Added value of the EURO-CORDEX high-resolution downscaling over the Iberian Peninsula revisited. Part II: Max and Min Temperature

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Abstract. In the recent past, the increase of computation resources led to the ~~appearance~~ development of regional climate models with increasing domains and resolutions, spa nn~~mm~~ing larger temporal periods. A good example is the World Climate Research Program - Coordinated Regional Climate Downscaling Experiment for the European domain (EURO-CORDEX). This set of regional models encompass the entire European continent, for a 130-year common period until the end of the 21st century, while having a 12 k~~K~~m horizontal resolution. Such simulations are computationally demanding, while at the same time, not always showing added value. This study considers a recently proposed metric in order to assess the added value of the EURO-CORDEX Hindcast (1989-2008) and Historical (1971-2005) simulations, for the maximum and minimum temperature over the Iberian Peninsula. This approach allows an evaluation of the higher against the driving lower resolutions relative to the performance of the whole or partial probability density functions, by having an observational regular gridded dataset as reference. Overall, the gains for maximum temperature are more relevant in comparison to minimum temperature, partially owed to known problems derived from the snow-albedo-atmosphere feedback. For more local scales, areas near the coast reveal ~~significant~~ higher added value in comparison with the interior, which displays limited gains and sometimes ~~significant~~ notable detrimental effects with values around -30%. ~~Nevertheless~~At the same time, the added value for temperature extremes reveals a similar range, although with ~~stronger~~ larger gains in coastal regions and in locations from the interior for maximum temperature, contrasting with the losses for locations in the interior of the domain for the minimum temperature.

1 Introduction

Climate change due to anthropogenic actions is one of the major challenges for the 21st century. Over the years, with the increasing public attention and motivated by the Intergovernmental Panel on Climate Change (IPCC), tools were developed for assessing past, present and future climate conditions, the so-called ~~lead to the further development of~~ Global Climate Models (GCM). ~~These simulations are the only gateway for assessing past, present, and future climate conditions.~~ However, while GCMs can capture the decadal variability and the overall large-scale circulations of the atmosphere and ocean (Meehl et al., 2007; Randall et al., 2007; Stocker et al., 2014), they reveal shortcomings, particularly at the local scales. These uncertainties are usually derived from the GCM low-resolution and thus the need of parameter~~s~~zation~~s~~ of small-scale processes (Prein et al., 2015). Due to these drawbacks, statistical and dynamical downscaling techniques were developed (Giorgi and Bates, 1989; McGregor, 1997, Wilby et al 1998, Khan et al 2006, Christensen et al., 2007; Rummukainen, 2010), thus establishing a new way of assessing climate at smaller scales. The latter makes use of Regional Climate Models (RCMs), which are an important tool in the representation of climate, since they are able to produce physically consistent regional and local circulations (Giorgi and Mearns, 1991; 1999; Leung et al., 2003; Laprise, 2008; Caldwell et al., 2009; Heikkilä et al., 2010; Soares et al., 2012a; 2012b; Cardoso et al., 2013; Rios-Entenza et al., 2014; Soares et al., 2014), nowadays with resolutions of tenths of kilometres, down to the ~~convective~~ convection permitting scales. The added value can be defined as the capability of a higher-resolution RCM in improving the representation of individual variables and~~or~~ processes in comparison to the driving or lower-resolution simulations, with observations as reference~~.~~ (Di Luca et al., 2012; 2013). Yet, increasing resolutions also imply growing computational costs, where not always these simulations reveal added value (Prein et al 2013; 2015; 2016; Torma et al., 2015, Rummukainen 2016; Soares and Cardoso, 2018; Cardoso and Soares, 2021; Careto et al 2021~~; Soares et al., 2021~~).

During the 21st century, the increase of computational resources has enabled the emergence of higher resolutions, higher temporal ranges, and larger domains for RCM simulations (Prein et al 2015). This evolution can be seen from the 50 km of the PRUDENCE project (Christensen and Christensen 2007), down to the 25 km from the ENSEMBLES project (van der Linden and Mitchell, 2009) and the more recent World Climate Research Program - Coordinated Regional Climate Downscaling Experiment for the European domain (EURO-CORDEX, Jacob et al., 2014; 2020) with its 12 k~~K~~m of horizontal resolution. Other examples are the ideal case studies using high-resolution simulations at the kilometre-scale (Hohenegger et al 2009, Froidevaux et al 2014, Imamovic et al 2017, Kirshbaum et al 2018) or the recent CORDEX Flagship Pilot Studies on Convection (Coppola et al. 2020; Ban et al., 2021; Pichelli et al., 2021). Nevertheless, the EURO-CORDEX simulations are a benchmark, covering the entire European continent, while spanning a large period and with a relatively high-resolution.~~.~~

EURO-CORDEX simulations are composed by a Hindcast, driven by the ERA-Interim reanalysis (Dee et al 2011), and a GCM-RCM downscaling experiment, where models are forced by the IPCC Coupled Model Intercomparison Project – Phase 5 (CMIP5) GCMs. Most studies focus their assessment for the precipitation variable. However, in the recent past, these simulations have been extensively evaluated, and important gains were found for variables such as temperature (Vautard et al., 2013, 2020; Kotlarski et al., 2014; ~~Casanueva et al., 2015;~~ Soares and Cardoso 2018; Ciarlo et al 2020; Herrera et al., 2020; Cardoso and Soares, 2021, Careto et al 2021). Vautard et al~~.~~ (2013) evaluated temperature for the Hindcast simulations finding an overestimation of extreme temperatures and heat waves for summertime over the Mediterranean, and an underestimation over Scandinavia. These differences were attributed to the convection and microphysics schemes, which affect ~~s~~ the flux partitioning and consequently the temperature. Moreover, despite the improvements, namely over coastline areas, the use of higher resolution did not show clear improvements in the representation of heatwaves. More recently, Vautard et al~~.~~ (2020) assessed the Historical EURO-CORDEX models reporting colder, humid, and more windy biases relative to observations, with joint liability across GCMs and RCMs. The authors also reported that no model stands out for all metrics considered. Also, Kotlarski et al~~.~~ (2014) assessed the summertime and wintertime temperature, precipitation, and mean sea level pressure from the Hindcast simulations for the 12 k~~K~~m and 50 k~~K~~m resolution, reporting a cold and humid bias over ~~for~~ most of Europe and seasons, together with a summer dry and warm bias in southern Europe. Yet the models were still able to capture the space-time variability of the European climate. ~~Casanueva et al, (2015) report improvements in high-resolution EURO-CORDEX ensemble, particularly in the spatial representation and correlation.~~ Herrera et al~~.~~ (2020), assessed the Hindcast models for the Iberian Peninsula against three observational datasets. While the models can reproduce the spatial pattern and variability, there is a dependence on the observational dataset considered. Nevertheless, the results reveal a higher agreement for temperature than for precipitation, decreasing for the extremes. The historical period simulations were also assessed for specific regions (Smiatek et al., 2016; Lhotka, 2018; Cardoso et al., 2019). Smiatek et al~~.~~ (2016) assessed precipitation and temperature for an alpine region, reporting a cold bias together with a more humid summer and winter. The authors describe that the models reveal no significant gains in comparison with previous experiments. On the other hand, Lhotka~~,~~ (2018) investigated the capability of EURO-CORDEX models in simulating heatwaves over central Europe, reporting an overall difficulty by models in reproducing these extremes. ~~Although RCMs reveal a good representation, these are usually attributed to different driving mechanisms in comparison to observations.~~ For Portugal, the temperature was evaluated in Cardoso et al~~.~~ (2019), where models can correctly describe the main orographic and coastal-related gradients, however, a cold bias is present for most RCMs. Nevertheless, the authors built a multi-model ensemble, which was able to ~~overperform~~ outperform the individual models. A common issue across all RCMs is related to the snow-albedo-temperature feedback, through a misrepresentation of the surface energy balance (García-Díez et al., 2015; Minder et al., 2016; Terzago et al., 2017). Uncertainties in the snow depth, melt and cover could have a potential impact on surface air temperatures around 0 ºC. Biases in the albedo representation leads to positive feedback, thus enhancing too cold temperatures during winter. ~~The higher-resolution simulations, with improved orography tend to overestimate snow depth over mountain ridges, at higher altitudes (Minder et al., 2016), while underestimate for lower altitudes. This results in higher snow cover for winter and an extended snowmelt in spring, thus leading to an underestimation of temperature, particularly minimum temperature (Terzago et al.,2017).~~

To assess the added value of the EURO-CORDEX high-resolution models against their forcing counterparts, Soares and Cardoso~~,~~ (2018) were the first to propose a new metric in order to gauge the quality of a simulation relative to their P~~p~~robability Density Functions (PDFs). They used a Distribution Added Value (DAV) to characteri~~s~~z~~e~~ the gains or losses of higher resolution simulations for precipitation for several Hindcast simulations, by comparing the high 12 k~~K~~m and the low 50 k~~K~~m resolutions, with the~~a~~ station-based dataset ECAD (Klein Tank et al 2002, Klok & Klein Tank 2009) as reference. The added value was shown, particularly for extreme precipitation, although not always the highest resolution displayed the most significant gains. Ciarlo et al~~.~~

(2020) used a similar probability density function -based metric ~~in order to~~to assess the added value of all available EURO-CORDEX and CORDEX-CORE (Gutowski et al., 2016) simulations for precipitation. Although added value of the high-resolution simulations is found, particularly for the tail end of the distributions, the authors also report~~ed~~ a significant uncertainty derived from the observational datasets. More recently, Careto et al~~.~~ (2021) revisited the added value from the EURO-CORDEX by implementing a similar methodology to this work over the Iberian Peninsula, considering the highest resolution observational dataset to date. ~~The DAVs were also applied to an alpine domain for the CORDEX-FPS Convection simulations (Soares et al., 2021) featuring an intermediate resolution of 15 Km and a convective permitting at 3 Km. The metric was used to assess the maximum and minimum temperature, by having the regular gridded E-OBs and station-based ECA&D datasets as benchmarks. However, although limited gains exist, the authors report an almost absence of added value by considering the entire PDF, while for extremes important losses were found. Nevertheless, as i~~In Di Luca et al~~.~~, (2013), sites located near the coast showed relevant gains. Cardoso and Soares~~,~~ (2021) assessed the temperature with the DAVs metric, for the lower (50 k~~K~~m) and higher resolution (12 k~~K~~m) Hindcast simulations, with the E-OBs regular dataset as a reference. The authors report~~ed~~ a difficulty in obtaining added value, partly owed to the assimilation of observations into the ERA-Interim. Still, gains are reported for the Mediterranean and British Isles, while losses are found for regions of complex terrain. Nevertheless, the authors found added value, particularly for maximum temperature extremes.

The DAV metric relies on comparisons from high/low-resolution models, with observations, regarding their PDFs, thus evaluating the gains or losses of RCMs against their driving ERA-Interim or GCM counterparts. DAVs is a versatile metric being able to be applied to either the entire PDF or to PDF sections, such as those related to extremes. In this study, DAVs will be used to assess the performance of maximum and minimum temperature for the Iberia Peninsula for all available Hindcast (1989-2008) and Historical (1971-2005) EURO-CODEX simulations. This assessment uses the Iberian Gridded Dataset (IGD, Herrera et al., 2019) as references. The IGD is a high-resolution dataset, built from an extensive station network, covering the Iberian Peninsula for the 1971-2015 period. Here, a new and unprecedented way of assessing the EURO-CORDEX simulations against observations at a similar scale is considered. The next section introduces the data and a description of the methods considered. The results and discussion are presented in the following section. Finally, the main conclusions are drawn in the last section.

