NHESS manuscript : NHESS-2023-82

Does a convection-permitting regional climate model bring new perspectives on the projection of Mediterranean floods?

We would like to thank the reviewers for the time and efforts they have dedicated to review our manuscript and for their useful and relevant comments. We believe that the comments truly helped to improve the manuscript. You can find below the responses to the requests and suggestions.

Reviewer 1

This paper assesses the use of convection-permitting regional climate models (CPMs) to improve the outputs of regional climate models (RCM), as climate projections could incorporate simulation of convection system storms in CPMs. CPMs could be applied to improve climate projections in the Mediterranean area, where floods are usually generated by convective storms. Simulations generated by a CPM are compared with the climate projections supplied by a RCM. Climate projections are bias corrected. Two hydrological models are used to transform climate projections into flood time series.

The paper is well written and organised. It can be considered for publication after addressing the comments included below.

We would like to thank the reviewer #1 for his/her positive evaluation of the manuscript. We answered all the comments below.

General comments

Convection-permitting regional climate models are a potential tool to improve the characterisation of convective storms in climate projections, as such events cannot be represented by the current climate models, given their spatial and temporal resolution. However, the analysis is limited to one climate model and one climate change scenario. Therefore, the conclusions could be highly limited to such a climate model and scenario. Why only one climate model is used? In addition, the selection of such a climate model and no other should be discussed. Why only the RCP 8.5 scenario is used?

To our knowledge, this study is the first one that focuses on Mediterranean floods using a convection permitting model to force two hydrological models. It is indeed limited to one convection permitting climate model (CPM) and one regional climate model (RCM) given the availability of these types of simulations. However, ALADIN and AROME are well known climate models that are well documented and used in the literature.

We are aware of the limitation using only 1 CPM and 1 RCM. Nevertheless, the aim of the study is not to provide robust future scenarios, but rather to develop a methodology that compares two climate models of different generations to assess both the added value in historical simulations and the differences of the projected signals.

Furthermore, convection permitting models are complex to develop and their simulations require large computational costs and storage capabilities. In this present study, for the sake of simplicity, we used only one CPM developed at CNRM. We chose this CPM as it was at the time of the study the first one available over this domain and all data were easily available and documented through different studies (Fumière et al., 2020; Caillaud et al., 2021; Lucas-Picher et al., 2023). Additional simulations should be performed in 2024.

We used the RCP 8.5 scenario because it is the only future scenario available for this simulation that was initially performed for the EUCP project (Hewitt and Lowe, 2018). Finally, by selecting the worst case scenario (i.e. RCP 8.5), we probably get the strongest climate change signal possible.This likely exacerbates the discrepancies between RCM and CPM future projections.

We are however aware that more CPMs and potentially other RCPs should be included in future work. We highlighted further this limitation in the revised version of the manuscript.

Furthermore, the paper should clarify if the climate model used in the study belongs to either AR5 or AR6 of IPCC.

We cannot say that the climate models in general belong to any of the assessment reports. Assessment reports are based on numerous studies using climate models that are part of projects, coordinated frameworks or experiences.

In this study, the GCM used was one of many models that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5), the RCM model was used for the CORDEX experiment and the CPM model was used for the EUCP project. The CMIP5 model simulations have been indeed assessed in the AR5. We will add a few more details about the simulations in the revised version of the paper.

The CREST distributed hydrological model has been calibrated fixing most of its parameters. A discussion should be included about why some parameters are fixed. A sensitivity analysis of model parameters could be useful to improve the understandability of the paper.

For CREST, different tests have been done with some combinations of parameters. Calibrations are long to run (>4 days). We made several tests, calibrating several free parameters spatially, or averaging parameters over the basins.

