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PRIMAVERA

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PRocess-based climate sIMulation: AdVances in high resolution modelling and European climate Risk Assessment

Deliverable D*8.2*

Comparison case study for Government of forms of climate information available from PRIMAVERA and from other sources

Deliverable Title	Comparison case study for Government of forms of climate information available from PRIMAVERA and from other sources		
Brief Description	Comparative examples of model-generated information suitable for decision-making in Europe, going across past approaches and including new evidence from intercomparison of PRIMAVERA and traditional modelling. This deliverable is distilled from al work in PRIMAVERA. the work that has been done for the stream 2 simulations.		
WP number	WP8		
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		P - Prototype	
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		PP - Restricted to other programme participants, including the Commission services	
		RE - Restricted to a group specified by the consortium, including the Commission services	
		CO - Confidential, only for members of the consortium, including the Commission services	

Table of Contents

PRIMAVERA

1. Executive Summary

This document sets the scene for the type of innovation provided to decision makers by the PRIMAVERA approach to global climate modelling. It compares traditionally established approaches revolving around downscaling, common to past CMIP exercises, to the approach in CMIP6. Two examples are presented, with a comparison of results, focussing on the simulation of precipitation and temperature in European river catchments, suitable for end users.

The outcomes show that PRIMAVERA high-resolution GCMs do provide an attractive alternative to traditional approaches, but best value for money would be in optimally combining new global and new regional modelling strategies.

2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOA, Part B Section 1.1) WP numbers are in brackets:

No.	Objective	Yes	No
A	To develop a new generation of global high-resolution climate models. *(3, 4, 6)*		X
B	To develop new strategies and tools for evaluating global high-resolution climate models at a process level, and for quantifying the uncertainties in the predictions of regional climate. *(1, 2, 5, 9, 10)*		X
C	To provide new high-resolution protocols and flagship simulations for the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project (CMIP6) project, to inform the Intergovernmental Panel on Climate Change (IPCC) assessments and in support of emerging Climate Services. *(4, 6, 9)*		X
D	To explore the scientific and technological frontiers of capability in global climate modelling to provide guidance for the development of future generations of prediction systems, global climate and Earth System models (informing post-CMIP6 and beyond). *(3, 4)*		X
E	To advance understanding of past and future, natural and anthropogenic, drivers of variability and changes in European climate, including high impact events, by exploiting new capabilities in high-resolution global climate modelling. *(1, 2, 5)*	X	
F	To produce new, more robust and trustworthy projections of European climate for the next few decades based on improved global models and advances in process understanding. *(2, 3, 5, 6, 10)*		X
G	To engage with targeted end-user groups in key European economic sectors to strengthen their competitiveness, growth, resilience and ability by exploiting new scientific progress. *(10, 11)*	X	
H	To establish cooperation between science and policy actions at European and international level, to support the development of	X	

	effective climate change policies, optimize public decision making and increase capability to manage climate risks. *(5, 8, 10)*		

3. Detailed Report

3.1 Introduction

PRIMAVERA Global Climate Models are designed to produce more trustworthy information about risks to European Society and business interests. The key to being trustworthy is process fidelity, that is, how realistic the simulated phenomena are when compared to the real, observed ones. The philosophy behind the complementary value of simulation and observations is similar to the new European Commission's concept of Digital Twins.

Given the scientific and technical challenges involved in weather and climate simulation, model configuration is shaped by scientific goals and end requirements, but strongly limited by computational resources.

