis data at the boundaries of the model domain), (ii) the downscaling and model interface SCALMET, and (iii) the hydrological model PROMET. The results of four hydrological model runs are compared to discharge recordings at the gauge of the Upper Danube Watershed (Central Europe) for the historical period of 1972–2000 on a daily time basis. The comparison reveals that the presented approaches allow for a more accurate simulation of discharge for the catchment of the Upper Danube Watershed and the considered gauge at the outlet in Achleiten. The correction for subgrid-scale variability is shown to reduce biases in simulated discharge compared to the utilization of bilinear interpolation. Further enhancements in model performance could be achieved by a correction of biases in the RCM data within the downscaling process. Although the presented downscaling approach strongly improves the performance of the hydrological model, deviations from the observed discharge conditions persist that are not found when driving the hydrological model with spatially distributed meteorological observations.

1 Introduction

Regional climate models (RCMs) have been used in a variety of studies to refine climate simulations or coarsely resolved (re-)analysis data from the global to the regional scale (Kotlarski et al., 2005; Jacob et al., 2007; Pfeiffer and Zängl, 2010). The resulting regional climate information is often utilized as input for models operating at the land surface, e.g. snow-models (Lazar and Williams, 2008) or hydrological models (Wood

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et al., 2004; Marke, 2008), in many cases with the aim to analyze climate change impacts at the land surface. However, the dynamical downscaling of global climate simulations or datasets by means of present generation RCMs is still computationally limited to spatial resolutions in the order of 10 × 10 km. A clear need has been identified to develop appropriate methods to overcome the scale mismatch between RCMs and impact models in order to permit the investigation of climate change impacts at the regional to local scale. Beside currently found limitations in the spatial resolution, the application of RCM data in climate change impact studies is often hampered by biases in the simulations (e.g., biases in simulated temperature and precipitation). Kotlarski et al. (2005) have compared simulations conducted with a large set of RCMs to different observation-based datasets for the area of Germany on a monthly time basis. Their studies reveal that biases exist that largely vary depending on the RCM, geographical region and the observation-based meteorological reference data considered.

Many studies have been carried out in the past in order to analyze biases in RCM simulations (e.g., Kotlarski et al., 2005; Jacob et al., 2007; Pfeiffer and Zängl, 2010) or the performance of downscaling techniques, mainly with focus on highly resolved spatial distributions of temperature and precipitation on a daily basis (e.g., Leung et al., 2003; Früh et al., 2006). However, existing studies often concentrate on the meteorological analysis of downscaling efficiency and do not consider their implications on the results of models operating at the land surface.

The current study addresses existing needs for downscaling techniques by expanding a pragmatic approach for the downscaling of precipitation (Früh et al., 2006) to various other meteorological variables. Furthermore, an approach is investigated that allows the correction of biases in various meteorological parameters within the downscaling process. A hydrometeorological model chain is set up for the period of 1971–2000 in order to analyze the effect of downscaling on river runoff simulations in the Upper Danube Watershed (Central Europe). It is composed by (i) the regional climate model MM5 (Grell et al., 1994) which is driven by ERA40 reanalysis data (Uppala et al., 2005) at its lateral boundaries, (ii) the downscaling and model interface SCALMET

(Marke, 2008), and (iii) the uncalibrated hydrological model PROMET (Mauser and Bach, 2009). The demands of the hydrological model on meteorological input data are comparatively high as the model requires high temporal (1 h) and spatial resolution (1 km) as well as a total number of seven meteorological parameters (precipitation, temperature, wind speed, air humidity, incoming shortwave and longwave radiation, surface pressure) for the process description at the land surface. The results of the hydrological model are evaluated on a daily time basis by comparing the discharge simulated for the outlet of the Upper Danube Watershed at Achleiten to discharge recordings.

