ABSTRACT: Climate information provided by global or regional climate models (RCMs) are often too coarse and prone to substantial biases for local assessments or use in impact models. Hence, statistical downscaling becomes necessary. For the Swiss National Climate Change Initiative (CH2011), a delta-change approach was used to provide daily climate scenarios at the local scale. Here, we analyse a Richardson-type weather generator (WG) as an alternative method to downscale daily precipitation, minimum and maximum temperature. The WG is calibrated for 26 Swiss stations and the reference period is 1980–2009. It is perturbed with change factors derived from RCMs (ENSEMBLES) to represent the climate of 2070–2099 assuming the SRES A1B emission scenario. The WG can be run in multi-site mode, making it especially attractive for impact-modellers that rely on a realistic spatial structure in downscaled time-series. The results from the WG are benchmarked against the original delta-change approach that applies mean additive or multiplicative adjustments to the observations.

According to both downscaling methods, the results reveal mean temperature increases and a precipitation decrease in summer, consistent with earlier studies. For the summer drying, the WG indicates primarily a decrease in wet-day frequency and correspondingly an increase in mean dry spell length of between 18 and 40% at low-elevation stations. By definition, these potential changes cannot be represented by a delta-change approach. In winter, both methods project a shortening of the frost period (−30 to −60 days) and a decrease of snow days (−20 to −100%). The WG demonstrates though, that almost present-day conditions in snow-days could still occur in the future. As expected, both methods have difficulties in representing extremes. If users focus on changes in temporal sequences and need a large number of future realizations, it is recommended to use data from a WG instead of a delta-change approach.

KEY WORDS: weather generator; statistical downscaling; climate change; daily temperature time-series; daily precipitation time-series; Switzerland

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1. Introduction

Given the expected changes in the global climate system over the 21st century (IPCC, 2013), the need for reliable and quantitative future projections on the local-to-regional scale is continuously growing (e.g. Fowler et al., 2007; Maraun et al., 2010). State-of-the-art regional climate models (RCMs) typically provide information at a spatial resolution of about 10–50 km. From an end-user’s perspective, projections at this spatial scale are often too coarse and are prone to substantial biases, making it impossible to directly use daily time-series of the RCMs for local assessments and in climate impact models. In order to provide bias-corrected local climate projections at daily resolution, further downscaling is necessary. Over recent years, a multitude of statistical techniques have been developed to bridge the gap between climate model output and the local scale (Maraun et al., 2010). For regions with complex topography such as the Alps, statistical downscaling is a particularly challenging task due to the fact that certain local-scale processes (e.g. valley cold pools, convective precipitation etc.) are not resolved by RCM simulations with a typical resolution of 10–50 km.

In Switzerland, the current climate change scenarios from CH2011 (2011) provide daily time-series of future temperature and precipitation at the station network of MeteoSwiss (Bosshard et al., 2011). These future time-series are based on a delta-change approach using 10 RCM-GCM-model simulations from the ENSEMBLES project (van der Linden and Mitchell, 2009). A number of impact studies have subsequently been performed in Switzerland based on these meteorological input data (e.g. Bosshard et al., 2013; Addor et al., 2014; CH2014-Impacts, 2014). The delta-change technique modifies the locally observed past weather record by applying an additive (temperature) or multiplicative (precipitation) adjustment to the observed record, based on the mean future change as projected by climate models (Maraun et al., 2010). The spatio-temporal correlation structure of the future data, downscaled with this approach...
is physically reasonable, as it reflects observed conditions. However, the sample is limited to the length of the observed record and the method is deterministic. It is further not capable of describing changes in variability, extremes or in the temporal structure of the data (e.g. changes in frequency or the autocorrelation of dry/wet sequences). The latter is a considerable downside of the delta-change approach for many impact applications, because the temporal structure of precipitation is indeed expected to change over Switzerland (Fischer et al., 2014). This is particularly true in the summer season, when all the ENSEMBLES models project a decrease in wet-day frequency and correspondingly an increase in the frequency of multi-day dry spells. From an impact perspective, changes in multi-day spells have severe consequences for agriculture and drought conditions (e.g. Calanca, 2007). It is hence crucial to realistically reflect the changes in the temporal correlation structure when providing future climate data. For the release of a next generation of climate change scenarios in Switzerland, improved scenarios at the daily scale should be made available that circumvent some of the inherent limitations of a delta-change approach and that match a wide range of climate impact applications (e.g. hydrological run-off models, crop yield models or ecosystem models).

To cope with future changes in the temporal structure of the downscaled time-series and to simulate an ensemble of different realizations of future climate, weather generators (WGs) are an appealing downscaling technique (Wilks and Wilby, 1999; Kilsby et al., 2007; Fatichi et al., 2011). Here, we use a recently developed weather generator by Keller et al. (2015) as our main downscaling technique that allows to specify changes in the temporal correlation structure, such as the wet-day frequency. In essence, the model of Keller et al. (2015) is a Richardson-type WG (Richardson, 1981; Dubrovsky, 1997). It explicitly models the temporal structure of precipitation occurrence and temperature while preserving the inter-variable relations. The WG can be run at multi-site mode so that the inter-station correlation is additionally maintained in the synthetic time-series (Wilks, 1998; Keller et al., 2015). This WG has been extensively validated against station observations over a typical catchment in Switzerland (Keller et al., 2015).

In this study, the WG is applied to provide synthetic future precipitation and temperature time-series for 26 Swiss stations. It is calibrated over a time-period of 1980–2009. As in CH2011 (2011), climate change information for the end of the 21st century (2070–2099) is obtained from regional climate model projections of the ENSEMBLES project.

