



CH2011 Extension Series No. 3

Climate scenarios of seasonal means: inter-variable and inter-seasonal correlations of change estimates

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Abstract

The CH2011 climate scenarios of seasonal means reveal how mean precipitation and temperature are expected to change in Switzerland during the 21st century. Uncertainty thereof was quantified and expressed with three estimates: a lower estimate, a medium estimate and an upper estimate for temperature and precipitation change and for all seasons separately. From an impact perspective, often input data is needed for temperature and precipitation together and for the full year. CH2011, however, gives no guidance on how to combine the climate change estimates when needed concurrently.

The extension article here investigates this issue further: With the help of the underlying model-simulated changes, we analyze the correlations between the changes in temperature and precipitation (inter-variable correlation) and between the changes of consecutive seasons of the same variable (inter-seasonal correlation). The analysis reveals that a firm conclusion on the inter-variable and inter-seasonal correlations is largely challenged by the limited set of independent models. Moreover, since the models often do not agree on a common sign in precipitation change, the inter-variable correlation and the correlation of precipitation change across seasons is weak and pre-dominantly not statistically significant. For the inter-seasonal correlation of temperature changes though, a positive correlation emerges in general. This means that a model with a warming signal above multi-model average in one season likely projects above-average warming in the next season, too and vice versa.

Where possible, our interpretation of the obtained correlations in the model-simulated changes is complemented by findings from the scientific literature or by physical arguments. Based on all these considerations, we find in total three configurations for which we recommend to connect the climate change estimates with either a positive or a negative correlation:

- a positive correlation for temperature change estimates of consecutive seasons, when considering the time horizons 2060 and 2085.
- a negative correlation between temperature and precipitation change estimates in summer, when considering the time horizons 2060 and 2085 over the regions CHNE, CHW, and CHS.
- a positive correlation between temperature and precipitation change estimates in winter, when considering the time horizon 2085 over the regions CHS and CHAE.

For these configurations a pair of change estimates should be combined as upper-upper, medium-medium, lower-lower in case of a positive correlation and as upper-lower, medium-medium, lower-upper in case of a negative correlation. For all other instances, in principle, all nine combinations have to be regarded as equally likely. However, the choice of combinations

ultimately depends on the sensitivity of the impact model. If the sensitivity of an application system is known well enough, only the impact-relevant combinations have to be sampled.

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Correlations between seasonal temperature and precipitation changes and between changes of consecutive seasons are investigated in the CH2011 climate scenarios of seasonal means.

For most configurations no firm conclusion on the relationships can be derived. For far lead-times, we partly find a negative correlation in summer and a positive correlation in winter between temperature and precipitation changes. We also recommend combining temperature change estimates with a positive correlation between consecutive seasons.

3

1 | The CH2011 climate scenarios of seasonal means

The CH2011 climate scenarios of seasonal means describe how seasonal temperature and precipitation may change in Switzerland in the 21st century. They are based on several regional climate models (RCMs) from ENSEMBLES (van der Linden and Mitchell 2009) that were all run assuming the A1B emission scenario (Nakicenovic and Swart 2000). The model-data were first spatially aggregated to five regions of similar size: northeastern Switzerland ("CHNE"), western Switzerland ("CHW"), Switzerland south of the Alps ("CHS"), western Alps of Switzerland ("CHAW") and eastern Alps of Switzerland ("CHAE"). For more information on the two newly defined regions CHAW and CHAE, we refer to Zubler et al. (2014) and Fischer et al. (2015).

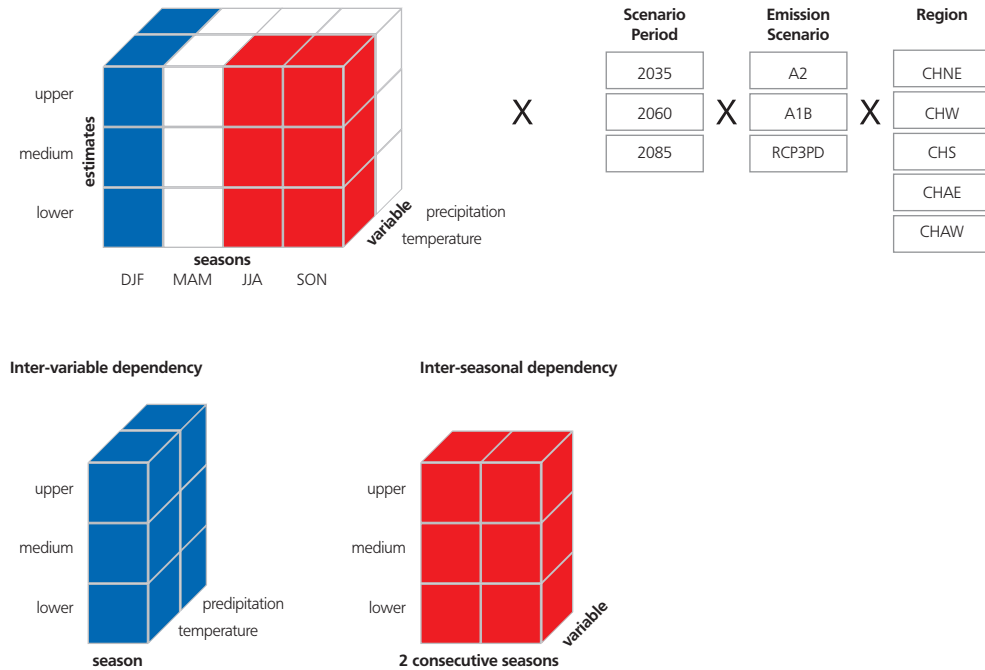
For each of the three future 30yr-long periods 2020-2049 ("2035"), 2045-2074 ("2060"), and 2070-2099 ("2085") a joint statistical assessment of several RCM-simulated changes was made with respect to the reference period 1980-2009 (Buser et al. 2009; Fischer et al., 2012). Those RCMs that were run by the same global driving fields were averaged beforehand. In total, eight model projections were included for the period 2035, and six model projections for the periods 2060 and 2085. The joint assessment of these simulated changes yields a consolidated statistical distribution of expected climate change. From the statistical distribution, the 2.5%, 50% and 97.5% percentiles were selected and disseminated as «lower estimate», «medium estimate», and «upper estimate». In CH2011, these change estimates were not interpreted in a probabilistic way, but were rather considered as three possible outcomes of future climate with no explicit probability statement (see Chapter 2.6 of CH2011, 2011 for more details). In the following, we refer to these three estimates of CH2011 as "change estimates".