Most CREST parameters do have a physical meaning. Among the 13 parameters, we fixed 7 of them. Some reasons explaining why we fixed them are:

- **IM** is the percentage of impervious area in %. The Gardon d'Anduze basin has a complex and pronounced topography with a mean slope of around 20 % (Roux et al., 2011). It is primarily rural and it contains little urbanized areas. Even if soils are thin, the area is not composed of natural impervious areas (Roux et al., 2011), and the presence of buildings and bare rocks is rare. Thus, we considered this percentage to be close to 0 (range between 0.00001 and 0.00002)
- **Ke** is the potential evapotranspiration adjustment factor (unitless). Here we have as input a reliable simulation of PE, and this parameter is not dominant for

Mediterranean floods. This parameter is adjusted on a monthly basis within the model outputs, but is not generally calibrated.

- **IWU**: (Initial soil saturation in %) and **isu** (Initial water storage in channel grid cells) are initial conditions, we do not need to calibrate them because we included a warm-up period in our hydrological simulations.
- **under** (Subsurface flow speed) and **leaki** (Reduction in interflow storage) are baseflow parameters. Since we focus on floods that occurred rapidly, these parameters are not the most important parameters to study floods, so we fixed them.
- **th**: Drainage area threshold for channel cells (number of cells). This value can easily be estimated by looking at maps from which drainage area streams start to form and convert them to a cell number.

Here are the results of two tests with free (left side) and the above fixed (right side) parameters. The simulation with fixed parameters shows a better ability to reproduce floods over this catchment, and biases of the river discharges are also lower, explaining why we chose to fix these parameters. Furthermore, we followed closely the advice from the CREST model creators, co-authors of this study, who helped us design this experimental setup.

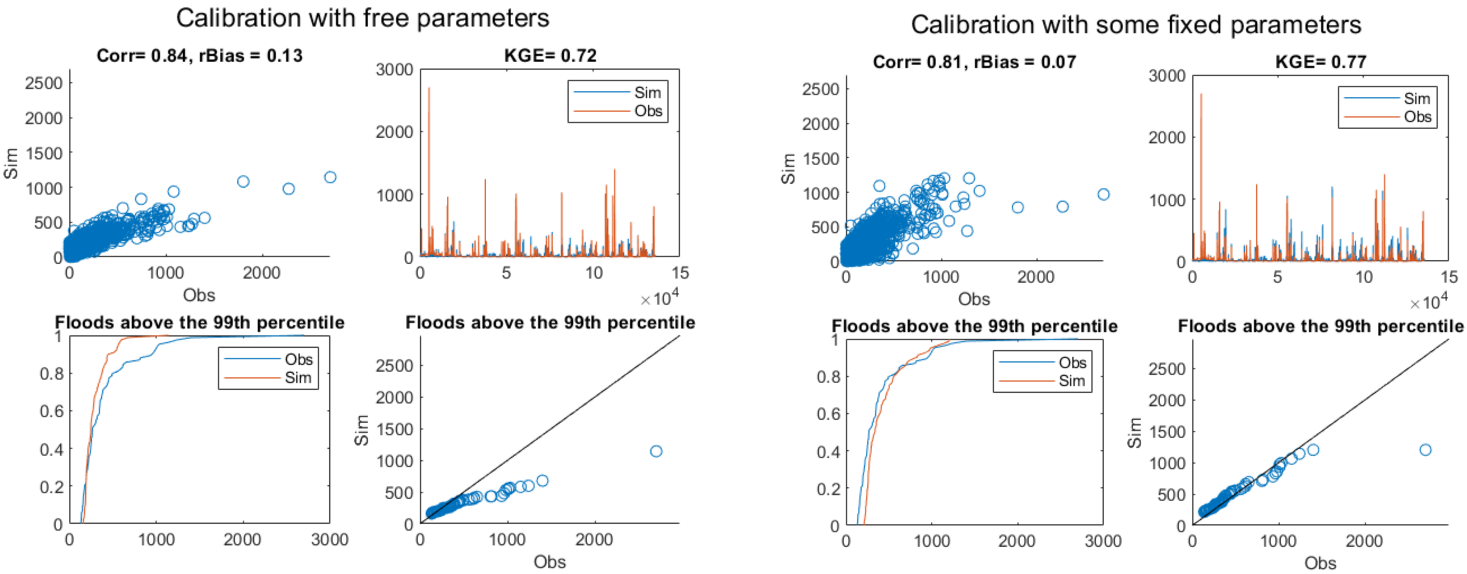

Figure 1: Results of CREST simulations (2002-2018 period) over the Gardon d'Anduze catchment with calibration of some free parameters (left panel) and with fixed parameters (right panel).

