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Assessing Multidomain Overlaps and Grand Ensemble Generation in CORDEX Regional Projections

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Key Points:

- Overlaps in multidomain CORDEX regional climate change projections (e.g., in the Mediterranean) may result in conflicting messages
- A variance analysis shows that domain contribution to the grand ensemble is generally small for several mean, extreme, and temporal indices
- We conclude that combining the available multidomain CORDEX simulations for a given region is an appropriate methodology

Supporting Information:

- Figure S1
- Table S1
- Table S2

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Abstract The Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative has made available an enormous amount of regional climate projections in different domains worldwide. This information is crucial for the development of adaptation strategies and policy-making. A relevant open issue in this context is assessing the potential multidomain conflicts that may result in overlapping regions and developing appropriate ensemble methods trying to make the most of all available information. This work addresses this timely topic by focusing on precipitation over the Mediterranean region, a first illustrative case study that is encompassed by both the Euro- and Africa-CORDEX domains. We focus on several mean, extreme, and temporal indices and use variance decomposition to assess the separate contribution of the domain and models to the climate change signal, concluding that the contribution of the domain alone is nearly negligible (below 5% in all cases). Nevertheless, for some cases, the combined model/domain effect triggers up to 40% of the total variance.

Plain Language Summary The Coordinated Regional Climate Downscaling Experiment (CORDEX) provides spatially detailed climate change projections for different regions across the world. These projections are obtained through numerical models that solve the governing equations of the atmosphere over spatial domains, which typically cover continental areas and encompass several regions. The regional climate change information generated by these models presents various sources of uncertainties. This work addresses the uncertainty related to the choice of domain, which has not been properly assessed to date, despite it can potentially affect vast regions of the world for which model simulations coming from different CORDEX domains are available. We focus on precipitation over the Mediterranean region, which is encompassed by both the EURO- and AFR-CORDEX domains, and quantify the separate contribution of the model and domain alone to the total uncertainty for the climate change signals. Our results indicate that this uncertainty comes mostly determined by the choice of model, with little variability coming from the domain. This would allow for combining different model simulations corresponding to overlapping domains since conflicting signals are very unlikely to occur. These findings may ease the decision-making process in regions for which multimodel and multidomain heterogeneous climate change information is available.

1. Introduction

Regional climate models (RCMs) are key tools to provide climate information at regional scales needed for impact and adaptation studies (Giorgi, 2019). RCMs are numerical models nested into global climate models (GCMs) solving the governing equations of the atmosphere over limited spatial domains at horizontal resolutions, which currently range from 0.11° to 0.44° (Gutowski et al., 2016). Because of their sensitivity to the size and position of the domain, as well as to the use of distinct parameterizations, regional climate information involves a range of uncertainties that need to be properly understood, particularly in the context of climate change where reliable projections are needed for adequate decision making.

Currently, the COordinated Regional climate Downscaling EXperiment (CORDEX) is the flagship initiative that provides an appropriate framework for evaluating some of these uncertainties affecting regional climate

