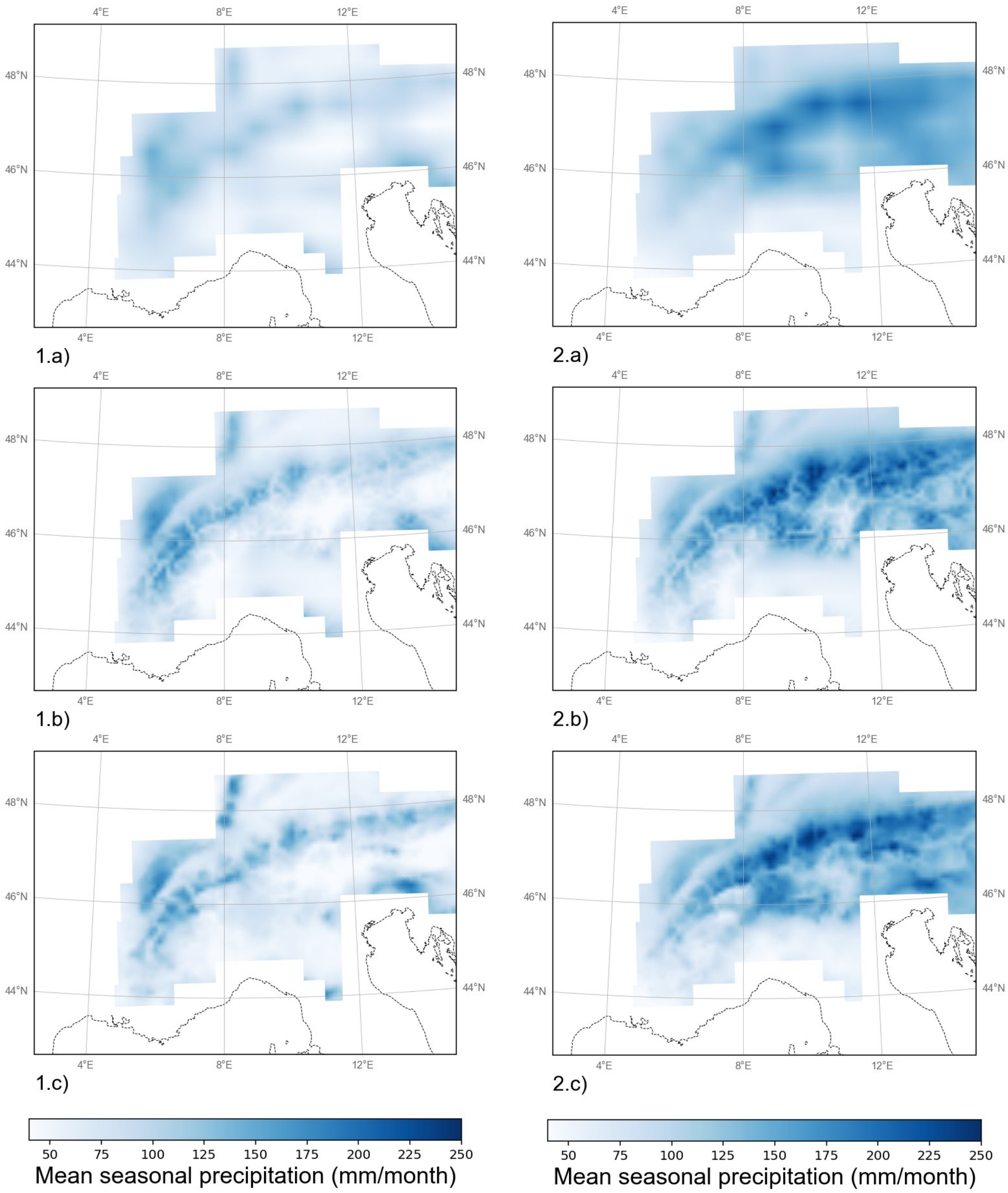
Authors’ response to the comments of the second reviewer