Section 4.1. The results are assessed qualitatively by using figures to compare outputs from different simulations. However, quantitative assessment of the results would be very useful for the reader. For example, comparison between model outputs shown in Figure 3 in terms of cumulative probability distribution could be improved by using similar metric to those used with the hydrological models.

Thank you for this interesting comment. We include below a new table that summarizes a quantitative assessment of the simulated precipitation that was added to the revised manuscript.

Model	**ALADIN**		**AROME**	
	raw	corrected	raw	corrected
Bias on median (%)	-27.2	0.4	-16.5	3.9
Bias on Q95 (%)	-40.4	1.3	-19.6	-3.4
Bias on Q99 (%)	-45.9	5.3	-12.2	0

Table 1: Evaluation of raw and corrected simulated precipitation with respect to the COMEPHORE observed dataset

Table 3 shows that the CREST performance is lower for all the metrics. It could be assumed that a distributed model could represent better rainfall-runoff processes in the catchment that a lumped model. However, if a distributed model has a lower performance than a lumped model, the lumped model should be preferred as it is simpler. Therefore, a comment should be included about why the CREST model is used in this study despite having a lower performance than a simpler lump model. In addition, maybe the lower performance of the CREST model could be increased by improving its calibration.

Distributed models are not necessarily better for representing rainfall-runoff processes, especially in small catchments (Reed et al., 2004; Best et al., 2015). Rainfall-runoff production and routing are indeed more conceptual in lumped models, but the small number of parameters and the efficiency of the calibration algorithms make them powerful tools for reproducing hydrological regimes and extremes. In fact, lumped models as GR models have been used by many studies for hydrological impact studies (Coron et al., 2017; Givati et al., 2019; Arsenault et al., 2020; Séne et al., 2023).

In addition, the study aims to compare the influence of the type of climate model and hydrological model on the simulation of historical floods and future signals. Here, even if CREST performance is a bit lower in reproducing discharge, the simulation of flood distributions is considered acceptable to address the scientific questions. We wanted to keep this model as one of the goals of this work was to assess the impact of the use of different hydrological models on the simulation of future floods. Interestingly, we were able to show that the choice of the hydrological model has a limited impact compared to the choice of the climate model to determine the future climate change signal on floods.

Regarding the improvement of the model calibration, we refer the reviewer to the answer to a previous comment. Many tests were made and we selected the best option in terms of performance.

Specific comments:

74. Do French Mediterranean region face intense floods with important damages and casualties every year? I think that such great floods happen from time to time, not every year.

The French Mediterranean region does face intense floods on average every year. Floods do not occur in every catchment every year, but every year, some basins of this region are affected by floods. The map below released by the French National Weather Agency (Météo France) presents the frequency of daily cumulative rainfall exceeding 200mm by districts (source: http://pluiesextremes.meteo.fr/france-metropole/IMG/sipex_pdf/nbj_sup200_1J_dep.pdf, version of April 2023)