The aim of this study is (1) to analyse local climatic changes focusing on the temporal sequences and changes in the temperature-precipitation relation (i.e. aspects of changes that are not “seen” in downscaled time-series based on delta-change), and (2) to investigate the generated time-series with a WG against those derived with a delta-change approach. The documentation of quantitative differences between the two methods is highly relevant for the release of new climate change scenarios in Switzerland.

2. Data

We use observational data from 26 stations of the Swiss National Basic Climatological Network (NBCN) (Begert, 2008) providing high-quality homogenized daily precipitation and minimum and maximum temperature (Begert et al., 2003), each reflecting a distinct climate region in Switzerland. The stations are spread out over Switzerland and cover a wide range of altitudes from 250 m a.s.l. (Lugano) up to 2500 m a.s.l. (Saentis) (Figure 1(a)). For instance, mean annual precipitation ranges from 600 mm (Sion) up to 2700 mm (Saentis). The station data related to the period of 1980 to 2009 are used here to calibrate and validate the WG.

To adjust the calibrated WG for future climate, we analyse RCM projections from the EU-FP6 project ENSEMBLES (van der Linden and Mitchell, 2009). We focus here on model changes between the scenario period 2070–2099 and the calibration period 1980–2009. In total, 12 model simulations spanning the whole period from 1950 to 2100 are used. This set of model simulations comprises a combination of eight different RCMs and six different driving global circulation models (GCMs) (Figure 1(b)). The RCMs were run assuming the greenhouse gas emission scenario SRES A1B (Nakicenovic and Swart, 2000) at a horizontal resolution of approximately 25 km.

3. Method

3.1. The multi-variate WG of Keller et al. (2015)

The multi-variate WG of Keller et al. (2015) is a Richardson-type WG (Richardson, 1981; Dubrovsky, 1997; Wilks, 1998), simulating daily time-series of precipitation, minimum and maximum temperature. First, daily precipitation occurrence is modelled based on a first-order two-state Markov chain using a wet day threshold of 1 mm day$^{-1}$. This discrete time-series model is fully determined by two transition probabilities: the probability that a wet day is followed by a wet day ($p_{11}$) and the probability that a dry day is followed by a wet day ($p_{01}$). Given a wet day, precipitation intensities are simulated from a mixture model of two exponential distributions, consisting of two rate parameters ($\beta_1$ and $\beta_2$) and one mixing parameter ($\omega$). Daily minimum and maximum temperature are modelled as a normal distribution with mean $\mu$ and standard deviation $\sigma$. In order to ensure inter-variable consistency between temperature and precipitation, the parameters of the normal distribution are conditioned on the precipitation state (i.e. separately for dry and wet days). Synthetic temperature time-series are then simulated by using a first-order autoregressive model (AR1) which maintains the observed temporal auto-correlation for each temperature variable and cross-correlation between the two temperature variables (see e.g. Richardson, 1981). All the WG parameters are determined for each of the 26 stations and each month individually in order to reproduce the monthly site-specific climatology and its annual cycle over a 30-year calibration period.
The precipitation model has been extensively validated over a typical Alpine river catchment (Keller et al., 2015). While mean local precipitation characteristics are well captured, limitations in the reproduction of multi-day variability including long spells and extremes have been unveiled. The temperature model has been validated over the 26 selected stations over Switzerland. The model successfully reproduces the inter-variable relations between minimum and maximum temperature and between precipitation occurrence and temperature (see Figure S1(a), Supplementary Information). The mean statistics are well captured but with a slight warm bias in the generated series. Similarly to the precipitation model, an underestimation of inter-annual variability, extremes and multi-day spells has been found (see Figure S1(b)). For more details on the multi-variate WG itself and on the performance of it we refer to the Appendix S1 and Figure S1 and to our previous study by Keller et al. (2015).

The WG of Keller et al. (2015) can optionally be run in multi-site mode, where the spatial dependencies between different sites are explicitly modelled by spatially correlated random number streams (Wilks, 1998; Keller et al., 2015). In this study, we focus on site-specific climatic changes. Therefore, the results at individual sites are irrespective of whether the WG was run in single-site or multi-site mode. Nevertheless, the option to provide...
spatially correlated future time-series is important for some applications, such as hydrological modelling (e.g. Khalili et al., 2011).

3.2. Perturbing the WG for future climate conditions
To adjust the calibrated WG parameters at the 26 stations for future climate (2070–2099), we used changes (relative to 1980–2009) in the daily precipitation and temperature statistics from RCM simulations at the grid-point closest to the station location (Wilks, 1992; Prudhomme et al., 2002; Kilsby et al., 2007; Jones et al., 2011).

Specifically, for adjusting the precipitation model, changes in precipitation sums (ΔS), wet day frequencies (Δπ) and wet-wet transition probabilities (Δp11) were taken into account (Wilks, 1999, 2010). The precipitation sums were adjusted by relative changes. In case of the wet day frequency and the wet–wet transition probability, that are both bounded by zero and one, the perturbation was applied to the log-odds transformed quantities (Wilks, 1999). Given the future parameters of S, π and p11 at the local scale, the future dry-wet transition probability p01 and the mean wet day intensity can be analytically derived (Wilks, 1999). Regarding the distribution of future wet day amounts, we perturbed the two rate parameters β1 and β2 by the same factor to match the future mean wet day intensity. This implies only a shift in the probability density function of the wet day intensity but no change in the shape of the distribution.

How large are these parametric changes of the precipitation model in winter and summer? As an example, we show results for winter and summer, namely for February and August, when the precipitation changes are most pronounced. The maps of the multi-model mean project for p01 and p11 only small changes in February over Switzerland and surroundings (Figure 2). Only along the southern Alpine ridge small positive changes in p01 can be detected. In general for February, the models do not agree on the sign of the change. In contrast, for August the most climate models (10 out of 12 models) suggest a widespread decrease in the two transition probabilities with larger magnitudes in p01. The changes in transition probabilities are rather homogenous in space.