2| How to combine the CH2011 change estimates?

4

The multi-model assessment was applied separately to multiple configurations, i.e., to all five regions, four seasons, three future periods, three emission scenarios and to two variables, totaling 360 instances with three change estimates each (lower, medium and upper estimate). From a practical point of view, impact model applications often require as input both temperature and precipitation, concurrently and for all seasons (illustrated in Figure 1 as a cube for any given region, future time period and emission scenario). Applying the correct inter-variable and inter-seasonal correlation structure is crucial: For instance, a strong warming combined with a substantial drying in summer has different consequences for agriculture than a scenario with only a weak change in precipitation (e.g. Calanca 2007; Watterson and Whetton 2011; Elkin et al. 2013)

Figure 1
Upper row: schematic illustration of the CH2011 scenario configurations for seasonal and regional means. The dimensions comprise 3 change estimates, 4 seasons, 2 variables, 3 future periods, 3 emission scenarios and 5 regions. Lower row: schematic of two example combinations that were the subject of investigation (blue: inter-variable dependency; red: inter-seasonal dependency). Illustration adapted from CH2014-Impacts (2014).

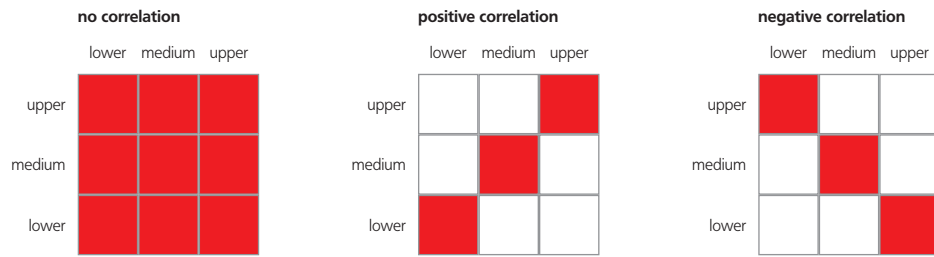


No guidance, however, has been given in CH2011 (2011) on how to combine change estimates for different variables and seasons: For instance, it remains unclear, (a) whether an upper change estimate of temperature in winter occurs more likely in combination with the upper, medium or lower change estimate of precipitation (blue in Figure 1) and (b) whether an upper change estimate of summer temperature coincides with the upper, medium or lower change estimate in fall (red in Figure 1). In absence of correlation (or knowledge thereof), a full exploration of any such combination alone yields $3^2 = 9$ pairs (Figure 2). If one knows the correlation, the number of combinations can be reduced to 3 pairs:

- In case of a *positive correlation*, the change estimates should be combined as: upper – upper, medium – medium, lower – lower (see Figure 2).
- In case of a *negative correlation*, the change estimates should be combined as: upper – lower, medium – medium, lower – upper (see Figure 2).

Figure 2

Combination possibilities in the CH2011 change estimates. In red are those combinations that need to be sampled in case of no correlation (left), positive correlation (middle) and negative correlation (right).



In practice, the number of simulations with an impact model is limited due to computational constraints. Any information on the correlation structure is hence of great value for the design of impact model experiments. In the following, we provide analyses of the inter-variable and inter-seasonal correlation structure in the CH2011 change estimates by re-visiting the underlying climate model projections.

3| Data Basis and Correlation Analysis

6

The correlation analysis is applied to exactly the same data set that was also used for the statistical multi-model assessment (i.e. eight model-simulated changes for the first future period and six model-simulated changes for the latter two periods) at the A1B emission scenario. Since in CH2011 (2011) the climate scenarios of seasonal means for the RCP3PD and A2 emission scenario were generated by linearly transforming the results that pertain to the A1B scenario (Fischer et al. 2012), our results and conclusions from the correlation analysis also apply to these additional two emission scenarios.

The 30-year mean changes in temperature and in precipitation vary in magnitude from model to model. On the one hand, this variability is caused by different transient climate responses of the climate models to the same future increase in greenhouse gas concentrations. On the other hand, the extent of model-simulated changes is affected by internal variability of the climate system (Kjellström et al. 2010; Deser et al. 2012). For Switzerland, such random fluctuations on decadal and multi-decadal scales (henceforth termed “internal decadal variability”) can for instance be caused by long-term variability of sea surface temperatures in the North Atlantic and corresponding long-term variability in circulation patterns over Central Europe (Knight et al. 2006; van Ulden and van Oldenborgh 2006). Especially for near-term time horizons and for precipitation projections in general, internal decadal variability represents a dominant source of uncertainty across the model-simulated changes (Fischer et al. 2015).

Correlation coefficients computed across the model data set are hence also affected by both, variability from model to model and internal decadal variability (see later). Two kinds of correlations are investigated:

- For any given region, season and future time-period: the *inter-variable correlation* between relative precipitation changes and temperature changes.
- For any given region and future time-period: the correlation between consecutive season-pairs of the same variable (termed *inter-seasonal correlation*), i.e., the correlation of changes in DJF with those in MAM, MAM with JJA, and so forth.

Due to the very limited data set to compute the individual correlations, we rely on the Spearman Rank Correlation Coefficient (Wilks 2011). This avoids the risk that a few outlying points may seriously affect the magnitude of correlation. The significance is tested using Student’s t-test with $n-2$ degrees of freedom, where n is the sample size. In case of a p-value below 0.05, we reject the null hypothesis of zero correlation. Concerning the detection or absence of significance in the later shown correlation coefficients, two considerations should be kept in mind:

- (a) Detecting a statistical significant relationship in the combined changes is hampered by the very limited sample size in our analysis. Even if a true correlation of say 0.6 exist, it can simply never be detected with statistical significance based on our limited sample. Statistically speaking, the probability of making an “error of the second kind” or “type II error” is very large (Wilks 2011).
- (b) In total, 60 correlation tests are carried out (i.e. for 5 regions, 3 future periods and 4 season(-pairs)). Consequently, the expected number of “type I errors”, i.e. the erroneous detection of a significant correlation, is $60 * 0.05 = 3$. So, we expect three spurious correlations indicated as significant.

