Anonymous Referee #3

Received and published: 6 April 2020 Review of Menegoz et al.

The referee comments are in italics, and the author responses have been written in blue

In this manuscript the authors present a set of simulations to study if their model can reproduce the observed trends of precipitations over the alpine region during the last century. For that purpose, they set their regional model domain to run at a high resolution so that the orography and subsequent feedbacks can be more accurately represented. They then compare their trends with observations from a set of rain gauges over Switzerland and argue about which of these trends can be represented. I think the paper is of interest to the community and I recommend its publication after some revisions have been performed.

We acknowledge the referee#3 for his/her encouraging general comments and we answer the point-by-point list of comments below.

Sections 4.1 and 4.2: The most characteristic pattern of your model is the drying on the Po valley over summer. This is most likely related to the evolution of convective processes in your model as the climate warms. The observations in the southern part of Switzerland do not capture this trend at all, therefore bringing doubts about the physical reliability of the simulated signal. I understand that it might be complicated to get station data over the Po valley, however some datasets like EOBS are open and provide data since 1950. You should compare at least if in these datasets there is also a similar signal to what the model predicts. In case that is not observed one should consider whether the observed trends are physical or a simple artifact coming from the parameterization of convective processes in your model.

This comment is fully in line with those of referee#2 who is suggesting to consider the ARCIS precipitation dataset, based on Italian station data interpolated to produce a gridded dataset available over 1961-2015 (Pavan et al., 2019). A description of the precipitation trends for seasonal mean as well as other precipitation indices reported in this dataset has been included in the manuscript. Additional panels has been included in the Figure 4 to show the trends over a shorter period (1958-2010; see the response to referee#2). This allows a more direct comparison with the study based on the ARCIS dataset as well as other ones only available for the last decades and not for the whole century. This is important since the regional trends over the last decades differ from those observed at the centennial scale. Interestingly, the main seasonal trends observed in the ARCIS network (Pavan et al., 2019; their Figure 8) are consistent with our model experiment (Figure 1 in the response to referee #2), with a strong drying in the Po Plain during winter, spring and summer that contrasts with precipitation increase in some mountainous areas during the same seasons. In autumn (SON), the 1958-2010 pattern widely differs from those simulated over 1902-2010, without any clear drying over the Po Plain and general precipitation increase, especially pronounced over the mountains. These signals are clear both in Pavan et al. (2019) and in our study (Figure 1 of the response to referee #2). Pavan et al. (2019) report a drying over large areas of the Po plain about 1 to 2 mm-day-1.year-1 in summer (their figure 8), which corresponds to a strong drying at the centennial timescale in areas where the seasonal precipitation rates ranges between 100 and 200 mm. This comparison gives confidence in the strong drying simulated with MAR over the Po plain.

Section 4.3: It would be a great addition to the paper to compare the trends observed in extreme precipitation with the Clausius-Clapeyron relation, or at least give an estimate on how much they change per degree of warming.

We acknowledge the referee #3 for this relevant comment. Our article is focusing mainly on precipitation changes, and not on temperature changes. However, we have considered further investigations using the temperature to question the relationship between these two variables. Over the MAR domain, the relationship between the averaged Rx1day anomaly and the annual temperature average anomaly is significant (p-value<0.05) and reaches a positive trend by 3.11% $°C^{-1}$ (Figure 1 in this response). This value is smaller than the Clausius-Clapeyron relationship that reaches in theory 6–7%.$°C^{-1}$ (Trenberth et al., 2003). It is also smaller than the value of 7.7%.$°C^{-1}$ reported by Scherrer et al. (2016) using meteorological stations available in Switzerland over the last century. This is now discussed in the revised manuscript. As described in the original manuscript, the increase in Rx1day intensity in the MAR simulation occurred during all the seasons (Figure 6 in the initial manuscript), even during the seasons and areas for which the seasonal mean of precipitation is decreasing (Figure 4 in the initial manuscript). However, due to internal variability, the Rx1day intensity shows a strong interannual variability (Figure 1 in this response). The centennial increase in Rx1day also shows a strong spatial variability, with values ranging between 0 and 40% (Figures 6 and 7 in the original manuscript).