Individual RCM results for the grid point closest to the station Lugano are shown in Figure 3. Almost all models project an increase in the monthly precipitation sums in February (filled squares in Figure 3a), which can be largely attributed to a combination of an increase in wet day frequency and intensity. For August, the RCMs consistently project a decrease in monthly precipitation sums, attributable to a reduction in the wet day frequency, while the models do not reveal a common sign of change in mean wet day intensity (Fischer et al., 2014). Concerning relative changes in the temporal dry-wet structure (Figure 3(b)), for August almost all models project a decrease in the wet-wet (p11) and dry-wet (p01) transition probabilities, implying a generally drier regime. However, there is no tendency towards more persistent conditions for that particular month and location. For February, half of the models project for this station an increase in the wet-wet (p11) and dry-wet (p01) transition probabilities, with no clear tendency towards more persistent precipitation events.

To adjust the temperature model for a future climate, we analysed the minimum and maximum temperature projected by the RCMs in terms of absolute changes in the 30-year mean (Δµ) and in terms of relative changes in the interannual standard deviation (Δσ) (Wilks, 1992, 2012). In order to maintain the projected inter-variable relation between precipitation occurrence and temperature, the parameters of the normal distribution are determined for dry and wet days separately, resulting in eight change factors (two temperature variables, two precipitation states, two statistical quantities). For each of these change factors a periodic spline fit was applied (Begert et al., 2003). Note, that the adjustment of the temperature model does not assume any changes in the cross-correlation and the temporal structure of temperature. The latter can change through the changes in the temporal structure of precipitation. Figure 3(c) and 3(d) again reveal the magnitude of RCM-simulated changes regarding the parameters of the temperature model: almost all RCMs project a stronger increase in daily maximum than daily minimum temperature (Δµ), implying a slight increase in the diurnal temperature range (Lindvall and Svensson, 2014). Also, a tendency towards a stronger temperature increase at dry days compared to wet days is visible. A similar analysis on variability changes (i.e. Δσ) reveals that the majority of models project a slight increase in summer and a slight decrease in winter. This is true for both temperature variables and irrespective of the precipitation state (not shown) (Scherrer et al., 2005).

3.3. Delta-change approach
As stated in the introduction, one of the aim of this study is to document the benefits and limitations of the future local projections with a WG against our benchmark time-series derived with a simple delta-change approach. To derive future local projections, we inferred future changes in the mean annual cycle of precipitation, minimum and maximum temperature as simulated by the RCMs over the grid-point closest to a station of interest. Future changes in the mean annual cycle were inferred by applying a spline function through the monthly mean changes. In case of precipitation, the changes were derived in relative terms (i.e. the ratio between the time-periods 2070–2099 and 1980–2009) and for the temperature variables we used absolute changes. The (relative) changes in the mean annual cycle were then re-combined with the daily observed record over the time-period 1980–2009 to generate time-series for the end of the century.

3.4. Analysis of the generated time-series
With the above-described downscaling method at hand, multiple realizations are generated for the calibration
The number of synthetic time-series however differs in three ways. First, the calibrated WG over 1980–2009 is run several times, resulting in an ensemble of 100 synthetic time-series of 30 year length, reflecting current climate conditions. Second, for 2070–2099 the calibrated WG is separately adjusted for each of the 12 model chains. Henceforth, a set of 100 × 12 time-series of 30 year length is generated, reflecting future climate conditions. Finally, the delta-change approach is applied to each model chain separately. It is a deterministic method, hence resulting in 12 time-series of 30 year length.

The generated time-series are compared to the observed record over 1980–2009 that is obviously just one realization. Due to the different sample sizes, care should be taken when comparing uncertainty ranges among the different approaches and observations. The smaller the sample size, the higher the uncertainty in estimating the empirical quantiles.

To analyse and compare results from the different downscaling methods, we compute a number of climate indices. Table 1 lists the definition of all the 11 climate indices used. The univariate fixed-threshold indices are based on the ETCCDI/RCD Climate Change Indices (Peterson et al., 2001; Klein Tank and Können, 2003). Further, we use quantile-based compound indices (dry-warm, wet-warm, dry-cold, wet-cold) as in Moran-Tejeda et al. (2012): warm events are days with daily maximum temperature exceeding the local 75th percentile, cold events are days with daily minimum temperature below the 25th percentile. Dry days are defined as in the WG’s occurrence model (precipitation amounts smaller than 1 mm day$^{-1}$).

The definition of wet days, however, differs: here only wet days with a precipitation amount larger than the local 25th percentile of the wet day intensity distribution are taken into consideration. The percentiles used to define these events were determined for each station and month separately.

4. Results

4.1. Changes in the annual cycle

The annual cycle of current and future monthly precipitation sums is shown for five stations, each with a distinct climatological characteristic (left panel in Figure 4). The precipitation sums at all stations exhibit a clear decrease in summer towards the end of the 21st century, with mean reductions of around $-9$ to $-36\%$. Winter precipitation tends to increase in southern Switzerland (station Lugano). These downscaled results are consistent with climate model projections at the grid point level (e.g. CH2011, 2011; Fischer et al., 2011). The right-hand panel of Figure 4 shows the partitioning of the monthly sums in terms of the wet day frequency (wdf) and mean wet day intensity (wdi). This reveals a summer precipitation decrease that is pre-dominantly caused by a reduction in the number of wet days, while the intensity remains similar as today. For northern and western Switzerland (compare stations Zurich and Geneva), the models project an increase in monthly sums for winter, spring and fall attributable to an increase in the mean precipitation intensity consistent with the model analysis of Rajczak et al. (2013). Even though the projections reveal for the stations
Figure 3. Projected future changes (2070–2099 vs 1980–2009) at the RCM grid point closest to the station of Lugano and for the month of February (left) and August (right). The scatter-plots show relative changes from RCMs in wet-day intensity versus frequency (a), relative changes in $p_{01}$ versus $p_{11}$ (b), absolute changes in minimum temperature conditioned on wet versus dry days (c) and the same for maximum temperature (d). The colours indicate the driving GCM. Filled and unfilled symbols in (a) and (b) indicate the future changes in monthly precipitation sums and in the lag-1 autocorrelation, respectively. The boxplots aside the axes summarize the univariate distribution of the corresponding quantity.
Table 1. Definition of climate indices.