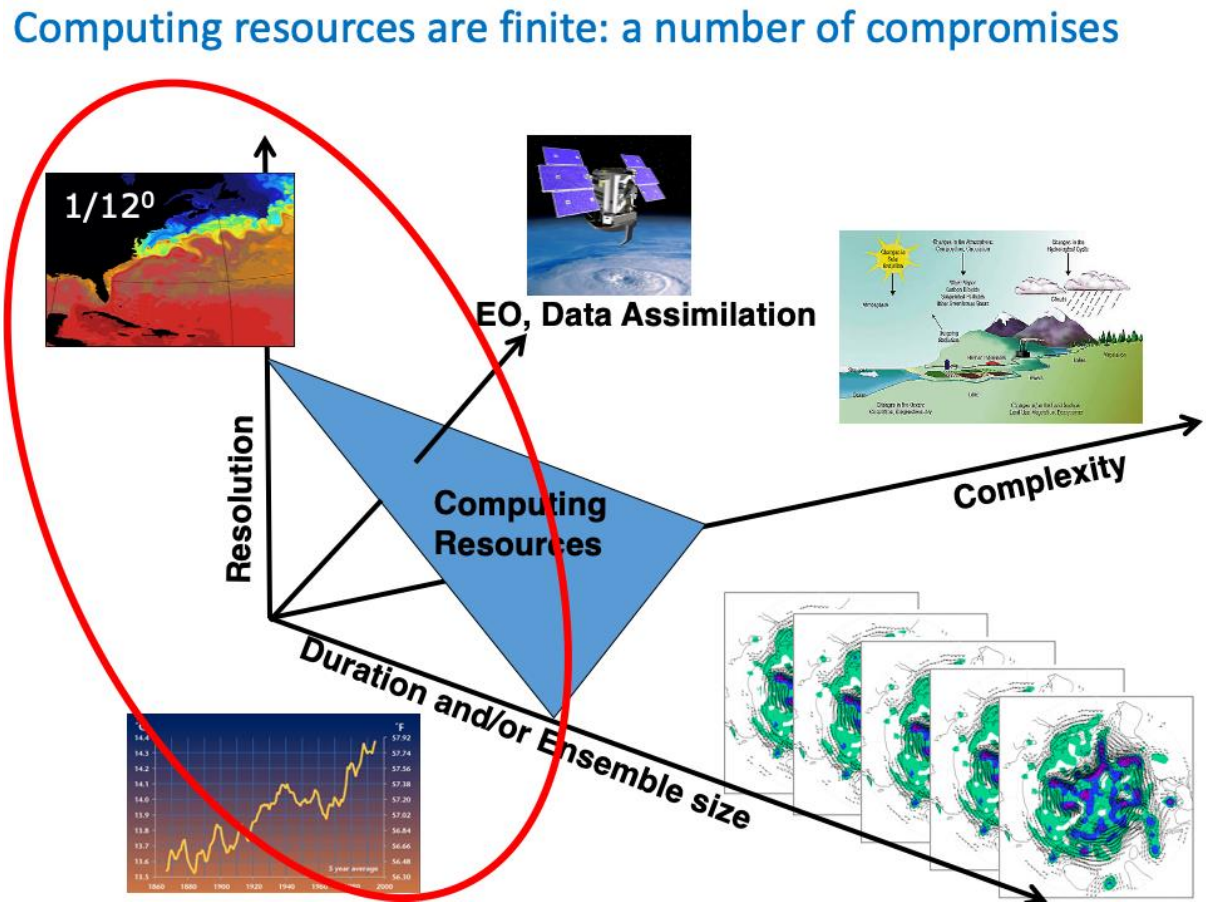

Figure 1: the multiple goals, requirements and limitations of state-of-the-art global climate modelling. The red ellipse is indicative of the PRIMAVERA focus.

In Figure 1 above, the various approaches to Weather and Climate simulation are illustrated, as well as the fact that they are bound by resource availability. PRIMAVERA concerned itself mostly with global high resolution, but ensembles were also exploited, albeit at a small size, and model complexity was relegated to the specific types that are suitable for high resolution.

Other communities, e.g. the Earth System Modelling community, else the regional climate modelling community, have made different investments, the first on more complexity, at the cost of resolution, the latter on larger ensembles and even higher resolution, sacrificing the global capability.

The simulation types considered are traditional GCMs, with resolutions applicable to both CMIP5 and CMIP6, CORDEX RCMs and PRIMAVERA GCMs. Their main characteristics are summarised in Table 1.

How valuable is each type of simulation? The answer lies in the specific goals and applications. Two examples can shed some light: European precipitation and precipitation and temperature means and variability in the Danube region.

Table 1: the different types of simulations available to European decision makers, in this case end users working with precipitation and temperature, including variability and extremes.

Source	**Type**	**Extent**	**Number of models**	**Sample size**
CMIP5,6	Climate Simulation Low Resolution	Global	30+	Tens of thousands of years
CORDEX	Climate Simulation High Resolution	Regional	22	Tens of thousands of years
PRIMAVERA	Climate Simulation High Resolution	Global	7	Thousands of years

3.2 Case study 1: European precipitation and its extremes

In the first example, PRIMAVERA GCMs were compared in terms of the added value of resolution to CMIP5 and CMIP6 traditional GCMs, which are coarse resolution, as well as CORDEX RCMs, with similar resolution, around 20km. The focus variables were mean and extreme precipitation, by season, over key river catchments in Europe, which is a useful exercise for both scientific investigation and hydrological applications.