2 Data and Methods

2.1 Iberian Gridded Dataset

Recently, Herrera et al. (2019) proposed a new regular gridded dataset, with a spatial resolution of 0.1º, based on a quality controlled observational network for the Iberian Peninsula ~~which~~ and includes 3486 and 275 stations for precipitation and temperatures, respectively. This dataset was built for the variables: daily precipitation, maximum, minimum, and mean temperature, spa nn~~mm~~ing a total of 45 years, from 1971 until the end of 2015. The authors compared this new dataset with version 17 of the E-OBS reporting its ability in reproducing the mean and extreme precipitation and temperature regimes more realistically. Moreover, for temperature, both observational datasets are comparable. The authors also compared the IGD with the ensemble version of the E-OBS (v17e) with a new probabilistic intercomparison analysis, concluding both datasets are statistically different, i.e., falls outside the observational uncertainty of E-OBS as given by the standard deviation of the ensemble.

2.2 EURO-CORDEX

The main objective from CORDEX is to generate a coordinated ensemble of high-resolution Regional Climate projections to provide, at a user-relevant scales, climate data for all regions from the world, supporting climate change impact and adaptation

research (Giorgi et al., 2009; Gutowski et al., 2016). EURO-CORDEX (Jacob et al., 2014; 2020) is a branch from the international CORDEX initiative and consists of producing simulations at three different resolutions (50 kKm, 25 kKm, 12 kKm) covering the entire Europe. Two types of simulations were produced. First, a Hindcast, for the 1989-2008 period and driven by the ERA-Interim reanalysis (Dee et al., 2011). Second, a Historical/Scenario simulation, driven by the Intergovernmental Panel on Climate Change Coupled Model Intercomparison Project – Phase 5 (IPCC-CMIP5) GCMs, covering the 1971-2100 period. Of these, only the Historical (1971-2005) will be considered. All simulations are available at the Earth System Grid Federation portal (Williams et al., 2011; https://esgf.llnl.gov/).

The information regarding the simulations for the Hindcast is summarised in Table S1 and for the Historical in Table S2. For all the simulations, the added value is computed for a common Iberian Peninsula domain, shown in Fig. 1, where a conservative interpolation (Schulzweida et al., 2009) of RCMs into the regular resolution of observations is first carried out. On the other end,

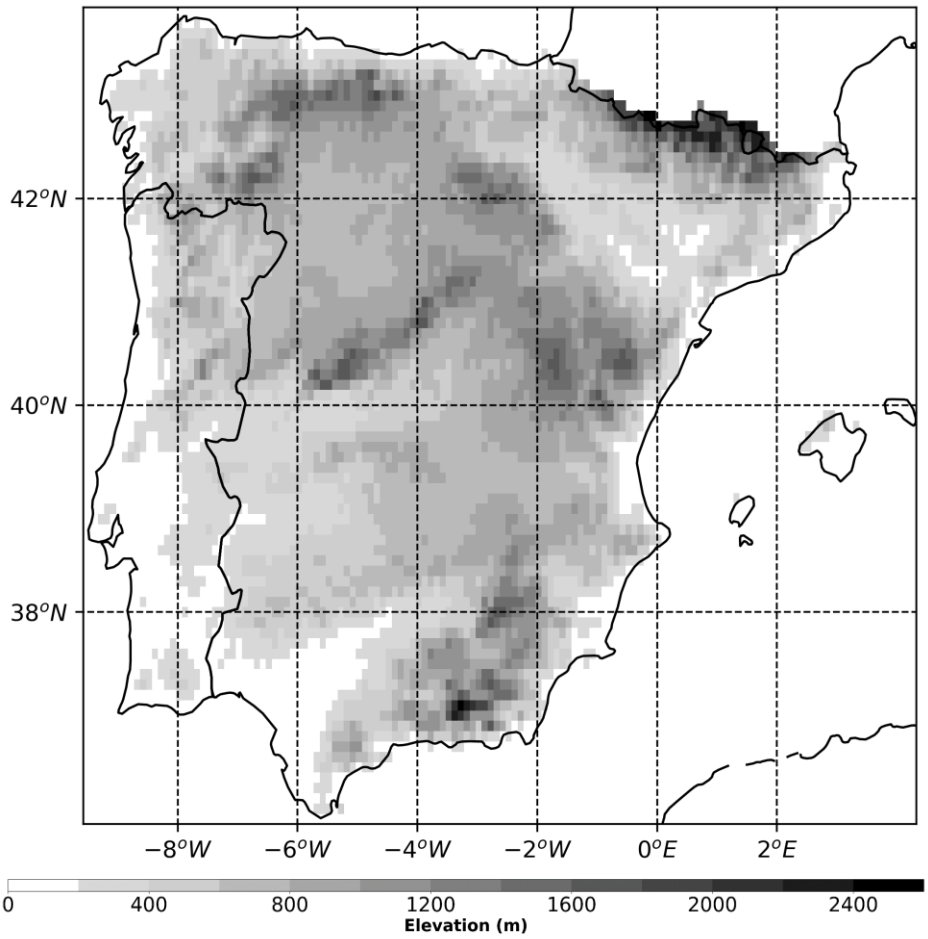

Figure 1. Orography from the Iberian Gridded Dataset for the Iberian Peninsula at 0.1º horizontal resolution

the observations were interpolated into each low-resolution GCMs (see table S2 for each GCM resolution) or ERA-Interim grid (0.75º). For temperature, a constant lapse rate of -6.5 ºC/km was considered for the interpolation. First, for each dataset, the effect of each orography was removed by adiabatically adjusting the temperatures to mean sea level. Afterward the horizontal interpolations, the temperature is adiabatically adjusted once again, to the orography from the target resolution, considering the same lapse rate.

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2.3 Distribution Added Value (DAV)

Soares and Cardoso, (2018) recently proposed a Distribution Added Value (DAV) metric which allows one to assess the performance of downscaling low-resolution GCMs or reanalysis in terms of Probability Density Functions (PDFs). The DAV metric is based on a PDF skill score proposed by Perkins et al. (2007) which measures the similarity between two PDFs. The first step is to build a PDF for each dataset. For maximum and minimum temperature, bins with a width of 1 ºC were chosen and the number of events is added for each bin. Next, each bin is divided by the sum of all events, thus resulting in an empirical relative frequency distribution. With this approach, one can more accurately compare the results across the different datasets as changes are more directly identified (Gutowski et al., 2007). Next, the Perkins score is given by the sum of the minimum bin value between the model and the observational PDF:

$$S = \sum_1^n \min\left(Z^m, Z^{obs}\right) \quad (1)$$

Where n is the PDF's number of bins, m denotes the high or the low-resolution model and obs is the observational PDF. For both temperatures, the limits are bounded between -50 ºC and 60 ºC, encompassing all of the observational temperature range. With the scores for all simulations, the DAVs are given by the normalised difference between the high-resolution model Perkins skill score and the lower resolution GCM or reanalysis Perkins skill score:

$$DAV = 100 * \frac{S_{hr} - S_{lr}}{S_{lr}} \quad (2)$$

with the subscript hr depicting the high resolution (RCM) and lr the low resolution (GCM or reanalysis). Thus, DAV represents the percentage of gains or losses w.r.t with respect to PDFs between the high and low resolutions models. If for a particular bin there is no data from either model or observations, then by definition the contribution of that bin would be 0. Moreover, an advantage of this metric is in its ability to be computed not only for the entire PDF but also for PDF sections, thus enabling an assessment for extremes. In this work, the extremes are also evaluated, where for maximum temperature, values above the observational 90th percentile are considered, while for minimum temperature, the values below the observational 10th percentile are taken into account. Therefore, a new relative frequency PDF is built only from the extremes.

For the assessment of the DAVs of temperatures, two approaches are considered. A first regional approach for the entire Iberian Peninsula, where the PDFs are built by pooling together all data, thus returning a representative result for the whole domain. The

second approach is composed by a spatialis~~z~~ation of the DAVs, where all data from within each individual low-resolution grid cell is pooled together, thus computing individual percentiles and PDF sets.

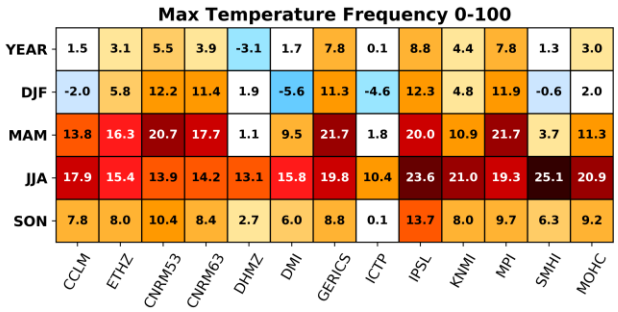
3 Results

3.1 Hindcast Simulations (1989-2008)

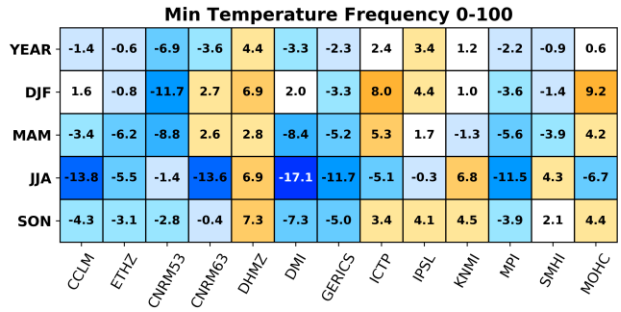
All PDFs shown in Fig. S1 either at the regular 0.1º resolution or ERA-Interim resolution reveal similarities with observations, anticipating an overall difficulty of the RCMs in obtaining added value. The temperature PDF follows approximately a Gaussian normal distribution, thus small changes in the mean or standard deviation could have major impacts on the DAVs results. This effect is particularly relevant for TASMIN, where all PDFs ~~reveal a closer proximity~~overlaps more reasonably than in comparison to TASMAX.

Figure 2a displays the results for the TASMAX considering the whole PDF. At the annual scale, all models except DHMZ reveal positive DAVs., where~~namely~~ GERICS, IPSL, and MPI ~~with~~ reveal percentages above 7.8 %. In fact, in Cardoso and Soares, (2021) the IPSL model also has ~~significant~~ higher gains for the Iberian Peninsula. The same models which display ~~weaker~~ smaller DAVs, below 3% at the annual scale, also reveal lower percentages for winter, with 4 RCMs having a small detrimental effect. These negative values for winter are enough to condition the yearly DAVs, since in spring and summer there is a higher added value for 6 and 9 models, respectively. From these, GERICS, IPSL and MPI standout with gains above 19 % for both seasons, reflecting in more noticeable DAVs at the annual scale. As for autumn, almost all models reveal some added value, although not as large as for spring or summer. For ICTP, this RCM also displays a similar performance to the driving simulation. In fact, this model also revealed neutral DAVS for spring, although gains around 10 % for summer, and small losses for winter. Another model with limited gains, but throughout the year, is the DHMZ, which despite the positive seasonal DAVs, at the annual scale a small detrimental effect is shown. The PDFs in Fig. S1 from the high-resolution models have a close representation relative the IGD. Particularly for the winter season, the already tightly packed PDFs, reveal a more difficulty for the higher resolution in obtaining added value in comparison to the other seasons. These results are in line with Herrera et al (2020), which evaluated the annual and seasonal means and variability for a set of Hindcast simulations. For temperature, the authors obtained small spatial biases and small standard deviation ratios between the models and the IGD.

