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

The manuscript by Ménégoz et al. investigates precipitation trends in the Alpine region through the aid of regional climate model MAR applied over the period 1903-2010.The model is forced by boundary conditions from ERA-20C. Details of climate change over the Alps, especially for precipitations, need to be clarified further. Local feedbacks respect to air mass temperature increase, soil conditions, moisture availability also in relation with altitude in addition to changes in the dynamics of weather patterns are all factors potentially affecting precipitation distribution. In that respect, regional climate models (RCM) are useful to enrich trends analysis and overcome some limitations posed by availability, coverage and representativity of observational networks. One aspect emphasized in this work is the estimate of the vertical gradient of precipitation, hardly quantifiable over a region from sparse observations. However, it is necessary to be very careful when comparing these results with observations due to inevitable systematic errors introduced by modelling. Biases may be different for different precipitation types. For example, I would tend to believe that the variations of the winter stratiform precipitation are more solid than the trends deduced for warm seasons precipitation, due to the well-known difficulties in representing local convection, starting from the diurnal cycle up to the poor ability to simulate well convective organization, especially when running at such intermediate resolution (7km). I think these limitations should be stated more clearly, especially in the introduction where a very optimistic idea is given about model ability to reproduce precipitation processes in such a complex geographical area. Nevertheless, I found this valuable work and now I will focus on some specific issues to improve the manuscript.

We acknowledge Federico Grazzini, acting as the referee #2, for his useful comments. To further investigate the details of climate change in the Alps, an analysis of atmospheric changes at the scale of Western Europe has been performed and included in the response to referee #1. This complementary analysis highlighted that the precipitation changes documented in our study are strongly related to the large scale moisture changes occurring over Europe and reproduced in the ERA-20C reanalysis that has been used as boundary conditions for the MAR experiment. A deeper analysis has also been carried out concerning the relationship between temperature and precipitation changes (see the response to referee #3), as well as a discussion on the convective processes in our model (included in this response). We fully agree that caution is required when studying convective processes with atmospheric models with such intermediate resolution (7 km) that is not adequate to correctly simulate local convective events. This has been underlined in the revised manuscript. Unfortunately, we cannot investigate the links between soil conditions and precipitation in our study because soil moisture is a variable that has not been saved in our model experiment. Finally, two separate periods have been considered to discuss precipitation changes, 1902-2010 and 1958-2010 (Figure 1 of this response, and updated Figure 4 in the revised manuscript). This allows a comparison with recent works focusing on the last decades and not over the last century. The comments are answered one by one below.

1) In the introduction, where primary observational datasets are introduced, perhaps it worth to consider also the recent ARCIS dataset ([https://www.arcis.it/wp/)](https://www.arcis.it/wp/) which consists of a high-resolution climate precipitation analysis for north-central Italy (1961-2015). See also Pavan et al. 2019 for a description of the dataset which covers the entire south-alpine area at high-resolution.

We acknowledge the referee for mentioning the ARCIS dataset (Pavan et al., 2019) that we did not know. A description of the precipitation trends for seasonal mean as well as other precipitation indices reported in this dataset has been included in the revised manuscript. The Figure 4 of our article that was describing the trends over 1902-2010 has been extended with additional panels showing the trends over the last decades (1958-2010). 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 diagnosed at the centennial scale. The main seasonal trends observed in the ARCIS network (see Pavan et al., 2019, Figure 8) are captured in the MAR model experiment (Figure 1 in this response), with a strong drying in the Po Plain during DJF, MAM and JJA that contrasts with precipitation increase in some mountainous areas during the same seasons. In Autumn (SON), the 1958-2010 pattern largely differs from those simulated over 1902-2010, without any clear drying over the Po Plain and a general precipitation increase, especially pronounced over the mountains. Our results are fully consistent with the results from Pavan et al. (2019) (Figure 1 of this response). The trend simulated and observed over 1903-1958 are shown in Figure 1 of this response, to explain how they can compensate signals estimated over the second half of the period. In particular, the winter increase in precipitation diagnosed over the whole period (1903-2010) is mainly related to a trend concerning the first half of the period (Figure 1a-b-c). The moistening occurring in autumn over 1958-2010 is partly compensated with the trends found over 1903-1958. Finally, the drying over the Po Plain is found almost for all the periods and the seasons.