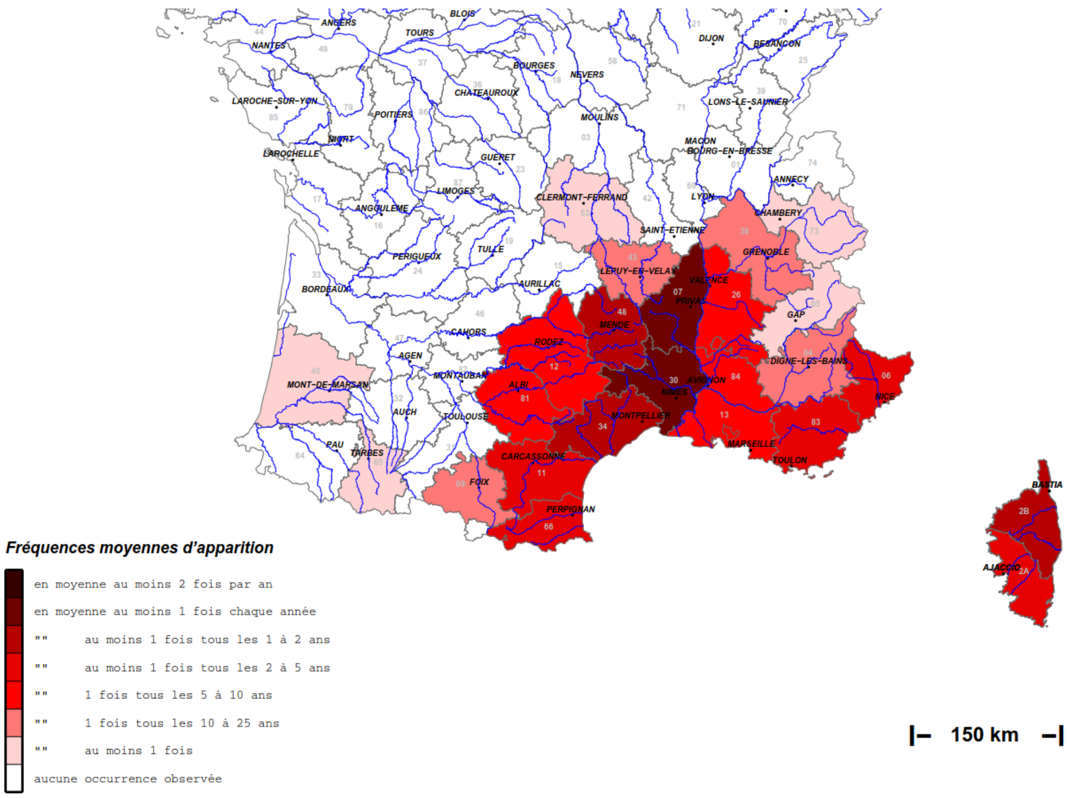

Figure 2 : frequency of daily cumulative rainfall exceeding 200mm over southern France

The color legend is from white (no occurrence) to dark brown (at least twice a year). The Gard and Ardeche districts experience on average one day above 200 mm of daily precipitation per year.

In terms of hydrological impacts, according to Boissier and Vinet (2009), it has been shown that above 100 mm/d, flood-related deaths are possible. The threshold of 190 mm in 24 hours, which is used by Météo France to describe a "torrential" downpour, causes at least one death on average one time out of three.

The website
http://pluiesextremes.meteo.fr/france-metropole/-Evenements-memorables-.html makes an inventory of extreme rainfall events. From that website, Mediterranean districts can be selected and the occurrence of such events and associated impacts become available.

129. Kendon (2010) cite is missing in the References Section.

Done, Kendon et al. (2012) was added to the Reference section.

147. What are CCLM and WRF? These acronyms should be either introduced in the paper or explained to readers.

These are acronyms of regional climate models. CCLM means COSMO-CLM (Climate version of Lokalmodell) developed by the German Weather Service (Baldauf et al., 2011). WRF means Weather Research & Forecasting Model developed by the National Center of Atmospheric Research (NCAR) in the USA (Powers et al., 2017). These acronyms and references will be added to the revised version of the paper

224-225. Some previous studies have used CNRM-AROME for assessing climate change, such as Monteiro et al. (2022). Such an application of CRRM-AROME should be investigated reviewing published works. In addition, the statement should be changed.