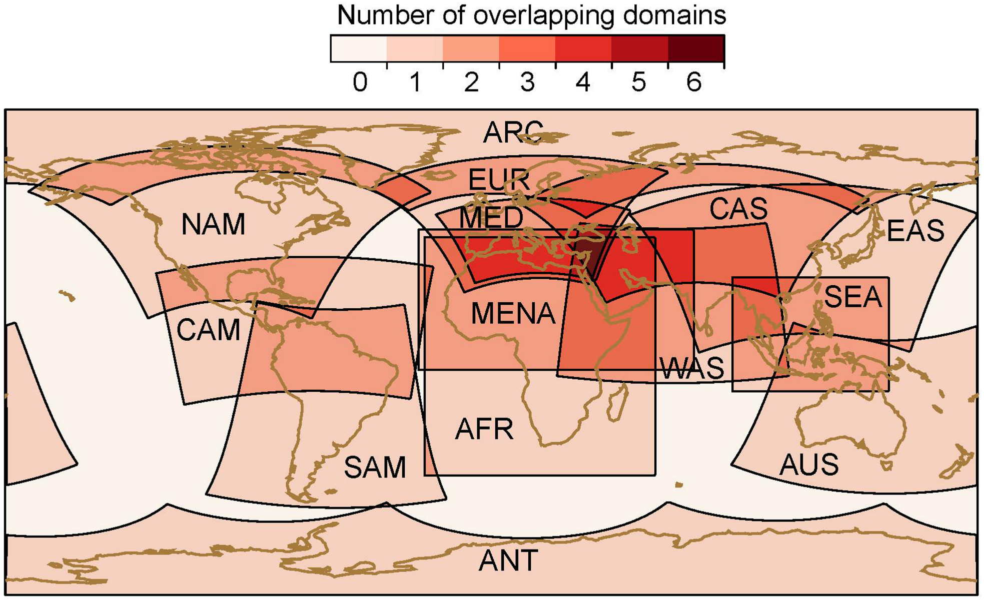

Figure 1. Number of overlapping CORDEX domains.

projections (Gutowski et al., 2016). In particular, CORDEX is formed by 14 overlapping continental-scale regional domains worldwide where different reanalysis and GCM-driven RCMs have been used to produce regional information building on a common framework, allowing intercomparison of results. This allows to assess the uncertainty related to the choice of domain for the overlapping areas.

In this context, several previous works have found that the position of the domain may play a role in the climate simulated by RCMs (Jones et al., 1995; Miguez-Macho et al., 2004; Seth & Giorgi, 1998; Sein et al., 2014).

Despite this, Jacob et al. (2012) considered six different CORDEX domains simulated by a single model but did not consider their overlapping areas. Instead, they assigned a given domain to each grid point, based on its continent, and disregarded the potential conflicting information arising from the different domains. Differently, recent studies tend to consider all the available simulations in overlapping regions trying to make the most of all available information (see, e.g., Spinoni et al., 2019, which considers global information from several overlapping CORDEX domains, or Fernández et al., 2019, and Zittis et al., 2019, which focus on particular regions). Despite the sensitivity to the choice of domain is presented, for example, by Zittis et al. (2019), to our knowledge, there is no study that explicitly quantifies the impact of the choice of domain in regional climate change projections considering an ensemble of different RCMs.

This knowledge gap is of particular relevance for vast regions of the world for which a number of RCM simulations coming from overlapping CORDEX domains are available (see Figure 1). One of these regions is the Mediterranean, a hot spot for climate change where projections indicate summer temperature increases of up to 7 K by the end of the century (Zittis et al., 2019) and a reduction of 10–40% in mean precipitation. The most comprehensive analyses of RCM projections over this region are those carried out by Giorgi and Lionello (2008)—who used CMIP3 and PRUDENCE results—and by Zittis et al. (2019)—who used CMIP5 and CORDEX results. The latter considered a grand ensemble formed by all overlapping CORDEX domains over the target area trying to make the most of all available information.

Within this context, we focus in this work on precipitation over the Mediterranean and assess the uncertainty arising from overlapping CORDEX domains simulated by a common set of models (section 2.1). To do this, we rely on the evaluation framework developed in the international action VALUE (section 2.3), which establishes a number of diagnostic indices covering the different forecast quality aspects. Ultimately, we explicitly quantify the variance explained by (i) the domain and (ii) the different models forming in the total multidomain grand ensemble focusing on several precipitation-related indices. We conclude that, in general, more than 80% of the variability is due to the models alone and, therefore, using multidomain grand ensembles stands as an appropriate strategy in overlapping regions since similar projection results are obtained when running the same RCM in two different domains. As such, results from one domain could complement the ensemble corresponding to a different one.

The results from this work will contribute to easing the decision making in regions for which heterogeneous regional climate projections coming from different model-domain combinations are available.