2 Study site

The current study has been conducted in the Upper Danube River Basin, a mountainous watershed situated in Central Europe, covering an area of 76 653 km^2 and territories in southern Germany, Austria, Switzerland, the Czech Republic and Italy (Fig. 1). The complex topography characterized by a relief stretching from altitudes of 287 m a.m.s.l. at the discharge gauge of the watershed at Achleiten up to 4049 m a.m.s.l. at Piz Bernina in the Alpine headwaters, induces strong meteorological gradients. Annual precipitation ranges from 550 to >2000 mm, annual mean temperatures from −4.8 to 9 °C, evapotranspiration from 100 to 700 mm per year and the resulting annual discharge from 150 to 1750 mm per year (Mauser and Bach, 2009). The majority of the Upper Danube's tributaries emerge in higher altitudes of the Alps and cross the lowlands towards the north in advance of their confluence with the Danube. The Danube itself leaves the watershed in a west to east direction in the northern part of the basin at the gauge in Achleiten (near Passau).

3 Methods

3.1 Models

The hydrometeorological model chain used in the current study is composed of four coupled components (see Fig. 2). The ERA40 reanalysis (Uppala et al., 2005) supplies the global meteorological data that are dynamically downscaled to a spatial resolution of 45 × 45 km by the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model MM5 (release 3.7.3) (Grell et al., 1994). MM5 has been set up for an area of about 3000 × 3500 km in the current study. Covering most of the European continent at a horizontal resolution of 45 km (see Fig. 3), the size of the model domain allows to capture all relevant synoptic scale phenomena governing the climate in our region of interest. The optimal configuration of MM5 in terms of physics parameterizations with focus on an accurate simulation of precipitation in Southern Germany and the Northern Alps, has been identified by Pfeiffer and Zängl (2010) on the basis of a contiguous ten year simulation of the 1990ies driven with ERA40 data. In the current setup, MM5 resolves the atmosphere with 29 layers up to a top lid pressure of 100 hPa with an enhanced resolution in the boundary layer.

The dynamical downscaling using MM5 is followed by a statistical downscaling performed within the model coupler and scaling tool SCALMET (Marke, 2008). SCALMET has been designed in the framework of the GLOWA-Danube project (www.glowa-danube.de) to allow for the analysis of climate change impacts on the water balance of the Upper Danube Watershed by performing a synchronized exchange of energy and water fluxes between meteorological and land surface models. As the downscaling in SCALMET is carried out during the runtime of the model system, the complexity of the applied downscaling techniques is strongly limited. In our study the coupler applies statistical downscaling functions with and without bias correction to translate from the RCM scale (45 × 45 km) to the scale of the hydrological simulations (1 × 1 km). The latter are carried out with the distributed, physically based hydrological model PROMET (Process of Radiation, Mass and Energy Transfer) (Mauser and Bach,

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2009). PROMET was initially designed by Mauser and Schädlich (1998) as a SVAT-type evapotranspiration model that has been applied at different spatial scales ranging from single field scale to mesoscale watersheds (100 000 km^2) and under a variety of climatological conditions (Bach et al., 2003; Strasser and Mauser, 2001; Ludwig and Mauser, 2000). Details on the hydrological model PROMET, the different model components and model validation can be found in Mauser and Bach (2009).

3.2 Downscaling

The two statistical downscaling approaches applied to correct for subgrid-scale variability and bias have both initially been developed for the downscaling of precipitation in alpine-scale complex terrain (Früh et al., 2006). The general concept behind the approach, however, allows for its application in downscaling of temperature, wind speed and air humidity as well. The approach is based on the application of a downscaling function for every month of the year and is described in detail in the following paragraphs. To clearly distinguish between the participating grid resolutions, the coarse RCM grid (45 × 45 km) is referred to by capital letters, whereas the fine resolution of the hydrological model (1 × 1 km) is referred to by small letters.

In a first step, the subgrid-scale variability with respect to the RCM grid is estimated for a given meteorological parameter and a given month of the year on the basis of a high resolution observed climatology x_{obs} (m), where x stands for the meteorological parameter and m for the considered month. The high resolution climatology used here covers the period of 1971–2000 and is generated by the meteorological preprocessor in the hydrological model PROMET as described in detail by Mauser and Bach (2009). The mean monthly conditions are aggregated from 1 × 1 km to the grid structure and spatial resolution of the RCM. This is done in such way that every raster element of the aggregated observed climatology X_{obs} (m) holds the area weighted mean value of all overlapping fine grid cells of x_{obs} (m). The coarse grid observations X_{obs} (m) are then bilinearly interpolated to the fine grid resulting in a set of raster elements $x_{\text{obs\_bil}}$ (m).