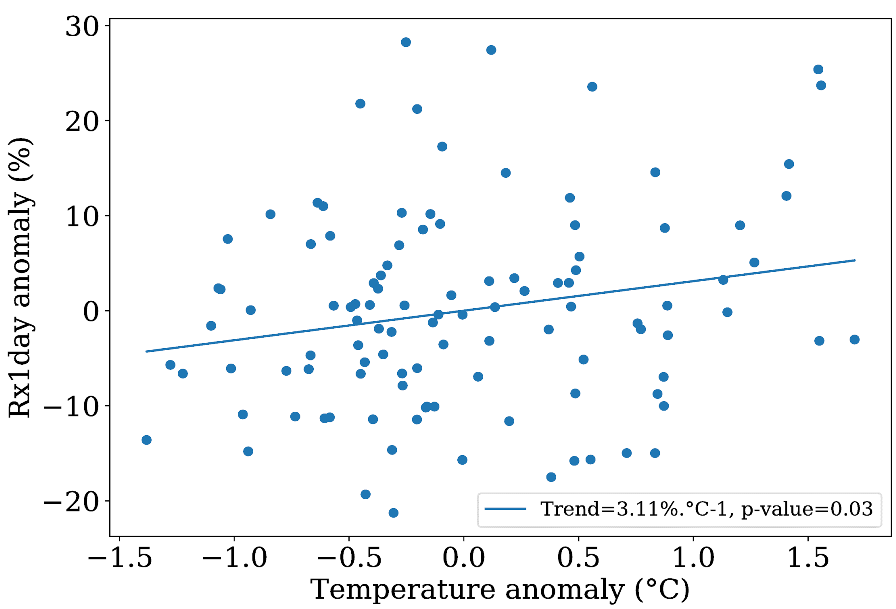

Figure 1: Rx1day anomaly (deviation from mean, %) as a function of the temperature anomaly simulated on average over the domain of application of the MAR model for the period 1903-2010. Anomalies are computed as differences between the annual mean and the average over 1903-2010 for temperature and Rx1day intensity, the latter computed as percentages.

The local relationship between the trend of annual surface air temperature versus the trend of Rx1day intensity is further investigated in Figure 2a, for grid points lower (blue) and higher (red) than 500 m.asl. There is no clear dependency between these variables over 1902-2010, except maybe for a subgroup of the blue points (right part of the plot). Overall, strong Rx1day increases are simulated both under high and low warming levels. The same conclusion is found when comparing the Rx1day trend with the temperature trend during the Rx1day (Figure 2b). Even when focusing on the more recent decades (1958-2010), a period when a strong warming took place, ranging between 0.15°C to 0.5°C per decade in our experiment (Figure 2c in this response), there is no clear local dependency between the temperature trend and the Rx1day intensity.