Thank you for highlighting this omission. We will add this study in the revised version of the paper.

297. Vrugt et al. (2009) cite is missing in the References Section.

We added this reference to the Reference section.

303-306. No information is supplied about how the soil parameters in both CREST and GR5H are estimated from available soil information.

The two hydrological models are calibrated. No soil information based on available local soil information is necessary to calibrate the models.

312. Only a few parameters of the CREST model have been considered in the calibration process. A description about why some parameters are fixed and others not should be included in the paper. In addition, a sensitivity analysis of the model parameters could be included in the paper to identify the parameters that can be fixed and the parameters that should be calibrated. Finally, a discussion should be included

in the paper about what hydrological processes are fixed and what processes are considered in the calibration process.

Thank you for this comment. We have already answered a similar comment above (third comment). To complete the previous answer, most studies using CREST have fixed parameters to produce hydrological simulation over catchments, for example Li et al. (2022).

361-362. Simulations are corrected in each cell separately. A sensitivity analysis could be included comparing the results correcting bias in climate projections at the regional scale and cell by cell. In addition, has spatial correlation between cells been considered? Correcting bias cell by cell could change spatial correlation patterns in precipitation.

We agree with the reviewer that using a bias correction method at the pixel scale can locally change the spatial coherence of precipitation patterns. However, we verified the precipitation patterns of the most intense rainfall events over the basin before and after bias correction. The precipitation patterns are minimally impacted by the bias correction. See the figure 1 in the answer to reviewer 2.

Table 1. Why nQ equals n plus 1? A comment could be included in the paper.

Thank you for this comment. It is a mistake of the transcription of the algorithm. n_Q is directly the number of timesteps exceeding the threshold. The way it is computed in the algorithm is $n_Q = j_{end} - j_{start} + 1$ with j_{end} and j_{start} respectively the indices of the last and first timestep exceeding threshold, but we prefer limiting this level of detail in the paper.

We will modify this table cell to " n_Q : number of timesteps exceeding the threshold".

483-489. After bias correction, both models underestimate precipitations associated with the highest quantiles. In addition, in Figure 3 for the period 2000-2018 both distributions are similar for quantiles close to 99.99. The main improvement of CPMs are supposed to be a better characterisation of the most extreme events. However, such an improvement cannot be seen in Figure 3. A comment should be included in the paper.

Bias correction performs as expected. All quantiles were corrected. As a result, the distributions of precipitation of AROME and ALADIN are similar after bias correction. The added value of CPM for simulating extreme events is visible on the raw CDF (top left panel) where the red curve is closer to the black one than the blue one. Note that the x axis of figure 3 is using a Gumbel transformation. The highest quantiles are stretched so the highest quantile here (0.9999) is an interpolation between the second and the last rainfall event.

614-616 and Figure 6. How simulated discharge with observed data represented by the green line in Figure 6 is obtained? The paper should include a description about how these simulations were obtained.

We will clarify this aspect in the revised version of the paper by adding a sentence line 598 : "The green line on the figure represents the hydrological simulations forced by the

COMEPHORE observed dataset that has been used for the calibration and could be considered as the reference simulation”.

619-623. This discussion should be clarified to improve the understandability of the paper.

We agree with the reviewer that those lines are unclear. We will rephrase them as follows:

“An improvement in flood frequency modeling is noticed after bias correction for all simulations. However, the CREST simulations still have a positive bias for flood frequency with higher values than the COMEPHORE driven simulation (2.9 and 3.3 floods per year for AROME and ALADIN respectively).”

623-624. CDFs of both climate models are similar after bias correction. In addition, it seems that ALADIN performs somewhat better than AROME, as ALADIN CDF is closer to observations than AROME CDF. A deeper discussion about why CPM improves flood characterisation in this catchment should be required.

We want to thank the reviewer for this remark. As shown by our results, the flood simulations are better with the raw outputs of the CP-RCM than the RCM. The results after bias corrections are impacted by the bias correction method and cannot be used to estimate which model compares the best with observations.

