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CH2018

Klimaszenarien für die Schweiz

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10. The CH2018 scenarios in use

Summary

As the most up-to-date collection of climate change information on Switzerland, the CH2018 scenarios are an important source of data for impact research and practical adaptation issues. The CH2018 scenarios are discussed for illustrative use cases to foster understanding as well as to demonstrate the wide application of the CH2018 data products.

- So-called “climate analogs” suggest that the future Swiss climate is similar to the present-day climate near the northern Mediterranean coastline.
- An application to runoff shows that decadal variability strongly modulates the long-term change. Thus, the transient evolution of climate variables should be taken into account in order to develop realistic expectations.
- Snow pack is a complex quantity formed by the interplay of a number of variables. Simulations for the Swiss Alps reveal that due to compensating effects, the combination of temperature and precipitation change is still an adequate predictor of the response.
- Weather generators are promising tools in efforts to overcome some of the limitations of the downscaling method used in CH2018. The recently developed Advanced WEather GENerator (AWE-GEN-2d) provides impact-relevant climatic variables at a high temporal and spatial resolution and is evaluated within the sister project Hydro-CH2018 for hydrological downscaling applications in a climate change context.
- A stakeholder dialog has been initiated to provide continued support and close interaction with users of the CH2018 scenarios. As a kind of “climate service”, this stakeholder dialog prepares the groundwork for an ongoing interaction between providers and users of the CH2018 scenarios under the umbrella of the recently founded National Center for Climate Services (NCCS).
- Due to the complexity of the CH2018 climate scenarios, there is no single physically consistent scenario for “strong climate change”. The most drastic changes in summer hot spells, extreme winter precipitation, or any other parameter are not all found in the same simulations. Thus, the behavior of the individual simulations should be considered when deriving an impact-specific climate change scenario from the range of CH2018 projections.

As the most up-to-date collection of climate change information on Switzerland, the CH2018 scenarios are an important data source for impact research and practical adaptation issues. To foster understanding as well as to demonstrate the wide application and ensure consistent treatment of the CH2018 data products, this chapter describes illustrative cases of the CH2018 scenarios in use (Chapter 10.1, Chapter 10.2), comments on the process of engaging with stakeholders to achieve a broader application of the scenarios (Chapter 10.3), and provides some guidance on their use (Chapter 10.4).

In order to better communicate and improve understanding of changing climatic conditions, such as “2.5 °C warmer and 20 % precipitation decrease”, the development and use of climate analogs is demonstrated (Chapter 10.1). These climate analogs express the projected changes in temperature and precipitation in terms of existing climates in other regions of Europe today.

In the following section, a first application of CH2018 scenarios in hydrology is discussed (Chapter 10.2). Because a lack of precipitation and low-flow conditions result in substantially reduced water availability and will likely challenge the current allocation of water use and rights, a case study (Chapter 10.2.1) looks into the use of CH2018 data in such an application context. It shows how the transient nature of the localized CH2018 projections yield a richer picture of expected impacts, depicting the compound influences of trend and variability. Given the relevance of snow conditions in the Alpine region, not least for ski tourism, the CH2018 scenarios are applied for a snow pack analysis (Chapter 10.2.2). These simulations demonstrate the application of CH2018 data in a multivariate context, using snow as an example of a complex entity formed through the interplay of precipitation with the environmental variables of temperature, sunlight, and wind. The hydrological example applications confirm the improvements in and better usability of the new CH2018 projections. Some of the remaining limitations of the downscaling method used in CH2018 can be addressed using *weather generators*. These statistical models that mimic natural variability on top of projected changes are discussed as an example of applying CH2018 data in technical development (Chapter 10.2.3).

Most users are not so much interested in the climate as such, but in the performance of the systems and infrastructures they are responsible for and depend upon. Such users thus care about the *impact* of weather and climate (see also the section about risk, Chapter 6). Consequently, in parallel to the development of the new climate scenarios, a dialog with public and private stakeholders has been established to facilitate optimal use of the CH2018 results. This dialog will continue past 2018 under the umbrella of the Swiss National Center for Climate Services (NCCS) and is pursued in the spirit of co-development of knowledge and co-design of decision-support systems (Chapter 10.3). Impact researchers who are not climate modelers will presumably be working together with regional climate modelers who have expertise in generating impact scenarios. Accordingly, the present chapter is intended as a contribution to this collaboration, aimed at a mutually beneficial improvement of understanding and the co-development of truly connected impact chains. This will not only further our knowledge, but also improve decision-making in the context of optimizing the performance of complex systems. Many such applications will consider only a subset of the complex CH2018 scenario data, as the entire range of projections may not be manageable computationally, or may not be relevant for a specific question. A section on best practices (Chapter 10.4) at the end of this chapter outlines how to make a selection of data with due care for consistency and robustness.

10.1. Analogs for the future Swiss climate

The projected climate changes in Switzerland as outlined in Chapter 4 can lead to significant modifications of the present-day temperature and precipitation climate. However, it can be difficult to grasp the meaning and consequences of, for instance, a 2.5 °C temperature increase in wintertime or a 20 % summer precipitation decrease. To better illustrate such changes, climate analogs can be useful. Climate analogs are locations that currently experience a climate that is similar to the projected (i.e., the future) climate of a given site of interest. The recent work by Dahinden et al. (2017) [69] introduced a method to identify such analogs based on the normalized similarity of climatological seasonal mean values of temperature and precipitation between the projected climate for a site of interest and the present-day climate of a potential analog.

Here, a modified version of this technique is applied to identify climate analogs for individual sites in Switzerland. Modifications concern (1) the bootstrapped use of the standard deviation of seasonal mean values for the reference site in the period 1981 - 2010 instead of the standard deviation in a pre-industrial control climate, (2) the use of ensemble median projections instead of individual model projections, and (3) the application of a dissimilarity threshold of 4 instead of 2, implying a less strict exclusion of poor analogs (see Equations 1 and 2 in [69]). For this purpose, the localized scenarios of Chapter 5 (QM to stations), the ensemble-median projected climate for RCP8.5, and the late scenario period (2085) are used. As potential analogs, 2472 stations in Europe for which the present-day climate of the reference period 1981 - 2010 can be derived based on available daily observation data are considered (data sources: ECAD, GSOD, and the automated MeteoSwiss network).

Figure 10.1 presents the results in terms of combined temperature and precipitation analogs for the four sites of Zurich/Fluntern, Weissfluhjoch, Lugano, and Sion. For all stations except Weissfluhjoch, the best analogs are found at more southerly latitudes and are mostly located in the Mediterranean region.

Exceptions are the third- and fifth-ranked analogs for Zurich Fluntern, which are located on the coast of the Black Sea (Sochi and Tuapse, Russia). For the high-Alpine site of Weissfluhjoch, the climate analogs are found in the Alpine region itself, but are located at lower elevations.