4 | Inter-variable correlation structure

7

Temperature and precipitation are atmospheric parameters that are closely inter-linked at multiple time-scales. To avoid confusion and later misinterpretations, we begin this section by summarizing the temperature-precipitation correlations on interannual and longer time-scales:

In Switzerland, it is well known that dry summers are often associated with warm summers, as are wet summers with cold summers. In contrast, winter temperature and precipitation are generally positively correlated (Figure A1 in Appendix). Hence, significant inter-variable correlations are observed and simulated on *interannual time scales* and it is not expected that these relations will fundamentally change in a future climate (see Appendix A1). Anomalous deviations in combined seasonal temperature and precipitation from year to year are largely caused by the prevailing synoptic weather situations evolving in the individual years. For instance, the frequency of warm and wet winters or cold and dry winters over Switzerland is strongly connected to the evolution of large-scale pressure variability over the North Atlantic (Adler et al. 2008).

Internal decadal variability of the climate system and associated circulation changes over Europe might modify the statistics of weather situations over Switzerland and hence might in parallel affect both temperature and precipitation on 30-year time-scales. But since internal decadal variability evolves randomly in each of the climate models, there is generally no significant correlation expected across the modeled 30-year mean changes in temperature and precipitation.

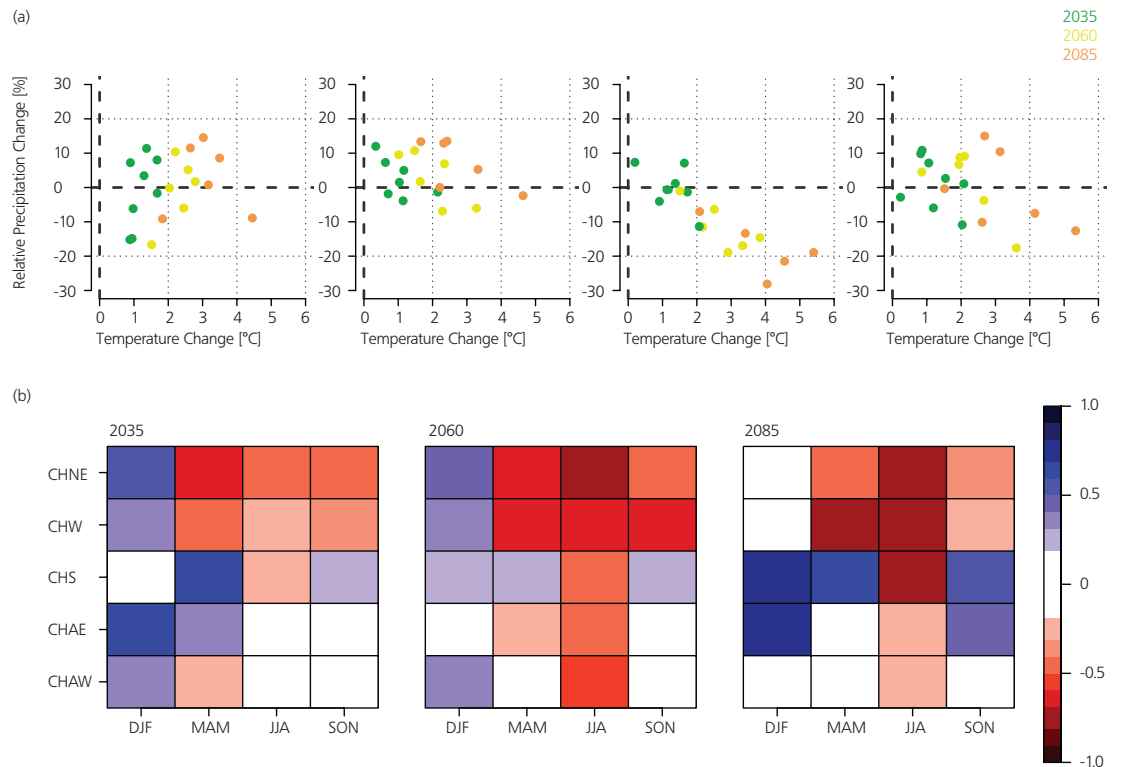
Regarding the *forced component* in temperature and precipitation changes (i.e. forcing through increased levels of greenhouse gas concentrations), a common misconception is to infer the joint probability simply from relationships on the interannual scale (e.g. to automatically infer that warmer winters in the future also imply wetter winters). This does not necessarily hold, as there are manifold physical mechanisms and feedbacks that may act and affect temperature and precipitation directly or indirectly in the long run. For instance, the wide-spread increase in temperature is to a first degree radiatively forced and therefore occurring in all seasons over Switzerland. On the other hand, the hydrological cycle is expected to change in fundamental and complex ways. For instance in summer, the reduction in seasonal mean precipitation is largely indirectly affected by dynamical mechanisms, in particular connected to the expansion of the Hadley circulation (Held and Soden 2006). In absence of internal decadal variability, the complex processes leading to long-term changes in temperature and precipitation are expected to steadily enforce in parallel to the rising amount of atmospheric greenhouse gas concentrations.

Depending on model-specific transient climate responses, the magnitude of temperature and precipitation changes however varies from model to model. If the model-specific changes are systematic, a correlation should unveil in the combined temperature-precipitation changes. For summer, this means that a model with a particularly strong warming would hence also simulate a stronger decrease in precipitation. Likewise, a model with a weak warming would project a weaker precipitation decrease than the majority of models. The presence of internal decadal variability as in the data here might partly weaken the relationship again. Moreover, in cases where seasonal mean precipitation has no consistent sign of change across the models and hence is pre-dominantly influenced by (random) internal decadal variability, we expect no correlation between temperature and precipitation changes.