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A downscaling function F_{vari} (m) is then calculated as:

$$F_{vari}(m) = x_{obs}(m)/x_{obs\_bil}(m) \quad (1)$$

This statistical downscaling approach considers the subgrid-scale variability of a given meteorological parameter while the mass and energy budgets imposed by the RCM simulations X_{sim} (h) are conserved for each hourly output-time step h. The approach is referred to by the abbreviation vari in the course of this study.

As biases in terms of deviations from observed climatological conditions exist in simulations of present-generation RCMs, the quality of the hydrological model results are expected to be compromised by applying uncorrected RCM simulations as meteorological drivers. Studies by Kotlarski et al. (2005) focusing on the area of Germany have revealed deviations between RCM simulations and observation-based meteorological data of up to 2 °C for mean annual temperature and of more than 50% for mean annual precipitation. Note, however, that the quality of the station recordings and their processing also need to be taken into account (Hagemann et al., 2001; Kotlarski et al., 2005; Pfeiffer and Zängl, 2010). As recordings in Alpine areas are predominantly taken in valleys rather than on mountain ridges, simple areal averages can be expected to be systematically biased and correction algorithms involve substantial uncertainty (Pfeiffer and Zängl, 2010). Furthermore, precipitation recordings suffer from a wind-induced underestimation of solid precipitation, especially in mountainous terrain (Sevruk, 1985). Beside the mean biases on the country or catchment scale, there exist also smaller-scale biases that cannot be compensated for by the consideration of subgrid-scale variability and the related shift of mass and energy within a given RCM grid box. Früh et al. (2006) show that RCMs often fail to accurately simulate the complex precipitation patterns in the Alps, which are characterized by precipitation maxima at the northern and southern rim of the Alps, whereas the inner Alpine valleys are comparatively dry (Frei and Schär, 1998). As shown by Wilby et al. (2000) and Marke (2008) the sensivity of hydrological models to biases in climate simulations is particularly severe in Alpine watersheds, where the seasonal storage of water in the snowpack to a large degree controls the discharge at the outlet of the watersheds.

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To correct RCM simulations beyond the scope of a shift of mass and energy within a given climate model grid box, a further processing step has been developed and integrated into SCALMET. Following Murphy (1999) and Früh et al. (2006) an empirical adjustment of RCM data based on local climate statistics is carried out by calculating a bias correction F_{bias} (m) in form of:

$$F_{\text{bias}}(\text{m}) = x_{\text{obs\_bil}}(\text{m}) / x_{\text{sim\_bil}}(\text{m}) \quad (2)$$

where $x_{\text{obs\_bil}}$ (m) are the aggregated monthly observations for 1971–2000 and $x_{\text{sim\_bil}}$ (m) are the mean monthly simulation results for 1971–2000, both bilinearly interpolated from the coarse to the fine grid. Combining the terms for the consideration of subgrid-scale variability and bias correction a downscaling function $F_{\text{vari\&bias}}$ (m) is calculated as:

$$F_{\text{vari\&bias}}(\text{m}) = F_{\text{vari}}(\text{m}) \cdot F_{\text{bias}}(\text{m}) \quad (3)$$

This downscaling function leads to a redistribution of the meteorological parameter considered on the catchment-scale deliberately accepting a possible "breach" of the mass and energy budget. It is referred to by the abbreviation vari&bias in the following.

The functions F_{vari} (m) and $F_{\text{vari\&bias}}$ (m) as derived under Eqs. (1) and (3) are calculated for the parameters precipitation, wind speed and humidity in advance of the coupled model runs and then are used within the downscaling process in SCALMET to multiply the bilinearly interpolated RCM simulations $x_{\text{sim\_bil}}$ (h) at each hourly time step h. The downscaling of temperature follows a very similar approach, with the difference that the multiplicative correction is substituted by an additive correction term. To derive the corresponding downscaling function, the multiplication and division in Eqs. (1)–(3) is simply replaced by addition and subtraction, respectively. While such additive correction would be feasible for the downscaling of most meteorological parameters as well, a multiplicative correction circumvents the generation of negative values in case of precipitation on the one hand, and avoids the production of precipitation in those cases where the RCM simulates dry conditions on the other hand. Figure 4 shows

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the downscaling function in form of an additive correction of sub-grid variability (left) and a combined correction of sub-grid variability and bias (right) of MM5-simulated temperature (ERA40 forcings) exemplarily for January. This month is characterized by rather large corrections in temperature simulated for the Upper Danube Watershed due to a mean overestimation of temperatures in the MM5 simulations of +0.8 °C. As illustrated, the combined correction of subgrid-scale variability and bias, compared to the correction of subgrid-scale variability alone, remarkably reduces simulated temperature in large parts of the Alpine foreland, whereas temperatures in the southern part of the Alps are slightly increased. Both approaches reflect altitudinal gradients by increasing temperatures in the Alpine valleys and reducing temperatures in the higher elevated parts of the Alps.