| Precipitation indices | Number of wet days (days with precipitation above 1 mm day$^{-1}$) relative to the total number of days within a given time-period (e.g. month) |
|-----------------------|--------------------------------------------------------------------------------------------------|
| Wet day frequency     | Mean precipitation amount at wet days                                                            |
| Wet day intensity     | Mean duration of consecutive dry days (days with precipitation below 1 mm day$^{-1}$)          |
| Temperature indices   |                                                                                                  |
| Summer days           | Days with maximum temperatures exceeding 25°C                                                   |
| Frost days            | Days with minimum temperatures smaller than 0°C                                                  |
| Warm spell duration index | Average number of days with a daily maximum temperature exceeding the local 90th percentile of the reference period (1980–2009) for at least 6 consecutive days. The index is calculated over May and September. The 90th percentile is calculated with a moving window of 5 days (CH2011, 2011) to allow for a varying annual cycle. |
| Compound indices      |                                                                                                  |
| Fresh snow days       | Wet days with maximum temperatures smaller than 4 °C (adapted from the definition by Zubler et al., 2014) |
| Dry-cold days         | Dry days at which daily minimum temperature is smaller than the local 25th percentile of the reference period (Morán-Tejeda et al., 2012) |
| Dry-warm days         | Dry days at which daily maximum temperature exceeds the local 75th percentile of the reference period (Morán-Tejeda et al., 2012) |
| Wet-cold days         | Wet days at which daily minimum temperature is smaller than the local 25th percentile of the reference period (Morán-Tejeda et al., 2012) |
| Wet-warm days         | Wet days at which daily maximum temperature exceeds the local 75th percentile of the reference period (Morán-Tejeda et al., 2012) |

If not indicated differently, the indices are defined based on the ETCCDI (Peterson et al., 2001; Klein Tank and Können, 2003). The indices labelled with a star (*) indicate the aspects for which the weather generator (WG) was compared with the delta-change approach. For the remaining indices a comparison is superfluous.

Sion and Davos almost no changes in the monthly sums during the transition seasons (compare for instance autumn at the station Davos), opposing tendencies in wet-day intensity and wet-day frequency can occur. This is in line with results by Fischer et al. (2014) and highlights the importance of analysing aspects of precipitation change beyond monthly sums.

The downscaled future series show an increase in temperature at all stations over the full year. Assuming the A1B emission scenario, minimum and maximum temperature rise by about 2–6 °C towards the end of the 21st century. A small part of this increase might be attributable to changes in precipitation occurrence. This is because the temperature variables are conditioned on the precipitation state with markedly different distributions at dry and wet days.

4.2. Changes in summer and frost days

The rising temperature in Switzerland is expected to prolong the growing season length and the duration of the warm season as we know it from today’s climate (Zubler et al., 2014). To investigate how the non-uniform temperature rise over the full year translates into the prolongation of the warm season at individual stations, we evaluate the occurrences of the first and last summer days within a year.

The variability and median estimates of the first/last summer days per year (and the time-span in-between) are shown for current and future climate and for nine stations, covering a wide range of altitudes and geographical locations (Figure 5(a)). Under current climate conditions (white bars), summer days occur at low-elevation sites from mid-May until mid-September with an interannual variability of approximately ±0.5 months. The average number of summer days per year amounts to about 40–65 days (not shown). The year-to-year variability of the first summer day is larger than that of the last summer day. The WG is able to reproduce the observed time-span of summer days with only small biases (dark grey bars). The biases are particularly small at stations where summer days occur frequently today (Lugano and Locarno), but larger where summer days are rarely observed (e.g. Davos and Saentis). The same is true for the reproduction of year-to-year variability.

Towards the end of the 21st century, the WG clearly simulates a prolonged period during which summer days can occur at all evaluated stations (mid-grey bars). The magnitude of change ultimately depends on the current mean annual cycle of temperature: if close to the threshold value of 25 °C, even a small shift in the temperature distribution might facilitate conditions for summer day occurrences. At high-elevated sites (e.g. at Grimsel) the future period of summer day occurrences extends over the whole summer months (JJA), while in today’s climate maximum temperatures do only very rarely exceed 25 °C. At lower-elevated sites, in particular for valley stations that experience warm and dry fall winds (e.g. Bad Ragaz), the WG projects a future average time-span of summer day occurrences that starts around one month earlier and ends around one month later (around March–October) compared to today. Regarding the variability in the estimates of first and last summer day, we found that at high-elevated sites the variability of the climate models regarding the first and last summer day is somewhat larger than at lower-elevated sites. The reasons are not clear, but it could be related to a higher model...
Figure 4. Expected future annual cycle of precipitation at the end of the 21st century at the five stations Zurich (SMA), Geneva (GVE), Lugano (LUG), Davos (DAV) and Sion (SIO). The left panel shows the 30-year climatological mean of monthly precipitation sums for current climate (1980–2009, dark grey) and the median estimate of the expected future monthly sums for the scenario period 2070–2099 assuming emission scenario A1B (light grey). The climate model uncertainty is indicated by the vertical bold lines (inter-quartile range) and the whiskers (10th–90th percentile). The right panel shows the future WG-simulated 30-year climatological mean of wet day frequency (red) and mean wet day intensity (blue). The shaded areas display the uncertainty of the climate model projections. The solid black line represents the observed record, the dashed line the WG simulations under current climate. Note, that the ranges of the y-axes vary between the different stations.
uncertainty at higher altitudes which in turn may originate from different topographies in the models.