In fact, it is this latter case that shows up in the majority of relations between relative precipitation changes and temperature changes over Switzerland (Figure 3): from autumn until spring over northeastern Switzerland, when models do not agree on a common sign of precipitation change, no inter-variable correlations can be inferred (Figure 3a). In summer though, a tendency for a negative correlation in the second half of the century emerges. Yet, even this correlation is not statistically significant. In fact, extending the same analysis systematically to all CH2011 regions does not yield statistically significant correlation coefficients, as Figure 3b shows.

Nevertheless, it is interesting to discuss in the following two particular features in a more qualitative way. We primarily focus on the latest time horizon (i.e. 2085), when the forced component of temperature and precipitation change is strongest. If a correlation does not emerge when the signal is strongest, it is unlikely that it will at earlier time horizons.

Figure 3
(a) Scatter-plots of 30yr-mean modeled temperature changes against relative precipitation changes over the region CHNE. The changes of the same future time-period are plotted with the same color. (b) Spearman correlation coefficients between temperature and precipitation changes for each season and region. The coefficients are shown for three projection periods. Note the absence of any significant relationship in this figure.



One consistent feature north and south of the Alps is a strong negative correlation between temperature- and precipitation changes in summer (Figure 3). This implies that a model with a stronger precipitation decrease also simulates a stronger temperature response. A negative correlation coefficient over these regions emerges in all of the three time-periods, which increases our confidence in the robustness of this result, as it can be assumed that the regional climate is qualitatively similarly affected throughout the century. Recent studies have partly associated the negative correlation in summer with soil-moisture temperature feedbacks, causing increased sensible heat fluxes if the soil dries enough and evaporation stops. This future long-term response may vary in strength across the models resulting in a negative correlation also on multi-decadal scale (Seneviratne et al. 2006; Seneviratne et al. 2013). The feedback becomes especially relevant over soil-moisture limited conditions, as is the case in summer over large parts of Southern and Central Europe towards the end of the century. For the Alpine regions CHAE and CHAW, Figure 3b reveals a summer correlation at 2085 that is only slightly negative. This could be related to the relatively weak precipitation decreases over these two regions (see Figure 1 in Fischer et al. 2015) that do not reduce soil moisture to the degree neces-

sary to trigger the above-mentioned mechanism, similarly as over large parts of northern Europe (Seneviratne et al. 2013).

One further noticeable feature in Figure 3b are rather large positive correlation coefficients over the southerly located regions (CHS and CHAE) during winter in 2085. It is also over these regions, where the majority of models project increases in mean precipitation as a result of higher intensities at the end of the century (Rajczak et al. 2013; Fischer et al. 2014). The reason for that is not clear to date but could be related to an enhanced moisture holding capacity (Allen and Ingram 2002; Held and Soden 2006).

In summary, for most seasons and regions, no robust correlation structure between temperature and precipitation changes can be identified. However, taking into account other lines of evidence, in summer north and south of the Alps (i.e. CHNE, CHW, CHS) a negative correlation should be taken into account for the latter two future time-periods. Furthermore, in winter at 2085 over the southerly located regions CHS and CHAE, the change estimates of temperature and precipitation should be regarded as positively correlated.

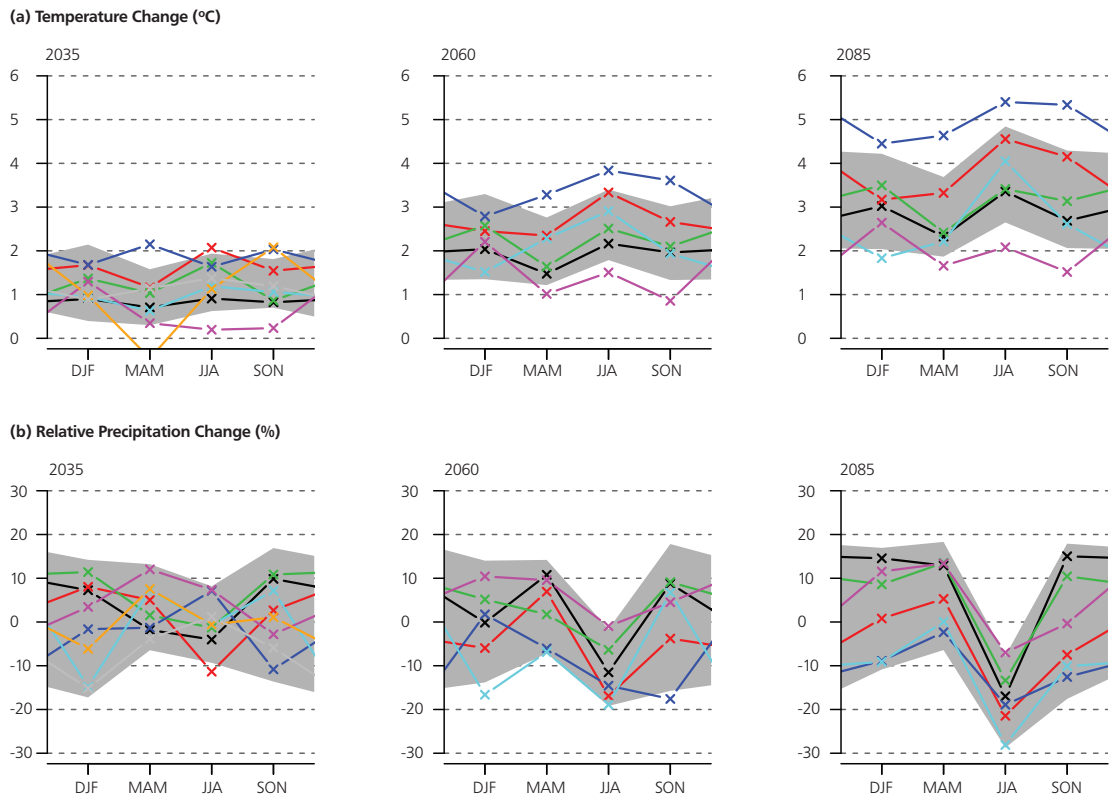
5| Inter-seasonal correlation structure

9

To give end-users more advice on how to combine the CH2011 estimates over the full year, we analyze the correlation of model-simulated changes in a similar way as in Section 4, but this time for all neighboring season-pairs of each variable separately. The aim is to obtain information whether for instance a model with a seasonal warming exceeding that of the other models also project the strongest warming in the next season. A similar ranking of each specific model across the seasons indicates a positive correlation, while a ranking that largely varies from season to season is an indication of uncorrelated or even anti-correlated data. With the help of the colored lines connecting the seasonal mean changes in Figure 4, the ranking from season to season can be visually inferred.

