Supplements

1 CanESM2 Large Ensemble

The first link is the Canadian Earth System Model, version 2 (CanESM2) large ensemble (LE) produced by the Canadian Centre for Climate Modelling and analysis (CCCma) (Fyfe et al., 2017; Kirchmeier-Young et al., 2017; Arora et al., 2011; Leduc et al., 2019). This large ensemble comprises 50 independent members from 1950 to 2100 with a spatial resolution of ~2.81° (T63) representing the internal (or natural) variability of the climate system by altering initial conditions, thus without changing the model structure or physics (Kirchmeier-Young et al., 2017; Fyfe et al., 2017). At first, a five member historical ensemble has been established initialized by 1000 iterations of a one-year equilibrium run of 1850 with preindustrial forcings (Kirchmeier-Young et al., 2017; Arora et al., 2011; Leduc et al., 2019). Within the timespan from 1850 to 2005, these members were forced by atmospheric changes, variability of the solar cycle, and explosive volcanoes, differing only in their initial state of cloud-overlap values (Leduc et al., 2019; Arora et al., 2011). Each of the five historical runs was further expanded from 1950 to 2100 by ten members through alterations of the initial cloud parameters (Leduc et al., 2019; Kirchmeier-Young et al., 2017; Fyfe et al., 2017; Sigmond et al., 2018). While natural and anthropogenic forcings were employed for the historical part of the members (1950 through 2005), the representative concentration pathway 8.5 (RCP8.5, van Vuuren et al. (2011)) emission scenario forced the simulations from 2006 and beyond (Kirchmeier-Young et al., 2017; Leduc et al., 2019; Fyfe et al., 2017; Sigmond et al., 2018).

The mismatch of spatial resolution between model outputs from the CanESM2-LE (~2.81° ≈ 310 km) and the hydrological model scale (500 x 500 m²) is likely to affect modelling results of the later. Thus, two common downscaling approaches (dynamical and statistical) were utilized consecutively to enhance the spatial resolution and foster the applicability for hydrological modelling.

2 CRCM5 Large Ensemble

The Canadian Regional Climate Model, version 5 (CRCM5; Martynov et al., 2013; Šeparović et al., 2013) was employed by the Ouranos Consortium on Regional Climatology and Adaptation to Climate Change to dynamically downscale the CanESM2-LE to 0.11° (~12 km) over two domains (Europe (EU) and northeastern North America (NNA)) for the available period from 1950 through 2099 and emission scenarios (historical until 2005, RCP8.5 from 2006 to 2100) (Leduc et al., 2019). These 50 transient simulations of the CRCRM5 Large Ensemble (CRCM5-LE; Leduc et al., 2019, data available at www.climex-project.org) provide the basis to assess the impact of climate change on hydro-meteorological extreme events for Bavaria and Québec. A comparison between the

CRCM5-LE and the E-OBS observational gridded dataset (Haylock et al., 2008) at the CRCM5 grid revealed biases for a historical period between 1980 and 2012 which show regional and seasonal variations in magnitude over Europe (Leduc et al., 2019). Within the study area of the hydrological Bavaria, a cold bias of down to -2 °C is dominant for long term mean air temperature values in all seasons but winter, where biases vary merely around zero (-1 °C to +1 °C). However, mountainous regions of the Alps and Alpine foreland exhibit a warm bias of up to +4 °C. Mean precipitation sums show a systematic wet bias throughout the year (Leduc et al., 2019), ranging from 1 to 2 mm d^{-1} in shallow areas and 2 to 4 mm d^{-1} in mountainous regions of the hydrological Bavaria, whereupon the larger bias occurs in winter.

Since this study focuses on high return levels of fluvial flood events, high intensity precipitation events of at least daily duration are important (Berghuijs et al., 2019; Keller et al., 2018; Merz and Blöschl, 2003). Hence, an adequate representation of these events in the historical or reference period of the RCMs compared to observations fosters the acceptance for impact studies. For our study area a comparison of moderate precipitation extremes of 10-year return levels between the RCM output and observations by Poschlod et al. (2021) revealed that differences in precipitation intensities of the RCM with a duration of 24 hours exhibit a slight overestimation north of the Alps (most of the areas below +20 %) and a smaller underestimation in the Alps (most parts above -10 %).

For further details on the performance of the CRCM5-LE over the respective domains and projected changes the reader is referred to Leduc et al. (2019) and Poschlod et al. (2021).

3 Bias correction

The biases in precipitation and air temperature of the CRCM5-LE during the historical period cannot be ignored within the study area, as they are supposed to affect the hydrological cycle simulated by the hydrological model (Poschlod et al., 2020; Maraun, 2016; Ehret et al., 2012; Teutschbein and Seibert, 2012). Thus, a quantile-mapping approach after Mpelasoka and Chiew (2009) (daily translation) was used to adjust the CRCM5-LE outputs required for the hydrological simulations (precipitation, 2m air temperature, relative humidity, surface wind speed, surface downwelling shortwave radiation) at the RCM scale. Therefore, the high resolution sub-daily climate reference (SDCLIREF; 500 x 500 m^2, 3-hourly data; not published) was aggregated to the RCM scale. Adjustments to the original approach (i.e., multiplicative and additive correction factors for variables other than precipitation (Willkofer et al., 2018), 3-hourly correction factors for every quantile bin and each month) allowed for its application to sub-daily data and a single set of correction factors derived from all 50 members of the ensemble was used for the adjustment of each member. Thus, the inter-member variability (i.e., natural variability) between all members was preserved. Prior to the bias correction of precipitation, the ratio of wet to dry days of the RCM

was adjusted to match the ratio of the observations by removing the ‘drizzle’ (insignificantly small precipitation values originating from the coarse scale of the RCM; Dettinger et al., 2004; Maraun, 2016). Since precipitation values below 1 mm d^{-1} do not significantly contribute to the overall precipitation sum (Dai, 2001) and this value is considered a standardized threshold (Kjellström et al., 2010; Maraun, 2016), we applied this threshold to the RCM precipitation data.
The quantile mapping approach is a common and frequently used method to adjust RCM outputs to match long term statistics of the observations as it often provides better adaptation to the observations than other methods and is applicable to climatic variables other than precipitation (Teutschbein and Seibert, 2012; Themeßl et al., 2011). However, this approach – as well as other bias adjustment methods – affects the distribution leading to changes in extreme values and consequently in altered climate change signals (Willkofer et al., 2018; Ehret et al., 2012; Maraun, 2016). This effect must be considered for the interpretation and discussion of the results. Furthermore, biases are further assumed to be stationary in space and time (Teutschbein and Seibert, 2012).

4 Statistical spatial downscaling

The bias adjusted data (~12 km x 12 km) were statistically downscaled to the hydrological model scale (500 m x 500 m). First, anomalies from the monthly mean state (1981-2010) were calculated for each timestep and CRCM5-LE grid cell center and subsequently interpolated with inverse-distance weighting to the SDCLIREF grid. After the anomaly fields have been interpolated, they were either multiplied by (for variables with an absolute zero value) or added to the reference fields of the SDCLIREF. To ensure mass conservation for each CRCM5-LE grid cell, the resulting downscaled fields were upscaled to the original CRCM5-LE grid to check for any necessary correction factors. The statistical downscaling was applied to each member individually.

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