(a)



(b)



(c)

(d)

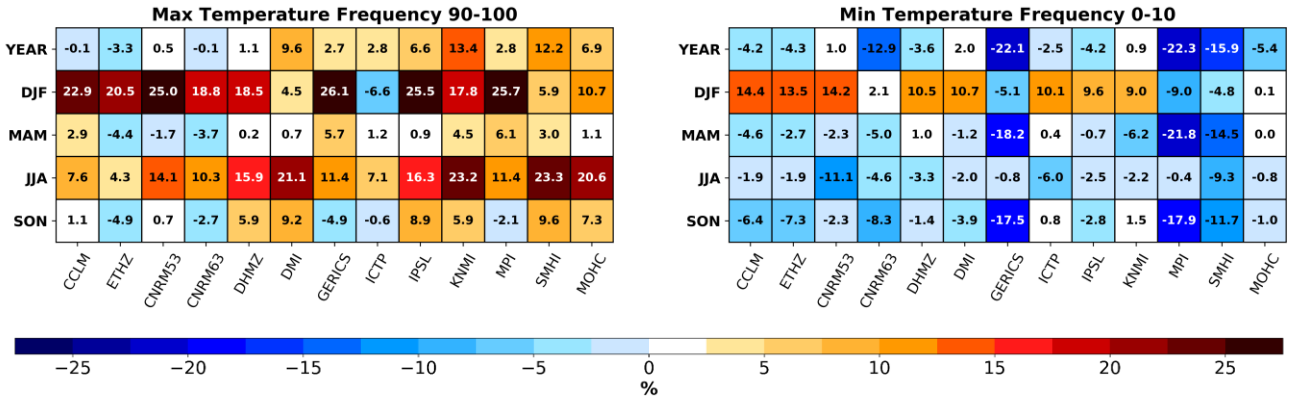


Figure 2. Yearly and seasonal distribution added values (DAV) of the Iberian Peninsula, between the RCMs and the ERA-Interim reanalysis for the 1989-2008 period, taken from the Hindcast EURO-CORDEX simulations, with the IGD regular dataset as a reference for (a) maximum daily temperature, considering the whole PDF, (b) minimum daily temperature considering the whole PDF. (c) maximum daily temperature extremes, only considering the values above the observational 90th percentile from maximum temperatures and (d) minimum temperature extremes only considering the values ~~above~~ below the observational 10th percentile from minimum temperatures. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into the ERA-Interim resolution

~~Scale also reveal lower percentages for winter, with 4 RCMs having a small detrimental effect. These negative values for winter are enough to condition the yearly DAVs, since in spring and summer there is a significant added value for 6 and 9 models, respectively. From these, GERICs, IPSL and MPI standout with gains above 19 % for both seasons, reflecting in stronger DAVs at the annual scale. As for autumn, almost all models reveal some added value, although not as significant as for spring or summer. For ICTP, this RCM also displays a similar performance to the driving simulation. In fact, this model also revealed neutral DAVS for spring, although gains around 10 % for summer, and small losses for winter. Another model with limited gains, but through out the year, is the DHMZ, which despite the positive seasonal DAVs, at the annual scale a small detrimental effect is shown. The PDFs in Fig. S1 from the high-resolution models have a close representation relative the IGD. Particularly for the winter season, the already tightly packed PDFs, reveal a more difficulty for the higher resolution in obtaining added value in comparison to the other seasons. These results are in line with Herrera et al. (2020), which evaluated the annual and seasonal means and variability for a set of Hindcast simulations. For temperature, the authors obtained small spatial biases and small standard deviation ra tios between the models and the IGD.~~

In the opposite sense, TASMIN displays an overall loss of value for the high-resolution simulations against the driving ERA-Interim reanalysis (Fig. 2b). The results here are a reflection of the smaller differences between the reanalysis and the IGD due to the incorporation of temperature observations into ERA-Interim (Prömmel et al., 2010), together with the overestimation of the temperature bins around 0 ºC for the RCMs (Fig S1 right side).~~The results here are a reflection of the smaller differences between models and observations, together with the overestimation of the temperature bins around 0 ºC for the RCMs (Fig S1 right side).~~ The RCMs reveal issues related to the snow cover, depth, and melt, which impacts the snow-albedo feedback and consequently the flux partitioning at the surface (García-Díez et al., 2015; Minder et al., 2016; Terzago et al., 2017)~~. Another reason could be owed to the incorporation of temperature observations into the ERA-Interim (.Prömmel et al., 2010).~~ The higher resolutions are able to represent the mountain ridges and valleys in more detail. However, this causes an overestimation of the snow depth in high altitudes and an underestimation at the lower altitudes (Tergazo et al., 2017). These biases, through the snow-albedo-feedback causes an underestimation (overestimation) of temperature at higher (lower) altitudes, not only for winter, but also for springtime due to an extended (reduced) snowmelt period (Minder et al., 2016). In the Iberian Peninsula there is not many locations with a

significant amount of snow. In fact, the PDFs of the RCMs for TASMIN in Figure S2 reveal a slight shift to the right for all seasons, indicating an overestimation of minimum temperature. Therefore, the issues related to snow and the ~~similarity~~ smaller differences between all PDFs at the low-resolution anticipates an overall difficulty in obtaining added value for the minimum temperature. Accordingly, 8 out of 13 RCMs in Fig. 2b for the annual scale reveal some losses, specially CNRM53 with -6.9 %. These detrimental effects come from the losses ~~for~~ of the individual seasons. While for TASMAX, summer had some of the highest scores in Fig. 2a, only 3 models show added value in Fig. 2b. The other 10 RCMs reveal detrimental effects, where from these, 5 reveal losses up to -11 %. For the other seasons, the ~~panorama is~~ values are not so different, with the majority of RCMs displaying losses up to -11.7 % for CNRM53 in winter. In fact, this RCM together with ETHZ, GERICS and MPI reveal the worst performance throughout the year in comparison to the driving simulation. Despite the overall lower values for TASMIN, 5 models are still able to display at least two seasons with added value. Only DHMZ ~~contradicts the~~ reveals a different result~~s~~ by obtaining positive percentages at the annual and seasonal scale.

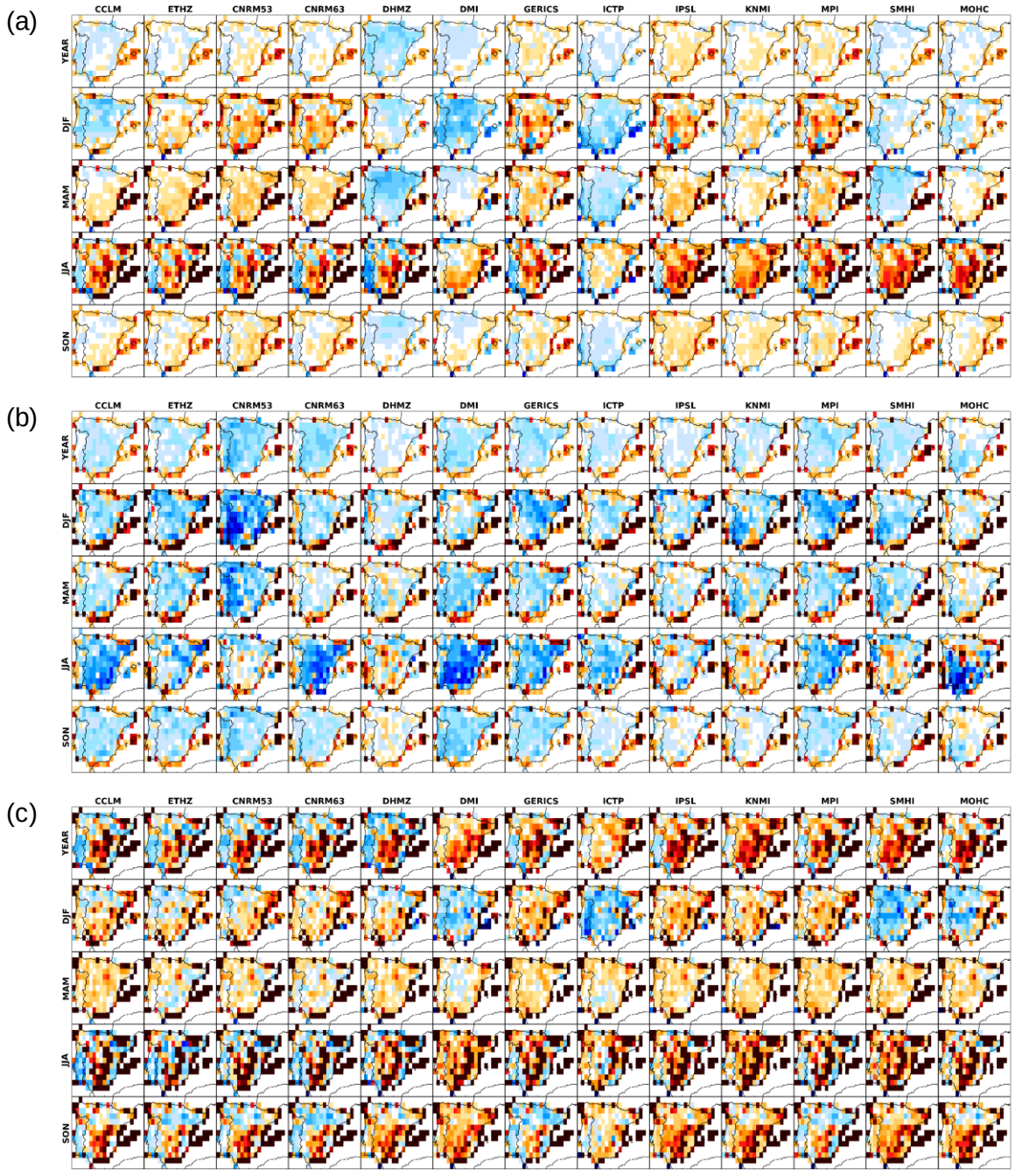
Figure 2c shows the TASMAX extremes, where only data above the observational 90th percentile set for the maximum temperatures are considered. The overall picture is different from Fig. 2a. At the annual scale 5 RCMs display DAVs ranging from -3.3 % to 1.1 %, while the other 8 models reveal added value, particularly DMI, KNMI, and SMHI. For winter, 9 models show a very ~~significant~~ noticeable added value, with percentages above 17.8 %. As before, the ICTP RCM stands out due to the negative DAVs of -6.6 %. Similar to winter, the summer also shows ~~significant~~ higher gains for 7 RCMs, ranging from 14.1 % to 23.3 %. For this season, the land-atmosphere feedback plays a major role, affecting the representation of convective clouds, since these are more locally driven for this time of the year, thus possibly affecting TASMAX (Knist et al., 2020). Therefore, high-resolution simulations ~~allied~~ together with improvements in the representation of ~~convective~~ convection activity results into added value for temperature ~~and also~~ and for precipitation (Careto et al., 2021), since most precipitation during this season is convective (Azorin-Molina et al., 2014). The DAVs for spring and autumn are however more limited, ranging from -4.9 % to 9.6 %, where 5 RCMs for spring and 3 for autumn reveal neutral DAVs representing a similar ~~a close~~ performance to the driving ERA-Interim in terms of the Perkins skill score. ETHZ and CNRM63 RCMs displays negative DAVs for both spring and autumn.