2. Data and Methods

2.1. CORDEX Simulations

We use only a subset of CORDEX GCM-RCM combinations, which are common across different domains covering the Mediterranean area. This constraint, required by our methodology (section 2.5), restricts the analysis to the European and African domains (see Table S1 in the supporting information). The Med-CORDEX domain, which would be the reference domain in the area, does not share any GCM-RCM combination with EURO-CORDEX for the same scenario and model resolution; see, for example, the GCM-RCM matrix in Fernández et al. (2019). The EURO- and AFR-CORDEX domains share a common area spanning 30° 30′N to 42° N and 10° 15′W to 38° E, which will be our target region in this study.

We considered five RCMs, namely: RCA4, RACMO22, HIRHAM5, CCLM4-8-17, and REMO2009. Model simulations across domains are not exactly equivalent for the HIRHAM5 and RACMO22 models. The latter uses a different RCM configuration for Europe (RACMO22E) and the tropical regions (RACMO22T). They mainly differ on the source of fixed fields (surface albedo and Leaf Area Index), and the European configuration includes a moist turbulent kinetic energy scheme within the boundary layer scheme (E. van Meijgaard, personal communication). HIRHAM5 simulations have different RCM version IDs (v1 and v2): v2 considers variable greenhouse gases according to the corresponding Representative Concentration Pathway (RCP), while HIRHAM5 v1 only gets the greenhouse effect through the GCM boundaries (O. B. Christensen, personal communication). We will consider the potential role of these differences in our results.

All simulations were downloaded from the Earth System Grid Federation (https://www.cordex.org/data-access/esgf). We obtained evaluation simulations (driven by the ERA-Interim reanalysis) and CMIP5 GCM-driven simulations for the historical and the RCP 4.5 and 8.5 scenarios. Here, we only show results for the high (RCP 8.5) emissions scenario (the same conclusions are found for the RCP 4.5 scenario).

2.2. Observational Reference

The observational reference against which the different GCM-RCM combinations listed in Table S1 are compared in this work is EWEMBI (Lange, 2019; 2018). This data set provides daily data for several meteorological variables (here we only use precipitation) for the entire globe at a 0.5° horizontal resolution (pretty similar to the 0.44° resolution of the CORDEX simulations analyzed), spanning the period 1979–2013. EWEMBI has been built based on different data sources, namely, ERA-Interim (Dee et al., 2011), WFDEI (Weedon et al., 2014), and the eartH2Observe forcing data (Dutra, 2015). Recently, it has been used to correct the climatic inputs needed for the ISIMIP2b project (Frieler et al., 2017) and has also contributed to the 2018 IPCC special report on the impacts of global warming of 1.5 ° C (https://www.ipcc.ch/sr15/).

2.3. Diagnostic Indices

In this work we build on the VALUE validation framework (Maraun et al., 2019), which has been recently used to conduct a comprehensive and detailed intercomparison of more than 50 statistical downscaling methods over Europe (Maraun et al., 2019). Throughout this work, we show figures for the representative indices mean precipitation (Mean); the maximum annual wet spell, represented by its median (WetAnnualMaxSpell); and precipitation over 95th percentile (R95pTOT). Nevertheless, the same analysis has been carried out for all the measures shown in Table S2, which evaluate the marginal, temporal, and extreme forecast aspects, and the results are summarized in figure 5. The performance of the different model simulations listed in Table S1 to reproduce these indices is analyzed in the next sections. Note that all simulations have been interpolated to the EWEMBI grid for direct comparison purposes.

2.4. Model Intercomparison

In order to compare the spatial patterns resulting from different model simulations, we use Taylor (2001) diagrams, which are an efficient way to illustrate the differences across models and domains. These diagrams display the centered root mean squared error, standard deviation, and correlation coefficient in one single plot for a given set of models with respect to an observational reference (EWEMBI in this case). Therefore, they provide a quick summary of performance a glance and also allow for an intercomparison of different model realizations.

The centered root mean squared error is defined as

$$\left(\frac{1}{N}\sum_{n=1}^{N}\left((f_n-\bar{f})-(o_n-\bar{o})\right)^2\right)^{\frac{1}{2}}, \tag{1}$$

where f_n and o_n are the values of the diagnostic indices for forecasts and observations at grid point n, respectively, and can thus be compensated by the forecast and observed means $\bar{f}$ and $\bar{o}$. In order to account for model (uncentered) error, we also consider the Mean Absolute Relative Error (MARE) in the Taylor diagram (shown as the color of the corresponding circles), which is defined as $\frac{1}{N}\sum_{n=1}^{N}|(f_n-o_n)|/o_n$.