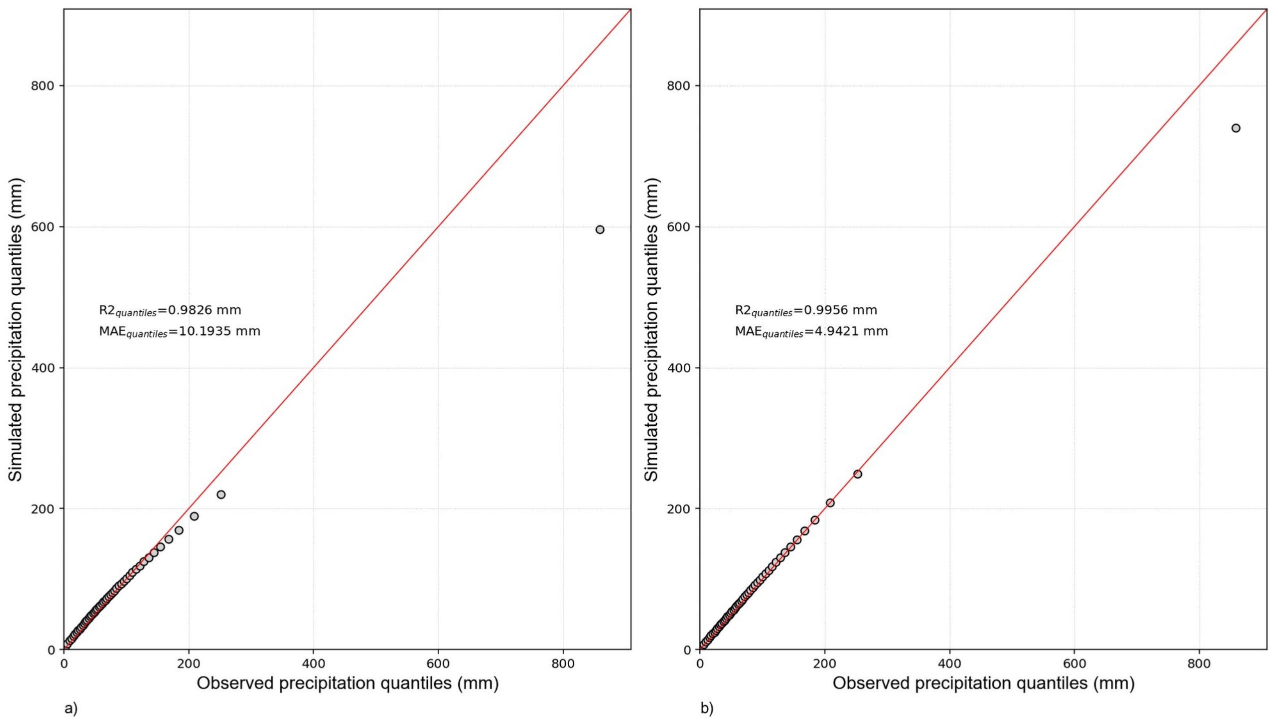
We thank the reviewer for the time and efforts put into reviewing our manuscript and for the valuable remarks made. Please find hereafter the reviewer’s comments (in italic), and our responses. Corrections added to the revised manuscript are indicated in bold blue.

1) « *The main idea that local precipitation is mainly driven by the amount of large-scale precipitation and the direction of wind relative to the topography seems to be applicable only for large-scale precipitation, but certainly not so for convective precipitation. The area where the methodology is being tested, Switzerland, experiences both types of precipitation, mainly depending on the season. The analysis of the method's skill is not seasonally stratified, so my concern is whether this skill is primarily derived from winter-time large-scale frontal precipitation. I think a seasonal stratification of the skill needs to be included and possibly discussed if there are seasonal differences. If they are, would the methodology need to include other fields, such as near-surface air temperature or air column stability, to account for convection?* »