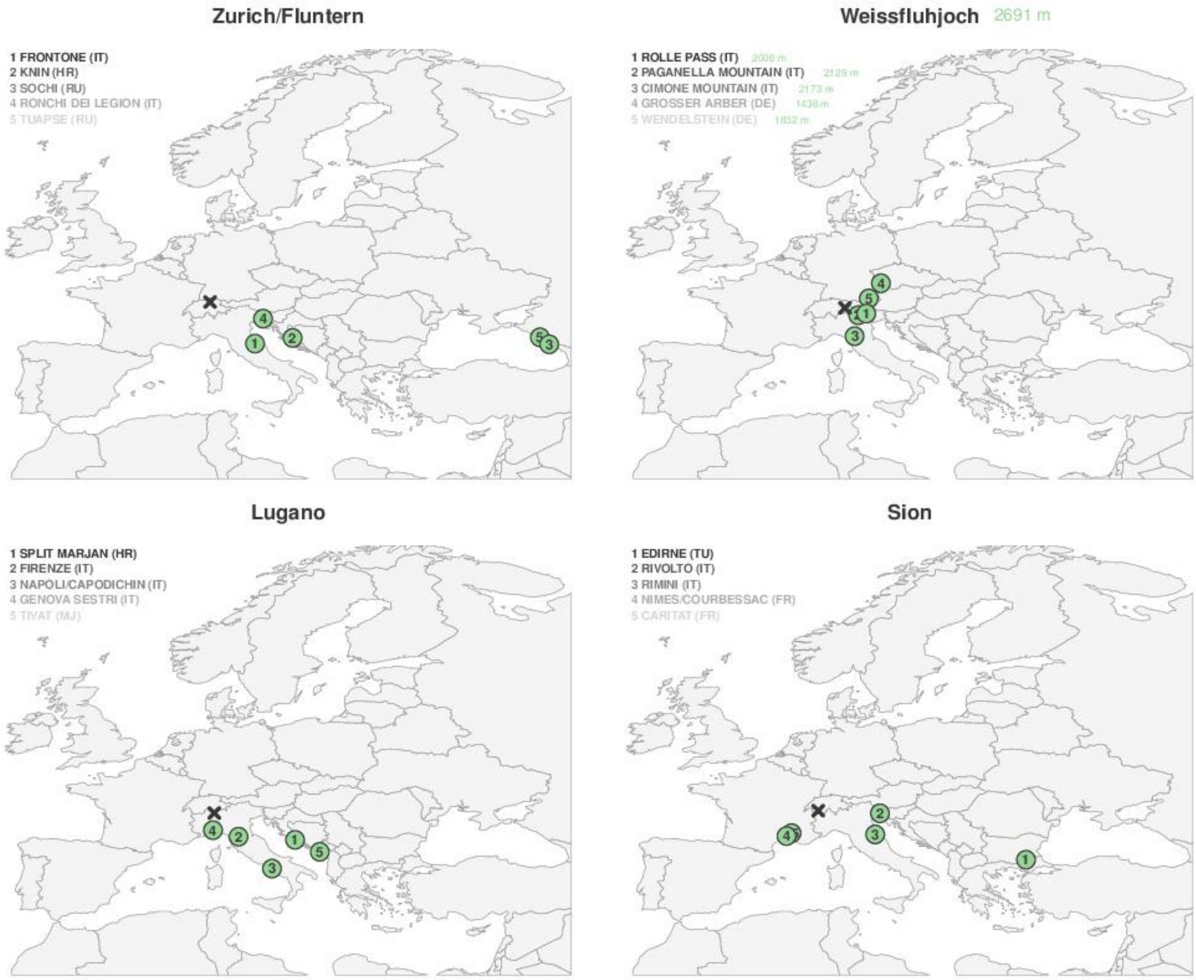

Figure 10.1. Combined temperature and precipitation climate analogs for the 2085 scenario period based on the ensemble median of all model chains for RCP8.5 and on the localized scenarios (QM to stations). Each panel presents the analogs for one of the four sites of Zurich/Fluntern, Weissfluhjoch, Lugano, and Sion (marked by a black cross). The names in the upper left part of each panel represent the five best analogs (top/black to bottom/grey indicating decreasing quality of the analogs in terms of their similarity to the projected climate for the respective site of interest). In addition, elevation information is provided for the site of Weissfluhjoch and its five analogs.

If projected future precipitation is disregarded and only temperature conditions are considered, the best climate analogs are typically found at even more southerly locations (Figure 10.2). For these analog stations, present-day temperature conditions are close to the projected climate at Swiss sites for RCP8.5 at the end of the century, but drier climates than projected for the Swiss sites typically prevail. This difference in precipitation is the reason why these sites are typically not among the combined temperature and precipitation analogs. For Zurich/Fluntern, the five best temperature analogs are located in the Spanish highlands and in Croatia on the Adriatic coast. The best analogs for Lugano and Sion are mostly found along the Mediterranean coastline. For Weissfluhjoch, again, geographically closer analogs that are located at lower elevations are found. An outstanding exception is the Russian site of Vajda-Guba, situated on a peninsula in the Barents Sea, which is the third-best temperature analog for Weissfluhjoch. This site is located at a much lower elevation compared to the other four analogs for Weissfluhjoch, but it has a similar temperature climate due to its northerly location.

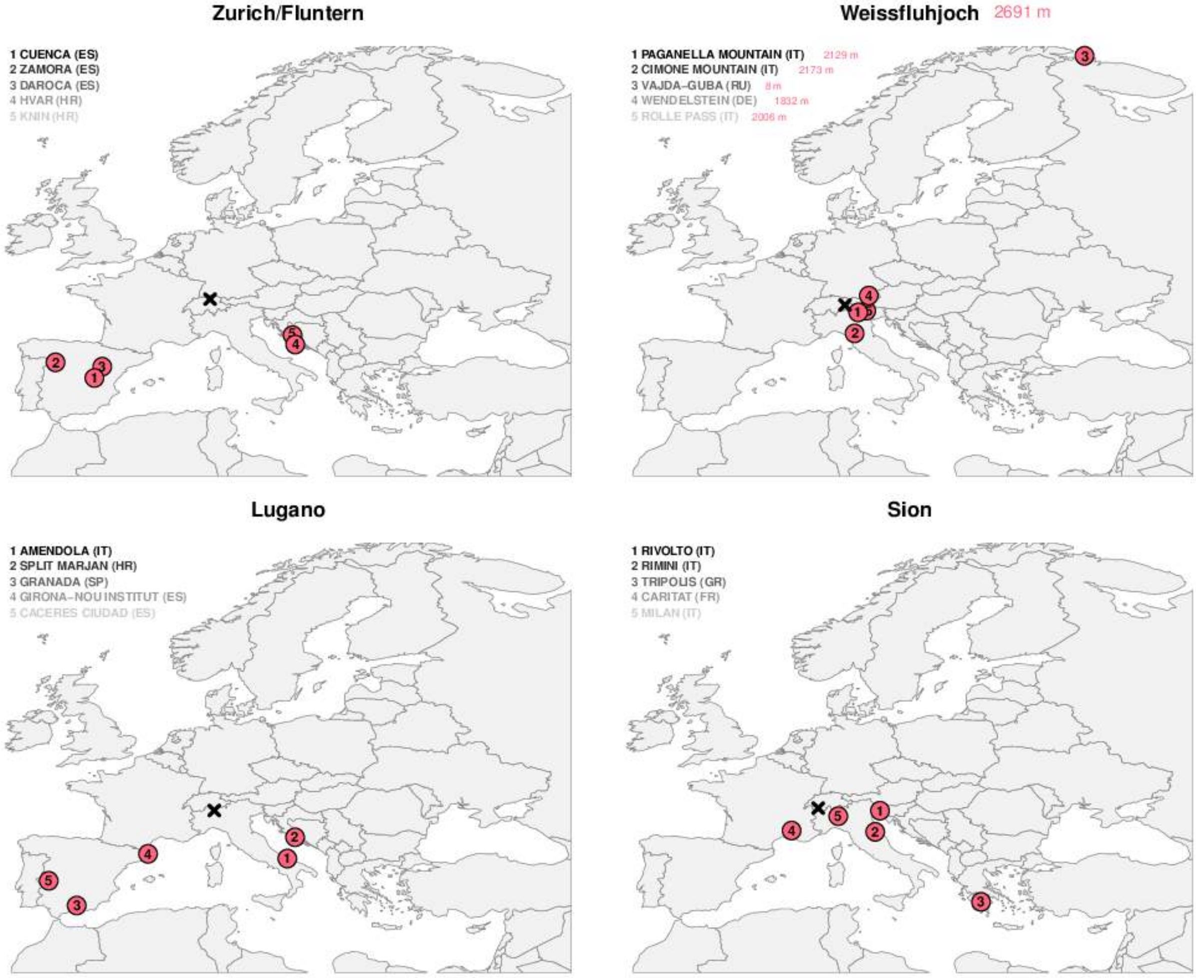

Figure 10.2. Temperature-only climate analogs for the 2085 scenario period based on the ensemble median of all model chains for RCP8.5 and on the localized scenarios (QM to stations). Each panel presents the analogs for one of the four sites of Zurich/Fluntern, Weissfluhjoch, Lugano, and Sion (marked by a black cross). The names in the upper left part of each panel represent the five best analogs (top/black to bottom/grey indicating decreasing quality of the analogs in terms of their similarity with the projected climate for the respective site of interest). In addition, elevation information is provided for the site of Weissfluhjoch and its five analogs.

It should be noted that these results provide an illustrative but only approximate picture of future climate change in Switzerland. Only seasonal mean values of temperature and precipitation are considered and, furthermore, only one similarity measure. Different variables and metrics might be more informative for specific applications. There are indeed limitations: Although temperature and precipitation may change to make a site's climate more similar to that of another, the amount of radiation or insolation (which depends crucially on latitude) will not. In addition, the final set of best analogs depends on the sample of all potential analogs considered (2471 sites in Europe in our case). Still, the results presented are considered to be useful for communicating the possible future of the Swiss climate in an illustrative manner.

10.2. Use cases in a hydrological context

Experience with the previous generation of Swiss Climate Scenarios, CH2011, has revealed a number of difficulties with the practical application of the data in research and adaptation, some of which could have been avoided through early interactions with users [287]. Below, two example applications of the CH2018 data products that have been produced in close collaboration between providers and users of the climate scenarios are presented. Both examples represent typical use cases in hydrology and illustrate the benefits and limitations of the new CH2018 scenario data. The station data of the DAILY-LOCAL dataset (Chapter 9) serves as the input of the impact models in both cases. The first example explores future changes in low-flow conditions for a typical Swiss catchment and sheds light on the benefit of continuous transient time series. This investigation is a contribution from the project "Hydro-CH2018", a sister project of CH2018 that aims to produce hydrological scenarios for Switzerland, a further "focus area" of the National Center for Climate Services. The second example explores the benefit of incorporating additional variables beyond temperature and precipitation. Both examples show the applicability and the capabilities of the CH2018 data, but also reveal certain limitations still present that call for future scientific developments. One appealing technique for overcoming some of these limitations involves weather generators. In Switzerland, two types of weather generators developed in the context of hydrology are presented in (Chapter 10.2.3).