Based on the crossing lines and hence differing ranks from season to season (Figure 4), it is expected that for the first future time-period there is no positive inter-seasonal correlation in temperature change or in precipitation change. When going to the farther lead-times though, the model ranking for seasonal mean temperature changes becomes more and more consolidated (e.g. for 2085 the blue line stays on top for all seasons, while the purple line has the lowest warming signal for most seasons). This is mainly because the forced component dominates the signal in all of the models and seasons. Precipitation changes, on the other hand, evolve with a large internal decadal variability in the individual models over the century, which is why the model ranking is less established compared to temperature changes.

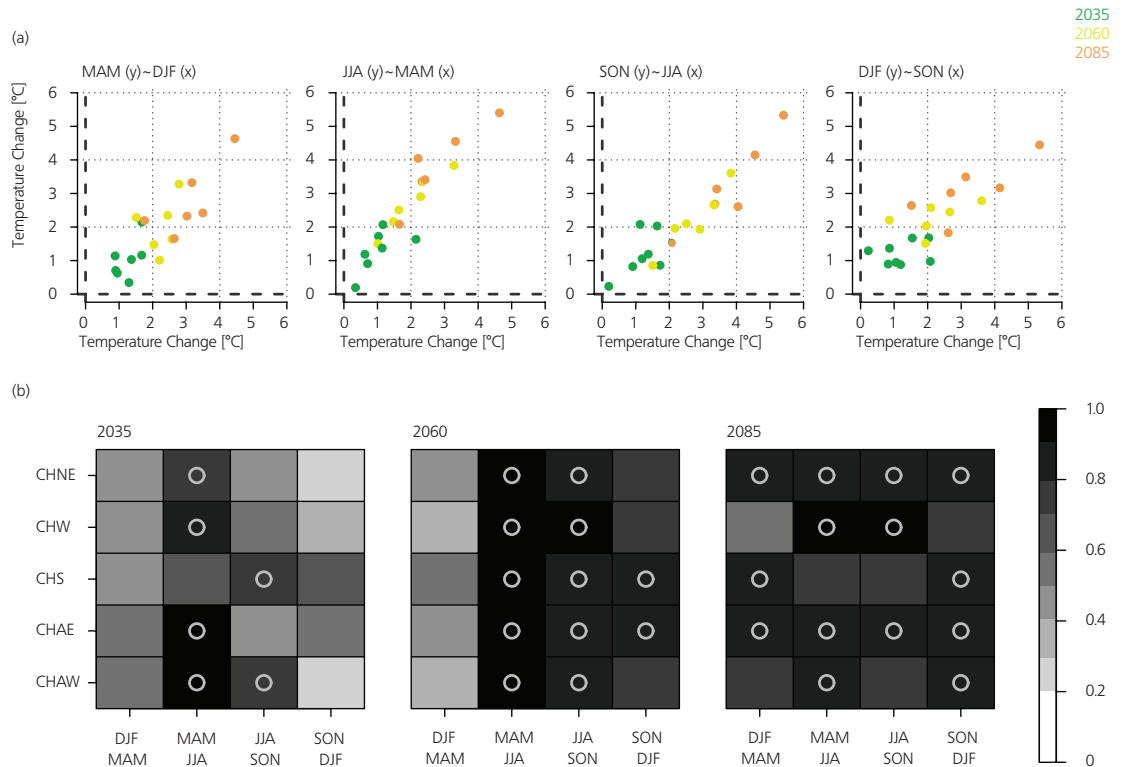
Figure 4
Model-simulated changes connected across the four seasons for (a) temperature and (b) relative precipitation over the region northeastern Switzerland. The connections are shown for the three future time-periods separately. The different colored lines correspond to the different climate models considered. For each of the plot, a ranking across seasons can be visually inferred. The grey shading shows the range spanned between the upper and lower estimate of CH2011 (2011).



Indeed, for the combined temperature changes a positive relationship is clearly visible in all four season-pairs and especially for the latter two time horizons (Figure 5a). This is also statistically confirmed by the correlation analysis and is true over all five regions (Figure 5b). The positive relationship generally becomes stronger in magnitude over the century and consequently more than half of the season-pairs are positive and significant in the second half of the century. This means

that over Switzerland a model with a warming signal exceeding multi-model average in one season likely projects warmer than average temperatures in the next season too and vice versa. This is also physically plausible, as it is to a first degree the transient climate response of the models to the same future amount of greenhouse gas concentrations that determines the ranking in temperature changes in the individual seasons.