Traditional GCMs provide a large sample size, a promise of formulation diversity (so, supporting robustness of results), and the benefit of state-of-the-art in model complexity, by incorporating all the latest parametrisations and process interactions. CORDEX models make use of a diversity of GCM drivers at the lateral boundaries, with a promise of covering large-scale circulation uncertainty, while affording high-resolution over a region of interest (in this case Europe), which is important for end-user applications, e.g. in this case for sufficiently resolving hydrological catchments, else detailed river catchments. Given their low cost, RCMs also provide large sample sizes, which are important for robust assessment of extremes.

High-Resolution GCMs, such as the ones in PRIMAVERA, provide the best of the two worlds, but due to computational costs sacrifice both model complexity (e.g. they do not include the carbon cycle) and sample size (most simulations comprise at most 3 ensemble members, although a few centres ran tens of simulations).

The results, presented in a paper by Demory et al. (2020) indicate that PRIMAVERA high-resolution GCMs have better skill at simulating European precipitation at the catchment scale than traditional CMIP5,6 GCMs. Further, PRIMAVERA GCMs present slightly better skill than CORDEX RCMs, despite the fact that PRIMAVERA GCMs were never tuned: not for global applications, nor for regional applications, which is, on the other hand, standard procedure for CORDEX models.

Demory et al. (2020) computed daily precipitation contribution to the mean (precipitation frequency x bin intensity), with exponential bins for the PRIMAVERA ensemble, the CORDEX EUR-44 ensemble and the observations. Their paper indicates that the CORDEX ensemble is unequivocally more skilled than the CMIP5 ensemble. The paper then goes into the more complex task of comparing the CORDEX and PRIMAVERA ensembles. Quoting directly from the paper, with adaptations for figure numbers:

> "Figure 2 shows the results of the comparison of the two ensembles for each region, season and bin rate interval (low/mid/heavy rain rates). Fig. 2b shows the same figure but for the ensembles reduced to the GCM families shared by the ensembles (4 GCMs, 17 RCMs).

For all regions, EUR-44 and PRIMAVERA ensemble means significantly differ (the part of the pie is coloured) from each other for the most intense rainfall rates in summer (JJA). EUR-44 indeed generally show a heavier precipitation tail in all regions, which is often significantly larger than PRIMAVERA. PRIMAVERA shows less contribution from these strong precipitation events, in better agreement with the observations in most regions, except the Alps. This conclusion is the most robust one and remains true when the strictest criteria of difference is applied. In the Alps, the heavy precipitation tail tends to be overestimated by CORDEX and underestimated by PRIMAVERA, so observations lie in between the two ensembles.

However, when a 20% undercatch error in the observations is assumed, EUR-44 are closer to the observed estimate. In other seasons, EUR-44 also have significantly larger contributions from intense precipitation compared to PRIMAVERA in many regions. They are in general further away from observations but closer to the synthetic observations accounting for precipitation undercatch.

When the same GCMs are used (Fig. 2b), the differences in the medium bins are only found in the centre or east of the domain (FR, CE, CA), which is potentially where EUR-44 are less influenced by the boundary conditions provided by the GCMs. In these regions, PRIMAVERA tend to simulate less contribution from these medium bins. This is in better agreement with the observations, even if the 20% undercatch error is taken into account. Both ensembles are the furthest away from the observations for the medium rain rates in winter and in spring, mostly overestimating precipitation. They are in best agreement with the observations in summer and autumn for these bins, except in the CA region where they both underestimate summer rainfall."