10.2.1. Transient projections of summer streamflow in the Thur basin

Background

The summer droughts of 2003 and 2015, and to a lesser extent 2011, are today regarded as extraordinary events for Switzerland that provide an indication of what might be normal by the mid-21st century (see [117]). Indeed, projections based on the CH2011 scenarios [56] revealed a strong intensification of hydrological droughts on the Swiss Plateau, especially for the second half of this century [115]. With the new CH2018 scenarios and their improved representation of changes in dry periods and updated summer temperatures and precipitation projections, an enhanced quality of summer streamflow projections is achievable. Furthermore, transient projections until the end of the century facilitate assessment of the direction of change, the variability of summer streamflow, and the speed of change under climate change conditions. This study presents a first glance at summer streamflow development for the Thur river.

The setting of the study

The hydrological model WaSiM-ETH Version 9.10 is applied to the Thur catchment. Calibrating the model against the observed discharge at Andelfingen (calibration period: 1991 - 1999) yields very good results, although a slight overestimation of low flow is inevitable. For details of the model validation, please refer to [288].

Because the bias-corrected CH2018 scenarios (see Chapter 5) provide the highest quality only for temperature and precipitation, here empirical, temperature-derived evapotranspiration estimates (Hamon equation) are used instead of complex evapotranspiration algorithms, which require the projection of less trustworthy meteorological variables (e.g., wind speed). It should be noted that this approach is still the subject of an ongoing discussion in the scientific community, as the Hamon equation is based on (past) empirical relationships that may not hold under future climate conditions. Here, input data quality is favored over the uncertain effect of empirical algorithms.

Data from various meteorological stations for temperature (4 stations) and precipitation (9 stations) within and around the catchment are used to interpolate the required spatial fields that drive the hydrological model for the reference period 1981 - 2010. Climate model data downscaled for the same stations but running from now until the end of the century (1981 - 2099) (see Chapter 5) are subsequently likewise interpolated. An interpolation technique that introduces as little artifact as possible is chosen. These long, transient time series of meteorological fields enable a transient simulation of hydrological responses. As each parameter at each station is bias-corrected independently, slight spatial inconsistencies can occur and likely affect the interpolated fields. The magnitude of this effect is unknown, but first tests suggest only marginal effects on the interpolated fields. Nevertheless, this issue must be considered when interpreting the results. To avoid arbitrary simulation results, all 9 ensemble members of the EUR-11 models under the RCP8.5 emission scenario are used (Table 4.1) rather than a selection of models. This approach captures climate model uncertainties and a wide range of the seasonal to decadal natural climate variability inherent in each model run. Summer streamflow is defined as the mean streamflow during July, August, and September. This selection is based on the current runoff regime type of the tributaries of the Thur that indicate a propensity for low flow especially during the late summer period.

Projected summer streamflow until the end of the century

Figure 10.3 depicts the mean summer streamflow for the measured discharge data (black), modeled discharge based on meteorological observations (red), and modeled discharge based on the downscaled 9 EUR-11 simulations (shaded areas; median: blue line). The hydrological model captures the range of summer streamflow values and broadly matches the observations. The overestimation of low flows found in the validation results thus does not affect the mean summer values. In contrast, the climate model data-driven simulations slightly underestimate (on average 3.4-6.0 $m^3 s^{-1}$ or -8 %) the summer streamflow (compared to the reference run). Note that differences between climate model data-driven hydrological simulations and the observation-based hydrological simulation for summer streamflow for an individual year should not be interpreted, as they result from different climate variabilities inherent in each model. Rather, only long-term climatological differences should be interpreted, either as a) biases, meaning the differences between climate model-driven simulations and the reference run, and the observations, respectively, or b) as a change signal – that is, the difference in streamflow between two time periods of the scenario run.

The summer streamflow values driven by the EUR-11 climate models reveal a median decrease of ~54 % from 42 $m^3 s^{-1}$ (reference period) to 19 $m^3 s^{-1}$ (2085) in the Thur catchment from the present day until the end of the century. This decrease is approximately linear, with considerable year-to-year variability and small decadal changes (Figure 10.3). The total ensemble spread (on average 52 $m^3 s^{-1}$) and the interquantile range (IQR, on average 22 $m^3 s^{-1}$) of these simulations are considerable yet quite stable over the entire simulation period. This reflects climate model uncertainty and natural climate variability.

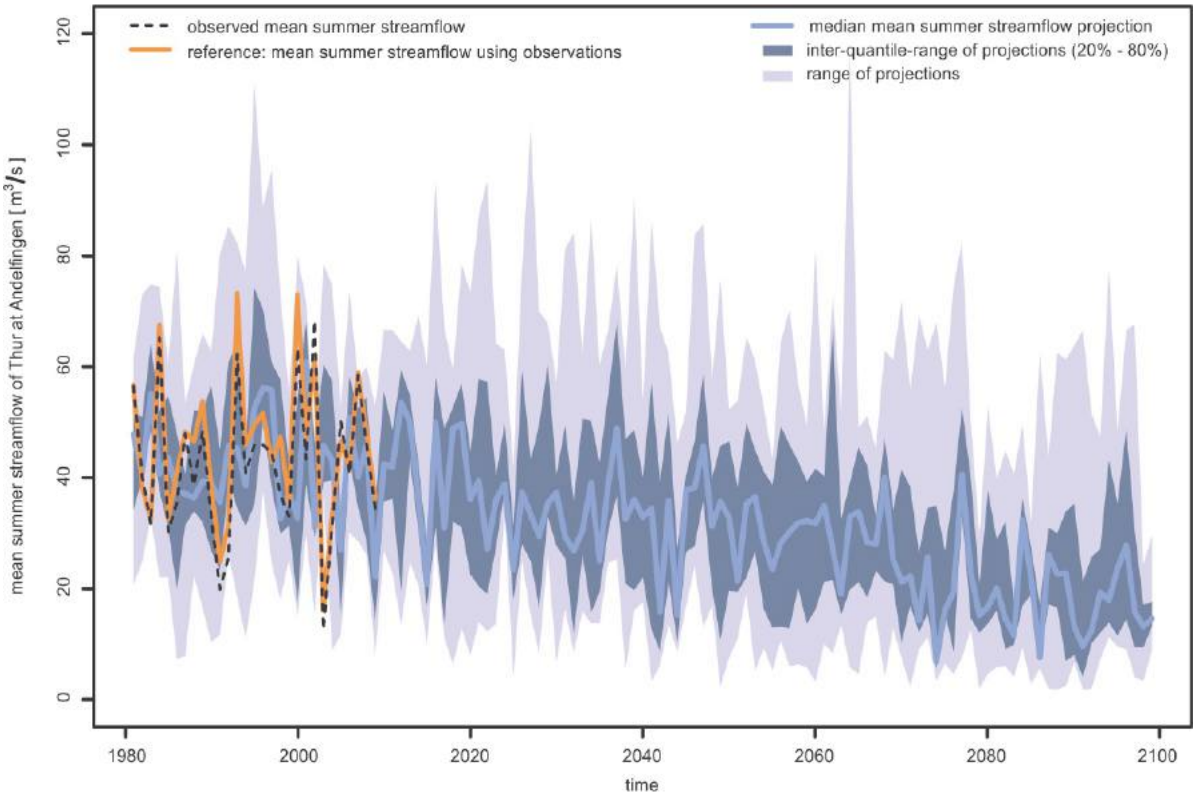

Figure 10.3. Summer streamflow in the Thur catchment for the period 1981 - 2100 represented by the ensemble median (blue line) with the interquantile range (blue shadings) and ensemble spread (purple shadings). The observed discharge (black line) and the simulated discharge driven by meteorological observations (red line) for the reference period 1981 - 2010 serve as benchmarks.

What is new?

The decline in the summer streamflow of the river Thur can likely be linked to a combination of decreased summer precipitation, enhanced evapotranspiration, and longer dry spells. In part, this decline was known from hydrologic scenarios based on CH2011 [115]. Unlike in the earlier study, an intensification of the climate change signal after mid-century is not projected; rather, the results show a steady decline starting in the present day. The transient simulations provide users an indication of the magnitude of the change in summer streamflow, the development of the change rate, and especially the year-to-year variability. Whether this summer streamflow projection holds for other drought-related indices must be addressed in further studies. This applies, for example, to *Q347*, a politically important index of low-flow conditions used in the Swiss national water protection law (Art. 4, Swiss Water Protection Act). Such information is relevant to discussions regarding how often an official *Q347* value should be updated or which value should be used in future water concessions. A comprehensive application of the new climate scenarios to transiently project this and many other hydrological parameters under climate change conditions for Switzerland is being conducted within the Hydro-CH2018 initiative led by the Federal Office of the Environment.