For the hydrological evaluation of the presented downscaling approaches, the statistical downscaling of vari and vari&bias is combined with a physically based approach used for the downscaling of surface pressure which is also required as input for the hydrological model. The method is based on the hydrostatic approximation and ideal gas law and is described in detail by Cosgrove et al. (2003). As recordings of incoming longwave and shortwave radiation are scarcely available, no statistical downscaling is carried out for these meteorological parameters. Instead, these parameters are bilinearly interpolated to the fine grid in case of all coupled model runs presented in this paper.

4 Results

The simulation results of the hydrometeorological model chain achieved with application of the statistical downscaling functions vari and vari&bias are shown in Fig. 5 together with the results obtained by using bilinearly interpolated MM5 simulations as well as meteorological observations as meteorological drivers. To provide the hydrological model a spin-up time of one year, the considered period of time is limited to the years 1972–2000.

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As Fig. 5a unfolds, PROMET driven by meteorological observations simulates daily discharge at gauge Achleiten with very good accuracy. The efficiency criteria of the coefficient of determination (R^2), as well as the Nash-Sutcliffe model efficiency (NSME) (Nash and Sutcliffe, 1970), with values of 0.9 and 0.84 for R^2 and NSME, respectively, justify the conclusion that PROMET is capable of simulating daily variability of water fluxes in the watershed with only small biases over a climatologic period of time. Figure 5b shows the results obtained when using bilinearly interpolated MM5 simulations to run PROMET. R^2 with 0.48 is much lower than that of the observation-driven model run. The value of NSME with -0.19 even indicates that the mean value of all discharge observations would have been a better predictor than the model system. The correction of subgrid-scale variability (vari) improves the quality of the hydrological simulations and leads to an R^2 of 0.56 and a NSME of 0.08. The additional correction of biases in the RCM simulations slightly reduces the value of R^2 to 0.53, but the NSME of 0.43 indicates an enhanced accuracy in simulated discharge. This can be explained by the fact that R^2 merely considers the covariance of discharge observations and simulations but not the difference between the observed and predicted parameter. As a result, R^2 can take high values even if the performance in terms of an exact reproduction of discharge volumes is poor. As the diagram in Fig. 5d further shows, the number of outliers is strongly reduced in case of the combined correction of subgrid-scale variability and bias in the RCM simulations. Despite all improvements in simulated discharge, the application of the downscaling functions vari and vari&bias did not reach the accuracy found in case of the observation-driven PROMET run.

5 Conclusions

A pragmatic approach for the downscaling of RCM-simulated precipitation, temperature, humidity and wind speed has been investigated in the framework of this paper in the context of hydrological modelling. The method gives the option to (i) only correct subgrid-scale variability and conserve mass and energy between the model scales or