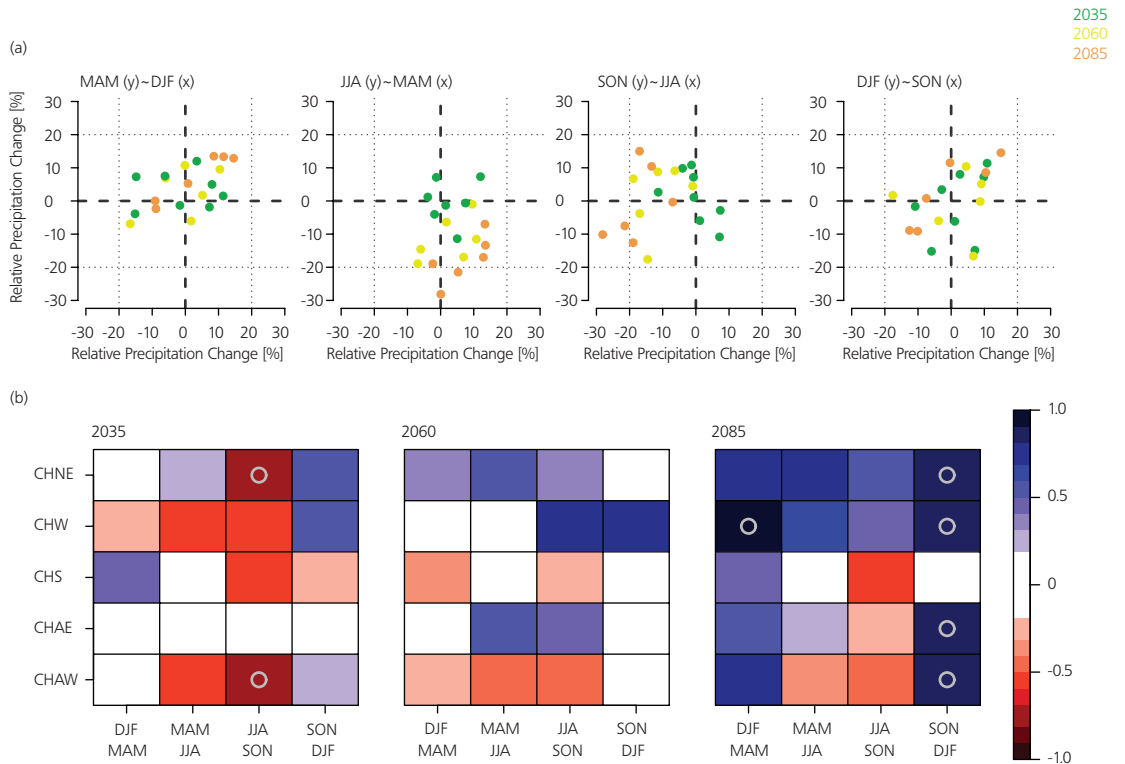
Figure 5
(a) Scatter-plots of 30yr-mean modeled temperature changes between neighboring seasons over the region CHNE.
(b) Spearman correlation coefficients between temperature changes of neighboring season-pairs and for each region. The coefficients are shown for all three projection periods and statistical significance (p-value < 5%) is marked with a grey circle. Note, that all relationships are positive.



For relative precipitation changes, the inter-seasonal correlation structure is much more diverse (Figure 6). First, the sign of correlation coefficient depends on region, season-pair and time-period. Second, the number of significant correlation coefficients between two neighboring seasons is limited to seven out of 60 pairs. As mentioned above, many of the model-simulated precipitation changes are random due to internal decadal variability, which is why we encounter no clear structure in precipitation change across seasons. Qualitatively though, two patterns can be inferred for the end of the century: (a) a generally positive correlation for all season-pairs north of Switzerland (i.e. CHNE and CHW) and (b) a generally positive correlation between the seasons from fall until spring (i.e. the season-pairs SON-DJF and DJF-MAM).

All in all, the correlation between consecutive seasons in precipitation change appears to be still too noisy and uncertain to make any recommendation how to combine the CH2011 change estimates (lower, medium and upper) across the seasons. For temperature in the second half of the century though, supported also by physical arguments, it is suggested to combine the temperature change estimates between neighboring seasons with a positive correlation.

Figure 6
The same as Figure 5
but for relative
precipitation changes.



6 | Conclusions and Implications for end-users

This CH2011 extension article aims to provide end-users more practical guidance on the combination of upper, medium and lower change estimates between temperature and precipitation and between consecutive seasons of the same variable. To this end, sample correlations in the underlying model-simulated changes were investigated for each region, season(-pair) and each future time-period separately. In many cases, the obtained correlation coefficients are not statistically significant. On the one hand, this can be related to the very small sample size that complicates the detection of weak-to-moderate correlations. On the other hand, it is a consequence of the special location of Switzerland in-between two large-scale precipitation regimes that change in a future climate: increases to the north and decreases to the south. Hence, the precipitation change signals over Switzerland often do not have the same sign across the models and are pre-dominantly affected by internal decadal variability. This precludes significant inter-variable and inter-seasonal correlations.

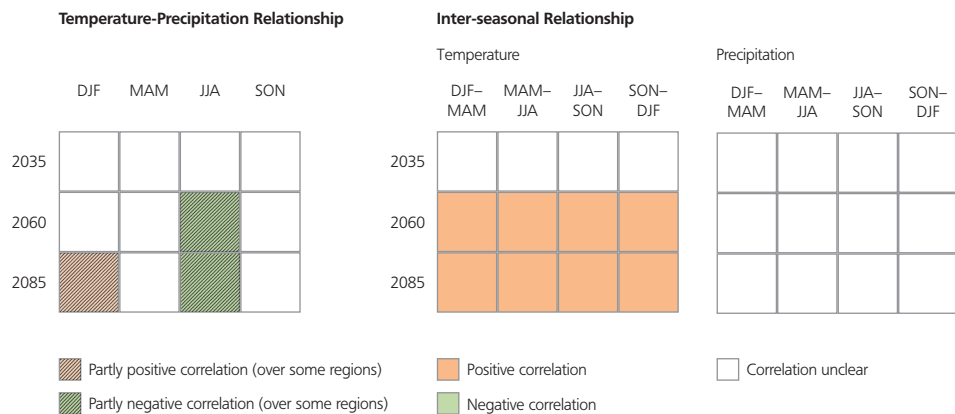
Given these challenges, we have complemented our interpretation of the correlations in the CH2011 estimates, where possible, by findings in the scientific literature or by physical arguments. As a summary, we present our findings of correlations between temperature and precipitation change estimates and between change estimates of consecutive seasons in Figure 7. In particular, we recommend: (a) to combine the temperature change estimates at 2060 and 2085 with a positive correlation between consecutive seasons (orange boxes); (b) to combine temperature and precipitation change estimates in winter at

2085 with a positive correlation when considering the regions CHS and CHAE (orange dashed boxes); and (c) to combine temperature and precipitation change estimates in summer at 2060 and 2085 with a negative correlation when considering the regions CHNE, CHW, and CHS (green dashed boxes).

For these three cases (a)-(c) this means that the number of combinations to sample from can be reduced from 9 combinations down to 3 for any given combination pair (see Figure 2 on how to connect the change estimates in detail). For all other instances the correlation remains unclear and we recommend to sample from all combinations.