10.2.2. The projected snow pack in the Alps toward the end of the century

Background

The snow pack in the Alps, as in any other mountain region, is a key component of the hydrologic cycle, storing water from the winter and releasing it in spring and early summer, when environmental and agricultural demands for water are usually greatest. The size of the snow pack can be expressed in snow water equivalent (SWE), which is the amount of water obtained from melting a sample of snow. SWE is expressed as the equivalent depth of water (mm w.e.) in that unit area. In most river basins in the Alps, snow is currently the largest component of water storage and is vulnerable to climate change due to its high temperature sensitivity. This study investigates how SWE develops with the projected changes in the main meteorological variables that determine the accumulation and ablation of the snow pack in the Alpine valley of Davos at roughly 1500 m a.s.l.

The setting of the study

The physical snow model SNOWPACK (version 3.41) and MeteoIO (version 2.6.1) were applied for pre-processing to calculate SWE [203, 18]. For the reference period (1981 - 2010), the following measured meteorological variables in hourly resolution were used: air temperature, precipitation, relative humidity, global radiation, and wind speed. Precipitation values have been corrected for under-catch in the case of sub-zero temperatures. Because SNOWPACK needs sub-daily values as input, the CH2018 scenarios (available only in daily resolution) could not be applied directly. For this reason, daily change values were calculated for each meteorological variable based on the difference or ratio between the daily values of the reference period and the scenario period. These delta values (i.e., one value per day) could then be used to perturb the measured meteorological variables in order to enable modeling of the SWE for the scenario period (2085) under the assumption of the RCP8.5 emissions. The annual cycle of these daily change values is based on bias-corrected seasonal scenarios at the station scale (see Chapter 5). The absolute mean annual cycles in both the calibration and scenario periods have been smoothed, taking the four seasonal means and interpolating them to 366 values with a spline-smoothing function. The change signal was applied on a daily basis: additive for temperature and wind and multiplicative for precipitation, relative humidity, and global radiation. Because CH2018 provides no information about longwave downward radiation, this important variable was parameterized with air temperature and relative humidity; as a result, longwave radiation is automatically enhanced in the scenario period due to the increasing air temperature and relative humidity. Three manually chosen climate model chains were used in order to demonstrate the possible variability originating from the choice of the climate model. The three model chains can be distinguished primarily by their low, medium, or high temperature response over the CHAE region.

Snow water equivalent at the end of the century

For the reference period, SNOWPACK is successfully able to model the annual SWE cycle (Figure 10.4). There is only a small overestimation in the accumulation period (November - mid-March) and a small underestimation in the ablation period (mid-March - April). The maximum SWE currently occurs in the middle of March, with values of about 260 mm. For the end of the century (2070 - 2099), the three climate model chains all show a clear change toward lower SWE values and a shorter period with snow on the ground. The maximum SWE seems to occur only about a week earlier. However, there is a large spread between the climate model chain with the greatest temperature sensitivity and that with the smallest. The decrease in maximum SWE varies between 10 and 60 %, that of seasonal mean SWE (Nov – Apr) between 40 and 80 %, and that of the snow cover period between 1 and 2.5 months. A comparison between the lowest SWE projection (red curve) and the currently observed minimum values during snow-scarce winters (not shown) reveals that such a – nowadays extreme – SWE evolution might be normal toward the end of the century.

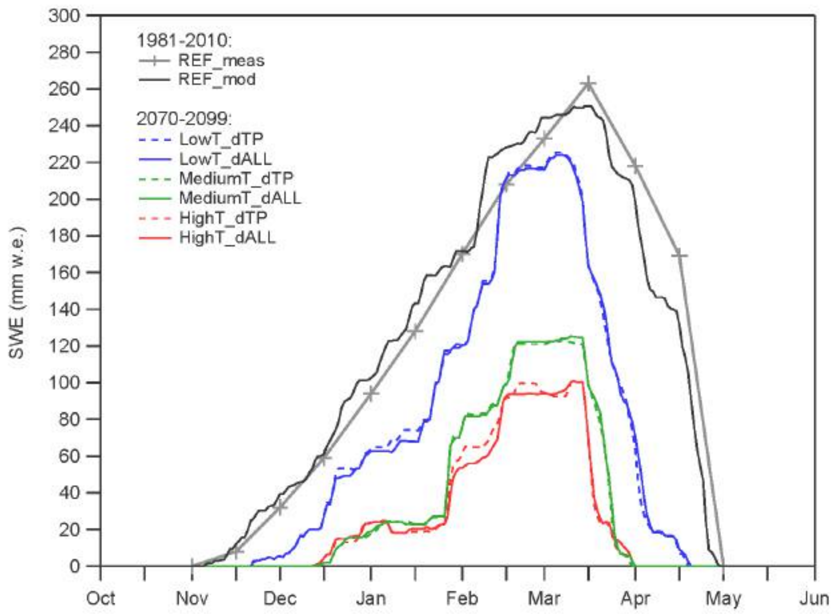

Figure 10.4. Mean SWE evolution for the 1981 - 2010 period (grey and black) and toward the end of the century in Davos at 1590 m a.s.l. for three climate model chains with differing temperature sensitivity. The low response is simulated by the ECEARTH-HIRHAM GCM-RCM model chain (blue), the medium response by IPSL-RCA (green), and the high response by HADGEM-CCLM5 (red). The dashed colored lines represent the future mean SWE evolution when only the projected temperature and precipitation changes are considered (dTP). The solid colored curves represent the future mean SWE evolution when the changes in global radiation, relative humidity, and wind speed (i.e., in all meteorological input variables) are also considered (dAll).

What is new?

The future decrease in SWE in the Alps due to climate change is not new and has thus far been explained by the dominating role of temperature, which determines whether snow or rain falls and how fast a snow pack melts. However, there was always the question of the impact of changes in relative humidity, global radiation, and/or wind speed. The CH2018 scenarios allow for the first time separate investigation of the impacts of changes in most of the major meteorological variables that are needed to force a physical snow model. The projected changes in these meteorological variables generally have the same sign (but different amplitude) for all three chosen climate model chains. With the exception of temperature, the spread among the different variables is relatively small – mainly due to the fact that the agreement between the various model chains is better in winter compared to summer.

The following changes in future SWE toward the end of the century are found for the RCP8.5 scenario when wind speed, global radiation, and relative humidity are modified individually for each of the three climate models (i.e., without changing temperature or precipitation). The projected changes for wind speed are very small and mostly negative. This implies that there are a few occasions with slightly less erosion and less snow melt, which increases the mean (Nov - Apr) SWE by about 8 %. The projected increase in precipitation is accompanied by a 5 - 10 % decrease in global radiation and a 1 - 5 % increase in relative humidity. This is physically meaningful in the sense that there are known processes that can explain these changes: Increasing precipitation may cause more cloudiness and more periods with high relative humidity values. On its own, the decrease in global radiation causes about a 13 % increase in SWE. Similarly, the increase in relative humidity alone results in a 6 - 9 % increase in SWE. It can be concluded that the impacts of the projected changes in global radiation, relative humidity, and wind speed are positive, almost model-independent, and, assuming linearity, sum up to an increase in SWE of almost 30 %. However, these individual changes are not independent of one another, and because the projected increases in global radiation and relative humidity cause a strong increase in downward longwave radiation, the combined effect (i.e., when considering the changes in all meteorological input variables) is almost the same as when considering only air temperature and precipitation. This has the advantage that earlier simulations, which only considered changes in temperature and precipitation are not obsolete.

The question remains whether these results are also valid for lower and higher elevations, or whether there is an elevation dependence for certain variables due to physical processes that become more or less relevant at lower or higher elevations. Additionally, this case study demonstrates that sub-daily CH2018 scenarios would be preferable for impact models that need to consider the daily evolution of the meteorological variables.

10.2.3. Weather generators

Localized projections of climate variables derived using the quantile mapping method have a number of limitations (Chapter 5.7), including the misrepresentation of spatial climate variability on short timescales and the lack of ensured intervariable consistency. Both are key concerns for hydrological applications. The severity of these limitations, however, depends on the specific impact considered.

Weather generators are promising tools in efforts to overcome some of these limitations. Weather generators are essentially statistical models to mimic the observed record. Once calibrated for a given location, they can generate an arbitrary number of synthetic time series of current weather that are all consistent with observations [142, 186, 383]. This ensemble of stochastically generated time series then allows researchers to investigate natural variability at the local scale. For the use of weather generators as a downscaling tool, the calibrated parameters of the generator are perturbed with changes derived from climate models. In this way, changes in the temporal correlation structure (e.g., alterations in the dry-wet sequences) can be incorporated. A further advantage of weather generators is their physical consistency between several variables, achieved by conditioning dependent atmospheric variables on the dry/wet state of a given day. In Switzerland, two different kinds of weather generators with differing levels of complexity have been developed over recent years to serve the hydrological community.