To test whether the prolongation is the result of a simple shift in the temperature distribution, we additionally compare our results to those derived with the delta-change approach. This yields future mean time-spans that are about 0.5 months shorter than those derived with the WG. The differences are of similar magnitude as those between the WG-derived time-series in current climate and observations, implying that the differences between the two approaches are predominantly a bias-effect of the WG. Indeed the WG suffers from a slight warm bias. For some stations in Southern Switzerland (i.e. Lugano and Locarno) time-series from the delta-change approach show first summer days up to one month earlier than in the case of the weather generator in particular years (compare the left end of the 95% interval). This is because the delta-change approach fully relies on the observed sequence. An occasional early warm day in winter/spring in the observed record will be fully retained in the future delta-change derived time-series and may turn into a summer day. The inter-quartile ranges are very similar for both approaches.

Similar to the number of summer days, the wide-spread future warming substantially shrinks the period during which frost days may occur in Switzerland (Figure 5(b)). Under current climate conditions, frost days occur at the highest elevated site almost throughout the year. Low stations such as Lugano exhibit frost-free days from the beginning of March until the beginning of December in today’s climate. Towards the end of the 21st century, the WG projects a decrease in the mean time span of frost days by approximately 2 months at high-elevated sites and by approximately 1 month at low-elevated sites. The increase in the frost-free period will have a considerable impact on the vegetation period (e.g. Scheifinger et al., 2003),

Figure 5. (a) Date of first and last summer day at nine different stations under current and future climate conditions. The observations are shown in white, the WG simulations for current climate in dark grey, and for future climate in middle grey. Results from a delta-change approach are shown in light grey. The boxes indicate the median estimate, and the lines indicate the variability in these quantities. The solid line shows the empirical inter-quartile range (IQR) and the dashed line the range between the 2.5% and 97.5% empirical quantile. Note, for observations the variability estimate represents inter-annual variability, for the WG run under current climate conditions it includes stochastic variability and for the future projections it includes climate model uncertainty as well as stochastic variability. So, the quantiles are estimated based on four different sample sizes: 30 for observations, 30 × 100 for WG in current climate, 30 × 100 × 12 for WG in a future climate and 30 × 12 for the delta-change approach.

(b) Same as for (a) but for frost days. Note that for the frost days, the calendar year is shown from August to August.
while the changes at higher altitudes may seriously alter the environmental conditions in high-Alpine regions (e.g. Beniston, 2003). Comparing these results to a delta-change approach reveals quite similar projections, implying that the detected changes are pre-dominantly a consequence of a simple shift in the temperature distribution. The differences in the projection of the last frost day between the WG- and delta-change approach is likely related to a bias in the WG, as already seen in the number of summer days.

4.3. Changes in the temporal structure

Given the summer-specific precipitation changes of a decreasing wet-day frequency and a rise in multi-day dry spells over Switzerland (Fischer et al., 2014), the question is how these temporal changes in the precipitation occurrence manifest themselves at station scale. Figure 6 displays changes in the mean dry spell lengths at all stations and for the winter and summer season. Comparing the WG-simulated mean dry spell lengths to the observed record reveals an almost perfect match with only a slight underestimation by the WG. Towards the end of the 21st century and for summer, the mean dry spell length is expected to increase all over Switzerland. Strongest increases are expected at low-elevation stations ranging from +18% up to +39%. The resulting future spatial pattern in summer remains consistent with that under current climate: regions that experience persistent dry periods today are likely to experience enhanced consecutive dry periods in future, while for Alpine and pre-Alpine regions the dry periods today are relatively short and the future changes small, ranging from +7% up to +17%. This is because precipitation at higher-elevated regions occurs more often intermittent due to convective systems. In contrast to summer, the winter mean dry-spell length decreases over entire Switzerland, with the exception of the eastern Alpine region (Davos, Sils and Samedan). The most pronounced reduction is projected to occur at the two lowland stations in southern Switzerland (Lugano and Locarno). There, the relative changes amount to approximately −20%.

A comparison to a delta-change approach is superfluous here, since by definition, the temporal sequences and hence spell lengths remain approximately the same when applying a delta-change approach.

The positive shift in the temperature distribution is expected to alter the temporal structure of temperature related events as well. In particular, the WG projects at all stations an increase in the number of warm spells as illustrated with the warm spell duration index (WSDI, for definition see Table 1) in Figure 7 at the end of the 21st century. Its magnitude, however, heavily depends on the locally observed distribution of daily maximum temperature: a positive temperature shift entails a different threshold exceedance for a wide or sharp climatological distribution. Here, at all stations, the future synthetic time-series of the WG contain warm spells that largely exceed those of the summer 2003 (blue asterisks) with record-breaking hot temperatures (Schär and Jendritzky, 2004; Schär et al., 2004). A marked north–south gradient is visible with larger median WSDI values in southern and south-western Switzerland (around 30–55 days), and in the inner-Alpine dry valleys Valais and Engadin (stations Sion, Graechen, Sils and Samedan). It is also these stations that experience the strongest percentage increases relative to 2003.