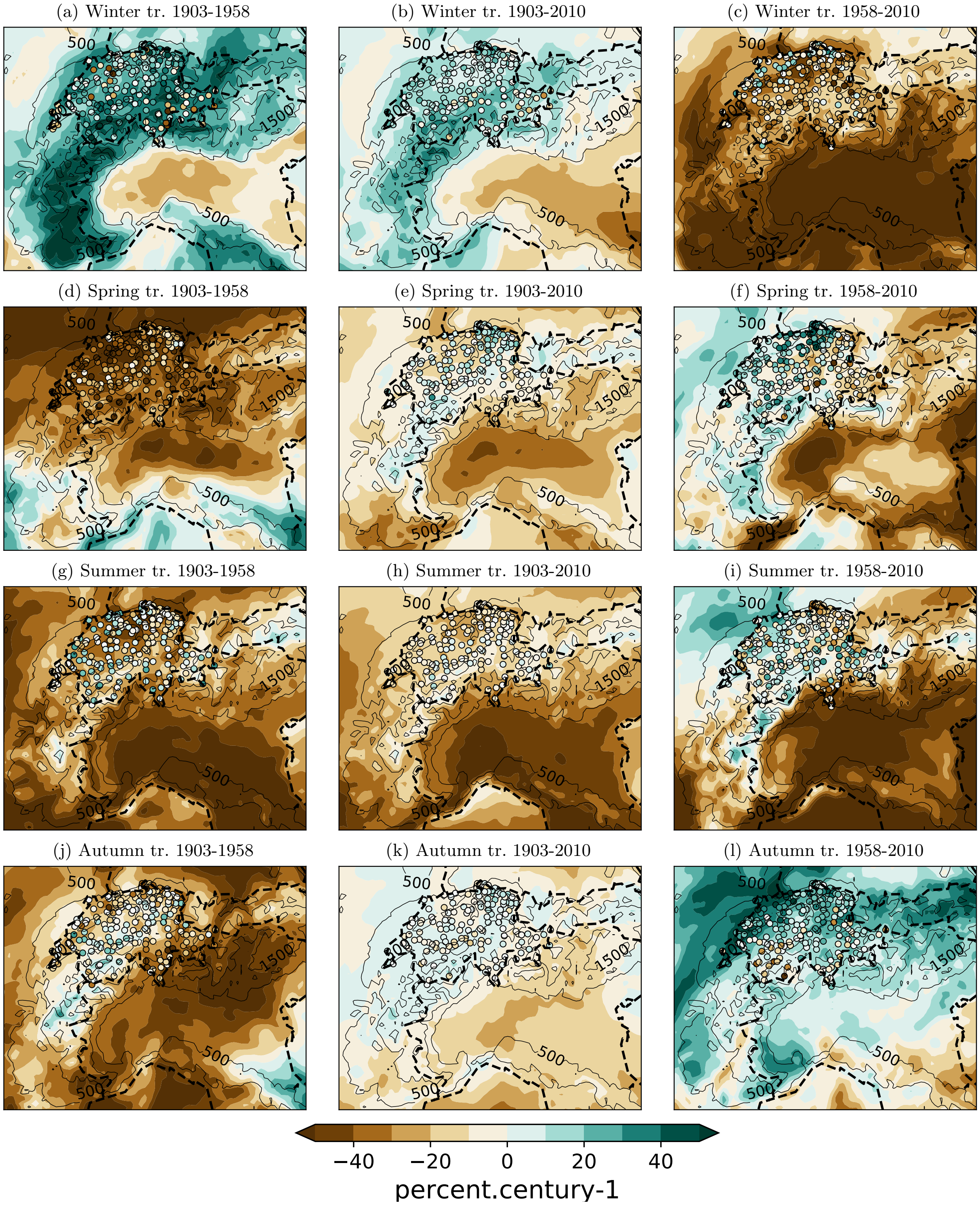

Figure 1: Seasonal linear trends (percent per century) of precipitation in winter (a-b-c), spring (d-e-f), summer (g-h-i) and autumn (j-k-l), over 1903-1958 (a-b-d-e), over 1903-2010 for (g-h-j-k) and over 1958-2010 for (c-f-i-l). 1000 m-spaced black contours show the topography in the 7km-resolution model, starting from 500 m.asl and frontiers are denoted with the black dashed lines. This figure has been included in the revised manuscript, in place of Figure 4.