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(ii) to include a bias correction in the downscaling process. As the approach is based on multiplicative or additive corrections it is computationally inexpensive and can be applied during runtime of a coupled model system. The method has been evaluated by comparison of daily discharge recordings to the simulations of a hydrometeorological model chain for the period 1972–2000 at the gauge of the Upper Danube Watershed in Achleiten. The results of this comparison prove that the downscaling approaches are capable of improving the performance of the hydrological model compared to the use of bilinearly interpolated MM5 simulations. Best results have been achieved when a bias correction is included into the downscaling process. Compared to an observation-driven model run carried out with the hydrological model PROMET, deviations from discharge recordings persist, which cannot be traced back to biases in precipitation, temperature, humidity and wind speed in terms of deviations from the mean monthly meteorological conditions observed for the study site. These differences in the hydrological model results can only be induced by differences in the temporal dynamics between the RCM data and the meteorological observations (e.g., rainfall intensities), by short-term differences in the meteorological fields, by differences in meteorological parameters that are not affected by the correction of biases (shortwave radiation, longwave radiation) or by an interaction of different hydrometeorological parameters. Additional studies are planned for the near future to further investigate these hypotheses. In the current model setup, part of the remaining inaccuracies in simulated discharge can be explained by the fact that the observation based meteorology of the ERA40 reanalysis influences the RCM simulations only every 6 h at the boundaries of the RCM domain. Other than in the “weather forecasting mode”, this “climate mode” does not include any reinitialization with observation-based data for the whole model domain. The spatial patterns and temporal dynamics within the RCM domain will hence never reproduce the exact observed temporal evolution of the small-scale meteorological conditions in the catchment. Furthermore, our downscaling approach developed to reproduce climatological means of hydrological key variables is expected to perform even better when validating on a monthly rather than on a very demanding daily time

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basis. As this study only considers MM5 simulations with a horizontal resolution of 45 × 45 km driven by the global boundary conditions of the ERA40 reanalysis, further studies will be needed to investigate the relative effects of global boundary conditions, different approaches of dynamical regionalization and various RCM grid resolutions on the results of impact models. A follow-up study is planned to answer these research questions. The ultimate goal of our studies consists in applying the downscaling techniques pesented here on the basis of a present day training period to future climate scenarios as suggested by the IPCC.

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References

Bach, H., Mauser, W., and Schneider, K.: The use of radiative transfer models for remote sensing data assimilation in crop growth models, in: Precis. Agric., edited by: Stafford, J., Werner, A., Wageningen, Academic Publishers, Wageningen, 35–40, 2003.

Cosgrove, B. A., Lohmann, D., Mitchell, K. E., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Marshall, C., Sheffield, J., Duan, Q., Luo, L., Higgins, R. W., Pinker, R. T., Tarpley, J. D., and Meng, J.: Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project. J. Geophys. Res., 108, 1–12, doi:10.1029/2002JD003118, 2003.

Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, Int. J. Climatol., 18, 873–900, 1998.

Früh, B., Schipper, J. W., Pfeiffer, A., and Wirth, V.: A pragmatic approach for downscaling precipitation in alpine-scale complex terrain, Meteorol. Z., 15(6), 631–646, 2006.

Grell, G. A., Dudhia, J., and Stauffer, D. R.: A description of the fifth-generation Penn State/NCAR mesoscale model (MM5), National Centre for Atmospheric Research, Boulder, NCAR/TN-398+STR, 1994.

Hagemann, S., Botzet, M., and Machenhauer, B.: The summer drying problem over Southeastern Europe: sensitivity of the limited area model HIRHAM4 to improvements in physical parameterization and resolution, Phys. Chem. Earth, 26, 391–396, 2001.
Jacob, D., Bärring, L., Christensen, O. B., Christensen, J. H., de Castro, M., Déqué, M., Giorgi, F., Hagemann, S., Hirschi, M., Jones, R., Kjellström, E., Lenderink, G., Rockel, B., Sánchez, E., Schär, C., Seneviratne, S. I., Somot, S., van Ulden, A., and van den Hurk, B.: An inter-comparison of regional climate models for Europe: model performance in present-day climate, Climatic Change, 81, 31–52, 2007.
Kotlarski, S., Block, A., Böhm, U., Jacob, D., Keuler, K., Knoche, R., Rechid, D., and Walter, A.: Regional climate model simulations as input for hydrological applications: evaluation of uncertainties, Adv. Geo., 5, 119–125, 2005.
Lazar, B. and Williams, M.: Climate change in western ski areas: potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100, Cold Reg. Sci. Technol., 51, 219–228, 2008.
Leung, L. R., Qian, Y., Bian, X., Washington, W. M., Han, J., and Roads, J. O.: Mid-century ensemble regional climate change scenarios for the Western United States, Climatic Change, 62, 75–113, 2004.
Ludwig, R. and Mauser, W.: Modelling catchment hydrology within a GIS based SVAT-model framework, Hydrol. Earth Syst. Sci., 4, 239–249, doi:10.5194/hess-4-239-2000, 2000.
Marke, T.: Development and Application of a Model Interface to couple Regional Climate Models with Land Surface Models for Climate Change Risk Assessment in the Upper Danube Watershed, PHD thesis, University of Munich, Digitale Hochschulschriften der LMU München, Munich, 2008.
Mauser, W. and Bach, H.: PROMET – a physically based hydrological model to study the impact of climate change on the water flows of medium sized, mountain watersheds, J. Hydrol., 376, 362–377, doi:10.1016/j.hydrol.2009.07.046, 2009.
Mauser, W. and Schädlich, S.: Modeling the spatial distribution of evapotranspiration on different scale using remote sensing data, J. Hydrol., (Special BAHC Issue), 212–213, 250–267, 1998.
Murphy, J.: An evaluation of statistical and dynamical techniques for downscaling local climate, J. Climate, 12, 2256–2284, 1999.
Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models, a discussion of principles, J. Hydrol., 10, 282–290, 1970.