The indices derived from a simple shift in the temperature distribution (delta-change approach) are close to those from the WG, but slightly shifted towards larger WSDI values. This is because future time-series from a delta-change approach contain warm spells that are at least as persistent or (through the shift in the distribution) even
of the year 2003 are by definition part of these time-series. On the other hand, the WG exhibits a negative bias in long-term memory and hence in WSDI (see Appendix S1). The warm spells generated with the WG are hence shorter than those derived with a delta-change approach. Note, that the auto-correlation parameter was kept constant in the WG setup for a future climate (see Section 4.2). As a result of its stochastic nature, the WG also generates larger variability at all stations compared to the delta-change result of its stochastic nature, the WG also generates larger variability at all stations compared to the delta-change approach. We found strongest variability in the southern part of Switzerland, ranging from 10 to 100 mean annual warm spell days. This implies that the large variability of the WG does not exclude the possibility of years with similarly frequent fresh-snow days as under current climate conditions (e.g. at Davos and Saentis).

Future fresh snow days derived via the delta-change approach are generally similar to that of the WG, but slightly fewer days are projected. This implies that the future fresh-snow days are mainly determined by changes in temperature and that this change is mainly a shift in the distribution rather than changes in the temporal structure.

In the following, we investigate more closely the effects of multi-variate changes using the example of the station Lugano by using four compound events: wet-cold, dry-cold, dry-warm and wet-warm (for definition see Table 1, or Moran-Tejeda et al. (2012)). By the definition of these indices, 25% of all summer or winter days (22 to 23 days) fall either in the category cold or warm (Figure 9). The partitioning between wet and dry, is defined by the exceedance of the 25th percentile of wet day amounts (wet) and by the
number of days with precipitation below 1 mm day$^{-1}$ (dry). For both, summer and winter, the number of observed dry days exceed those of wet days and hence dry-warm and dry-cold events are larger than the other two counterparts (see Figure 9 top). At the end of the 21st century, the generated time-series are pre-dominantly of mode dry-warm with a smaller contribution of wet-warm (second bar from top). Given the general rise in temperature, the future number of warm events occurs three times more often than under current climate conditions. In fact, 77% of all days in summer and 66% of all days in winter will have maximum temperatures above the 75th percentile of today. The absolute change in the dry-warm events is stronger than for the wet-warm events and the changes are stronger in summer than in winter. This reflects the fact that temperature changes are larger in summer than in winter.

The dominant increase in dry-warm could result from both, a temperature increase and an increase in the number of dry days, especially in summer. In two sensitivity experiments with the WG, we only changed one component (temperature or precipitation), while keeping the other constant (third and fourth bar from top in Figure 9). From these additional experiments, it is evident that the future change in the compound events is pre-dominantly an effect of changes in the temperature distribution, while changes in precipitation are of minor effect. This is confirmed by results of the delta-change approach (bottom of Figure 9), which come close to the results of the WG in standard mode. This underscores again the dominance of temperature change, since the delta-change approach does not include any changes in wet-day frequency.

5. Discussion

We presented results of a multi-variate WG over Switzerland for current and future climate. The results are compared with those of a delta-change approach. Both approaches correct for systematic biases originating from the RCMs. In fact, the calibrated WG parameters are also perturbed in a delta-change context. The future time-series generated by the two methods are consistent in the multi-variate structure: future temperature values are either implicitly conditioned on daily precipitation (delta-change approach) or explicitly (WG). The two approaches also reflect multi-variate changes in that every model is downscaled separately.

The WG, however, as represented here, brings further benefits: multiple realizations of unlimited length to get a better account of uncertainty and variability, while the delta-change approach is of deterministic nature and limited to one single realization of the real climate. Most importantly, different evolutions of the temporal sequences (in temperature or precipitation) can be generated that are consistent with a current or future mean climate. Impact applications sensitive to the temporal structures or other complex sensitivities can benefit from such WG-generated time-series.

Whether the downscaled time-series with a WG are superior to a downscaling with a simple delta-change approach depends on the focus of analysis. If an impact
is particularly sensitive to the very long spells (be it precipitation or temperature), a careful inspection of the changes from climate models is advisable before applying a resource-intensive downscaling method. In cases, where the dry-wet structure of a model projection does not change, applying a delta-change approach might be as good or even superior to a WG. This is because the WG of Keller et al. (2015) exhibits a bias in long-term memory due to the rather simple first-order Markov chain in precipitation occurrence and the first-order autoregressive model for temperature. Future time-series derived with a delta-change approach contain at least the longest measured spells in the observational record (e.g. the exceptional warm spells from 2003). For the situation of Switzerland, it might therefore be justified to use a delta-change approach as downsampling technique for a near-term future, when the changes in the dry-wet structure are minor (Fischer et al., 2014). This, however, comes at the expense of lacking an account of the variability and a large sample, as the delta-change approach is deterministic.

The situation however is different if the dry/wet structure is projected to change, such as in the summer season in Switzerland towards the end of the 21st century. The WG is able to represent changes in dry and wet spell lengths. Through the conditioning of daily minimum and maximum temperature on precipitation occurrence, the temporal sequences of temperature can change, too, even if its autocorrelation is assumed to be the same as observed (as is the case here). This effect is important when the conditional distributions on precipitation occurrence are distinctly different and it can be exacerbated if additionally the conditional changes are different. Applying the delta-change approach results in future temporal sequences, that almost perfectly correlate with the observed record, but are potentially shifted in the daily mean. For precipitation, dry/wet spell lengths remain as today, even though we know from the regional climate models that this is not the case. Similarly, warm and cold spells may change only to the degree that the mean shift increases the likelihood of a certain threshold exceedance.

Overall, the WG presented proves to be a useful approach to generate large number of realisations of site-specific, multi-variate, daily time series for current and future climate in consistency with changes taken from RCMs. Therefore, the WG can potentially be expanded beyond the implementation presented here, such as to further variables or to a realistic representation of extreme values and changes thereof.