However, we have to stress that the choice of the combination strategy for the uncertainty analysis of impact models largely depends on the envisaged application and its sensitivity to the inter-variable and inter-seasonal correlation structure (e.g. Fronzek et al. 2011; Wetterhall et al. 2011; Hirschi et al. 2012). If the sensitivity and hence the impact response surfaces of a particular application is known well enough, only those combinations would have to be sampled that are impact-relevant. But this also means that even in cases where the relationship is given through (a)-(c), the choice of combination should be guided through the sensitivity of the impact model: for instance, if the impact application is sensitive to a high temperature increase with a weak summer precipitation deficit (i.e. upper change estimate in temperature with upper change estimate in precipitation), the effects under this relationship should be explored too.

Figure 7
Summary on the combined relationships recommended to connect the CH2011 change estimates across variables and seasons.



The recommendations given here reduce the number of combination possibilities from the CH2011 projection cube to a limited degree only. In case one wants to fully explore the uncertainty space of the CH2011 scenarios, still an overwhelmingly large number of combination samples remains. What is needed in the future from climate model data providers are multi-variate probabilistic projections. This is a field of active research and over recent years a number of studies have been published on this topic (Beniston 2009; Déqué 2009; Tebaldi and Sanso 2009; Buser et al. 2010; Harris et al. 2010; Watterson 2011). In general, the complexity in producing joint PDFs is much larger compared to univariate PDFs and involves many more assumptions and uncertainties. In this regard, projections of climate indicators, constructed from multiple variables or across several seasons and tailored to a specific application,

could represent a simple and promising alternative to assess combined changes and associated uncertainties (e.g. Fischer and Knutti 2013; Zubler et al. 2014). Alternatively, large numbers of stochastic time series from weather generators could also be used to provide future climate information representing realistic inter-variable and inter-seasonal behavior (Keller et al. 2015). To accommodate the need of multi-variate climate projections, a transdisciplinary approach is necessary that involves climate scenario providers and impact modelers to understand the detailed needs (Salzmann et al. 2013). Currently, more information on inter-variable and inter-seasonal correlations is expected to become available from the analysis of new regional climate downscaling projections such as CORDEX (Jacob et al. 2013; Kotlarski et al. 2014).

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Technical Appendix

A1 Inter-variable correlation structure on an interannual scale

To better understand the seasonal dependency between precipitation and temperature, the correlation is further investigated on an interannual scale. Pearson correlation coefficients are computed from detrended time-series of absolute seasonal mean temperature (in K) and absolute precipitation (in mm). This is done for the same nine homogenized long-term station observations (Begert et al. 2005) that were already used for estimating internal variability during the generation of the scenarios of seasonal means (CH2011 2011; Fischer et al. 2015). The following time-windows are considered: 1864–2009 for Zurich, Basel, Berne, Geneva, Lugano, and Sils Maria; 1876–2009 for Davos; 1901–2009 for Château d'Oex and 1919–2009 for Grand-St-Bernhard. Complementary to station observations, we further analyze the temperature-precipitation relationship on an interannual scale in each model simulation separately. This is done individually for two 50yr-long time-periods: 1961–2009 and 2051–2099. To detrend model and observation data, we subtract a fourth-order polynomial, fitted through the original time-series that represents in our case the long-term response of the respective variable to global temperature increases (see also Hawkins and Sutton 2009). The residuals from this fit are subsequently used in the correlation analysis. Significance in the correlations is tested in the same way as in case of 30yr mean changes.

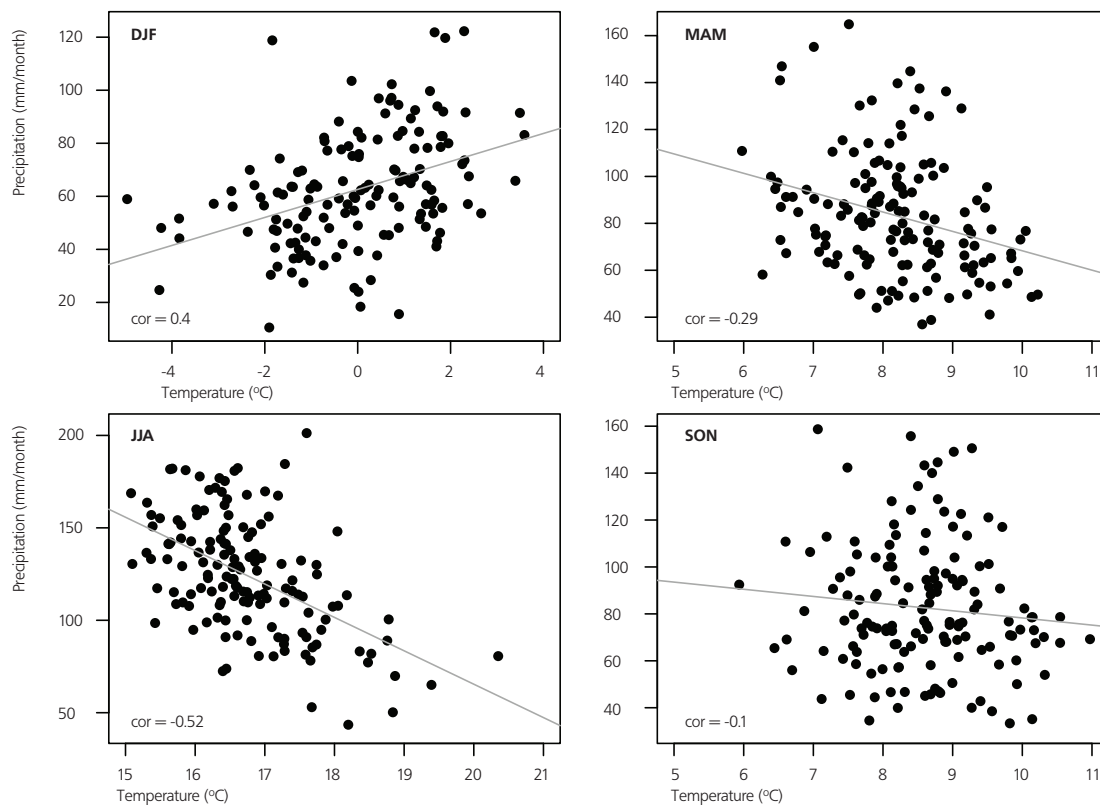
In Figure A1a the inter-variable relationship in yearly granularity is exemplary presented as scatter-plots for the station measurements of Zurich. In the summer season a highly significant negative relationship with a correlation coefficient of around -0.5 is obtained. The outlier with seasonal mean temperature exceeding 20°C represents the summer 2003. The correlation in summer implies that hotter summers are more often associated with drier conditions and vice versa, related to the fact that large-scale dynamics play a less decisive role and dry conditions favor more sunshine and less evaporative cooling (e.g. Schär et al. 2004; Trenberth and Shea 2005). Positive soil moisture-temperature feedbacks at soil moisture-limited regimes have been suggested as a further contributor for the anti-correlation (e.g. Seneviratne et al. 2006; Fischer et al. 2007; Hirschi et al., 2011). The negative summer relationship is observed over all nine considered station measurements (Figure A1b). Similarly but weaker in magnitude, the measurement sites point to a negative relation in the spring season. In contrast, the relation in winter is generally positive with correlation coefficients of around 0.4 north of the Alpine ridge. This means that warmer winters are more often associated with wetter winters and vice versa. In terms of weather situations over Switzerland, a positive relationship can be understood in light of warm moist air, which