Pfeiffer, A. and Zängl, G.: Validation of climate-mode MM5-simulations for the European Alpine Region, Theor. Appl. Climatol., 101, 93–108, 2010.
Sevruk, B.: Systematischer Niederschlagsmessfehler in der Schweiz, in: Der Niederschlag in der Schweiz. Beiträge zur Geologie der Schweiz – Hydrologie, 31, edited by: Sevruk, B., Schweizerische Geotechnische Kommission, Zürich, 65–75, 1985.
Strasser, U. and Mauser, W.: Modelling the spatial and temporal variations of the water balance for the Weser catchment 1965–1994, J. Hydrol., 254(1–4), 199–214, 2001.
Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, V., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 reanalysis, Q. J. Roy. Meteor. Soc., 131, 2961–3012, doi:10.1256/qj.04.176, 2005.
Wilby, R. L., Hay, L. E., Gutowski, W. J., Arritt, R. W., Takle, E. S., Pan, Z., Leavesley, G. H., and Clark, M. P.: Hydrological responses to dynamically and statistically downscaled climate model output, Geopyhs. Res. Lett., 27, 8, 1199–1202, 2000.
Wood, A. W., Leung, L. R., Sridhar, V., and Lettenmaier, D. P.: Hydrological implications of dynamical and statistical approaches to downscaling climate model outputs, Climatic Change, 62, 189–216, 2004.

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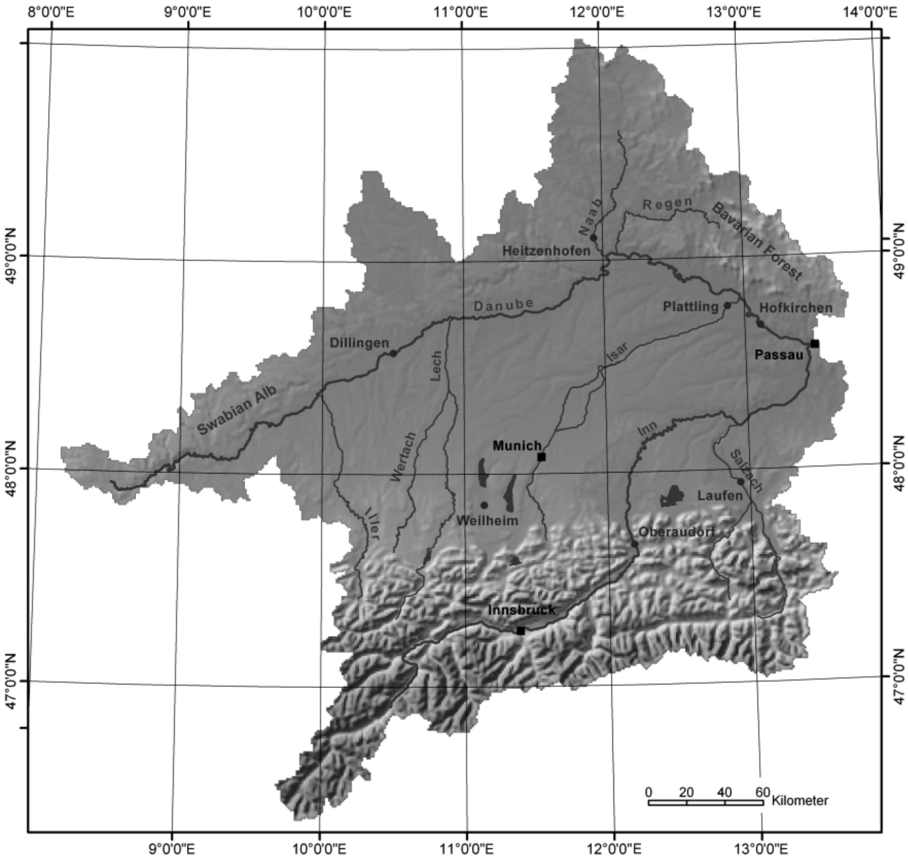

Fig. 1. The test catchment of the Upper Danube Watershed.

