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Key Points:

- CPRCMs improve summer season maximum temperature representation, especially on a ground-station-based evaluation
- CPRCMs amplify heatwave maximum temperature changes over the Alps and the northern GAR, combined with the strongest projected drying
- CPRCMs ensemble reduces heatwave metrics change signal inter-model spread except for the dry spell length

Supporting Information:

Supporting Information may be found in the online version of this article.

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Heatwave Future Changes From an Ensemble of Km-Scale Regional Climate Simulations Within CORDEX-FPS Convection

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Abstract As global temperatures continue to rise, the impact of heatwaves becomes increasingly striking. The increasing frequency and intensity of these events underscore the critical need to understand regional-scale mechanisms and feedback, exacerbating or mitigating heatwave magnitude. Here, we use an ensemble of convection-permitting regional climate models (CPRCMs) to elucidate future heatwave changes at fine spatial scales. We explore whether the recently highlighted drier/warmer signal introduced by CPRCMs improves summer temperature extremes representation and if it modulates future heatwave changes compared to convection-parameterizing regional climate models (RCMs). In historical runs, CPRCMs show a more realistic representation of summer maximum temperature especially on a ground-station-based evaluation. CPRCMs project substantially drier conditions than RCMs. This is associated with a modulation of heatwave temperature changes which show diversified spatial patterns, magnitudes, and signs. CPRCMs ensemble shows an overall reduction in heatwave metrics future changes inter-model spread compared to the RCMs ensemble.

Plain Language Summary Heatwaves are progressively having a bigger impact on communities and ecosystems. The growing frequency and intensity of these events highlight the need to understand regional mechanisms and feedback that can either worsen or mitigate increasing heatwave trends. We use an ensemble of very high-resolution regional climate models (CPRCMs, ~3 km) to explore changes in heatwaves at fine spatial scales. We investigate if the drier and warmer conditions characterizing CPRCMs improve the accuracy of summer temperature extremes and how they affect future heatwave patterns compared to lower-resolution regional climate models (RCMs). In historical simulations, CPRCMs provide a more accurate representation of summer maximum temperatures, especially on a station-based evaluation. CPRCMs predict drier conditions than RCMs. This dryness affects heatwave temperature changes according to varied spatial patterns, magnitudes, and trends. Overall, the CPRCMs ensemble shows less uncertainty in predicted heatwave changes compared to the RCMs ensemble.

1. Introduction

Among the weather extremes exacerbated by a warmer climate, heatwaves stand out as one of the most concerning phenomena, triggering massive impacts on ecosystem services and societies (Seneviratne et al., 2021). Mid-latitude heatwaves are mainly associated with co-located blocking with Rossby waves breaking and disruption of zonal westerlies, promoting the northward expansion of subtropical belt ridges (Sousa et al., 2018). Large-scale forcing can be in turn modulated by local soil moisture-temperature feedback loops (S. I. Seneviratne & Koster, 2012). These latter drive partitioning of latent and sensible heat fluxes, impacting surface air temperature, particularly in soil moisture-limited regions (Santanello et al., 2018) with a knock-on effect on planetary

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boundary layer dynamics and mesoscale circulation features (Taylor et al., 2007, 2012). The response of these processes to a warming climate is still relatively poorly represented in state-of-the-art climate models (Van Oldenborgh et al., 2022). This is especially true for regional patterns (e.g., Vautard et al., 2023). Regional climate models (RCMs) are crucial tools for the representation of heat extremes thanks to the inclusion of finer-scale process feedback (Molina et al., 2020). Despite an overall improved representation of temperature extremes compared to global climate models (GCMs), reproducing extreme temperature features and trends is still challenging (Vautard et al., 2021). Besides a varying dependency on the driving GCM (Karypidou et al., 2023), RCMs still parameterize many relevant processes (Hohenegger et al., 2009), have limitations in representing land-atmosphere interactions (Barlage et al., 2021) and, generally, do not consider time-evolving aerosols (Schumacher et al., 2024).

In this study, we leverage the first very high-resolution regional climate model ensemble of twelve convection-permitting scales (~ 3 km) RCMs (CPRCMs) performed within the CORDEX Flagship Pilot Study on convection (CORDEX-FPSCONV, Coppola et al., 2020) over the Greater Alpine Region (GAR), a well-known hotspot of climate change (Bakke et al., 2023). A relevant body of literature has examined the added value of the ensemble, for example, improved representation of precipitation extremes moving to an explicit deep convection representation (Ban et al., 2021). Less attention has been given to temperature extremes modulation (Sangelantoni et al., 2023, S23 hereafter; Soares et al., 2022). S23 reveal that CPRCMs introduce a warmer signal during heatwaves and throughout the warm season w.r.t. RCMs at coarser resolution of about 12 km. The signal in S23 stems from stronger land-atmosphere coupling leading to drier soils combined with longer dry spell lengths, and with implications for temperature representation in CPRCMs. However, disentangling the contribution of land-atmosphere coupling versus “atmospheric-only” processes to this signature remains crucially challenging. Ha et al. (2022) have demonstrated that for similar tropospheric temperature ranges the convection triggering is suppressed in CPRCMs.