2.5. Variance Decomposition: Domain Versus Model Contribution

We characterize uncertainty as to the multimodel multidomain ensemble of climate change signals for the different indices and apply variance decomposition to decompose the total variance into terms due to the domain, the models, and the interactions of both. Following Déqué et al. (2012), we denote X_{ij} the measure of a given index at a given grid point for model i (1 to 15; check Table S1) over domain j (1 or 2, for EURO- or AFR-CORDEX). The total observed variance V of X_{ij} can be decomposed into three terms as $V = M{+}D{+}MD$, where M is the contribution of the models alone, D is the contribution of the domains alone, and MD is the remaining *combined* contribution that can not be split apart. These terms are defined as

$$M=\frac{1}{15}\sum_{i=1}^{15}\left(X_{i\cdot}-X_{\cdot\cdot}\right)^2,$$

$$D=\frac{1}{2}\sum_{j=1}^{2}\left(X_{\cdot j}-X_{\cdot\cdot}\right)^2,$$

$$MD=\frac{1}{2}\sum_{j=1}^{2}\frac{1}{15}\sum_{i=1}^{15}\left(X_{ij}-X_{i\cdot}-X_{\cdot j}+X_{\cdot\cdot}\right)^2,$$

where $X_{i\cdot}$ is the mean across domains for each model, $X_{\cdot j}$ is the mean across models for each domain, and $X_{\cdot\cdot}$ is the grand-mean, across all models and domains. The contribution of each term to the total variance can be expressed as a percentage by dividing by the total variance V.

Note that we are interested in disentangling domain uncertainty from modeling uncertainty and, therefore, we combined GCM and RCM uncertainty by considering each GCM-RCM pair as a different model. Note that, in this way, we avoid the problem of the sparse GCM-RCM matrix, which led Déqué et al. (2012) to make simplifying assumptions to be able to estimate the terms above. Here, the above variance decomposition is a mathematical identity, and there are ensemble members to fill all the terms in all the summations; thus, no simplifying assumptions are required.

3. Results

First, we analyze the performance and similarity of the five RCMs appearing in Table S1 under "perfect boundary" conditions, driven by ERA-Interim over the two different domains (EUR- and AFR-CORDEX). We use the Taylor diagram to intercompare the performance of the models to reproduce the diagnostic indices of Table S2 using the 20-year period 1989–2008, common to ERA-Interim and CORDEX simulations.

Figure 2 shows the Taylor diagrams for mean precipitation, precipitation above the 95th percentile (R95pTOT), and the median of the annual wet spell maxima (WetAnnualMaxSpell), respectively. Rather than the individual model performance, we are interested here in the differences due to the choice of domain. Therefore, we focus on the differences of each pair of dots representing the same RCM when run over the EURO- and the AFR-CORDEX domain (the two dots are joint with a line for facilitating the comparison). As compared to the variability of the total ensemble in the Taylor diagram, the interdomain variability—represented by the length of the joining lines—is in general small for all RCMs and indices considered. This is particularly the case for mean precipitation and R95pTOT, whereas this behavior is more subtle for WetAnnualMaxSpell (this is in agreement with the results obtained for the climate change deltas).