2) At line 306 you state that the annual mean of your reconstructed climatology 1971-2008 is higher in the northern part of the Alps than in the south, and assume that is consistent with observations. This sounds like a wrong assumption since the annual precipitation maxima are recorded in the southern side of the Alps. Isotta et al. 2014 and Crespi et al. 2018, for example, is showing that annual maxima (EURO4M) are larger on the southern-side compared to the moist northern rim, where it rains more frequently but with less intensity. Piedmont-Ticino-Lombardy and Julian/Carnic Alps and some part of the northern Apennine are well known to be hot spots of heavy precipitation in the Alpine area.

We partly agree with this comment. Precipitation rates are actually underestimated in the MAR experiment compared to the EURO4M reanalysis in the Piedmont-Ticino-Lombardy area and in some part of the northern Apennine, where strong precipitation annual mean are observed (Isotta et al., 2014). However, for the French side, the annual mean of precipitation rates are stronger in the North than in the South, both in the observations (Isotta et al., 2014) and in the model (Figure 1 of the manuscript). These seasonal features as well as the differences between model and observations have been detailed in the revised manuscript. In addition, there is a confusion in this comment between the annual mean and the mean of the annual maximum (mean of Rx1day over a long period). At L.306 of the discussion manuscript, only the annual mean of precipitation is discussed (and not the mean of the annual maximum). The mean of the annual maximum (mean of Rx1day) over the last decades is shown in figure 7a, where maximum values are actually stronger in the southern flanks of the Alps in both the model and the observations, as stated in the initial manuscript lines 473-484.

3) Your study area leaves out the eastern alpine region, which, as mentioned above, shows the annual maxima (the Carnic Alps). I found this choice a bit weird. Maybe justify this or reconsider in consideration of the title of the work from which one assumes all the Alpine range is considered

Unfortunately, we cannot cover the full alpine domain in our study, because the model domain is too small. This will be underlined in the manuscript, and a larger domain will be considered in further studies to allow more investigations covering the whole European Alps.

4) A precipitation bias on the northern side is evident in the MAR experiment, and this should be considered more through the text.

This bias has been discussed in detail in the initial manuscript (L304-323). As stated in the discussion article, the comparison between the MAR outputs and the EURO4M dataset suggests a strong overestimation of the annual mean precipitation in the Northern side of the Alps (Figure 1b of the manuscript). Over France, the SPAZM dataset, based on statistical interpolation of meteorological station data and calibrated to fit hydrological simulations at large basin scale, suggests higher precipitation rates at high elevation in comparison with EURO4M (Figure 1d of the manuscript). This suggests large uncertainties in observational datasets at high elevation, a point that limits the possibility to evaluate model outputs for these areas.

5) The mean seasonal trends are not in total agreement with other works, especially over cold seasons. MAR positive trends are to be found in winter and Norther-Western Alps while in other seasons and regions the trend in the mean is mostly negative or neutral. From observational datasets (namely Isotta et al. 2014, Pavan et al. 2019) we see a positive and significant trend in Autumn more than winter, mostly affecting regions with higher annual rainfall (south-side of eastern Alps and northern Apennine). This is also consistent with the findings of Brönnimann et al., 2018.

As stated previously, a comparison of the MAR outputs over the last decades and not over the whole century (Figure 1 in this response, included in the revised manuscript), shows a good agreement between the model and the observations (Swiss station data as shown in Figure 1 as well as the changes described in Isotta et al. 2014 and Pavan et al. 2019), in particular for the moistening observed in autumn and the drying observed in winter that is a feature only visible for the last decades and not for the last century.