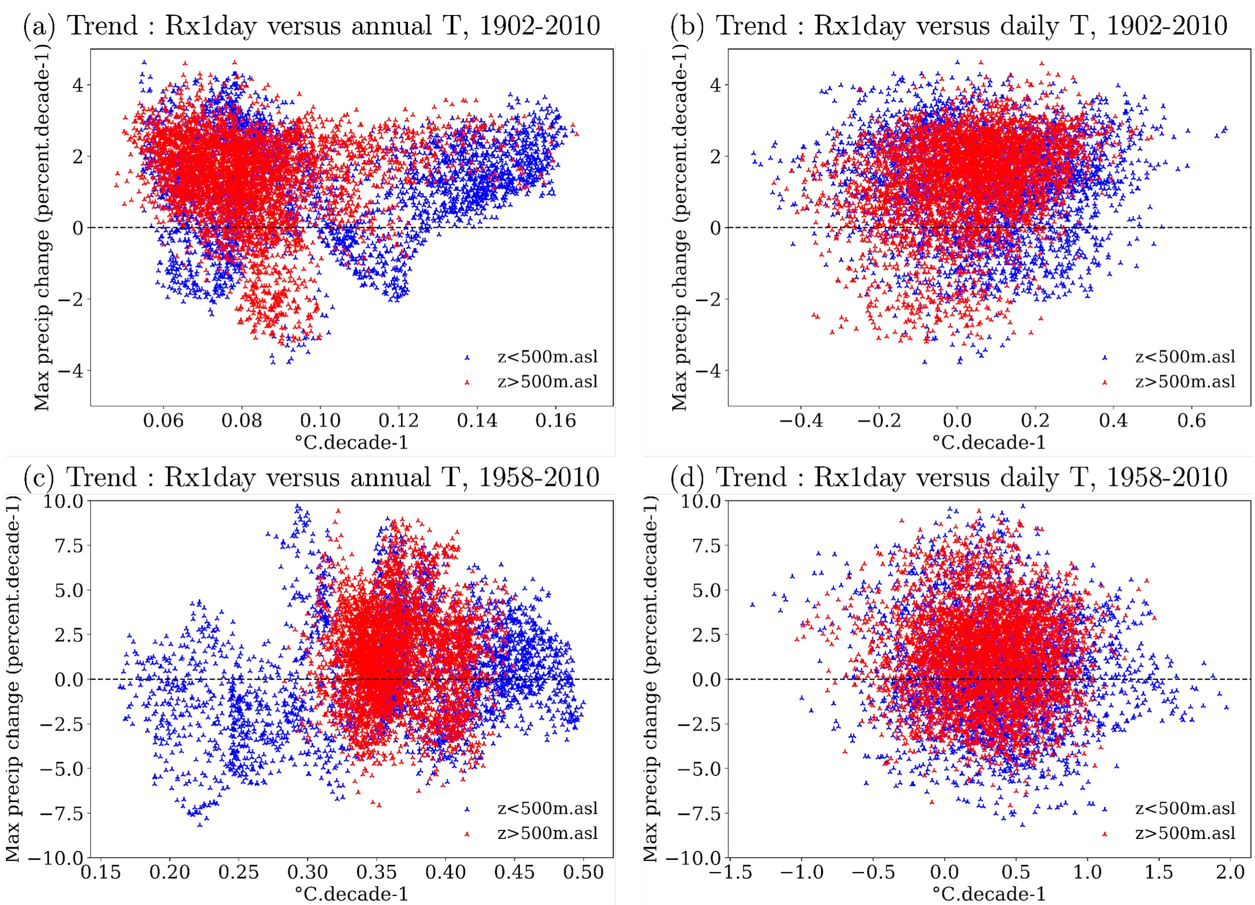

Figure 2: Trend of Rx1day versus trend of temperature over 1903-2010 (a-b) and 1958-2010 (c-d), for annual mean temperature (a-c) and daily temperature during the Rx1day (b-d). It is not planned to include this figure in the revised manuscript.

A deeper analysis of the relationship between temperature and strong precipitation has been conducted below by superposing the areas where the increase of annual Rx1day is positive and significant (Figure 3a in this response) with other variables (hatched areas for Rx1day signal superposed to other variables in Figure 3b-c-d-e-f). The increase in Rx1day intensity is simulated both in areas with a strong warming (e.g. Apennines) or a moderate one (e.g. over the Alps at high elevation; figure 3b). The temperature change during the Rx1day is positive and strong in the Apennines in the Western and Northeastern parts of the Italian Alps (up to 4°C.century-1) whereas it shows smaller variations in the Northern flank of the Alps, with even negative trends over the Jura (up to -4°C.century, Figure 3c). Nevertheless, the increase in the Rx1day intensity projects well on the pattern correlation between the Rx1day and the annual temperature. These findings suggest that warmer temperatures favour strong precipitation events at the annual timescale, but the lack of correlation between the trends in Rx1day and the trends in temperature (Figure 1 in this response) demonstrates that other processes than temperature changes affect the Rx1day intensity. One of them is the shift of the seasonality of the occurrence of Rx1day. As shown in Figure 3e, the Rx1day occurs, on average over 1902-2010, from July over the Northern flank of the Alps (day 180 to 210) to August-September (day 210 to 270) over the Southern flank of the Alps. In the Jura, the increase in Rx1day intensity is associated with a Rx1day shift from the summer to the autumn (+30 to +60 days). This explains the small and even negative centennial trend (Figure 3c) of temperature during the Rx1day in this area. Conversely, the strong warming occurring in the Southeastern flank of the Alps and over the Appennine is not associated with any clear change of the seasonality of the Rx1day (Figure 3f). Over Switzerland, Brönnimann et al. (2018) also suggested a shift of the seasonality of the Rx1day. Here, even with a similar finding, caution is required with this assumption since the shifts described in figure 3f are not significant (p-value>0.05). Rx1day positive trends are also simulated in other areas with both limited warming and without any shift of the seasonality of the Rx1day occurrence, and in particular in the Alps at high elevation (Figure 3). This suggests that other processes are at play to drive increases in the Rx1day intensity. Further investigations are required to disentangle which of them could drive these changes, both in the atmosphere (e.g. moisture flux and convergence at different elevations) and at the surface (e.g. soil conditions including moisture availability).