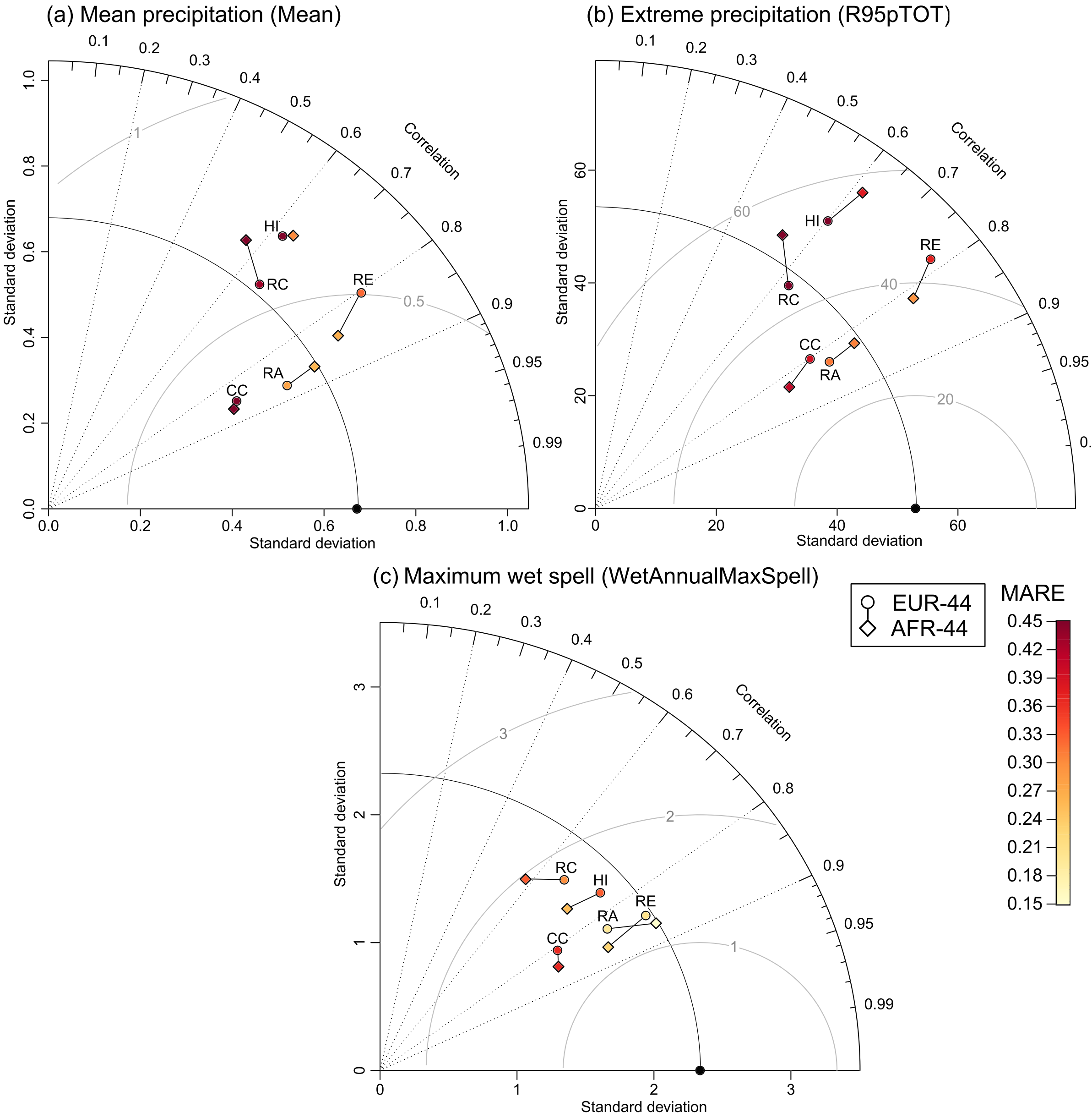

Figure 2. Taylor diagrams intercomparing the performance of the different reanalysis-driven RCMs considered in this work for both the EUR- (circles) and AFR-CORDEX (diamonds) domains. Model results are evaluated against EWEMBI observations to reproduce (a) mean precipitation, (b) R95pTOT, and (c) WetAnnualMaxSpell. Colors indicate the mean absolute relative error (MARE). RA, HI, RC, CC, and RE stand for RACMO22, HIRHAM5, RCA4, CCLM4-8-17, and REMO2009, respectively, and labels are located near the EURO-CORDEX domain results.