744-745. There are two brackets after a and b. One bracket should be deleted.

Done.

Section 4.5. Comments about np and POT boxplots in Figure 8 are missing.

A comment about the length of precipitation events (np) will be added as follows :

For np (line 752) “There is no clear signal about the changes in the length of precipitation events (np) and the total precipitation (Ptot) amount of flood producing rainfall events. However, the maximum…”

For POT metric, the complete description and comments about flood peaks are in section 4.4, as figure 7 is a detailed version of POT boxplots of figure 8.

Figure 8. In the boxplot of FI, the y-axis scale should be changed, as boxplots are excessively small to assess the results.

Here is the corrected figure :

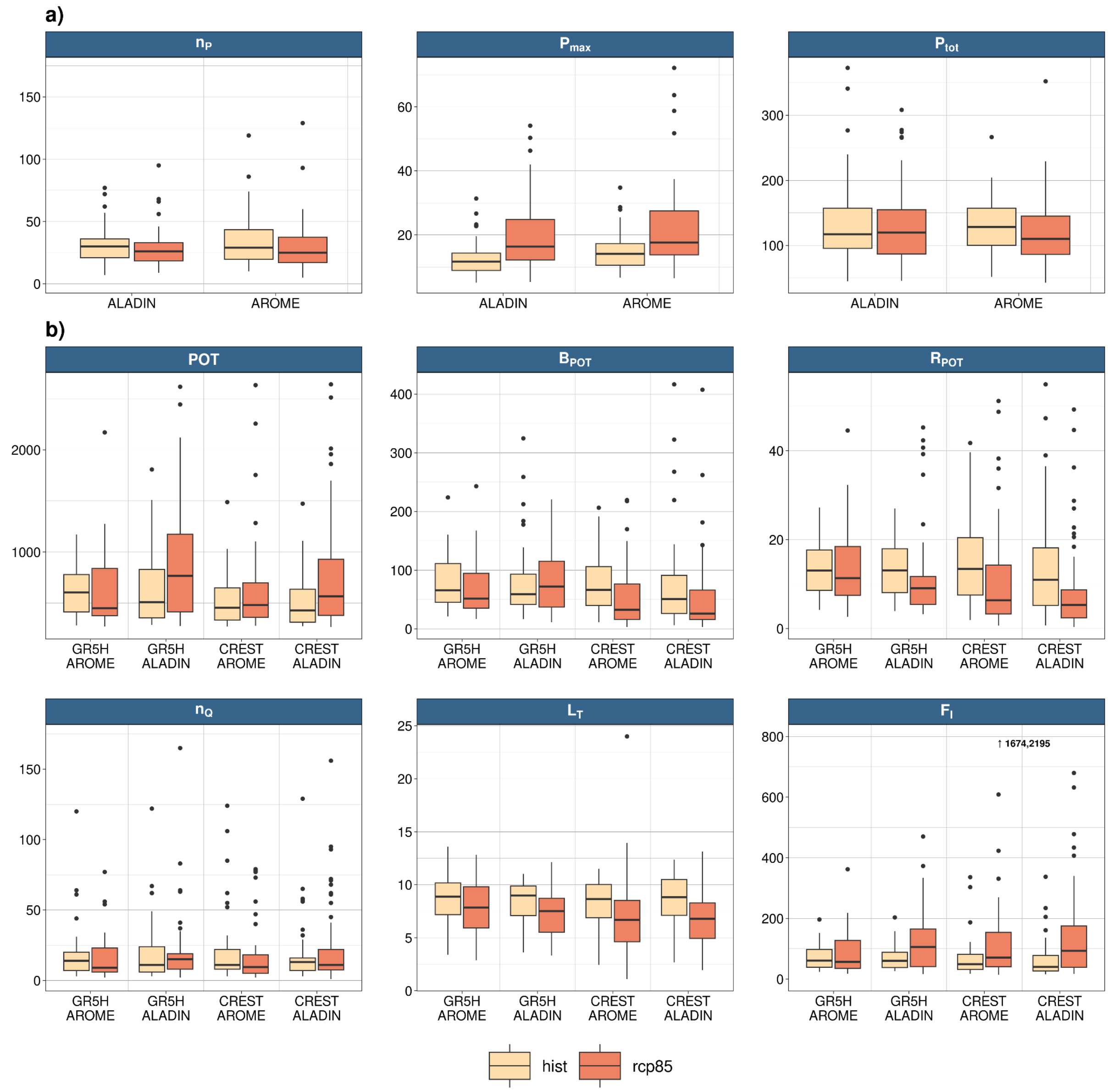

Figure 3 : Updated version of paper figure 8 with hidden outliers

813-815. The added value of CPM can be seen before bias correction. After bias correction, outputs of CPM are similar to those obtained with RCM. This should be clarified in the conclusions.

Indeed, this will be specified in the conclusions :

lines 813-815 : “The added value of the CPM can be clearly seen on rainfall simulation before correction, with a much better representation of extremes with AROME compared to ALADIN, the latter showing a strong underestimation. CDFT bias correction method homogenizes both distributions by removing biases.”

821-824. It is stated that similar results are obtained regardless the hydrological model used. A comment about the limitations of the distributed model to simulate floods in this catchment should be added, given that a simpler lumped model supplies better results.

We will add this detail in the conclusion.

Comment to the reviewers and editor

Since the submission of the paper, a problem has been identified in the AROME future simulations. As mentioned by Caillaud et al. (2023) : “For CNRM-AROME41t1, a bug was recently found in the GHG concentrations : they evolve, but do not completely follow the RCP8.5 scenario.”