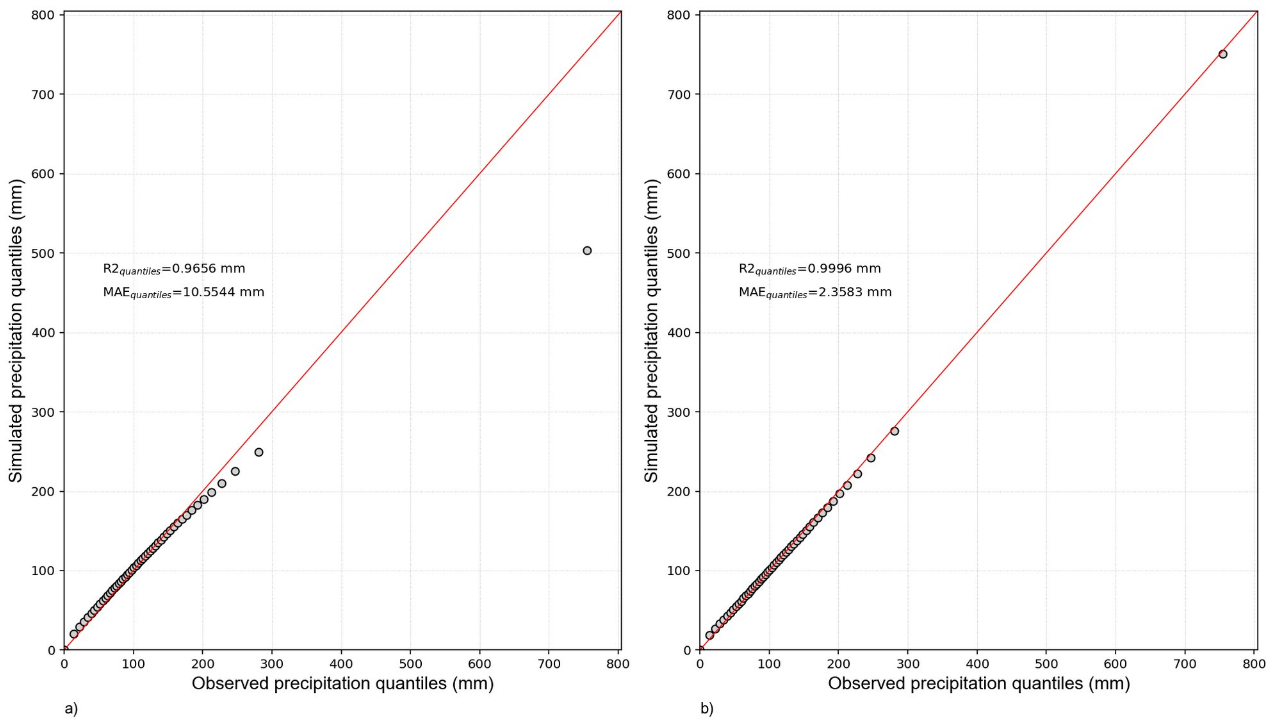
[Response] Thank you for this comment, as it touches upon a critical aspect of the precipitation regime in the Alps as well as to a limit of our model. We give hereafter the same response we made to one of the first reviewer’s comments. By construction, GeoDS focuses on orographic precipitation and does not solve local convection, essentially occuring during summer. Although the downscaling works well annually, decreased performances could be expected during summer. To assess the robustness of the method seasonnally, we analysed the climatologies and quantile-quantile plots of winter and summer precipitation over the whole period. Results are presented hereafter.



<u>Figure 1</u> : Average winter (DJF, left panel) and summer (JJA, right panel) precipitation for the $Ref_{interpolated}$ *(a), the GeoDS downscaled (b) and the native high resolution (c) versions of the Alpine Precipitation Grid Dataset over the period 1971-2019 using a 10km input DEM.*



<u>Figure 2</u> : Comparison of winter (DJF) observed precipitation quantiles and a) Ref$_{interpolated}$ b) downscaled with GeoDS precipitation quantiles using a 10km input DEM.



<u>Figure 3</u> : Comparison of summer (JJA) observed precipitation quantiles and a) Ref$_{interpolated}$ b) downscaled with GeoDS precipitation quantiles using a 10km input DEM.

The algorithm performs better during summer than winter, both statistically and in term of spatial distribution of precipitation. Besides biases in regions like the Slovenian Alps (discussed in the paper), the model exhibits an important dry bias in the Austrian Alps (north-east edge of the massif) during winter. Although these results may be counterintuitive at first glance, they can be explained by taking the following elements into account. A first explanation lies in how the large-scale precipitation data to downscale were built for this study. As explained in section 2.1.2, we upscaled the native APGD dataset to a regular 50km Cartesian grid to obtain a pseudo GCM output. This allows to feed GeoDS with debiased data and ensures that errors between downscaled precipitation patterns and the observations are primarily caused by the downscaling method, rather than propagating from the large-scale model (naturally, biases are expected to come from ERA5 winds as well. However, we lack an observational dataset to correct them). Since the APGD is derived from a well-distributed rain-gauge stations network, it captures precipitation patterns associated with local convection. Although upscaling the APGD smoothes this summer signal, it still appears in the large-scale data used as GeoDS inputs, and therefore, in the downscaled precipitation fields as well.

A second potential reason for the good model-data agreement during summer is that moisture feeding convective precipitation is primarily advected, rather than locally recycled. Using ERA-40 data, Sodemann and Zubler (2009) estimated the beta ratio (defined as the fraction of precipitation inside a domain that originates from evaporation inside the same domain, Schär et al., 1999) over the Alps to about 15.5 % for summer (below 1% during winter). So, although convection of local evaporation is not negligible, most summer moisture (primarily coming from land evaporation) still needs to be advected through large-scale circulation. Even if the dominant summer driver of condensation may be thermic convection rather than classic orographic uplift, the model is still able to consistently distribute fine-scale precipitation over the domain based on monthly average wind, indicating where moisture primarily comes from.