6. Summary

The applicability of a WG as a downscaling method has been tested over Switzerland in order to generate enhanced daily and local climate scenarios that go beyond the delta-change approach. The multi-variate WG has been used to downscale future daily weather time-series (precipitation, minimum and maximum temperature) at 26 stations over Switzerland. The weather generator was calibrated at the individual stations over a reference period of 30 years (1980–2009) and run under future climate conditions for the scenario period 2070–2099. The statistically downscaled time-series were analysed in terms of changes in the annual cycle, the temporal correlation structure as well as in terms of inter-variable relations. Where possible, the results were compared with the time-series derived with a delta-change approach that serves as a benchmark.

Towards the 21st century and assuming an A1B emission scenario, a decrease in precipitation sums along with a decrease in the wet day frequency is projected over entire Switzerland during summer. As a consequence, mean dry spell lengths intensify by around 18–40%. Mean wet day intensity is expected to increase in northern and western Switzerland during winter, spring and fall, resulting in an increase in monthly sums. In winter, precipitation sums are expected to increase in southern Switzerland. As a consequence, the mean dry spell lengths will be reduced over southern Switzerland.

For the future climate in Switzerland about 66–77% (instead of 25%) of all days will exceed the local 75th percentile of today’s daily maximum temperature. As a consequence, the pre-dominant mode of future climate at Swiss stations will be dry and warm, as defined from today’s climate. However, the effect of temperature is more dominant compared with precipitation. The warming will result in more frequent and more persistent warm spells during summer, with a distinct north-south gradient. The projected warm spells at the individual stations largely exceed those of the record-breaking hot summer of 2003. As a consequence of the temperature rise, the number of fresh snow days decreases, at low-elevation stations by around −50 to −100%, at high-Alpine stations by only around −20%. The projections from the WG, however, come with a large stochastic variability and include the possibility of individual years with a similar number of snow days on average under current climate.

The comparison of the WG with a delta-change approach shows specific benefits and limitations for both methods. The choice of method ultimately depends on the sensitivity of the impact system. The single-site WG, in its current form, adds important complementary information with respect to a delta-change approach, such as changes in the temporal structure and an account on projection uncertainty on the local scale. On top of that, the WG of Keller et al. (2015) has the option to be run in multi-site mode. For impact modellers such as hydrologists, that rely on a correct spatial structure in meteorological input variables over a catchment, this offers a great opportunity to explore future climate impacts with different realizations.

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Supporting Information

The following supporting information is available as part of the online article:
Appendix S1. Multi-site and multi-variate WG of Keller et al. (2015).
Figure S1. Validation of multi-site temperature model under current climate conditions (1980–2009).
(a) Inter-variable consistency for the station Zurich.
(b) Temporal correlation structure of the lower quantile of Tmin (left) and the upper quantile for Tmax (right) at the station Lugano. (c) Observed (left) and simulated (right) spatial pattern of simultaneous occurrence of warm days (Tmax,0) > Tmax,q75).