A weather generator for use as a downscaling model was recently developed in Switzerland [181] to address specific scientific questions such as the comparison of stochastic uncertainty with other sources of uncertainty. To serve a broad segment of the impact community, the degree of complexity and associated calibration requirements of this weather generator was purposely kept low. The generator consists of several Richardson-type weather generators calibrated at several stations. The time series are generated in such a way that the spatial correlation structure of observations (and hence the spatial amount of precipitation over a catchment) is preserved [382]. The precipitation model was extended by conditioning daily temperature on the generated precipitation state. The weather generator has been extensively validated [181] and took part in the validation experiments of the COST VALUE initiative (http://www.value-cost.eu). A key advantage of the Keller et al. weather generator is the incorporation of the spatial correlation structure of daily precipitation (Figure 10.5). It performs well for mean conditions and moderate indices. Limitations include a somewhat weaker performance for extreme value statistics and an underestimation of interannual variability. In Keller et al. (2017) [182], the weather generator was tested in a climate change context and applied to a hydrological model for an intercomparison of different downscaling methods [288].

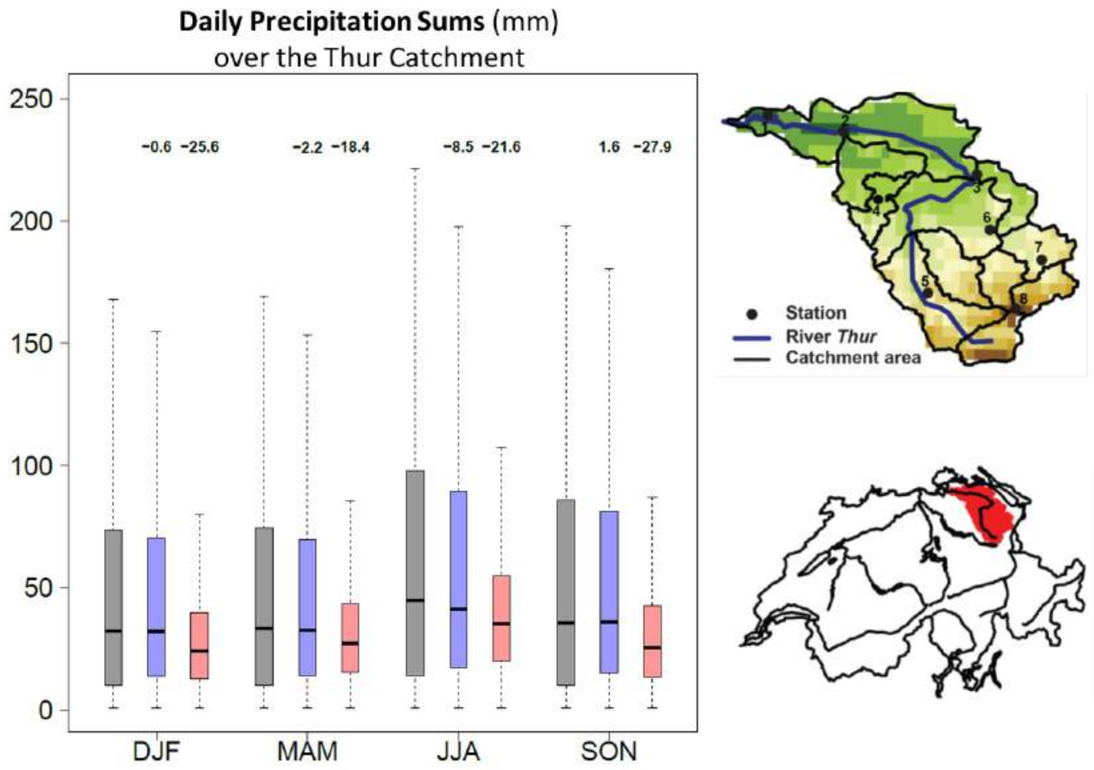

Figure 10.5. Daily non-zero precipitation sums over the catchment for the four seasons during the period 1961 - 2011. The daily precipitation intensity of the eight stations is summed, and days with an area sum of zero are excluded. Box plots of observed daily sums (grey), simulated time series accounting for the spatial structure (blue), and uncorrelated time series in space (red) are shown. The weather generator was run 100 times over a 51-year time period. The numbers (in percentage) above the blue and red boxes represent the relative deviation of the simulated median from the observed median. Figure from [181].

A need often expressed by climate change impact researchers is that for sub-daily input data on several physically consistent variables. The weather generator of Keller et al. (2015) [181] is not designed for such applications, and hence more complex tools are required.

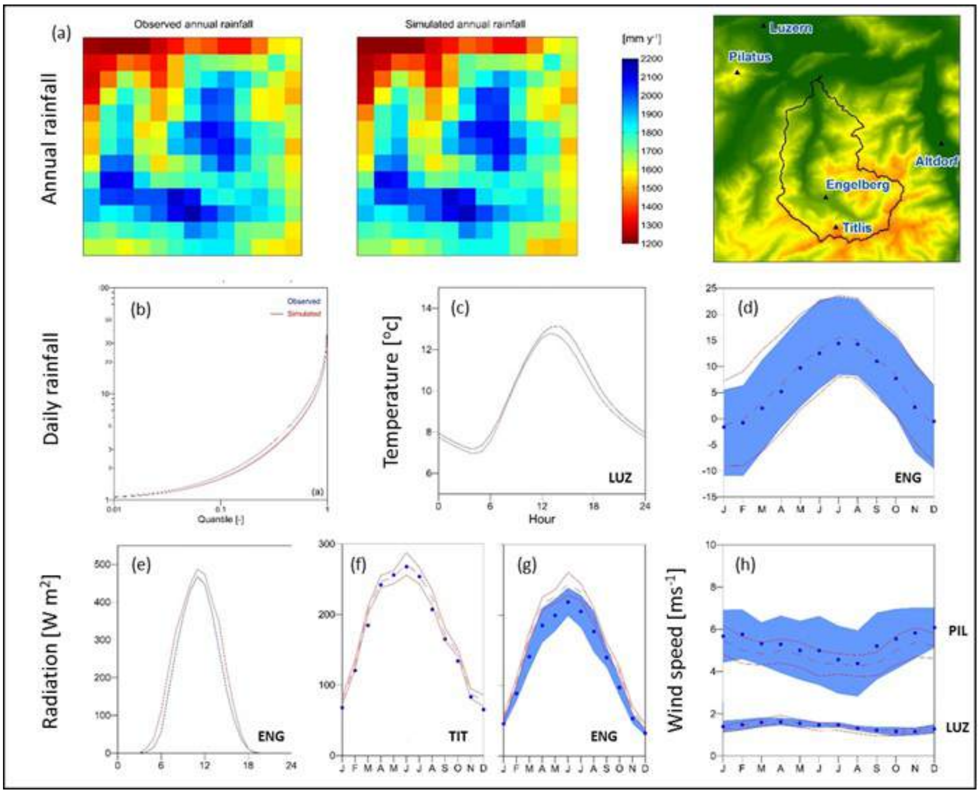

Figure 10.6. Example of present climate representation (1981 - 2012) by AWE-GEN-2d for the Engelberg area. (a) Median observed annual rainfall and mean of the median of the simulated ensemble; (b) inverse cumulative distribution function of the daily rain intensity over a given 2 x 2 km^2 grid cell; (c) observed and simulated average daily cycle of near-surface (2 m) air temperature for Luzern station; (d) observed and simulated near-surface (2 m) air temperature for each month for Engelberg station (blue dots and red dashed lines represent observed and simulated median values, respectively, and bounded blue and red areas represent observed and simulated 5 - 95 % quantile range, respectively); (e) observed and simulated average daily cycle of incoming shortwave radiation for Engelberg station; (f) and (g) observed and simulated incoming shortwave radiation for each month for Titlis and Engelberg stations, respectively; and (h) observed and simulated near-surface wind speed, considering terrain effects, for each month for Pilatus and Luzern stations. The climate ensemble was generated using 50 realizations of 30 years each (figures from [256]). The same datasets were used for the calibration and validation of the model.