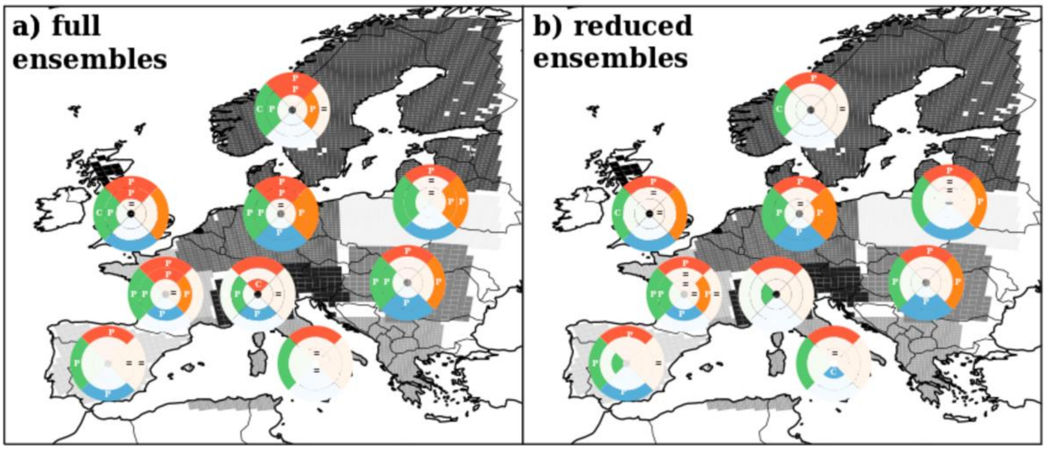

Figure 2. PRIMAVERA – CORDEX intercomparison. For each season (clockwise from the top: summer, autumn, winter, spring, right panel of Fig. 1 in Demory et al. 2020), region, and precipitation intensity interval (low rain rates=inner part, mid rain rates=middle part, high rain 930 rates=outer part), a colour indicates that the CORDEX and PRIMAVERA ensembles are significantly different, a "P" or "C" letter indicates that PRIMAVERA or EUR-44 are closer to the observations, respectively, an '=' sign indicates that both ensembles are close to observations. a) Map for the full PRIMAVERA and EUR-44 ensembles (listed in Tables 1 and 2); b) Map with reduced PRIMAVERA and EUR-44 ensembles using GCMs of the same family.

3.3 Case study 2: Precipitation and temperature in the Danube catchment

A detailed comparison of the skill in reproducing temperature and precipitation (means and variability) was undertaken in PRIMAVERA WP10/11, working with end users who simulate water resources (river discharge and irrigation demand) in the Danube catchment.

Two figures illustrate the evolution from CMIP5 GCMs, to their use via CORDEX downscaling, and direct use of PRIMAVERA high-resolution GCMs.

Figure 3 shows the normalised error (catchment average) in the simulation of precipitation for both means (left panel) and variability (right panel). Figure 4 shows the same information, albeit for temperature. For precipitation, it is not clear that CORDEX provides better value in terms of means when compared to CMIP5 GCMs, with possibly a larger number of simulations overestimating precipitation. PRIMAVERA GCMs seem to underestimate temperature but are likely indistinguishable from CMIP5 GCMs. CORDEX RCMs seem to introduce a slightly larger error in the simulation of precipitation variability. PRIMAVERA high-resolution GCMs are similar to CMIP5 GCMs in terms of variability.