The impact on temperature change has been tested and is marginal since the RCM emissions and temperature are correct and the lateral boundaries forcing takes over from internal CPM forcing.
This issue will be revealed in a coming note.

References

Arsenault, R., Brissette, F., Chen, J., Guo, Q., and Dallaire, G.: NAC2H: The North American Climate Change and Hydroclimatology Data Set, Water Resour. Res., 56, e2020WR027097, https://doi.org/10.1029/2020WR027097, 2020.

Baldauf, M., Seifert, A., Förstner, J., Majewski, D., Raschendorfer, M., and Reinhardt, T.: Operational Convective-Scale Numerical Weather Prediction with the COSMO Model: Description and Sensitivities, Mon. Weather Rev., 139, 3887–3905, https://doi.org/10.1175/MWR-D-10-05013.1, 2011.

Best, M. J., Abramowitz, G., Johnson, H. R., Pitman, A. J., Balsamo, G., Boone, A., Cuntz, M., Decharme, B., Dirmeyer, P. A., Dong, J., Ek, M., Guo, Z., Haverd, V., Hurk, B. J. J. van den, Nearing, G. S., Pak, B., Peters-Lidard, C., Santanello, J. A., Stevens, L., and Vuichard, N.: The Plumbing of Land Surface Models: Benchmarking Model Performance, J. Hydrometeorol., 16, 1425–1442, https://doi.org/10.1175/JHM-D-14-0158.1, 2015.

Boissier, L. and Vinet, F.: Paramètres hydroclimatiques et mortalité due aux crues torrentielles. Etude dans le sud de la France, in: Actes du 22ème colloque de l’Association Internationale de Climatologie, 1er au, 79–84p, 2009.

Caillaud, C., Somot, S., Alias, A., Bernard-Bouissières, I., Fumière, Q., Laurantin, O., Seity, Y., and Ducrocq, V.: Modelling Mediterranean heavy precipitation events at climate scale: an object-oriented evaluation of the CNRM-AROME convection-permitting regional climate model, Clim. Dyn., 56, 1717–1752, https://doi.org/10.1007/s00382-020-05558-y, 2021.