Similar to Fig. 2c~~b~~, the TASMIN extremes DAVs are computed only from the values below the 10th observational percentile from minimum temperatures, which ~~also~~ revealed ~~significant~~ notable losses. In this case, 4 RCMs display ~~strong~~ detrimental effects, namely GERICS and MPI with losses superior to -22 %. In fact, these two RCMs together with SMHI also reveal negative DAVs for the individual seasons, particularly spring and autumn. From all seasons, only winter ~~reveals~~ has a somewhat ~~significant~~ high added value for 8 RCMs, with values around 10 % up to 14 %. For this season, the 10th percentile threshold is well below 0 ^{o}C, implying a limited influence from the problems related to snow melt in the models. For the other seasons and models, the performance of the RCMs is close to the driving simulations, hence the near-neutral percentages. The exception is CNRM53 for summer with -11.1 %. For spring and autumn, the 10th percentile threshold is positive and near 0 ^{o}C, which means a strong influence from these problematic bins. On the other end, for summer the cut-off threshold is well above 0 ^{o}C, but at the same time there is little to no snow within the domain during this season.

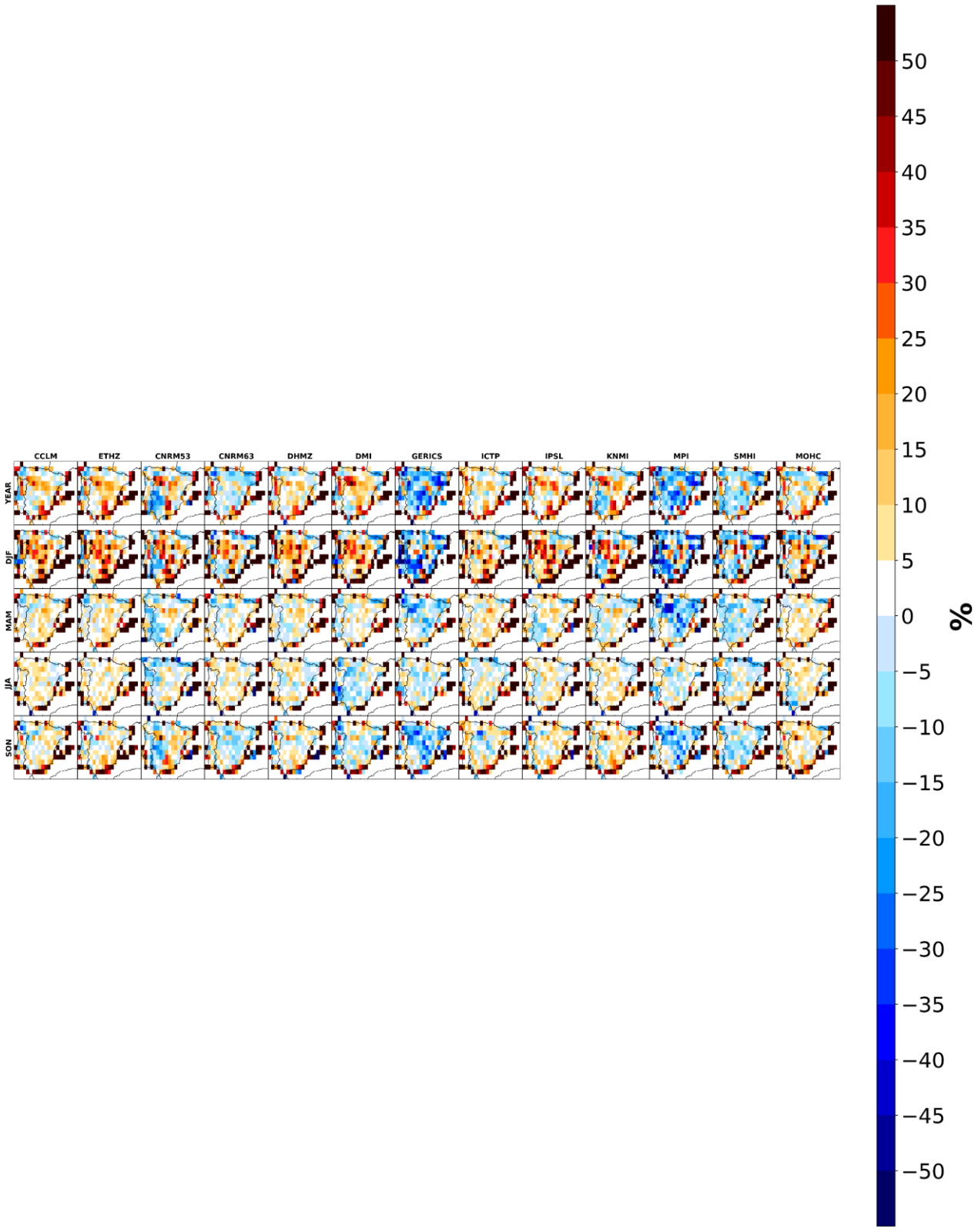
Figure S2 from the supplemental material shows a similar metric, where all RCM and driving ERA-Interim data were first interpolated into the IGD resolution. The same orographic correction was implemented together with the interpolation procedures. The results shown in Fig. S2 reveal an overall negative DAVs value in comparison to Fig. 2. Despite the differences, the RCMs still display a similar inter-model variability, particularly for both TASMAX and TASMAX extremes (Figs. S2a and S2b). The main differences between both approaches occur for TASMIN (Fig. S2b), where the vast majority of RCMs and seasons display more evidently detrimental effects with this second methodology. As for the TASMIN extremes, while in Fig. 2d winter had most models showing ~~significant~~ noteworthy gains, in Fig. S2d~~,~~ the annual scale and all the seasons either display neutral DAVs or

~~significant~~ high losses. With this approach the high-resolution orography is incorporated into the ERA-Interim. This fact results in substantially improving the low-resolution PDF, hence the lower values. However, since the ERA-Interim is downscaled, not only spurious values are introduced, but also enhanced due to the orography change, increasing the uncertainty associated with this second approach.

Figure 3 shows the same DAVs metric as in Fig. 2, but instead of pooling together all values from the Iberian Peninsula, only the data within each low-resolution grid cell is considered, thus having its own independent percentile set and PDFs. The spatial



(d)



295 **Figure 3. Yearly and seasonal spatial distribution added values (DAV) of the Iberian Peninsula, between the RCMs and the ERA-Interim reanalysis for the 1989-2008 period, taken from the Hindcast EURO-CORDEX simulations, with the IGD regular dataset as a reference, for (a) maximum daily temperature, considering the whole PDF, (b) minimum daily temperature considering the whole PDF, (c) maximum daily temperature extremes, only considering the values above the observational 90th percentile from maximum temperatures for each ERA-Interim grid point and (d) minimum daily temperature extremes, only considering the values below the observational 10th**
300 **percentile from minimum temperatures for each ERA-Interim grid point. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into the ERA-Interim resolution.**

DAVs for TASMAX ~~taking into account~~considering the whole PDF are shown in Fig. 3a, where the gains are mostly focused on coastal sites, particularly over the Mediterranean. Previous works such as Di Luca et al~~.~~ (2013), Vautard et al~~.~~ (2013) and~~,~~ Cardoso and Soares~~,~~ (2021)~~, and Soares et al. (2021)~~ also show added value in coastal sites, namely for the Mediterranean coast, mostly owed to a better representation of the land-sea boundary and associated differential warming, and due to improvements in the representation of breezes. The overall results correlate well with those shown in Fig. 2a i.e., models with ~~strong or~~ most points with added value will inevitably reveal gains at the Iberian Peninsula scale and vice-versa. At the annual scale, relevant gains of about 25%, particularly in the Balearic Islands are shown in coastal areas, while the gains are limited in points of the interior, where for instance the negative values for DHMZ dictate the losses found in Fig. 2a. RCMs such as GERICS, IPSL, or MPI which reveal slightly positive DAVs for most points, have the highest score for the entire Iberian Peninsula (Fig. 2a). Seasonally the picture is different. Summer is revealed to have the largest differences~~most range~~ between the coast side and the interior. Still, all models ~~display~~ have ~~significant~~ notable gains over central Spain and losses over Portugal. Winter shows 6 models with negative DAVs throughout the domain, namely DMI and ICTP. In the opposite sense, the other RCMs for winter display ~~significant~~ higher added value throughout the entire domain. Spring also emerges with some gains for 10 RCMs, contrasting with autumn, where models reveal a similar performance to the driving simulation. The exception for autumn is Gibraltar due to a ~~strong~~ relevant detrimental effect. In fact, in the other seasons and at the annual scale, Gibraltar has ~~significant~~ a large negative DAV~~losses~~.

While the maximum temperature revealed some widespread gains, the picture for TASMIN in Fig. 3b is quite different, still correlating well with the results for the regional overview (Fig. 2b). The DAVs for minimum temperature reveal losses in the interior for all time scales, while a ~~significant~~ positive added value occurs in coastal sites. At the seasonal scale, ~~the same~~ RCMs such as CCLM, CNRM63 DMI for summer or CNRM53 for winter, which reveal~~sing~~ ~~significant~~ detrimental effects in locations from the interior also show~~ed~~ ~~significant~~ noteworthy losses in Fig. 2b. An exception is the MOHC RCM for summer, which despite the ~~strong~~ high losses for the southern region of the Peninsula, the ~~significant~~ larger gains in points over the north and Balearic Islands ~~were~~ are able to even out the results obtained at a regional scale.

The TASMAX extremes (Fig. 3c) reveal more variability in comparison to Fig. 3a. Still, a good agreement to the Iberian Peninsula DAVs (Fig. 2c) is found for almost all seasons. At the annual scale, the lower values for the 5 RCMs identified in Fig. 2c are due to losses located over Portugal and northern Spain, while the other models reveal ~~significant~~ larger gains in the central regions of Spain. For winter, Fig. 2c revealed most models with maximum DAVs, except in 4 RCMs. This ~~significant~~ high added value for this season comes from the widespread positive percentages over the domain and some coastal points (Fig. 3c). The models with lower values in the regional overview, reveal a detrimental effect for most of the peninsula, masking the added value for points located near the coast. For spring, although there is a widespread positive added value for the entire domain, the results show the opposite in Fig. 2c. These differences highlight the fact that the results in Fig. 2 are not a spatial mean from the DAVs in Fig. 3 and care must be taken in the comparison. For summer, the spatial variability for all RCMs is higher in comparison to winter and spring. For this case, ~~significant~~ larger added values are found over a north-south stripe located at the centre of the peninsula, surrounded by a mix of negative and positive DAVs. The same pattern can be seen for autumn for 9 RCMs, although limited to the southern half of the domain. Similar to spring, autumn also showed lower DAVs in Fig. 2c. These lower values in the regional DAVs are derived from the losses over Portugal and northern Spain. However, the other RCMs, apart from ICTP, all reveal added value throughout the domain, corroborating the results in Fig. 2c.