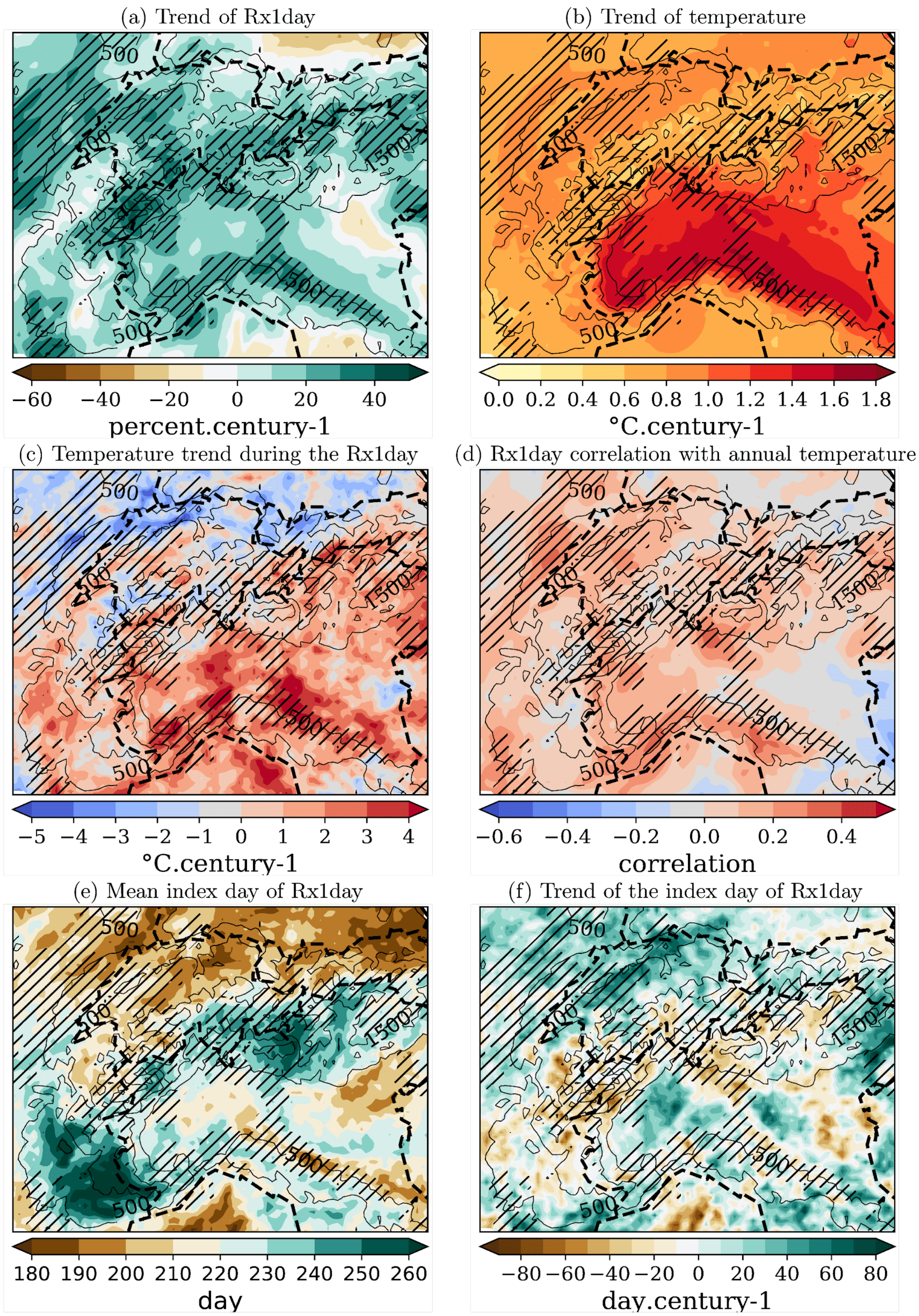

Figure 3: Rx1day intensity trend (a) temperature trend (b), temperature trend during the Rx1day occurrence (c) and correlation between Rx1day and annual temperature (d). Mean (e) and trend (f) of the occurrence day of Rx1day over 1903-2010. In all the panels, the hatches highlight the areas where the Rx1day trend is positive and significant (p_value<0.05). Temperature increase and change of the convective versus total precipitation ratio are significant (p-value<0.05) everywhere, whereas the trend (f) of the occurrence day of Rx1 is not significant (p-value>0.05). This Figure has been included in the revised manuscript.