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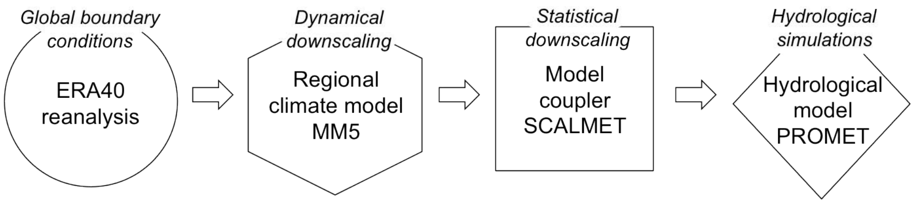

Fig. 2. Schematic overview of the hydrometeorological model chain used in the current study.

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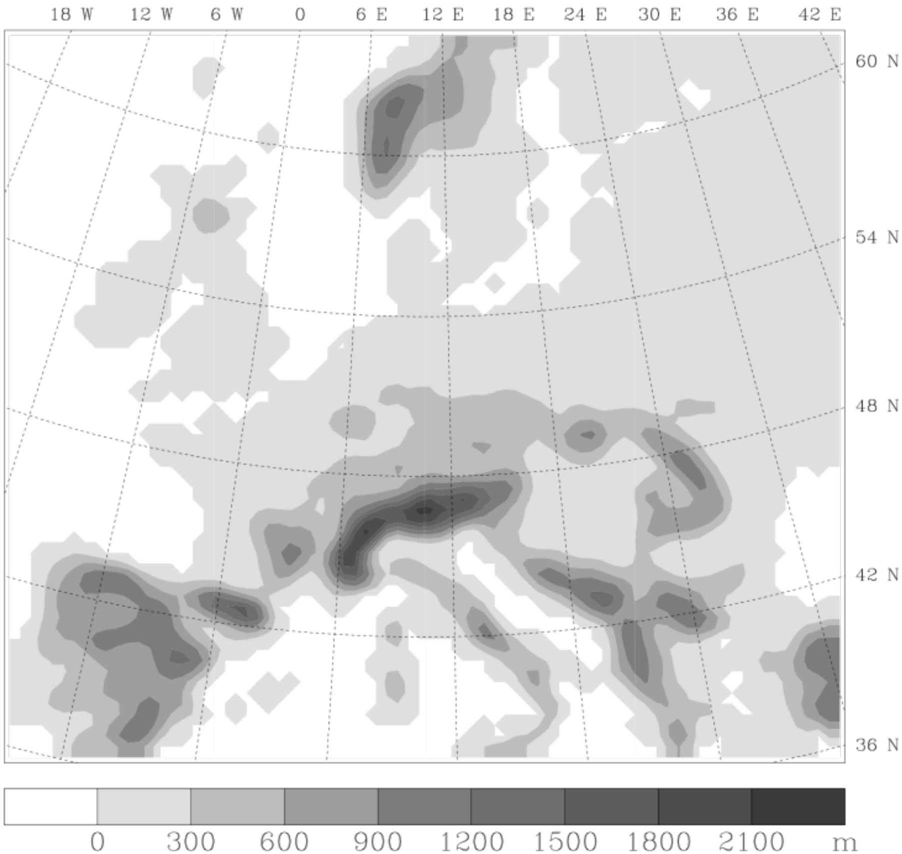

Fig. 3. Model domain of the regional climate model MM5.