The next panel shows the results for the TASMIN extremes (Fig. 3d). In Fig. 2d, the annual, spring, summer, and autumn revealed losses. However, in Fig. 3d, the models do not reveal such detrimental effects, with neutral DAVs in the interior and ~~significant~~ larger gains for locations near the coast. The exceptions are GERICS, MPI, and SMHI with ~~strong~~ noteworthy losses at the annual

scale, winter, and autumn in agreement with Fig. 2d. As for winter, 8 RCMs reveal ~~significant~~ noticeable added value not only for coastal sites but also for points scattered in the interior. In fact, these same 8 RCMs also showed ~~significant~~ larger gains for the Iberian Peninsula DAVs in Fig. 2d.

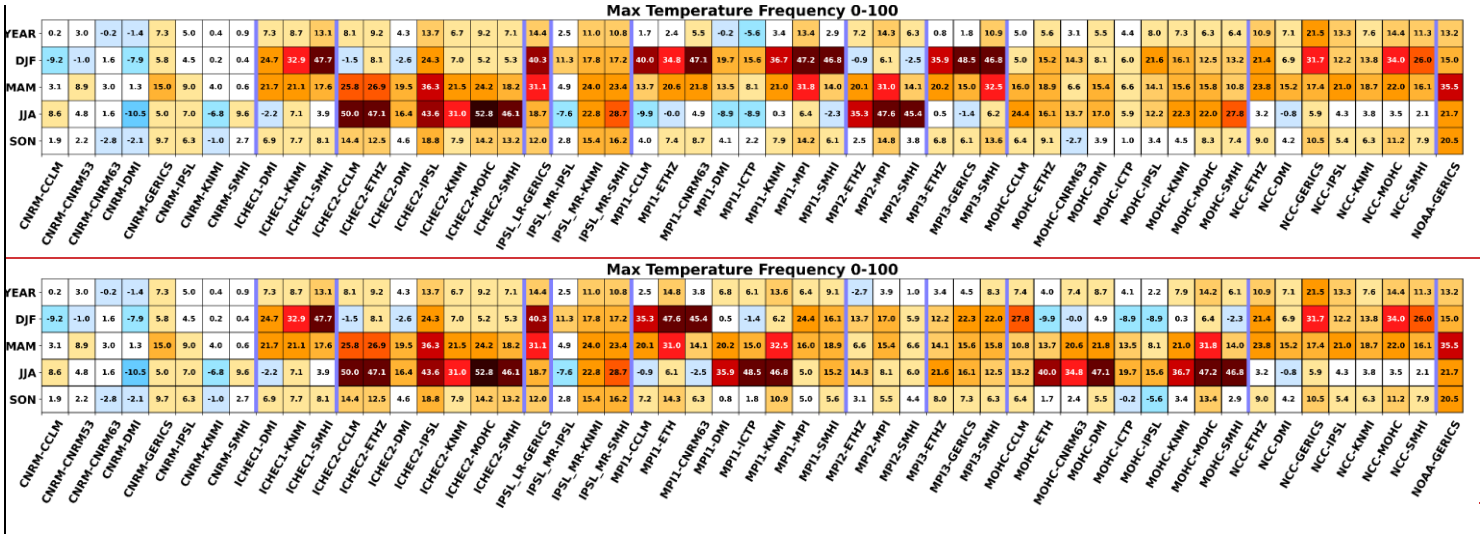
3.2 Historical (1971-2005)

This section presents the results obtained by applying the DAVs to all available Historical simulations from EURO-CORDEX for the same Iberian Peninsula domain. In the supplementary material Figs. S3 and S4 show the PDFs for all considered high and low-resolution simulations. Although the longer time spann ~~m~~ relative to the Hindcast simulations, all PDFs still reveal a close representation to each other and to the observations, in terms of location and shape parameters, indicating a good overlapping of all PDFs., ~~in particular for TASMIN~~. Once again, this fact could anticipate an overall difficulty of models displaying added value. Moreover, the same issues found in the Hindcast simulations due to snowmelt, snow cover, and snow depth are still present in this case, not only for the high-resolution but also for the driving GCMs as well. However, for the lower resolutions, these uncertainties are not as pronounced as in the higher resolutions, since the ability of GCMs in reproducing the orographic features are reduced. Moreover, as with precipitation (Careto et al., 2021), the GCM-RCMs pairs reveal a higher variability in comparison with the ERA-Interim driven models.

Figure 4a shows the results of DAVs for TASMAX by considering the whole PDF. At the annual scale, there is some added value, particularly for models driven by IPSL, MPI1, NCC, and NOAA GCMs, peaking at 21.5 % for NCC-GERICS. Regarding the seasonal added value, 21 GCM-RCM pairs, namely models forced by ICHEC, IPSL, MPI, ~~and MOHC~~, reveal ~~significant~~ noteworthy added value for either summer or winter, with gains well above 30 %. At the same time, for the same models, if summer ~~has significant~~reveals positive values ~~gains~~, winter reveals some losses or neutral values and vice-versa. These losses can be ~~significant~~noticeable, almost reaching -10 ~~5~~%. Other pairs, such as IPSL_MR-IPSL, ~~MOHC~~MPI1-ICTP, or ~~MOHC~~MPI1-~~IPSL~~ DMI also reveal this behaviour, although with more limited gains. Nevertheless, for the intermediate seasons, the same GCM-RCM pairs mostly display added value, particularly for spring. On the other hand, RCMs driven by the CNRM GCM reveal an absence of added value. Apart from isolated gains, only the GERICS display gains throughout the year. Other 14 pairs also show relevant gains for all seasons, with ICHEC2-IPSL, IPSL_-GERICS, MPI1-~~KNMI~~MPI , ~~and MOHC-MOHC~~ standing out with values above 25%. For the MOHC driven models, only the autumn displays lower values in comparison with the other seasons. ~~On the contrary~~ In a similar sense, all models driven by the NCC GCM reveal ~~significant~~ high added values for the first half of the year, yet the second half shows limited gains, particularly summer.

The overall results for RCMs driven by the same GCM are similar for most cases, while no connection is found between models forced by different GCMs. ~~The overall results are similar across RCMs forced by the same GCM, while no connection is found for each downscaled GCM.~~ This lack of connection was also reported in Careto et al. (2021) for the EURO-CORDEX precipitation. Still, the lower DAVs for some GCMs groups might be relate to the quality of the driving simulation itself, namely across the lateral boundary forcing zone. Following Brands et al. (2013), from all GCMs considered, MPI and MOHC outperforms the others for these regions. However, RCMs driven by either GCM still exhibit ~~significant~~ higher added value in some cases, while CNRM driven models have losses. In fact, the CNRM GCM in McSweeney et al. (2015) reveal a good performance, together with NOAA, MOHC and MPI. Yet, most RCMs driven by the last three GCMs have a ~~significant~~ notable added value. Moreover, the same authors state that IPSL_MR and NCC have an intermediate performance, while ICHEC and IPSL_LR stand out with a poorer performance. Also, ~~Jury et al. (2015) identifies IPSL_MR GCM as having a poor performance, particularly for upper-air variables over the forcing region for the EURO-CORDEX RCMs. Not only the performance of the individual GCMs impact the added value, but also their resolution, as it is expected higher~~

(a)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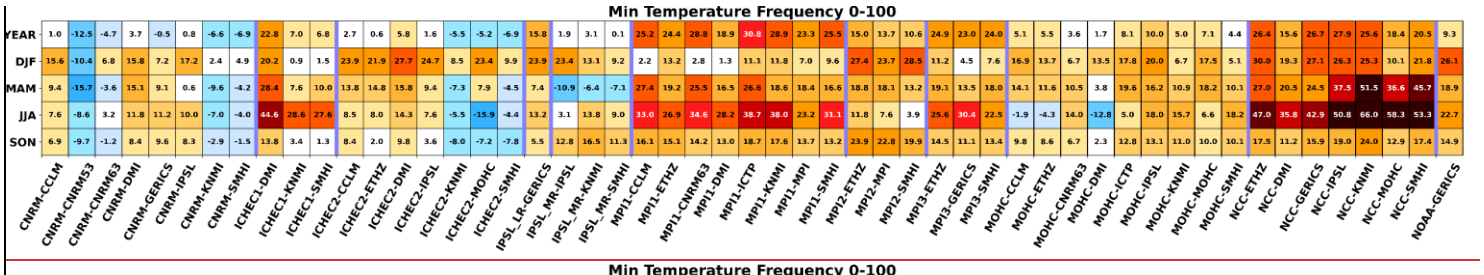
(b)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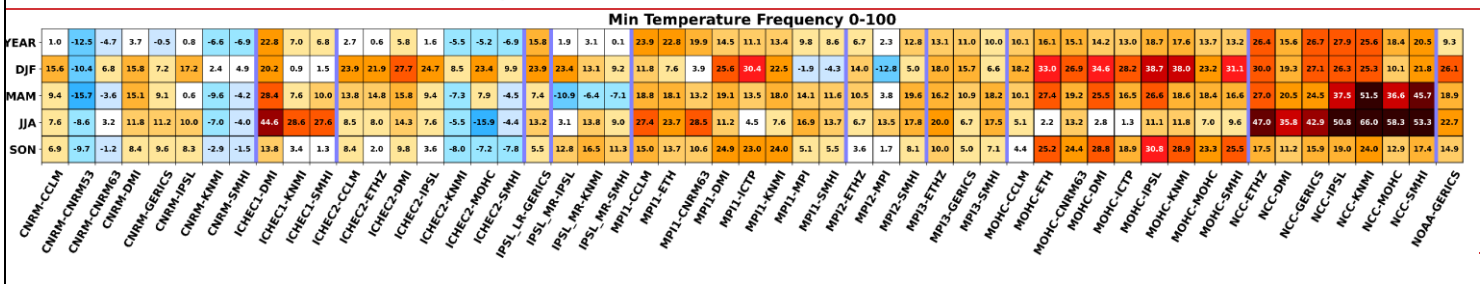
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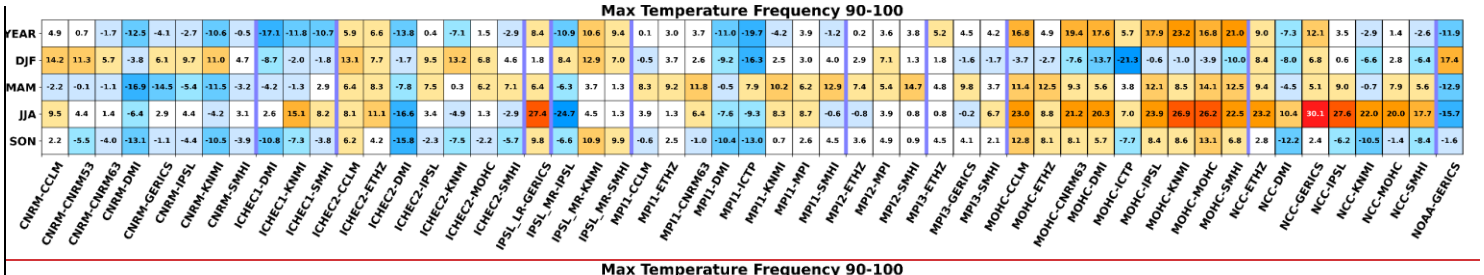
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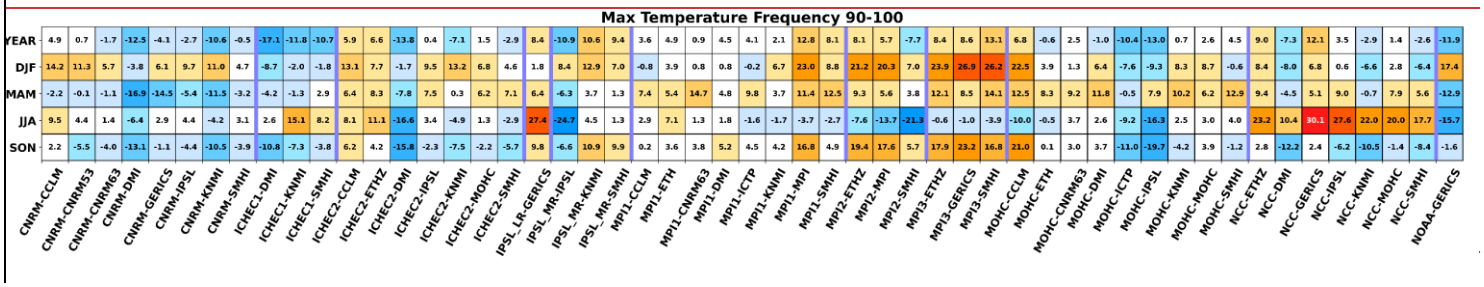
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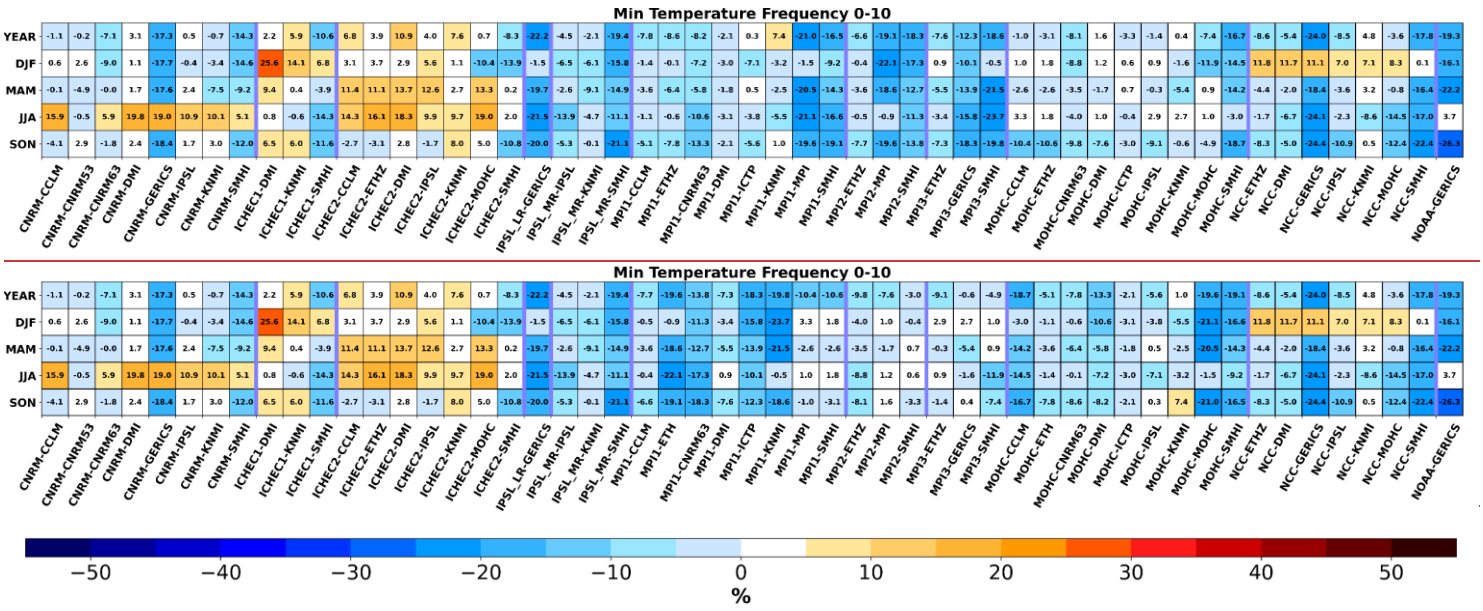