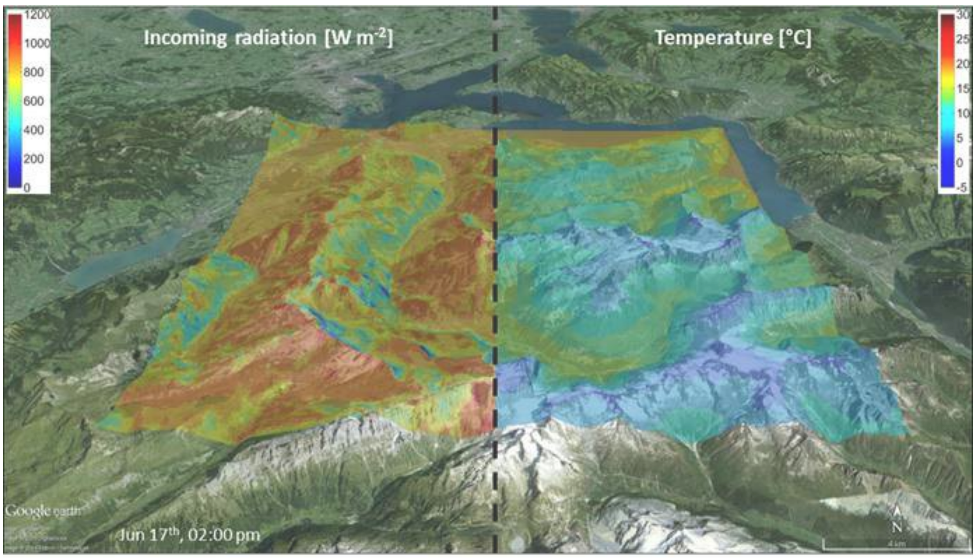

Figure 10.7. Example of a high-resolution simulation with AWE-GEN-2d. Incoming shortwave radiation (left) and temperature (right) are simulated for a spatial resolution of 100 x 100 m^2 and a temporal resolution of 1 h.

One such more complex tool is the new stochastic Advanced WEather GENerator for a 2-dimensional grid (AWE-GEN-2d), which was recently presented by Peleg et al. (2017) [256]. In fact, it is a substantial evolution and combination of four preceding models: (i) AWE-GEN (Advanced WEather GENerator [176, 93]), (ii) STREAP (Space-Time REalizations of Areal Precipitation [255]), (iii) HiReS-WG (High-Resolution Synoptically conditioned Weather Generator [257]), and (iv) WINDS model [44]. AWE-GEN-2d combines physical and stochastic approaches to simulate key climate variables (e.g., precipitation, cloud cover, near-surface air temperature, solar radiation, vapor pressure, atmospheric pressure, and near-surface wind) at high spatial and temporal resolution. The use of combined stochastic-physical methods makes it possible for researchers to account for the dependence between meteorological variables and to simulate them at sub-daily temporal scales; this typically exceeds the capabilities of empirical-statistical weather generators because the statistical correlations at sub-daily scales are complex to model. AWE-GEN-2d is used to simulate the impact of future climate scenarios and their variability on hydrological scenarios in Switzerland as part of the Hydro-CH2018 initiative.

AWE-GEN-2d requires spatially distributed data for calibration. These include time series from ground stations, gridded data from remote sensing, and areal averaged data from reanalysis products. The resolution of the calibration data determines the resolution of the simulated fields (e.g., 2 km x 2 km and 5 min for precipitation when using the MeteoSwiss weather radar composite, and 100 m x 100 m and 1 h for other climate variables when using hourly data from ground stations).

AWE-GEN-2d is parsimonious in terms of computational demand and is therefore particularly suitable for studies in which exploring internal climatic variability at multiple spatial and temporal scales is fundamental. The model is suitable for studying the impacts of stochastic climate variability, spatial heterogeneity, and temporal and spatial resolutions of climate forcing, as well as for climate downscaling. In this respect, the model can also be conveniently used in the context of climate change by modifying the model parameters using climate data derived from dynamical climate models. For Hydro-CH2018, the model is re-parameterized to be consistent with the projections of the present report. The re-parameterization of the sub-daily climate variable is achieved by scaling the parameters of the climate models from daily to hourly resolution. The use of AWE-GEN-2d as a stochastic downscaling technique can allow the investigation of the role of natural variability in future climate scenarios (e.g., [94]). This enables an explicit quantification of the uncertainty associated with the natural variability of climate, which cannot be explored either by direct use of climate model scenarios or by any other common downscaling techniques. However, although the model can reproduce the variability related to the chaotic nature of climate (i.e., for stationary climate), it cannot reproduce multi-decadal variability when this is associated with deterministic non-stationary processes such as changes in ocean circulation, changes in atmospheric circulation, volcanic activity, changes in carbon dioxide concentration, solar cycle variability, or poor sampling of low-frequency periodic processes.

Applications of the model include modeling of environmental systems in which high spatial and temporal resolution of meteorological forcing is crucial for the correct simulation of hydrological, ecological, agricultural, and geomorphological processes. Due to its convenient re-parameterization for the future climate, it can also be efficiently used in climate impact and adaptation studies at the river-basin scale.

The weather generator was calibrated and validated for the Engelberg region, an area with complex topography in the Swiss Alps (see [256]). Model tests show that the climate variables are generated by AWE-GEN-2d with a level of accuracy sufficient for most practical applications. Examples of the model's high-resolution outputs and performance are given in Figure 10.6. Further details can be found at: http://www.hyd.ifu.ethz.ch/forschung/models/awe-gen-2d.html.

10.3. Stakeholder dialog

ETH Zurich, MeteoSwiss, and the University of Bern have been preparing and running model simulations to provide new climate scenarios to Swiss citizens in general and to the Swiss adaptation and mitigation community and climate-impact modellers more specifically. Feedback from the European climate scenarios community was gathered at an early stage in a two-day workshop. This was complemented by an external study on users' needs [230]. This study highlighted the fact that only approximately half of the respondents (all of whom had a professional interest in climate change) had made use of CH2018's predecessor, CH2011 [56]. When asked about specific variables, actual use dropped to about a quarter of respondents [230 p. 36]. Depending on the variable, another quarter to a third of respondents had skimmed the brochure or the variables (ibid.). The study also revealed that the use of the summary was equally high for scientists and practitioners, whereas the background report was used predominantly by the scientists [230 p. 37]. In order to meet producers' (and users') expectations, the study concluded with five recommendations for CH2018: namely, to i) address a more diverse set of users, ii) allocate more resources for dissemination, iii) provide personal advice, iv) incorporate information on the impacts of climate change, and v) provide an online platform to access the raw data [230].

Since 2017, a stakeholder dialog has been running alongside the development of the climate scenarios. This dialog has brought together scientists and both public and private organizations that anticipate or experience impacts of climate change. Taking on board the recommendations of the report on users' needs [230], the CH2018 stakeholder dialog enables the exchange of experiences among stakeholders and between stakeholders and climate scientists. The structure and process of the stakeholder dialog are based on the experiences of other countries producing climate scenarios, as well as on the CH2018 predecessor CH2011 [325]. It is also inspired by the experiences of the authors with similar processes in the context of climate adaptation studies [328].

However, because the modeling activities had proceeded beyond a stage at which larger stakeholder requests could be incorporated, the influence of the stakeholder dialog on modeling decisions was restricted to the recommendations of the MeteoSwiss (2016) report [230]. Consequently, in the dialogs, emphasis was placed on questions regarding presentation, delivery, support, and additional products. To a great extent, the stakeholder dialog thus focuses on enhancing understanding and improving the decision-making context of individual users in relation to climate change. Hence, the stakeholder dialogs represent an important contribution in transforming the scenarios from "pure" climate information into a climate service. As a forum for discussion and reflection, the stakeholder dialogs should ideally be able to improve understanding also among the stakeholders as to where climate-critical thresholds and decision-restraining factors are located in their activities. Thus, the dialog itself can be seen as a climate service as well.

The stakeholder dialog has three phases. In phase one, a pilot project with exploratory interviews and discussions with a subset of stakeholders was completed in early Summer 2017. The goal was to discuss the current use of climate information and services, as well as to solicit feedback on a draft process of the stakeholder dialog. In this pilot phase, the dialog team met with six individual organizations including federal and cantonal administrations, an industry association, a non-governmental organization, and a private infrastructure utility. The pilot phase with exploratory interviews represents the innermost circle in Figure 10.8.

Based on the insight derived from phase one to focus more on the use of a particular variable rather than on many, phase two revolves around urban heat. The reasons for selecting this issue include high scientific confidence as well as its links to many sectors through urban adaptation. In phase two, "pull-style dialogs" with key stakeholders began in Spring 2018. The selection of these "key" stakeholders was based on the Swiss Federal Council's adaptation strategy [114], which identifies "the greatest challenges in adapting to climate change in Switzerland" according to the vulnerabilities of sectors to key climatic changes [114 p. 8]. For example, some of the challenges the energy sector faces are related to "greater heat stress in agglomerations and cities” (ibid.). The stakeholder selection process sought to encompass a number of relevant challenges and sectors, as well as to include a heterogeneous sample of organization forms, ranging from federal and cantonal administrations to the private sector, industry associations, and NGOs. To ensure that key stakeholders were involved in the dialogs, active efforts by the team to ensure their inclusion were made – the “pull-style” method. Additionally, various other relevant organizations have been notified of the ongoing dialogs and invited to join on a voluntary basis. This approach is referred to as the “push-style” (see Figure 10.8).