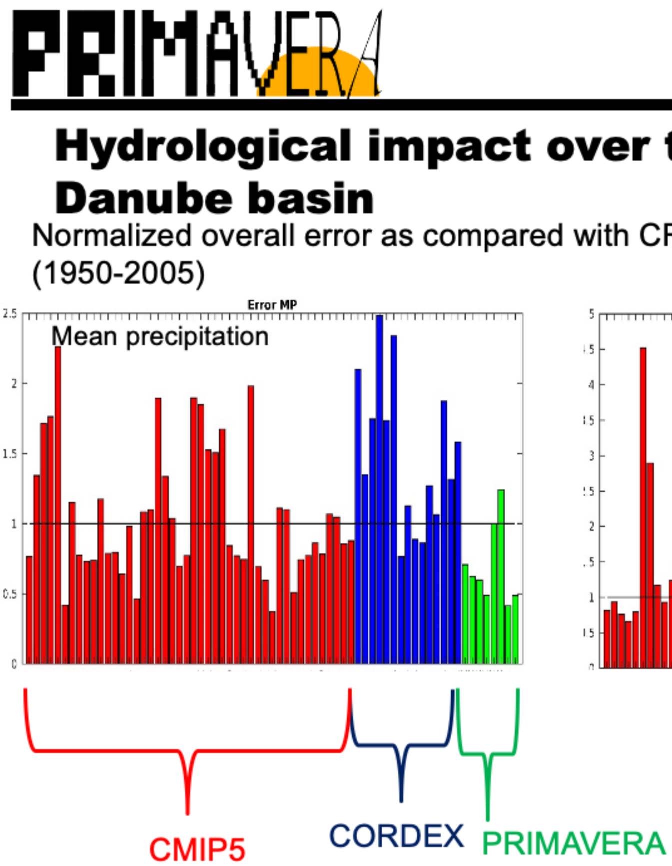

Figure 3: precipitation mean error (left) and error in the simulation of variability (right) in simulations of the Danube catchment in CMIP5 GCMs, CORDEX RCMs (driven by CMIP5 GCMs) and PRIMAVERA high-resolution GCMs.

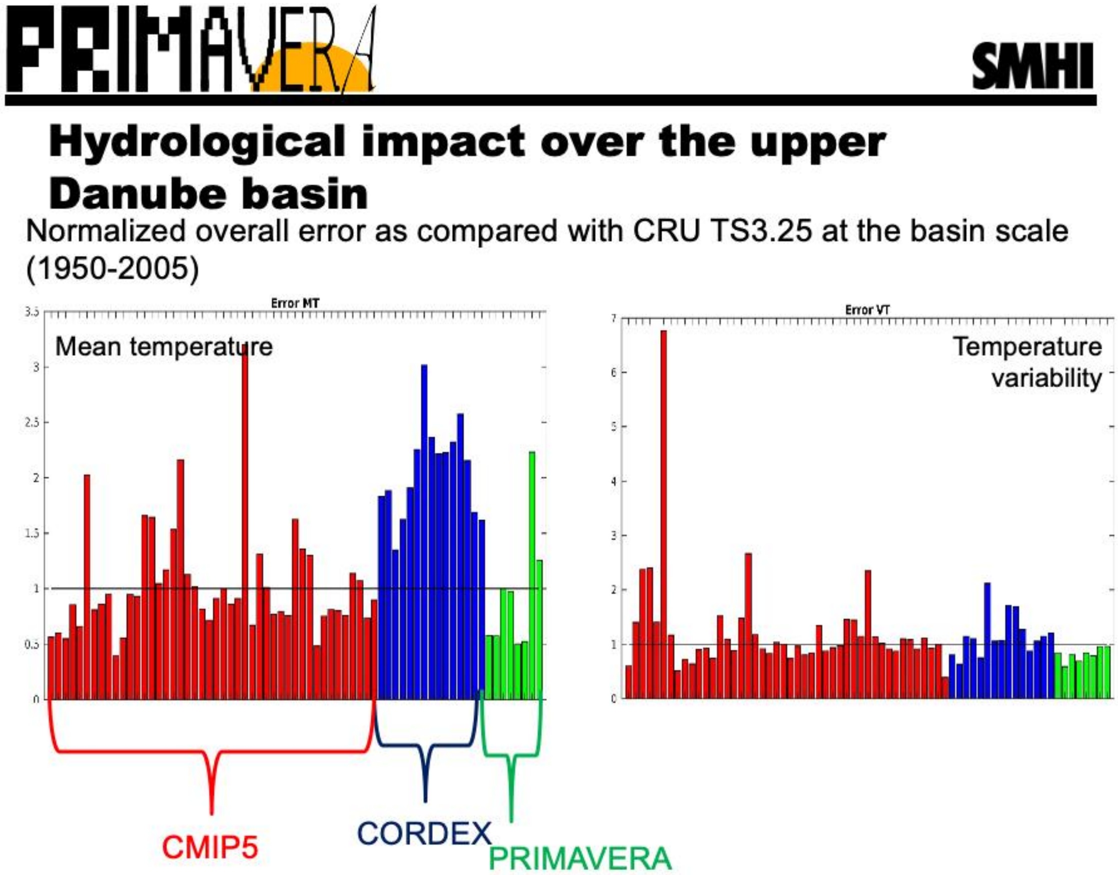

Figure 4: temperature mean error (left) and error in the simulation of variability (right) in simulations of the Danube catchment in CMIP5 GCMs, CORDEX RCMs (driven by CMIP5 GCMs) and PRIMAVERA high-resolution GCMs.