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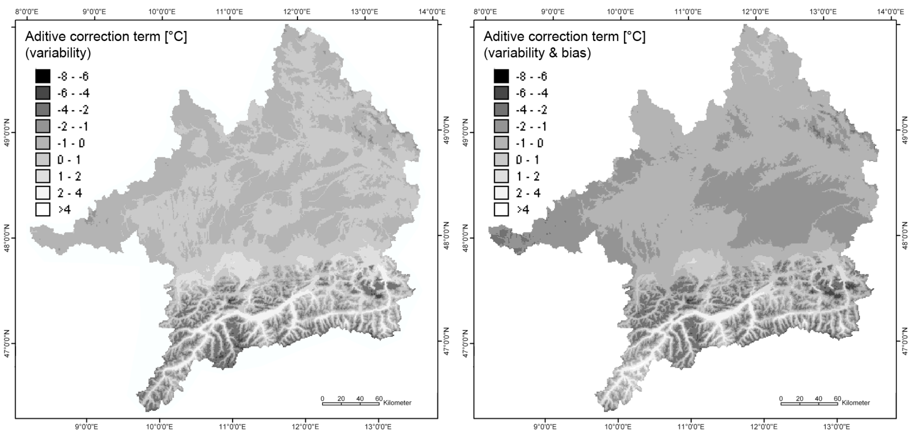

Fig. 4. Downscaling function for the correction of subgrid-scale variability (vari, 1 × 1 km) in MM5-simulated temperature (45 × 45 km) for January (left) and function for a combined correction of subgrid-scale variability and bias (vari&bias) in MM5-simulated temperature (ERA40 forcings) for January (right).

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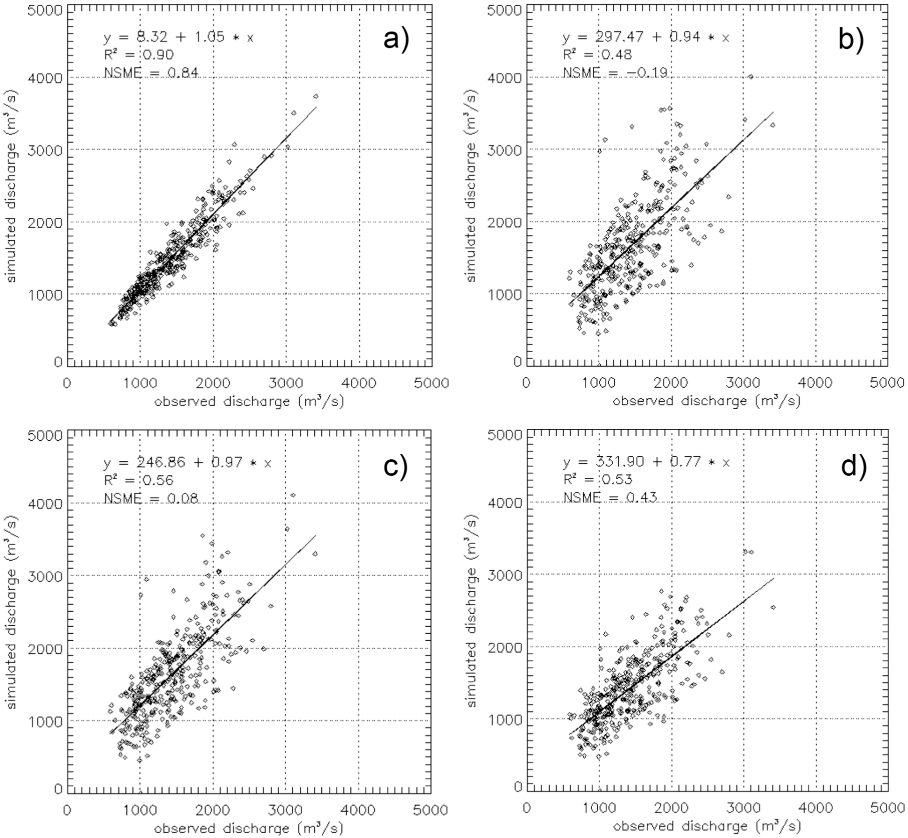

Fig. 5. Simulated versus observed daily discharge according to hydrological simulations driven by **(a)** meteorological observations, **(b)** bilinearly interpolated MM5 simulations, **(c)** downscaled MM5 simulations (vari) and **(d)** downscaled and bias corrected MM5 simulations (vari&bias) 1972–2000. The MM5 simulations are driven with ERA40-forcing.

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