References

Addor N, Rössler O, Köpflin N, Huss M, Weingartner R, Seibert J. 2014. Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. Water Resour. Res. 50(10): 7541–7562.
Begert M. 2008. Die Representativität der Stationen im Swiss National Basic Climatology Network (Swiss NBCN). Scientific Report MeteoSwiss: Zurich, Switzerland, 127, 40 pp.
Begert M, Seiz G, Schlegel T, Musa M, Baudruch G, Moesch M. 2003. Homogenisierung von Klimaserien der Schweiz und Bestimmung der Normwerte 1961–1990. Scientific Report MeteoSwiss: Zurich, Switzerland, 67, 170 pp.
Beniston M. 2003. Climatic change in mountain regions: a review of possible impacts. Clim. Change 15: 5–31, doi: 10.1007/978-94-015-1252-7.
Bosshard T, Kotlarski S, Ewen T, Schär C. 2011. Spectral representation of the annual cycle in the climate change signal. Hydro. Earth Syst. Sci. 15(9): 2777–2788, doi: 10.5194/hess-15-2777-2011.
Boisson T, Carambia M, Goergen K, Kotlarski S, Krahe P, Zappa M, Schär C. 2013. Quantifying uncertainty sources in an ensemble of hydrological climate-impact projections. Water Resour. Res. 49(3): 1523–1536, doi: 10.1002/wrr.15133.
Calanca P. 2007. Climate change and drought occurrence in the Alpine region: How severe are becoming the extremes? Glob. Planetary Change 57(1–2): 151–160, doi: 10.1016/j.gloplacha.2006.11.001.
Calanca P. 2011. Swiss Climate Change Scenarios CH2011. C2SM, MeteoSwiss, ETH, NCCR Climate and OcCC: Zurich, Switzerland, 88.
Calanca P. 2014. Impacts. 2014. Toward Quantitative Scenario of Climate Change Impacts in Switzerland. OCCR, FOEN, MeteoSwiss, C2SM, Agroscope, and ProClim: Bern, 136 pp.
Collins M, Booth BB, Harris GR, Murphy JM, Sexton DMH, Webb MJ. 2006. Towards quantifying uncertainty in transient climate change. Clim. Dyn. 27(2–3): 127–147, doi: 10.1007/s00382-006-0121-d.
Dubrovsky M. 1997. Creating daily weather series with use of the weather generator. Environmetrics 8(5): 409–424, doi: 10.1002/(SICI)1099-095X(199710)8:5<409::AID-ENVI261>3.0.CO;2-0.
Fatici S, Ivanov VY, Caporalì E. 2011. Simulation of future climate sce- narios with a weather generator. Adv. Water Resour. 34(4): 448–467, doi: 10.1016/j.adwres.2010.12.013.
Fischer AM, Weigel AP, Buser CM, Knutti R, Küsnacht HR, Liniger MA, Schär C, Appenzeller C. 2011. Climate change projections for Switzerland based on a Bayesian multi-model approach. Int. J. Climatol. 32(15): 2348–2371, doi: 10.1002/joc.3396.
Fischer AM, Keller DE, Liniger MA, Rajczak J, Schär C, Appen- zeller C. 2014. Projected changes in precipitation intensity and frequency in Switzerland: a multi-model perspective. Int. J. Climatol. 34: 3204–3219, doi: 10.1002/joc.4162.
Fowler HJ, Blenkinsop S, Tebaldi C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling tech- niques for hydrological modelling. Int. J. Climatol. 27: 1547–1578, doi: 10.1002/joc.
IPCC. 2013. Climate Change 2013: The Physical Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovern- mental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York, NY, 1535.
Jones PD, Harpham C, Goodess CM, Kilby CG. 2011. Perturbing a weather generator using change factors derived from regional climate model simulations. Nonlinear Processes Geophys. 18(4): 503–511, doi: 10.5194/npg-18-503-2011.
Keller DE, Fischer AM, Frei C, Liniger MA, Appenzeller C, Knutti R. 2015. Implementation and validation of a Wilks-type multi-site daily precipitation generator over a typical Alpine river catchment. Hydrol. Earth Syst. Sci. 19(5): 2163–2177, doi: 10.5194/hess-19-2163-2015.
Kilsby CG, Jones PD, Burton A, Ford AC, Fowler HJ, Harpham C, James P, Smith A, Wilby RL. 2007. A daily weather generator for use in climate change studies. Environ. Model. Softw. 22(12): 1705–1719, doi: 10.1016/j.envsoft.2007.02.005.
Klein Tank AMG, Können GP. 2003. Trends in indices of daily tempera- ture and precipitation extremes in Europe, 1946–99. J. Clim. 16: 3665–3680.
Lindvall J, Svensson G. 2014. The diurnal temperature range in the CMIP5 models. Clim. Dyn. 44: 405–421, doi: 10.1007/s00382-014-2144-2.
Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon EJ, Wil- mann M, Brien M, Rust HW, Sauter T, Them Dell MJ, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof CJ, Vrac M, Thiele-Eich I. 2010. Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. Rev. Geophys. 48(3): RG3003, doi: 10.1029/2009RG000314.
Morán-Tejeda E, Herrera S, Iglesio López-Moreno J, Revuelto J, Lehmann A, Beniston M. 2012. Evolution and frequency in Switzerland: a multi-model perspective. In European summer heatwaves. Nature 432(6972): 559–560, doi: 10.1038/nature02300.
Nakicenovic N, Swart R. 2000. In IPCC Special Report on Emissions Scenarios.Special Report on Emissions Scenarios. Nebojsa N, Robert S (eds). Cambridge University Press: University Press, Cambridge, UK and New York, NY, 612.
Peterson TC, Folland C, Graus C, Hogg W, Moksitt A, Plummer N. 2001. Report on the Activities of the Working Group on Climat Change Detection and Related Rapporteurs 1998–2001. WMO Geneve, Switzerland, 143.
Prudhomme C, Reynard N, Crooks S. 2002. Downscaling of global climate models for flood frequency analysis: where are we now? Hydrol. Processes 16(6): 1137–1150, doi: 10.1002/hyp.1054.
Rajczak J, Pall P, Schär C. 2013. Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. J. Geophys. Res. 118(9): 3610–3626, doi: 10.1002/jgrd.50297.
Richardson CW. 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resour. Res. 17(1): 182–190, doi: 10.1029/WR017i001p00182.
Schär C, Jendritzky G. 2004. Climate change: hot news from summer 2003. Nature 432(7017): 559–560, doi: 10.1038/432559a.
Schär C, Vidale PL, Lüthi D, Frei C, Häberli C, Liniger MA, Appen- zeller C. 2004. The role of increasing temperature variability in European summer heatwaves. Nature 427(6972): 332–336, doi: 10.1038/nature02300.
Scheifinger H, Menzel A, Koch E, Peter C. 2003. Trends of spring time frost events and phenological dates in Central Europe.
Scherrer SC, Appenzeller C, Liniger MA, Schär C. 2005. European temperature distribution changes in observations and climate change scenarios. Geophys. Res. Lett. 32(19): L19705, doi: 10.1029/2005GL024108.

Van der Linden P, Mitchell JFB. 2009. ENSEMBLES: Climate Change and its Impacts at Seasonal, Decadal and Centennial Timescales. Summary of Research and Results from the ENSEMBLES Project. Met Office Hadley Centre: Exeter, UK, 160.

Wilks DS. 1992. Adapting stochastic weather generation algorithms for climate change studies. Clim. Res. 22: 67–84.

Wilks DS. 1998. Multisite generalization of a daily stochastic precipitation generation model. J. Hydrol. 210(1–4): 178–191, doi: 10.1016/S0022-1694(98)00186-3.

Wilks DS. 1999. Multisite downscaling of daily precipitation with a stochastic weather generator. Clim. Res. 11: 125–136.

Wilks DS. 2010. Use of stochastic weather generators for precipitation downscaling. WIRES Clim. Change 1(6): 898–907, doi: 10.1002/wcc.85.

Wilks DS. 2012. Stochastic weather generators for climate-change downscaling, part II: multivariable and spatially coherent multisite downscaling. WIRES Clim. Change 3(3): 267–278, doi: 10.1002/wcc.167.

Wilks DS, Wilby RL. 1999. The weather generation game: a review of stochastic weather models. Prog. Phys. Geogr. 23(3): 329–357, doi: 10.1177/030913339902300302.

Zubler EM, Scherrer SC, Croci-Maspoli M, Liniger M a, Appenzeller C. 2014. Key climate indices in Switzerland; expected changes in a future climate. Clim. Change 123(2): 255–271, doi: 10.1007/s10584-013-1041-8.