Figure 4. Yearly and seasonal distribution added values (DAV) of the Iberian Peninsula, between the RCMs and the CMIP5 GCMs for the 1989-2008 period, taken from the Historical EURO-CORDEX simulations, with the IGD regular dataset as a reference for (a) maximum daily temperature, considering the whole PDF shown in the left panels of Figure S3, (b) minimum daily temperature considering the whole PDF shown in the right panels of Figure S3, (c) maximum daily temperature extremes, only considering the values above the observational 90th percentile from maximum temperatures and (d) minimum daily temperature extremes, only considering the values below the observational 10th percentile from minimum temperatures. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into each CMI5 GCM resolution. The thick blue lines separate the RCMs driven by different GCM.

Jury et al. (2015) identifies IPSL_MR GCM as having a poor performance, particularly for upper-air variables over the forcing region of the EURO-CORDEX RCMs.

~~gains for models forced by GCMs with lower resolutions. However, for~~For temperature, the effect of the orographic correction with a constant lapse rate in the interpolation may also be a relevant factor affecting the individual DAV. ~~might have a stronger impact.~~ In the end, the scores obtained for the low-resolution might dictate the ability for RCMs to improve the signal. For instance, at the annual scale, the RCMs driven by GCMs with high Perkins skill score, such as CNRM with 0.84, reveal lower DAVs in comparison with other pairs. While at the same time, RCMs forced by GCMs also with high scores, such as MOHC with 0.85 or NCC with 0.86 still reveal noteworthy added value. This suggest that other factors may play a relevant role, such as how well the low resolutions depict storm tracks. An RCM driven by a low-resolution which reveals such biases will not be able to correct this signal. In fact, following Zappa et al (2013) ICHEC and MOHC GCMs reveal a correct placement of the storm tracks relative to the ERA-Interim reanalysis. On the other end, CNRM has a too southward placement, while the other models tend to have a too zonal storm-track.

Contrary to the results shown in the Hindcast, the TASMIN for the EURO-CORDEX Historical simulations mostly reveal ~~significant added~~positive values (Fig. 4b). For this case, both the low and high-resolution models are affected by the same problems related to snow (García-Díez et al., 2015; Terzago et al., 2017), namely at the annual scale and the colder seasons. The inter-model variability for TASMIN is higher in comparison to TASMAX in Fig. 4a, with values ranging from -17.3 % to 66 %. At the annual scale, most models reveal added value, except for CNRM driven RCMs, and for some models forced by either ICHEC2, IPSL_LR,

and ~~MPI2~~MOHC. Seasonally, the pairs with ~~significant~~ notable gains for the annual scale, also shows ~~relevant~~ higher added values. From these, highlight to NCC driven models, with ~~significant~~ larger gains for spring and summer, although winter and autumn also reveals added value around 20%. Moreover, 4 GCM groups displays added value for at least one season, with percentages above ~~25~~ 30 %. On the other hand, three RCMs forced by CNRM and other three by ICHEC2 have ~~significant~~ noticeable losses, namely CNRM-CNRM53 for winter and spring, or ICHEC2-MOHC for summer.

From the PDFs in Fig S4, one can infer the ~~significant~~ large gains found for TASMIN ~~and also~~and for TASMAX in Fig. 4. In Fig. S4, the GCMs ~~have a tendency to~~tend to underestimate maximum temperature, while minimum temperature is overestimated. Moreover, the ~~standard deviation~~variability from the GCMs is lower in comparison to the observations. For the high-resolution models, these issues are partly corrected, hence the added value (Fig. S3). However, for maximum temperature, the RCMs still tend to underestimate TASMAX. As for TASMIN, the issues related to snow-albedo-feedback are more evident for the high-resolution models~~, due to overestimation of snow~~ (Minder et al., 2016) enhanced by the higher definition of topographic features. On the contrary, the RCMs reveal a closer mean and standard deviation relative to the IGD. Nevertheless, these issues might cause an overall underestimation of the mean for TASMIN. Cardoso et al~~.~~ (2019) for Portugal and Vautard et al~~.~~ (2020) for the Iberian Peninsula also found a cold bias for mean temperature from the Historical RCMs. These biases were also present in the forcing models, matching the results found here.

The next panel shows the results for the TASMAX extremes (Fig. 4c). The added value is limited in comparison to Fig. 4a, with more models revealing detrimental effects at the annual scale and for at least 3 seasons. In fact, 12 GCM-RCM pairs reveal this pattern~~,~~ sometimes with losses ~~superior to~~surpassing -10 %, capped at -24.7 % for IPSL_MR-IPSL at the summer season. Yet, ~~27~~ 26 pairs reveal positive DAVs for at least 3 seasons, with a focus on either winter or summer, whose values range approximately from ~~10~~ 5 % to 30 %. For the Hindcast simulations (Fig. 2c), only the winter and summer seasons ~~had~~ have ~~significant~~ added value, whereas the values for spring and summer were limited and sometimes negative. ~~MPI1-MPI and models forced by MPI2 and MPI3 GCM~~MOHC driven models also reveal ~~significant~~ large gains for ~~autumn~~summer, well above ~~16~~ 20 % in most cases. Moreover, in some cases, t~~T~~he~~se~~ results for the TASMAX extremes differ, where ~~significant~~ noticeable added value occurs for seasons whose models had a worse performance in Fig. 4a. This behaviour is particularly evident for models driven by ICHEC or NCC GCMs. ~~Moreover~~Also, pairs that ~~had~~ have ~~significant~~ higher gains in Fig. 4a, reveal either an absence or a loss of value, occurring namely for MPI1 and MPI3 driven models for the winter and for the summer season~~s~~ for RCMs forced by MPI2~~ and MPI3~~.

Contrary to the previous cases, there is an overall detrimental effect for the cold extremes (Fig. 4d), in line with the results shown in the Hindcast simulations (Fig. 2d). These ~~strong~~ losses are associated with the known problems derived from the snow-albedo-atmosphere feedback, however, in this case, the low-resolution GCMs are also somewhat affected. Still, 1~~58~~ out of 53 GCM-RCM pairs reveal losses at the annual scale higher than~~superior to~~ -10 %, whose effects are also extended for the individual seasons. Only a few RCMs still display added values, on the order of 10 %. From these, highlight to models forced by CNRM for the summer season, and also for models driven by NCC for winter.

As with the Hindcast simulations and in Careto et al~~.~~ (2021) for the EURO-CORDEX precipitation variable, a second method was implemented (Fig. S5), where all high and low-resolution models are interpolated into the IGD resolution. The interpolation of the IGD ~~causes a slight deterioration of the PDF~~reduces the variability, ~~particularly~~ thus the probability of~~for the~~ extremes is lower.~~,~~ By interpolating the low-resolution GCMs with an orography correction, the results are substantially improved, thus increasing the score of the GCMs and reducing the DAVs. In fact, it is precisely what occurs for TASMAX and TASMIN in Figs. S5a and S5b, where the overall DAVs are lower, although still agreeing with Fig. 4 for the most part. As for the extremes (Figs. S5c and S5d), the results reveal a similar range to Fig. 4, but some differences arise. For instance, the TASMAX extremes, despite revealing ~~weaker~~ lower gain in comparison to Fig. 4c, IPSL_LR-GERICS clearly displays a ~~significant~~ large added value throughout the

year. As for the TASMIN extremes, the results correlate well with those displayed in Fig. 4d, although with more pronounced losses. Similar with the ERA-Interim, downscaling the GCMs this way causes spurious values, increasing the uncertainty associated to the DAVs.