is often advected via extratropical cyclones favoring precipitation, such as during positive phases of the North Atlantic Oscillation (e.g. Madden and Williams 1978; Adler et al. 2008). Similarly, cold weather situations in these regions are often associated with the advection of cold and dry air masses from the northeast, thereby also contributing to a positive relation (e.g. Weusthoff 2011). In autumn, though, the temperature-precipitation relationship generally remains uncorrelated over the nine selected station observations.

To what degree do the model-chains reproduce the observed temperature-precipitation relations on an interannual scale? For an earlier RCM set over the Alpine region, Buser et al. (2010) found negative co-variabilities in summer for both control and future climate and for all of the analysed models. Here, we investigate the temperature-precipitation relation aggregated over the five CH2011 regions (Figure A2a). Aggregating the data might be one of the reasons, why the observed relations at station measurements are only partly reproduced over the regions here, as it may affect the multivariate structure. In summer, the analysis shows that almost every model is subject to a significant negative relationship over the whole of Switzerland, qualitatively in line with observations. This relation equally holds for past and future conditions. During winter, about half of the models simulate warmer winters concurrently with wetter conditions and vice versa, while the other half of the models simulate no significant dependency. These relations are generally retained for future climate conditions. In fact, the obtained summer and winter correlation coefficients for a given model and region align close to the diagonal (black and red dots in Figure A2b), implying that not only the sign qualitatively agrees but also that the magnitude of relation on the interannual scale is similar for past and future climate. This is also the case during autumn, when the relationship is generally weak regardless of the chosen time period. In spring, though, there seems to be a shift toward a stronger negative relationship with future global warming (almost all orange dots lie below the diagonal in Figure A2b). The reason for this shift is currently not known but could be related to increased occurrences of weather types that already shape today's summer climate and/or to higher evaporative demand similar to the summer season.

Figure A1
(a) Seasonal scatter-plots of absolute precipitation (y-axis, in mm/month) against absolute temperature (x-axis, in °C) for station observations in Zurich over 1864-2009. The time-series are detrended prior to the analysis. The grey line through the data-points represents the least-squares regression-line (note the absence of significance in autumn).
(b) Seasonal correlation coefficients for nine long-term MeteoSwiss measurement sites. Bold numbers indicate statistical significance (p -value < 0.05).

(a)



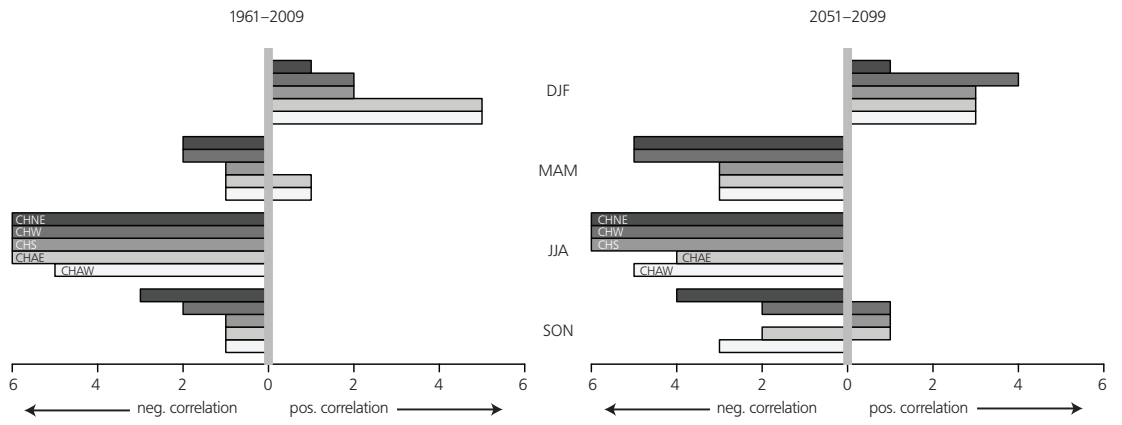
(b)

	Winter DJF	Spring MAM	Summer JJA	Autumn SON
Zurich	0.40	-0.29	-0.52	-0.10
Basel	0.36	-0.23	-0.48	0.05
Geneva	0.45	-0.19	-0.40	0.10
Berne	0.44	-0.22	-0.50	-0.01
Lugano	0.20	-0.37	-0.46	-0.05
Sils Maria	0.27	-0.10	-0.31	-0.05
Davos	0.18	-0.21	-0.35	-0.28
Château-d'Oex	0.25	-0.20	-0.44	-0.20
Grand-St-Bernhard	0.04	-0.23	-0.5	-0.46

Figure A2

(a) Number of model chains simulating either negative or positive inter-variable relationships over the five CH2011 regions in a 50yr-long period (1961–2009, left panel; 2051–2099, right panel). Note, that only statistically significant correlations (p-value < 5%) are counted and that the model time-series are detrended before the analysis. (b) Scatter-plot of future versus past correlation coefficients in each season, region and model. The grey solid lines mark the magnitude of correlation beyond which the correlation becomes significant at a sample size of 50 data points.

(a) Number of Models with significant correlations (p-value < 5%)



(b) Scatter-plot of future versus past correlation coefficients