Note that WetAnnualMaxSpell is a very sensitive index with a lot of dispersion, with areas in northern Africa where two consecutive wet days are extremely unlikely to happen (see Figure S1). Note also how the HIRHAM5 shows a substantial difference in the MARE for the three indices, which cannot be detected if only the centered bias is taken into account. In the case of the REMO2009, there is a small difference in centered bias, which becomes more apparent if we look at the MARE. Conversely, RCA4 has a comparatively higher centered bias for both mean and extreme precipitation.

These results evidence that the influence of the choice of domain is small when the different RCMs are used in perfect boundary conditions, that is, driven by reanalysis data.

Second, in order to assess whether or not the choice of the domain significantly affects the climate change signals for the different indices considered, we analyze the uncertainty/variability projected over the

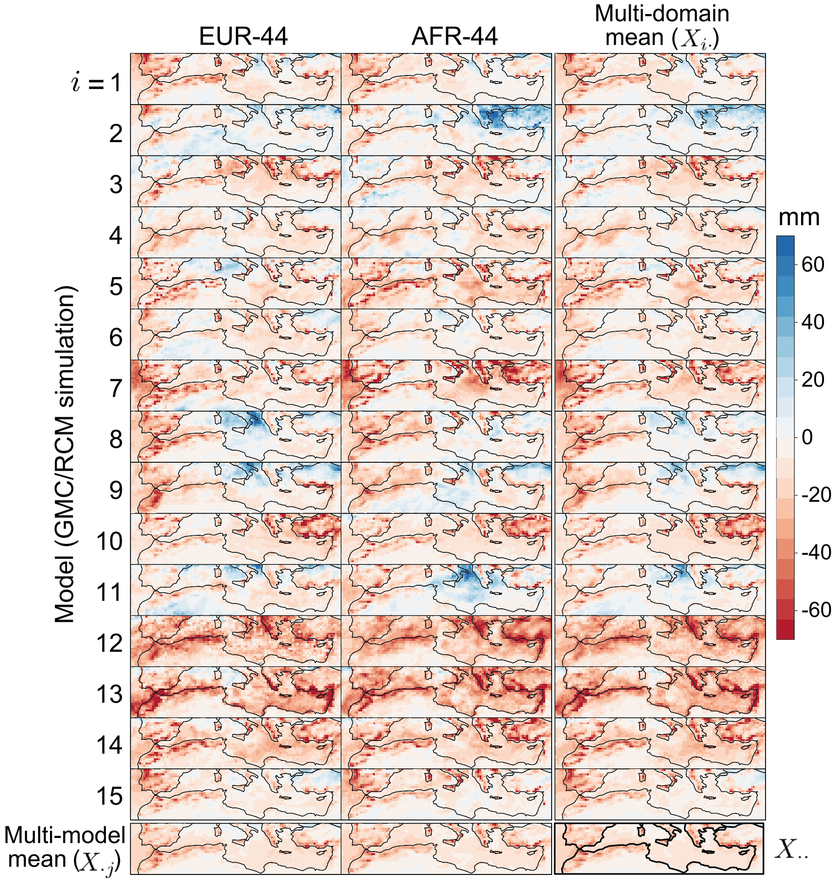

Figure 3. Projected delta changes for R95pTOT for the period 2071–2100 under the RCP8.5 scenario (taking as baseline 1971–2000), as given by the different models analyzed (in rows) when they are run over the EUR- and AFR-CORDEX domains (left and middle column). The bottom row corresponds to the multimodel mean (for each domain) and the right column shows the multidomain mean (for each model).

Mediterranean by the grand multidomain multimodel ensemble obtained considering all GCM-driven RCM simulations available in Table S1. For simplicity, we will refer to each GCM-RCM combination as "model" from now on and would not analyze the separate contribution of GCMs and RCMs.

As an illustrative example, Figure 3 shows the delta changes projected for R95pTOT for the period 2071–2100 (taking 1971–2000 as baseline) under the RCP8.5 scenario. Rows 1–15 correspond to the different models (i.e., GCM-RCM combinations) listed in Table S1, when they are run on the EUR- and AFR-CORDEX domains (left and middle column, respectively). In addition, the bottom row corresponds to the multimodel mean (for each domain) and the right column shows the multidomain mean (for each model). This figure shows some variability across the two domains and in some cases even conflicting climate change signals for particular small regions (e.g., southern Italy in Model 8). Nevertheless, even for extreme indices like R95pTOT, when the full ensemble mean for each domain is considered, these differences become almost negligible (bottom row, left and middle columns), providing thus similar climate change signals. Thus, there is no conflict when using regional climate information from any of the two ensembles.