6) It would be interesting to discuss more the Autumn season in which precipitation in the Alpine area is more intense and often produced by an "optimal" synergy of synoptic-scale systems, which convey towards the region the necessary moist convergence, and mesoscale convective systems (Grazzini et al. 2019). In this respect, a RCM output may be useful to investigate the changes in the relative contributions of large-scale vs mesoscale systems to precipitations.

The seasonal cycle of precipitation over the European Alps differs widely depending on the area considered. One maximum of precipitation is found in the Eastern part of the Alps in summer whereas small precipitation rates occur at the same time in both the South and the West of the Alps (Figure 3 of the manuscript and Figure 2a-b-c-d in this response). In these areas, a maximum of precipitation is found either in spring, autumn or winter depending on the area considered (Figure 2a-b-c-d in this response). The maximum values of Rx1day are indeed found in autumn (Figure 6g in the manuscript). These seasonal features are described in the manuscript.

Here, further investigations concerning the relative contributions of convective versus stratiform precipitations have been conducted (Figure 2 in this response). Stratiform precipitation is mainly related to large-scale atmospheric circulation and convective precipitation can be related either to local processes or to a mix between large-scale circulation and local processes, conditions favourable to extreme events of precipitations (Grazziani et al., 2020). The convective precipitation represents a significant part of total precipitation in summer, from 10% to 50% at high elevation areas and even stronger ratio in the plain, with values varying between 60% and 90% in the model experiment (Figure 2g in this response). This ratio is smaller than 10% in winter and takes intermediate values in spring and autumn from 10% to 40% (Figure 2e-f-h in this response). The trend of the convective to total precipitation ratio is shown over 1902-2010 (Figure 2i-j-k-l) and 1958-2010 (Figure 2m-n-o-p). Over the last century, a significant negative trend from 5% to 20% of this ratio is simulated everywhere except at high elevation during all the seasons but the winter. In winter, a slight increase (<5%) is found, but it is generally not significant (p-value>0.05). Similar winter trend is found over 1958-2010, whereas the trend widely differs depending on the period considered for the three other seasons. Over 1958-2010, a strong increase in the convective to total precipitation ratio is simulated during the summer in large areas of the Alps (figure 2o), and to a lesser extent during the spring (figure 2n), whereas this signal is smaller in autumn (figure 2p). However, the signals simulated over 1958-2010 are not significant (p-value>0.05).

The interpretation of these contradictory signals (1903-2010 versus 1958-2010) is not straightforward, because convective precipitation depends on several variables, including atmospheric moisture availability at different levels in the atmosphere, soil moisture and temperature of both the atmosphere and the surface. The significant decrease of the convective to total precipitation ratio over 1902-2010 might be induced by changes of atmospheric moisture, with, for example, increase of moisture transport at large-scale that would impact differently stratiform and convective precipitation. Anyway, the intensified warming that took place during the last decades in areas with sufficient soil moisture is generally expected to favour an increase of the convective processes, as found in our experiments over 1958-2010 and suggested for future scenarios in high elevation areas by Giorigi et al. (2016). Here, the resolution used in our experiment (7km) could also have induced artefacts because the convective processes might be partly resolved with such intermediate resolution, whereas the convective parameterisation is still switched on. Further tests should be conducted with various resolutions to get sufficient confidence when simulating the convective changes over the Alps. This approach would complement the tests of different convective scheme in MAR experiments recently done with the MAR model (Doutreloup et al., 2019). Here, the results concerning the convective to total precipitation ratio are published in this response, but they have not been included in the final version of the article.