Small comments:

-L56 Name the reasons: snow cover feedback etc…

-L100 Mention the typical timescales of the NAO

-L183: 7km horizontal resolution on the gray zone of convection, is your parameterization prepared for running at those scales? If it is not scale dependent, did you test the behavior of the model when switching it off? At these scales, convection should appear already in a quite nice form, the use of a non-scale dependant parameterization might do more harm than good to the dynamics of the model. Perhaps in the future you should consider running a similar simulation turning off the parameterization of deep convection. I understand that this might be beyond the scope of this study, but you should mention that the model will likely be subject to some of the recursive biases of parameterized convection such as too frequent and too light precipitation spells.

-L206: show the domain in a plot with the orography plotted and showing the size of your relaxation zone and the different analysis areas (SA, NWA, NEA).

-L210: what is the resolution of ERA-20C? I think you should specify somewhere that the use of a regional model at such resolution is necessary to capture the spatial heterogeneity of the orography. Otherwise people might wonder why did you not simply use the reanalysis for looking at the trends.

-L337: It is interesting to note that the large amounts of precipitation measured during summer at mid altitudes (~6-8 mm/day; 500-1500m) cannot be predicted by the model. I guess these are likely stations strongly affected by convective precipitation, as the bias does not appear in winter. I wonder if this might happen due to including too much convective mixing in the atmosphere by your convective parameterization, therefore making precipitation to be too light where it should be much more stronger and intense.

-L431: I think you mean Figure 4a?

-L428-434: There are too many indexes used here that have not being presented before, some of them do not have names that make them easy to identify what they mean (SDII, STP, MNWS...), you should rewrite this part presenting the indexes before you analyze their trends. You should consider also a better naming for the indexes, SDII could just be daily , STP just P season etc…

-L445: I do not agree that the model and the observations are consistent. The observations tend to show a very weak signal if any, while the model specially in the southern part shows a very negative signal that is not captured by the southernmost stations at all.

-L540: As I mention in the first comment one should check if the trend in the Po valley has been observed. This is a very important question. The climate projections from the EURO-CORDEX ensemble show a similar behavior for the future climate (decrease in mean precipitation explained by decrease in frequency). If this behavior has not being measured in the observations one would wonder about the reliability of these projections, which is indeed a very important result. This is critical as the use of a convective parameterization biases very strongly the precipitation frequency of the models, therefore it might be just the parameterization over-reacting to a perturbation in temperature.

-Table 1: I like the idea of explaining all the indexes in a table, but I think the description of the indexes should also appear in the text at least the first time they are used.

We have considered all these minor comments to prepare a new version of the manuscript. We fully agree with the comments concerning the resolution used that falls in the "grey zone", for which convective processes are partly resolved by the model dynamics, whereas the convective parameterization is still active. Further studies using different resolutions, switching on-off the convection parameterisation, non-hydrostatic configurations are different options that should be considered in future studies based on regional climate model experiments (some of these tests are already available in Doutreloup et al., 2019). Concerning the drying in the Po plain, and as mentioned before, this signal has been reported in the observations described in Pavan et al. (2019), which give confidence in this signal simulate with RCMs. Finally, the indices considered in the study and detailed in Table 1 have been presented in the text of the revised manuscript (Section 2.4), these are typical names from the World Meteorological Organization, named as the ETCCDI indices (Peterson et al., 2001; http://etccdi.pacificclimate.org/list_27_indices.shtml).

Reference:

Doutreloup, S.; Wyard, C.; Amory, C.; Kittel, C.; Erpicum, M.; Fettweis, X. Sensitivity to Convective Schemes on Precipitation Simulated by the Regional Climate Model MAR over Belgium (1987–2017). Atmosphere 2019, 10, 34.