When analysing the seasonal performances of the model, it should be kept in mind that we set beta and delta values (dimensionless parameters that modulate the effect of topography on fine-scale precipitation) based on 1) the optimisation of several statistical indicators 2) the comparison of precipitation spatial patterns on an annual basis. Investigating a seasonal parametrisation of GeoDS may help improving the model's performances, especially during winter, for which the model exhibits a dry bias.

2) « *Regarding the manuscript itself, the paragraphs are really long. This could be improved to help the reader discern the chain of thought and to better locate paragraphs in a second reading. For instance, the introduction contains just one long paragraph (!), but this problem is also present in other sections. As a broad rule of thumb, a paragraph should be devoted to developing only one idea/message.* »

[Response] Thank you for bringing this up, as it does indeed make the text difficult to read in several places. This aspect was improved in the revised version of the manuscript.

3) « *Regarding the data description, did the data present gaps? Were they somehow filled? The precipitation data were aggregated to monthly sums. If gaps were present, were those months proportionally rescaled?* »

[Response] The high-resolution precipitation data were provided by MeteoSwiss on a daily basis over the domain shown on Figure 9.c (page 23), from January 1, 1971, to December 31, 2019. No gaps were identified in the original dataset (17 897 daily maps covering the same area). The method used by Isotta et al. (2014) to build this continuous dataset combines : 1) the collect of station measurements accross the whole domain, each undergoing a quality control procedure (checks for coding problems and for spatial consistency, identification of suspicious time series) 2) interpolation steps to estimate precipitation in ungauged areas.

As indicated in the dataset documentation (https://surfobs.climate.coperni-cus.eu/documents/ProdDoc_APGD.pdf), the spatial analysis for a day D is achieved in 4 steps :

« *(1) Spatial interpolation of the climatological mean precipitation measurements for the calendar month of D (reference period 1971-1990);*

(2) Calculation of relative anomalies of station measurements of D with respect to the climatological mean from step 1;

(3) Spatial interpolation of relative anomalies;

(4) Multiplication of the resulting anomaly field with the climatological mean field. »

A detailed description of the dataset and the method used to build it is available in Isotta et al. 2014 (DOI : 0.1002/joc.3794). We did not modify the native data before aggregating on a monthly basis.

Please note that spatial gaps appeared at the edges of the area when generating large-scale data. This was caused by the definition of the 50km grid and the conservative interpolation used for the coarsening : when a target grid point overlapped at least one native cell with NaN value, the whole grid point was converted to NaN. This is why the spatial extent of the domain shown in several figures (e.g. Fig4, Fig7) is smaller than area covered by the original APGD. We acknowledge that the upscaling step led to cutting off several areas of interest from the final analysis (like the Apennines, Italy). However, it allowed us to feed GeoDS with debiased inputs and to isolate errors caused by the downscaling step.

[Revised version] : « ... the efforts made to reduce the risk of systematic underestimates at high elevations. **No gaps were identified in the original dataset (17 897 daily maps covering the same area)**. Although given on a 5km scale... »

4) « *'*using a first order conservative remapping from the Climate Data Operator package*'. The CDO package offers several remapping options. I guess that in this case, the proper way to coarsen the data is to calculate the average of the high-resolution data within the low-resolution cells and not by interpolation. Was the coarsening conducted so?* »

[Response] The coarsening was indeed conducted so, using the cdo remapcon command. This ensures that the large-scale precipitation data of any coarse grid point corresponds to the average area-weighted precipitation of overlapped native APGD cells. A clearer description of the upscaling process was added to the revised version of the manuscript.

[Revised version] : « ...we degraded the APGDm target dataset to a regular 50 km Cartesian grid using a first order conservative remapping from the Climate Data Operator package (version 2.4.4). **With this method, the large-scale precipitation data of any coarse grid point corresponds to the average area-weighted precipitation of overlapped native APGD cells**. This ensures spatio-temporal consistency between precipitation fields at low and high resolutions... »

5) *«* 'On a global scale, the algorithm...' *Global scale sounds strange here. The authors probably mean the regional average. »*

[Response] The sentence was rephrased in the revised version of the manuscript.

[Revised version] : « **At the regional scale (Fig.8.a), the algorithm is slightly less accurate**...»