In phase three, a quantitative survey of stakeholders including questions on their usage of and needs regarding climate services was sent out in the first half of 2018. These stakeholders are located in the outer circle of the CH2018 stakeholder dialog (Figure 10.8). About 500 organizations, mainly organized interest groups from the private sector and NGOs, as well as municipal, cantonal, and federal administration officials, were targeted as recipients of the survey. Other activities, such as workshops and training sessions, were held in close consultation with the stakeholders in phase two. At the time of this report’s publication, the evaluation of the collected data from the CH2018 stakeholder dialog is still ongoing.

Although the CH2018 project ends in Autumn 2018, the established interactions and dialogs should be continued and possibly institutionalized. The National Centre for Climate Services (NCCS) is committed to ensuring that climate information and climate services will be used by the federal, cantonal, and municipal administrations, as well as by civil-society groups and private-sector unions and associations. In the long term, the NCCS will be the knowledge broker for enquiries on climate services and will engage in various networking activities to ensure the inclusion of stakeholders.

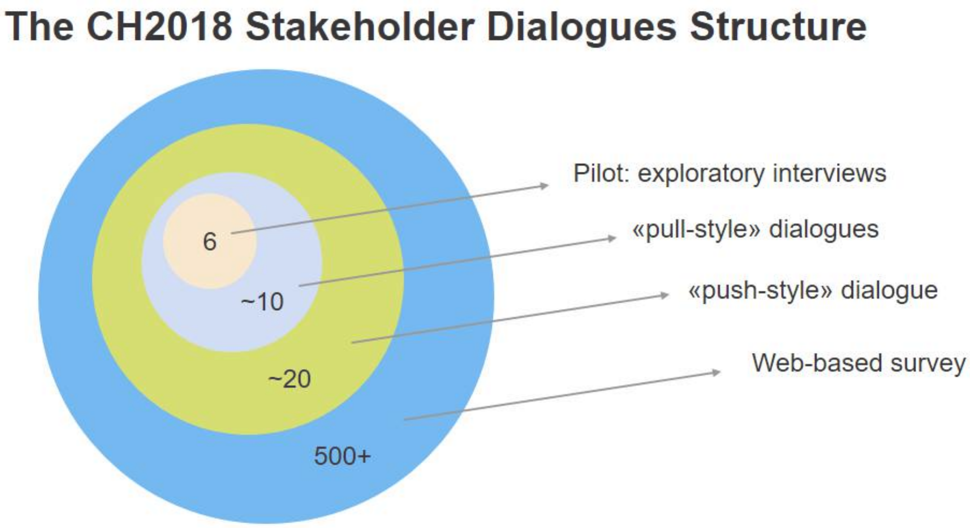

Figure 10.8. Schematic depiction of the CH2018 Stakeholder Dialogs. Inner circle: In phase one, the dialog process and structure was tested through exploratory interviews with six organizations. Inner-middle circle: Based on the Swiss adaptation strategy [114], active efforts to include approximately 10 key stakeholders in the dialogs were made in a “pull-style” fashion to ensure their participation in the process. Outer-middle circle: An additional set of stakeholders was informed about the process using a “push-style” method. The initiative to join the dialog remains with the respective organizations. Outer circle: A larger set of organizations, ranging from Swiss municipalities to organized sector interest groups, were asked about their use of climate information through a web-based survey.

10.4. Best practices for scenario selection

The CH2018 projections consist of a complex set of data. The 30-year averaged model data and indices listed in Table 9.3 and presented in chapters 4 to 6 vary along three different dimensions: time periods, RCPs, and climate-uncertainty quantiles. The CH2018 projections can thus be illustrated by a "scenario cube" [57] (Figure 10.9). The scenario cube represents the full complexity of the climate simulations in aggregated form. When working with the aggregated CH2018 datasets, considering the entire cube ensures that all information contained in the projections will be used. However, this is not always possible due to limited resources, nor is it always necessary in order to extract the information of interest.

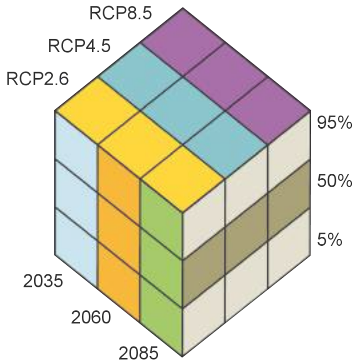

Figure 10.9. Scenario cube illustrating the possible combinations of time period, forcing scenario, and climate uncertainty inherent in the CH2018 projections (after [57]).

Because the climate projections are based on somewhat arbitrarily selected emission scenarios or RCPs, best practice does not necessarily require the consideration of all possible combinations covered by the scenario cube. In the context of adaptation to climate change, it is not crucial where the uncertainty originates (anthropogenic forcing or climate uncertainty). Rather, the relevant information concerns the full range of possible future outcomes from the lower end of the RCP2.6 mitigation scenario projection to the upper end of the RCP8.5 high-emission scenario projection. The statement, for example, that "global surface temperature change by the end of the 21st century is unlikely to exceed 2 °C for RCP2.6" [169] is not very informative for adapting to climate change, since the non-mitigation scenarios must be considered as a possible future outcome as well. In an adaptation context, it therefore makes sense to define an "adaptation scenario" – a climate change scenario defined in much the same way as the RCPs, i.e., by the conscious selection of a meaningful and consistent set of outcomes within the projected ranges. For example, a scenario for risk-adverse adaptation could be defined by taking the upper end of the projected summer temperature range for RCP8.5, i.e., the highest of the values displayed in Figure 4.4 in each region (this corresponds to choosing one element of the scenario cube). Because the projected ranges represent the statistics of the whole climate model ensemble available, this selection is robust. A similar approach was used to define the "Starker Klimawandel" (strong climate change) scenario in the Swiss Federal Council's strategy for climate change adaptation [116].

The difficulty with defining a climate change scenario in this way is that a strong change in summer temperature does not imply a similarly strong change in winter temperature, nor a similarly strong change in other seasons, or in variables other than temperature (Figure 10.10). In other words, the projections assessed for a given variable, index, or season are not necessarily correlated. For example, although the simulations with strong summer drying highlighted in Figure 10.10 exhibit a pronounced winter wetting, the correlation between summer and winter precipitation is not generally very high.

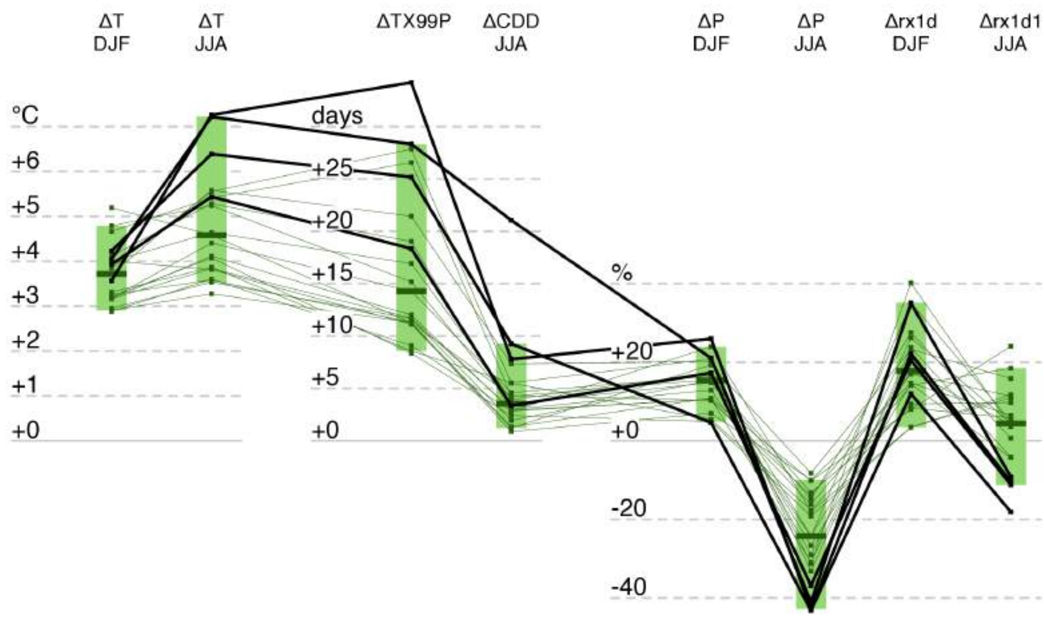

Figure 10.10. CH2018 projection ranges for different variables/indices and seasons (DJF/JJA) for the region CHW and RCP8.5 at the end of the century, including changes in seasonal mean temperature (ΔT), very hot days (ΔTX99P), consecutive dry days (ΔCDD), seasonal mean precipitation (ΔP), and mean seasonal 1-day precipitation maximum (Δrx1d). Fine lines correspond to individual simulations connected across the different changes (circles in Table 4.1). Bold lines indicate the simulations showing the strongest summer drying (ΔP JJA). The data corresponds to the SEASONAL-REGIONAL and INDEX-REGIONAL datasets (Chapter 9).