The next set of figures displays the DAVs results from Fig. 4 but extended for a spatial overview (Figs. 5 to 8). Overall, as with the Hindcast (Fig. 3), the added value is more focused over the coastal regions, primarily owed to the better representation of land-ocean boundaries (Di Luca et al., 2013; Vautard et al., 2013; Cardoso and Soares, 2021 ~~; Soares et al., 2021~~). Still, all figures reveal a good agreement with the DAVs shown in Fig. 4 by considering the entire Iberian Peninsula. Moreover, as with Hindcast, the results from Fig. 4 are not a mean obtained from the spatial DAVs in Figs. 5 to 8 but a result from pooling together all the information from within each low-resolution grid point instead of pooling together the information from the entire domain. ~~.~~

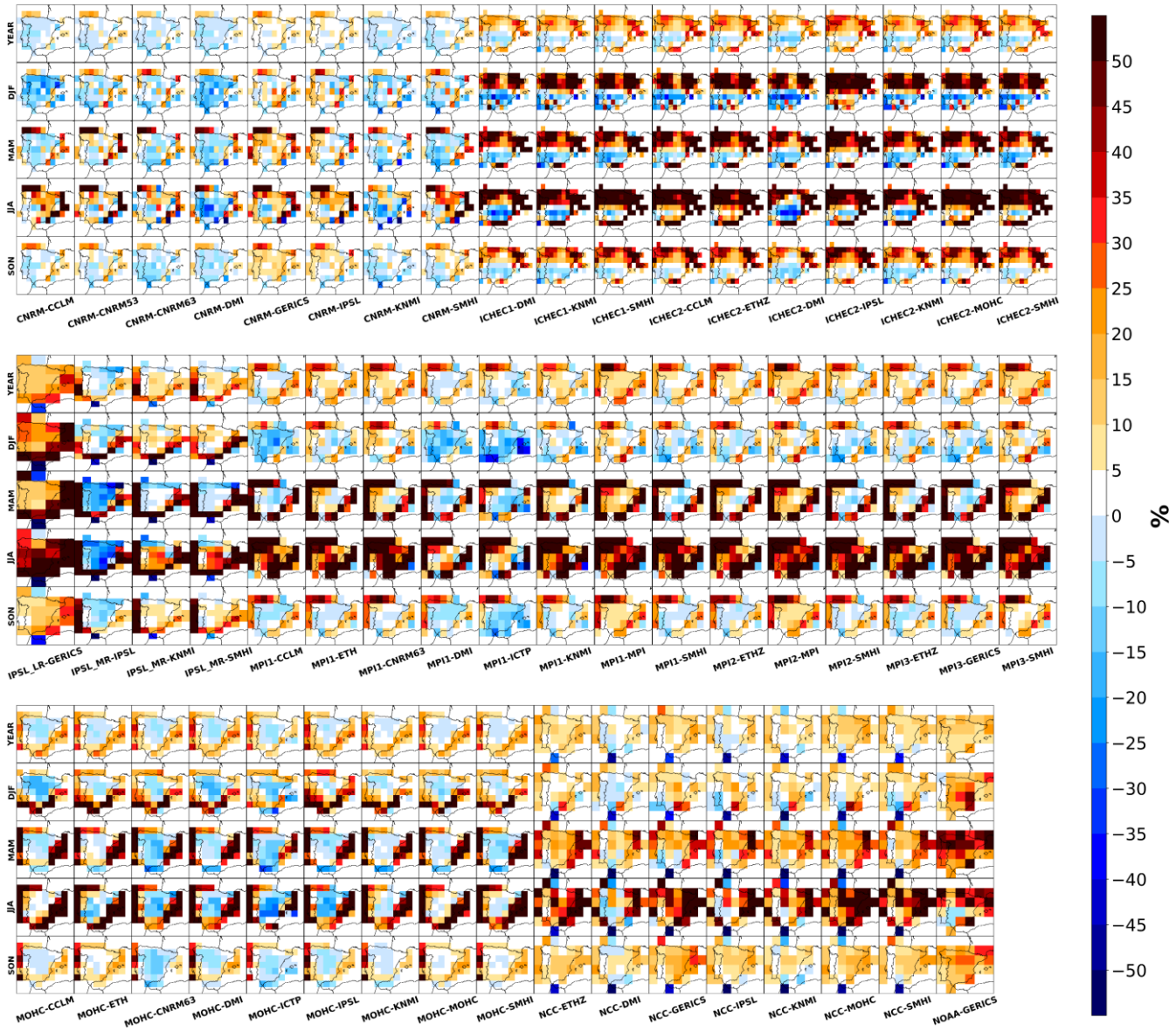
Figure 5 displays the results for TASMAX. For CNRM, the gains are more focused on spring and summer, and are particularly evident near the coast. However, ~~strong~~ notable losses still occur for most of the interior of the Iberian Peninsula for all seasons, namely for winter and summer. As for ICHEC driven RCMs, both reveal a very ~~strong~~ high added value in the northern half of the domain. From this group, highlight to ICHEC2-IPSL RCM, which reveals a positive added value throughout the year and for the entire domain, resulting in an overall good performance in Fig. 4a. IPSL-LR-GERICS also reveal a ~~significant~~ noteworthy added value, apart from a point located over Gibraltar, correlating well with the results shown in Fig. 4a. On the other hand, IPSL_MR, all MPI, and MOHC driven RCMs reveal similar behaviours among themselves, with gains focused in coastal areas. This occurs primarily for spring and summer, resembling the DAVs for the models forced by CNRM, although with a higher amplitude. Differently to most of the previous cases, the models driven by NCC display gains for the entire domain, with losses over Gibraltar, like IPSL-LR-GERICS.

The spatialisz~~z~~ation of TASMIN is shown in Fig. 6, revealing a similar pattern as in Fig. 5, with gains in the coast and detrimental effects in the interior, although displaying a stronger contrast. Depending on the strength of these detrimental effects, the results for Fig. 4b might reveal neutral or even losses. For instance, the ~~strong~~ large losses found for CNRM-CNRM53 for all time scales or IPSL-MR-IPSL for spring effectively impacted the regional overview.

Figures 7 and 8 show the results for the extremes for TASMAX and TASMIN, respectively. For the ~~hot~~ maximum temperature extremes, related to heat waves, the gains over the coastal regions are even more relevant than in Fig. 5. Nevertheless, the losses found for the interior are able to even out these gains, leading to the limited added value in Fig. 4c. In a way, these limited DAVs in the interior of the domain are the values that determine if a specific model shows added value in the DAVs considering the entire ~~Iberia. This is particularly relevant for the TASMIN extremes. Fig. 4d displayed most pairs with a detrimental effect for the entire domain. However, significant gains are still found for the coastal regions in almost all cases. The importance of the spatial overview is highlighted here. While a particular model reveals losses for the whole domain, this fact might not be true at a more local scale.~~

~~4 Conclusions~~

~~In this work a Distribution Added Value metric proposed by Soares and Cardoso, (2018) is used to gauge the added value of higher resolution simulations confronting each low-resolution driving GCM or Era-Interim, with the IGD observations over the Iberian Peninsula as a baseline. The DAVs were applied to the EURO-CORDEX Hindcast (1989-2008) and Historical (1971-2005) simulations for the variables maximum and minimum temperatures. Overall, the high-resolution models are able to provide added value. For the heat and cold extremes, the results are more limited, namely for TASMIN. In fact, minimum temperature reveals some difficulties in obtaining added value for the Hindcast simulations and also for the extremes in the Historical simulations, owed to problems associated with the snow-albedo-atmosphere feedback, derived from uncertainties related to snow cover, depth,~~



490 **Figure 5. Yearly and seasonal distribution added values (DAV) of the Iberian Peninsula for the Historical (1971-2005) EURO-CORDEX RCMs, with the IGD as a reference for the maximum daily temperature, considering the whole PDF. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into each CMI5 GCM resolution.**

Iberia. This is particularly relevant for the TASMIN extremes. Fig. 4d displays most pairs with a detrimental effect for the entire
495 domain. However, higher gains are still found for the coastal regions in almost all cases. The importance of the spatial overview is highlighted here. While a particular model reveals losses for the whole domain, this fact might not be true at a more local scale.

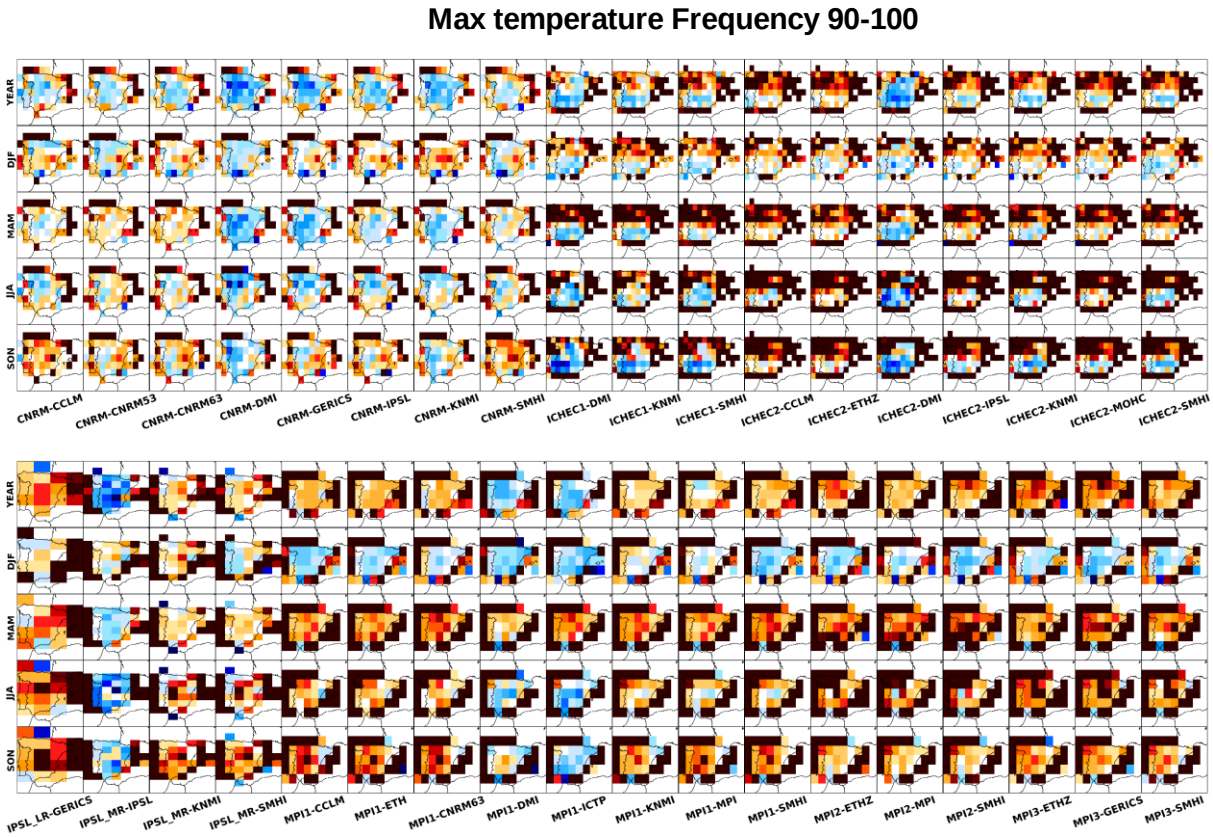
4 Summary and Conclusions

In this work a Distribution Added Value metric proposed by Soares and Cardoso (2018) is used to gauge the added value of higher resolution simulations confronting each low-resolution driving GCM or Era-Interim, with the IGD observations over the Iberian