References:

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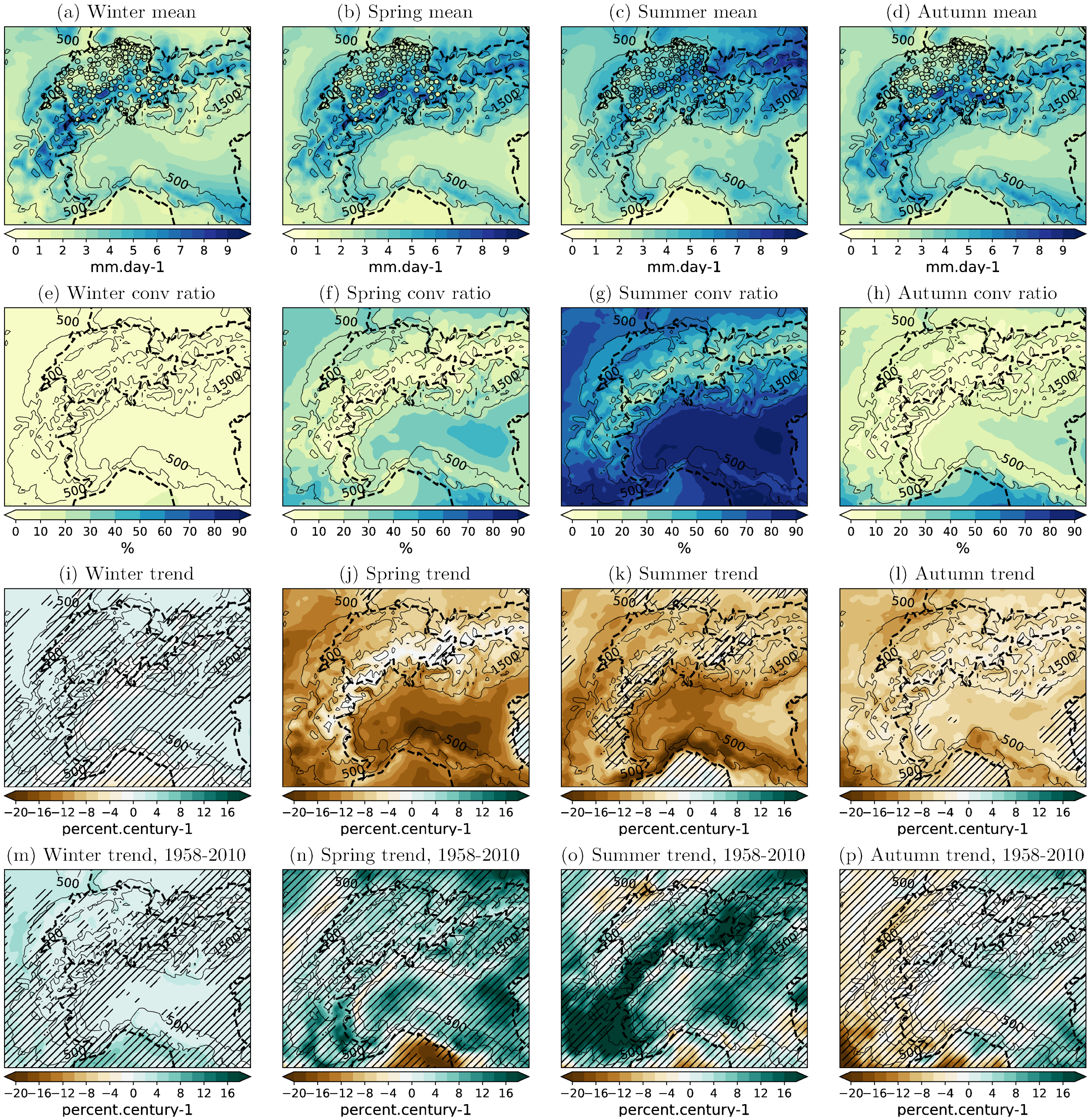

Figure 2: Seasonal mean of precipitation (a-b-c-d) for station data (dotted) and model data (shading). Seasonal contribution of convective to total precipitation (e-f-g-h) and their linear trends per century over 1903-2010 (i-j-k-l) and over 1958-2010 (m-n-o-p). Non-significant trends (p-value>0.05) are hatched. 1000 m-spaced black contours show the topography in the 7km-resolution model, starting from 500 m.asl and frontiers are denoted with the black dashed lines. This figure has not been included in the revised version of the manuscript.