In order to obtain a quantitative assessment of the above results, we apply the variance decomposition method described in section 2.5 to separate the contribution of the choice of model and/or domain to the total variance exhibited by the grand (models + domains) ensemble. Most of the total variability comes determined by the choice of model (Figure 4, bottom), whereas the contribution of the choice of domain is very small (Figure 4, middle). For some indices (e.g., WetAnnualMaxSpell) the combined model/domain effect is relatively important. Nevertheless, it is still small when compared to the model component.

Given the spatial homogeneity of the contribution of the different components to the total variance (Figure 4), we summarize in Figure 5 (which shows spatially averaged results) the variance decomposition

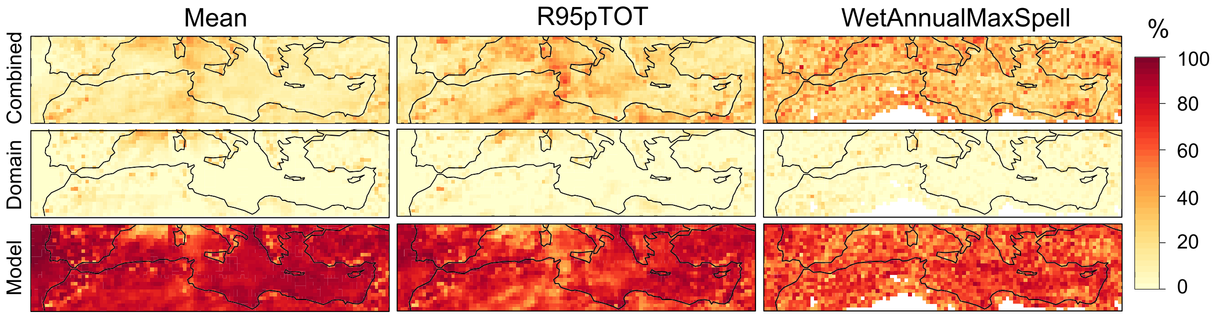

Figure 4. Relative contribution of each component (model, domain, and model/domain; in rows) to explain the total variability found in the projected delta changes for mean precipitation, R95pTOT, and WetAnnualMaxSpell (in columns) for the period 2071–2100 under the RCP8.5 scenario (taking as baseline 1971–2000).

analysis performed for the projected delta changes for all the indices in Table S2. In this Figure, we separate the analysis by season, except for the annual cycle and the extreme precipitation. These results show that the effect of the choice of domain alone, with a contribution of less than the 5% to the total variance in the worst case, is very small. Also, the model contribution alone is around 70% for all metrics (note that it is higher in winter than in summer in all cases), with the exceptions of the Simple Day Intensity Index, which falls to 55% for the JJA season, and median of the annual wet spell maxima, which is still more than 60%. If considered annually, model contribution alone is above 80% for the mean precipitation amount (Mean), the percentage of wet days (R01), both transition probabilities (DWProb and WWProb), and the median of dry spell maxima (DryAnnualMaxSpell).

It is also interesting to note that the combined model/domain contribution ranges from 15% to around 35% (depending on the index). This contribution cannot be attributed to either the model or the domain and is indicative of varying interdomain variability across the different models. This is reflected in Figure 3, which shows, for instance, higher interdomain variability for Models 2 and 7 compared to Models 6 and 13.

As shown by Figure 4, mean precipitation is highly dependent on the model considered. Still, some areas exhibit a high combined effect, for instance, the Atlas mountains, the Corso-Ligurian basin, and the Strait of Sicily. This combined effect is amplified for the case of R95pTOT, for which it reaches a 40% for some small regions—nevertheless, most of the variance comes still from the choice of model. For the case of WetMaxSpell, this combined effect is disseminated along the whole Mediterranean area, with no particular pattern. This is due to the high sensitivity of this extreme measure, ranging from just 1 day in some areas in the north of Africa to 18 days in the northwest of the Iberian Peninsula (see Figure S1, which shows the observed values).