Peninsula as a baseline. The DAVs were applied to the EURO-CORDEX Hindcast (1989-2008) and Historical (1971-2005) ~~And melt (García-Díez et al., 2015; Minder et al., 2016; Terzago et al., 2017). These uncertainties substantially affect the PDFs from the RCMs around 0 ºC. This poor representation has a more significant impact on the Hindcast simulations, where the ERA-Interim reanalysis does not reveal these kinds of issues, probably owed to the incorporation of temperature observations (Prömmel et al. 2010). Nevertheless, the finer details from the downscaling allow a more spatial variability of temperature, which in the end could result in added value. This fact is particularly relevant for coastal regions, where the improvements of the boundary between ocean and land result in significant added value. For the Historical, no connection is found between each GCM downscaling group, while the results for multiple RCMs forced by the same GCM reveal a similar range. Each driving simulation has its own resolution and performance, which could impact the added value from the higher resolution as in Careto et al. (2021) for precipitation, however the interpolation with the orographic correction might in the end have a more significant impact~~

Figure 6. Yearly and seasonal distribution added values (DAV) of the Iberian Peninsula for the Historical (1971-2005) EURO-CORDEX RCMs, with the IGD as a reference for the minimum daily temperature, considering the whole PDF. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into each CMI5 GCM resolution.

simulations for the variables maximum and minimum temperatures. Overall, the high-resolution models are able to provide some added value, particularly for TASMAX. On the other end, minimum temperature reveals some difficulties in obtaining added value for the Hindcast simulations, mainly when the whole PDF is considered and also for the extremes in the Historical simulations, partly owed to problems associated with the snow-albedo-atmosphere feedback, derived from uncertainties related to snow cover, depth, and melt (García-Díez et al., 2015; Minder et al., 2016; Terzago et al., 2017). These uncertainties substantially affect the PDFs from the RCMs around 0 ºC, by overestimating the frequency of events in comparison with the observations. This poor representation has a more significant impact on the Hindcast simulations, where the ERA-Interim reanalysis does not reveal these kinds of issues owed to the incorporation of temperature observations (Prömmel et al. 2010). Nevertheless, the finer details from the downscaling allow a more spatial variability of temperature, which in the end could result in to added value. This fact is ~~A second methodology was also implemented, following the results for Soares et al. (2021) and the secondary results in Careto et al. (2021). The interpolation from the high-resolution observations to each of the low-resolution model grids degrades the observational PDF. However, by interpolating the driving low-resolution with a high-resolution orographic correction unrealistic values can be created through the interpolation. In this case, the low-resolution scores are improved, resulting in an overall lower DAV.~~



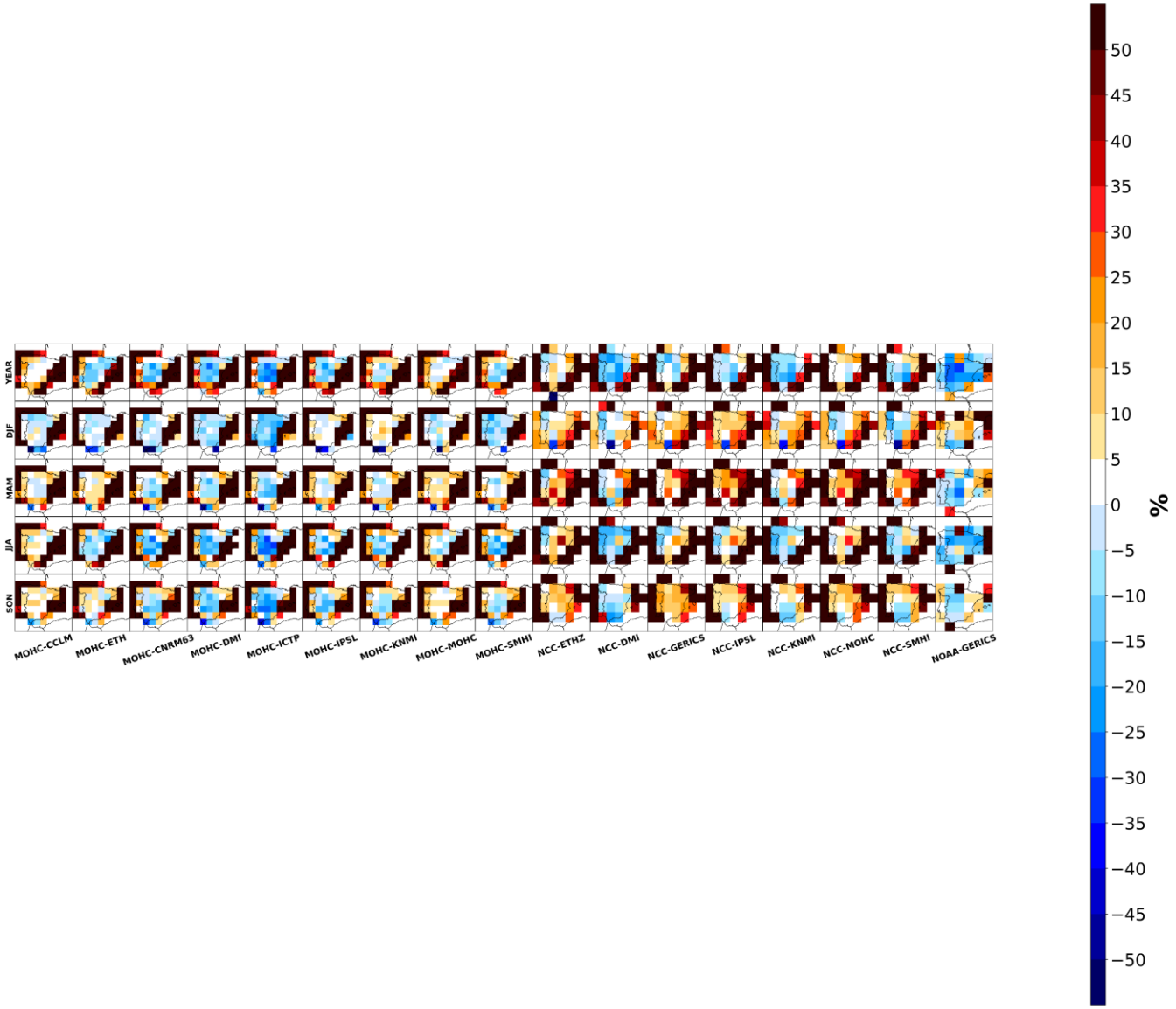


Figure 7. Yearly and seasonal distribution added values (DAV) of the Iberian Peninsula for the Historical (1971-2005) EURO-CORDEX RCMs, with the IGD as a reference for the maximum daily temperature, only considering the values above the observational 90th percentile from maximum temperatures for each GCM grid box. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into each CMI5 GCM resolution.

particularly relevant for coastal regions, where the improvements of the boundary between ocean and land result in larger gains in comparison to points located in the interior. For the maximum and minimum temperature extremes, the results are more limited. Still for the TASMAX extremes winter and summer reveals an evident added value, contrasting with the neutral or negative DAVs for spring and autumn. As for the TASMIN extremes, depending on the season, the DAVs depend more on the season. For instance, the 10th percentile for winter is too low, not incorporating the problems around 0 ºC, thus revealing some added value. The opposite occurs for spring and autumn which revealed more neutral values. As for summer the temperatures are too high for snow in most part of the territory, yet the models still revealed losses.

For the Historical simulations, no connection is found between each GCM downscaling group, while the results for multiple RCMs forced by the same GCM reveal a similar range. Each driving simulation has its own resolution and performance, which could impact the added value from the higher resolution as in Careto et al (2021) for precipitation. However, the interpolation with the

~~Data availability~~

~~All model and observational datasets are publicly available. The regional and global model data is available through the Earth System Grid Federation portal (Williams et al., 2011; https://esgf.llnl.gov/). The ERA-Interim reanalysis is available at the ECMWF portal (https://www.ecmwf.int/). The Iberia01 dataset is publicly available through the DIGITAL.CSIC open science service (Herrera et al., 2019a, https://doi.org/10.20350/digitalCSIC/8641).~~

Figure 8. Yearly and seasonal distribution added values (DAV) of the Iberian Peninsula for the Historical (1971-2005) EURO-CORDEX RCMs, with the IGD as a reference for the minimum daily temperature, only considering the values below the observational 10th percentile from maximum temperatures for each GCM grid box. All RCM data were previously interpolated to 0.1º regular resolution from the observations, while the observations were interpolated into each CMI5 GCM resolution.

orographic correction considering a constant lapse rate might in the end have a more significant impact in the performance of the individual GCMs and RCMs. Moreover, other factors such as the parametrizations of smaller scale processes and the representation

of feedback systems can have a major impact in how a variable represent reality. Another factor that may play a major role is related to how well do GCMs represent storm tracks. If a GCM is not able to properly represent storm tracks, then the downscaling RCMs will inherent these issues.

Similar to the Hindcast simulations, the gains of the Historical spatial DAVs are also more focused in coastal regions. Models which reveal more substantial gains and neutral or slightly positive DAVs in the interior, tend to have higher values at the Iberian Peninsula scale. Although, care must be taken when comparing the spatial and regional DAVs as both follow slightly different approaches. Still both methods correlate well, primarily for the whole PDF case. As for the extremes, the different thresholds for each individual point makes it difficult for a direct comparison.

A second methodology was also implemented, following the secondary results in Careto et al (2021). In this case, all data is interpolated with an orographic correction to the resolution from the observations. The interpolation from the high-resolution observations to each of the low-resolution model grids degrades the observational PDF. However, by downscaling the driving low-resolution with an orographic correction considering a constant lapse rate, unrealistic values can be generated, not only due to the interpolation, but also derived from the higher resolution orography. This method substantially improves the representation of temperature at the cost of not considering land-atmosphere feedbacks, thus resulting in a larger uncertainty. In fact, for this case, the low-resolution scores are improved, resulting in an overall lower DAV.

The higher resolution EURO-CORDEX models do reveal some added value for temperature. In many situations the RCMs can improve the lower-resolution signal, all relative to the observational dataset considered. For instance, in the Historical simulations, the high-resolution mitigate the annual and seasonal biases from the GCMs, due to a better representation of the observable PDF. On the other hand, the problems found for the RCMs, particularly for the Hindcast simulations do affect the DAV values negatively, as revealed by the negative values found. Nevertheless, the higher resolution, together with a finer representation of the local topography, improved coastal resolution and consequently land-sea contrasts and local feedback systems, which ultimately leads to an add value.

Data availability

All model and observational datasets are publicly available. The regional and global model data is available through the Earth System Grid Federation portal (Williams et al., 2011; https://esgf.llnl.gov/). The ERA-Interim reanalysis is available at the ECMWF portal (https://www.ecmwf.int/). The Iberia01 dataset is publicly available through the DIGITAL.CSIC open science service (Herrera et al., 2019a, https://doi.org/10.20350/digitalCSIC/8641).

Author contribution

J Careto computed all results and developed the manuscript with contributions from all co-authors. PMM Soares and RM. Cardoso developed the metric in which this paper is based on. S Herrera, J Guitérrez, PMM Soares and R Cardoso previously developed the observation based Iberian Gridded Dataset.

Competing interests

The authors declare that they have no conflict of interest.

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