For the simulation of Danube catchment temperatures, CORDEX RCMs introduce a significantly larger error than CMIP5 GCMs, while PRIMAVERA high-resolution GCMs produce better simulations than CORDEX RCMs, albeit slightly worse than CMIP5 GCMs. For temperature variability, all three sets are rather similar.

In summary, PRIMAVERA high-resolution GCMs seem to outperform CORDEX RCMs in terms of means, while variability shows mixed results. This region is well known for causing RCMs to display a large temperature warm bias, because it is far away from the West boundary, where North Atlantic cyclones enter the domain, and the RCMs are left to rely on the quality of their physical parametrizations (and dynamics) to simulate the local climate.

3.4 Discussion

The two examples are good demonstrations of the compromise in resources, particularly in case 2, where the CMIP5 ensemble is significantly larger than the CORDEX and PRIMAVERA ensembles.

In both examples provided here PRIMAVERA GCMs seem to be able to outperform CORDEX RCMs, albeit only verified so far for a very small range of variables and for very specific applications.

An important caveat in the intercomparison is that PRIMAVERA GCMs were not tuned when switching from low to high resolution, because the focus of PRIMAVERA was on understanding the role of resolution, not on obtaining bias reduction by any available means, so that the project was open to the possibility that biases might increase with higher resolution. In that light, the PRIMAVERA bias reduction results are an added bonus.

With that, due to computational costs, it is not clear that PRIMAVERA GCMs were fully spun-up before starting the simulations in 1950, e.g. in terms of their deep soil state, something that both CMIP5 GCMs and CORDEX GCMs can afford to do for far longer periods of time. What are the consequences of a shorter spin-up period in PRIMAVERA, and how does this explain the results seen so far? If CORDEX RCMs fail to deliver added value to CMIP5 GCMs, then it is possible that:

A) GCMs used by CORDEX were not sufficiently run to equilibrium, producing significant biases, e.g. a N-S temperature gradient, which produce poor large-scale circulation, but CORDEX RCMs are partially able to cope, given their tuning;
B) GCMs used by CORDEX are run to a good equilibrium, but produce bad circulation, due to insufficient resolution (e.g. the storm track), but CORDEX RCMs are partially able to cope;
C) GCMs used by CORDEX are run to a good equilibrium, and produce good large-scale circulation, but CORDEX RCMs are of poor quality, e.g. in terms of their physical parametrisations;
D) both GCMs and RCMs produce good quality information, but the scale interactions are limited in range, thus limiting the quality of the final outcome.

Given what we have found in the two case studies, the most likely candidates are B), C) and and D), depending on the combination of GCM and RCM.

In terms of PRIMAVERA, the models analysed so far seem to be able to produce good jet dynamics, good storm tracks, good position and frequency of blocking (albeit not persistence), good extratropical cyclones (position, frequency and a sizeable portion of the intensity spectrum). As a result, PRIMAVERA GCMs produce good temperature and precipitation in terms of means, variability and extremes. This indicates that the shorter spin-up period is not detrimental, but, at the same time, it is not demonstrated that it is not artificially causing good results, e.g. due to soil memory, even after 20 years. Given the fact that the models were spun up and then started in the 1950s, however, the very variable oceanic forcing in that period, and the variability imposed by historic changes (GHGs, volcanoes), there was plenty of chance to erase that initial signal from 1950 into the period compared to observations.

In any case, the PRIMAVERA set represents a smaller resource in terms of sampling, which is particularly important for extremes. What remains to be seen is how many members of the other ensembles can be retained once certain quality criteria are introduced. End-user case studies are delving into this issue now that PRIMAVERA data sets are available.

3.5 Lessons learned

From the intercomparisons performed so far, the best possible use of resources would be in using PRIMAVERA GCMs at 20km for the large scale circulation to force RCMs in convection-permitting mode, so as to reduce the likelihood of biases due to the lateral boundary forcing and to maximise the number of years of simulations at scales capable of resolving extremes, particularly extreme precipitation, but also winds embedded in small and intense extra-tropical cyclones.

3.6 References

Demory, M.-E., and Coauthors, 2020: Can high-resolution GCMs reach the level of information provided by 12-50 km CORDEX RCMs in terms of daily precipitation distribution? Geosci. Model. Dev., revised. https://doi.org/10.5194/gmd-2019-370

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