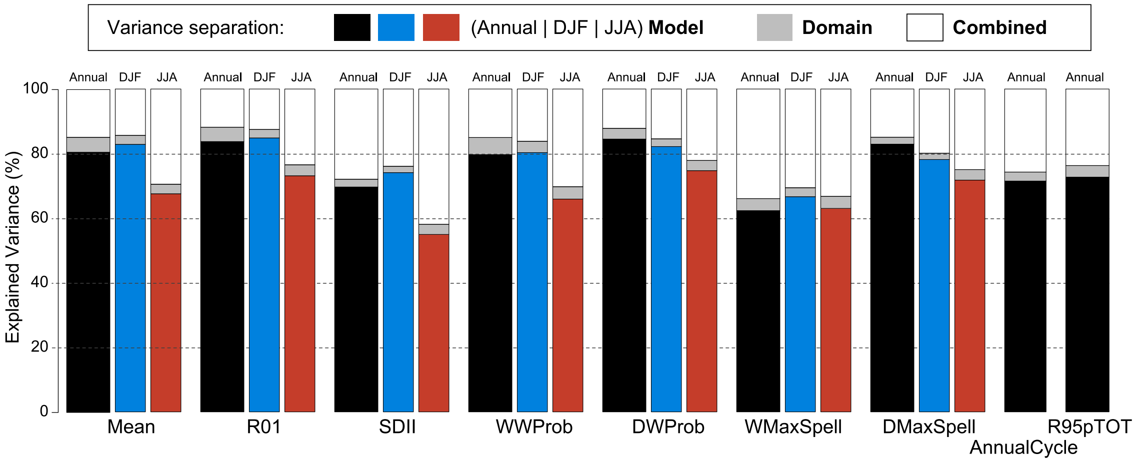

Figure 5. Summary (spatial average) of the variance decomposition of the projected delta changes (2071–2100 with respect to 1971–2000) for all diagnostic metrics considered. Within each bar, the colored/gray/white part corresponds to the model/domain/combined contribution to the total variance. Except for the AnnualCycleRelAmp and R95pTOT, results are presented for the whole year (black) and boreal winter (DJF: blue) and summer (JJA: red).

4. Conclusions

This work aims to fill a relevant knowledge gap that can potentially affect vast regions of the world for which RCM-based simulations coming from different overlapping CORDEX domains are available: How important is the uncertainty due to the choice of the domain as compared to that derived from the choice of RCM in regional climate change projections? To answer this question, we focus on precipitation over the Mediterranean region—which is encompassed by both the EURO- and AFR-CORDEX domains—and use a variance decomposition method to quantify the separate contribution of the model alone and the domain alone to the climate change signal for a set of diagnostic indices, which have been established in the international action VALUE and characterize different validation aspects. Our results indicate that, taking into account all indices and seasonality, the variability due to the choice of model alone ranges from 60% to 80%, being the contribution of the choice of domain less than 5% in all cases. This suggests the suitability of multidomain grand ensembles for overlapping regions, since similar projections are obtained when the same GCM-RCM combination is run in different domains.

From the above results, we can conclude that the ensemble of a particular domain can be enlarged using as proxies additional GCM-RCM runs from an overlapping domain. Therefore, the use of a multidomain multimodel grand ensemble seems to be an appropriate methodology of opportunity to make the most of all available information in overlapping regions.

We plan to broaden this study by applying the same methodology to other variables and other regions of the world where RCM-based simulations coming from different CORDEX domains are also available. So far, a preliminary analysis for mean temperature over the same Mediterranean region reveals similar results, being the effect of the choice of domain very limited (and the contribution of the model alone above 95% for mean temperature).

The results from this study will help different users' communities to better frame their decisions for impact applications in those regions for which RCM-based information coming from different domains is available.

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