Without further investigation, a climate change scenario can therefore only be defined for one variable, region, and season in order to avoid physically improbable combinations that are not supported by the underlying simulations. This might be enough to assess some climate impacts that essentially depend on a single climate variable. However, impacts may result from the interplay between different variables or from the interaction across different seasons of the year, calling for multivariate, multi-seasonal scenarios. These scenarios should be plausible combinations of different variables (as well as plausible combinations across different seasons or regions), i.e., they should be consistent. To derive a consistent climate change scenario, one must look for underlying climate simulations that simulate the day-to-day variation in different climatic variables in a physically consistent manner. For the example of summer temperature change, the climate simulations often exhibit a strong summer warming in combination with a strong reduction in summer precipitation (Figure 10.10). This would justify the definition of a “strong climate change” scenario as a combination of upper-end temperature change and lower-end precipitation change, as it was indeed defined in the aforementioned adaptation strategy [116]. With the addition of other variables and indices, the definition of a scenario becomes more complex, as there may be both strongly correlated and largely uncorrelated parameters. This means that there is no single physically consistent scenario for “strong climate change”. This can also be seen from Figure 10.10. To reduce complexity, four different possible manifestations of “strong climate change” in Switzerland have been summarized using four alternative climate change scenarios. The CH2018 climate scenarios focus on qualitatively diverse changes:

1. *Dry summers*: decrease in summer precipitation and increase in summer temperature and in the maximum number of *consecutive dry days* (*CDD*)
2. *More hot days*: increase in the temperature of the *hottest day of the year* (*TXx*) and in the number of *very hot days* (*TX99P*).
3. *Heavy precipitation*: increase in frequency and intensity of rare (*rx1d*) to extreme (*x1d100*) precipitation events

4. *Snow-scarce winters*: reduction in snow cover and frequency of snowfall and rise of zero-degree line due to rising winter temperature

Each of these scenarios is designed to represent the scope of possible changes that could plausibly occur within the range of projections in CH2018, assuming no mitigation of climate change. Accordingly, the scenarios are generally defined by the “likely range” of the projections (Chapter 4.7.4) for RCP8.5 and period 2060 (see Table 13.1). The exception to this rule is the scenario *heavy precipitation*, which is defined by the central projected values (the multi-model-median). This is because the projected range is strongly influenced by statistical uncertainty (as opposed to climate model uncertainty). For scenarios 1, 2, and 4, the median over the five CH2018 regions is used as a representative value for Switzerland as a whole. For scenario 3, the maximum change over the five CH2018 regions is taken.

Each of the four scenarios, however, only combines those changes that coexist in a subset of the CH2018 ensemble. For example, the simulations with pronounced dryness in summer (scenario 1) are not the same as those with a strong increase in heavy precipitation in winter (scenario 3). It should be noted that these scenarios represent the changes that can result from a superposition of both forced change and natural variation (Chapter 7), since the distinction between the two is irrelevant for the purposes of adaptation.

Complementing the four scenarios of “strong climate change”, one scenario for “weak climate change” has been defined: *When climate mitigation takes hold*. This scenario describes the four manifestations of climate change (scenarios 1 - 4) in the case of an ambitious mitigation path compliant with the 2 °C target (Chapter 2.2, Table 13.3).

In summary, the CH2018 climate scenarios depict the range of possible climatic changes in Switzerland. This range encompasses the scope of climate mitigation from a coordinated worldwide effort exhausting all mitigation options to a complete failure to mitigate, as well as the scientific uncertainty of climate simulation (Chapter 2.7).

The climate change scenarios outlined above show that “strong climate change” or “weak climate change” can mean different things, and different impacts will stand out in each scenario. Thus, in order to select the correct scenario for the study of a certain type of impact, a good understanding of its causes is necessary. First, a quantitative knowledge of the main climatic phenomena causing various impacts is required; these may be appropriately captured by model variables or derived indices, depending on the level of detail of the impact analysis. Second, the sensitivity of the impact system must be known (e.g., in the form of an impact model, impact response surfaces, etc.). The sensitivity of the impact system is often derived by studying climatic impacts under current or past climate conditions. This analysis should also reveal which part of the projected range of climatic changes is of interest (median, extreme case, lower quantile, etc.). Finally, the formulation of the impact model used determines whether individual simulations are needed or whether the statistics of the model ensemble (i.e., quantiles) provided by the CH2018 projections are sufficient for an impact analysis (e.g., the 95 % quantile of summer temperature increase).

Applications in research on the impacts of climate change typically require coherent time series of several variables and high temporal and spatial resolution. This calls for the use of individual simulations, which are available for the model variables listed in Table 9.2. As discussed above, physical consistency is essentially ensured in this case (except that quantile mapping can potentially destroy some of the multivariate structure). However, by selecting just a few individual simulations, one loses information on robustness (e.g., the simulation with the largest temperature increase is not necessarily the one with the strongest summer drying). In other words, the selected simulations do not cover the entire scenario cube. For a robust impact assessment, however, one should retain as much spread as possible in the parameters to which impacts are sensitive (e.g., changes in winter temperature and summer precipitation). A ranking of individual simulations can be useful as a basis for selecting a small simulation set that meets this requirement. Table 10.1 shows a simulation ranking for six climatic parameters selected from the CH2018 projections.

GCM	init	RCM	DJF ΔT (°C)	JJA ΔT (°C)	ΔTX99P (days)	JJA ΔCDD (days)	DJF ΔP (%)	JJA ΔP (%)	DJF Δrx1d (%)	JJA Δrx1d1 (%)
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E	3.2	4.1	8.4	2.4	4.9	-19	3.5	11
ICHEC-EC-EARTH	r3i1p1	DMI-HIRHAM5	2.9	3.3	11	1.3	11	-10	8.0	24
ICHEC-EC-EARTH	r12i1p1	CLMcom-CCLM4-8-17	3.2	4.4	14	4.6	16	-29	26	4.4
ICHEC-EC-EARTH	r12i1p1	CLMcom-CCLM5-0-6	3.2	3.8	12	3.0	13	-24	35	4.9
ICHEC-EC-EARTH	r12i1p1	SMHI-RCA4	4.1	5.3	19	2.8	11	-31	22	-11
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	4.0	7.2	28	21	21	-41	35	-9.2
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM5-0-6	3.7	5.6	21	7.4	20	-31	40	3.6
MOHC-HadGEM2-ES	r1i1p1	ICTP-RegCM4-3	3.8	5.6	28	5.5	5.4	-18	9.4	9.7
MOHC-HadGEM2-ES	r1i1p1	KNMI-RACMO22E	4.8	5.2	15	3.6	15	-15	28	0.70
MOHC-HadGEM2-ES	r1i1p1	SMHI-RCA4	4.7	5.4	27	4.3	10	-14	17	11
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	3.3	3.9	8.6	5.5	21	-33	24	-4.1
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM5-0-6	3.3	3.6	11	4.2	16	-27	14	-4.3
MPI-M-MPI-ESM-LR	r1i1p1	SMHI-RCA4	4.0	4.6	17	3.9	17	-24	18	4.1
MPI-M-MPI-ESM-LR	r2i1p1	MPI-CSC-REMO2009	2.9	3.6	9.1	2.8	24	-18	3.5	12
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6	4.0	3.8	11	1.2	19	-8.2	23	16
MIROC-MIROC5	r1i1p1	SMHI-RCA4	5.2	4.6	11	0.89	7.0	-10.0	15	6.5
CCCma-CanESM2	r1i1p1	SMHI-RCA4	3.6	7.3	34	7.8	26	-43	22	-10
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4	4.2	6.4	25	9.3	4.6	-43	12	-18
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	3.9	5.4	18	3.4	17	-37	20	-11
NCC-NorESM1-M	r1i1p1	SMHI-RCA4	3.2	4.1	12	2.9	11	-16	14	18
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4	3.0	3.5	12	1.9	15	-13	8.3	5.9

Table 10.1. Ranking of individual simulations underlying the CH2018 projections (multi-model set indicated by circles in [Table 4.1]) according to different variables/indices for different seasons (DJF/JJA) for the region CHW and RCP8.5 at the end of the century. Shown are changes in seasonal mean temperature (ΔT), very hot days (ΔTX99P), consecutive dry days (ΔCDD), seasonal mean precipitation (ΔP), and mean seasonal 1-day precipitation maximum (Δrx1d). For each parameter, the colored areas indicate the four highest values (pink), lowest values (yellow), and values closest to the median (grey). Note that this ranking depends on the region considered and does not generally apply to the localized datasets derived by quantile mapping.