Caillaud, C., Somot, S., Douville, H., Alias, A., Bastin, S., Brienen, S., Demory, M.-E., Dobler, A., Feldmann, H., Frisius, T., Goergen, K., Kendon, E., Keuler, K. G., Lenderlink, G., Mercogliano, P., Pichelli, E., Soares, P. M. M., Tölle, M., and Vries, H. de: Mediterranean Heavy Precipitation Events in a warmer climate : robust versus uncertain changes with a large convection-permitting model ensemble, https://doi.org/10.22541/essoar.168987136.64498273/v1, 2023.

Coron, L., Thirel, G., Delaigue, O., Perrin, C., and Andréassian, V.: The suite of lumped GR

hydrological models in an R package, Environ. Model. Softw., 94, 166–171, https://doi.org/10.1016/j.envsoft.2017.05.002, 2017.
Fumière, Q., Déqué, M., Nuissier, O., Somot, S., Alias, A., Caillaud, C., Laurantin, O., and Seity, Y.: Extreme rainfall in Mediterranean France during the fall: added value of the CNRM-AROME Convection-Permitting Regional Climate Model, Clim. Dyn., 55, 77–91, https://doi.org/10.1007/s00382-019-04898-8, 2020.

Givati, A., Thirel, G., Rosenfeld, D., and Paz, D.: Climate change impacts on streamflow at the upper Jordan River based on an ensemble of regional climate models, J. Hydrol. Reg. Stud., 21, 92–109, https://doi.org/10.1016/j.ejrh.2018.12.004, 2019.

Hewitt, C. D. and Lowe, J. A.: Toward a European Climate Prediction System, Bull. Am. Meteorol. Soc., 99, 1997–2001, https://doi.org/10.1175/BAMS-D-18-0022.1, 2018.

Li, Z., Gao, S., Chen, M., Gourley, J. J., Liu, C., Prein, A. F., and Hong, Y.: The conterminous United States are projected to become more prone to flash floods in a high-end emissions scenario, Commun. Earth Environ., 3, 86, https://doi.org/10.1038/s43247-022-00409-6, 2022.

Lucas-Picher, P., Brisson, E., Caillaud, C., Alias, A., Nabat, P., Lemonsu, A., Poncet, N., Cortés Hernandez, V. E., Michau, Y., Doury, A., Monteiro, D., and Somot, S.: Evaluation of the convection-permitting regional climate model CNRM-AROME41t1 over Northwestern Europe, Clim. Dyn., https://doi.org/10.1007/s00382-022-06637-y, 2023.

Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., Coen, J. L., Gochis, D. J., Ahmadov, R., Peckham, S. E., Grell, G. A., Michalakes, J., Trahan, S., Benjamin, S. G., Alexander, C. R., Dimego, G. J., Wang, W., Schwartz, C. S., Romine, G. S., Liu, Z., Snyder, C., Chen, F., Barlage, M. J., Yu, W., and Duda, M. G.: The Weather Research and Forecasting Model: Overview, System Efforts, and Future Directions, Bull. Am. Meteorol. Soc., 98, 1717–1737, https://doi.org/10.1175/BAMS-D-15-00308.1, 2017.

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D.-J., and DMIP Participants, and: Overall distributed model intercomparison project results, J. Hydrol., 298, 27–60, https://doi.org/10.1016/j.jhydrol.2004.03.031, 2004.

Roux, H., Labat, D., Garambois, P.-A., Maubourguet, M.-M., Chorda, J., and Dartus, D.: A physically-based parsimonious hydrological model for flash floods in Mediterranean catchments, Nat. Hazards Earth Syst. Sci., 11, 2567–2582, https://doi.org/10.5194/nhess-11-2567-2011, 2011.

Séne, S. M. K., Faye, C., and Pande, C. B.: Assessment of current and future trends in water resources in the Gambia River Basin in a context of climate change, In Review, https://doi.org/10.21203/rs.3.rs-3143338/v1, 2023.