This study focuses on the potential implications of these findings on changes in heatwaves in a future climate. The research question is whether the warming/drying at km-scale as seen in the S23 model runs can be expected to be time-stationary or amplified/reduced in a warmer future climate. In the next Section 2 data sets used will be described; Section 3 describes the results, and in Section 4 we provide a discussion and the conclusions.

2. Materials and Methods

2.1. CORDEX-FPSCONV Ensemble

We analyze an ensemble of 12 CPRCM simulations performed within the CORDEX-FPSCONV, over two periods: historical (1996–2005) and future (2090–2099). All the CPRCMs (2–4 km resolution) except for the UK Met Office and Justus-Liebig-University simulations are driven by the corresponding convection-parameterizing RCM (12–15 km resolution). Although the UK Met Office group is not using the intermediate dynamical downscaling step, they are providing the data from the UM model at the resolution of 12 km, which is used for comparison.

In a one-way double-nest setup (GCM-RCM-CPRCM), the RCMs are in turn driven by a subset of five CMIP5 GCMs (Table S1 in Supporting Information S1). An overview of the multi-physics ensemble setup can be found in Ban et al. (2021). The three modeling systems are forced by an observed radiative forcing in the historical period and by the high-emission RCP8.5 scenario in the future climate integration. The study area consists of the Greater Alpine Region (Figure S1a in Supporting Information S1).

2.2. Reference Data Sets

We use different reference products to evaluate RCM and CPRCM ensembles' summer daily *maximum temperature* ($T_{\max}$) and *precipitation* (pr) during the historical period. For the $T_{\max}$, we take advantage of both gridded and point-scale observational data sets. As a gridded product, the European Meteorological Observations with 5 km horizontal resolution (EMO-5, Thieme et al., 2022). As station-scale product, we use the quality-controlled, sub-daily, station-based Met Office HadISD (Dunn et al., 2016). Observational sites elevation is shown in Figure S1b in Supporting Information S1.

For pr, we use EMO-5 and the list of high-resolution gridded data sets reported in Table S2 in Supporting Information S1.

2.3. Heatwave Metrics

Analyses involve eight heatwave-related metrics, described in Table S3 in Supporting Information S1. Here, we define a heatwave as a period of at least three consecutive days with Tmax equal to or above a daily based 90th percentile of the historical period per ensemble member (Russo et al., 2015). The 90th percentile is derived over a 31-day time window centered on each summer calendar day. Heatwave metrics are computed for each year of the two time periods. In case of more than one event per summer, we select the event with the highest heatwave magnitude representing the largest cumulative deviation from the standardized climatology (see HWMId definition below). Future period heatwaves are derived over the summer 90th percentile of the historical period. Five out-of-eight metrics represent relevant features of heatwaves: mean Tmax (HWTXm), max Tmax (HWTXx), magnitude (HWMId), persistence (HWper), and frequency (HWf). Two metrics are considered as a proxy of surface moisture availability and based on latent heat (LH) flux during heatwave days both in terms of physical values (HWLH) and in terms of standardized anomaly (evaporative deficit, HWLHdef, Careto et al., 2018). Finally, summer mean dry spell length (DSL) is regarded as a heatwave preconditioning factor. In the next section, results from RCM and CPRCM ensembles during the historical period and for the projected change signal will be presented. All the heatwave metrics are computed on the models' original grid, then bilinearly interpolated on a common grid (RCMs: 15 km, CPRCMs: 3 km) to compute ensemble statistics. When compared to observations, RCMs and CPRCMs are interpolated to the reference products grid.

2.4. Analyses

Historical period RCM and CPRCM ensembles Tmax-based heatwave metrics are evaluated through a comparison with EMO5 data set. DSL is evaluated in comparison with EMO5 and with high-resolution observed data sets (Section 2.2). Moreover, the added value of CPRCMs in reproducing station-scale summer Tmax statistics is examined through the Distribution Added Value, DAV (P. M. M. Soares & Cardoso, 2018) derived in correspondence with HadISD sites (Figure S1b in Supporting Information S1). DAV represents a percentage improvement produced by the higher versus the lower resolution over the S score (Perkins et al., 2007). This latter corresponds to the common area between observed and simulated summer Tmax probability density functions (distribution hereafter). Two DAV configurations are considered. (a) Where distributions are built considering all values of summer Tmax and (b) where distributions are built only on summer Tmax exceeding the historical 90th.

Future changes in heatwave metrics are examined by comparing the mean values of the future and historical periods (2090–2099 and 1996–2005 respectively) for the two-resolution ensemble median. Statistical significance is derived with bootstrapping method, generating distributions of random resampling (1000 times for each grid point) of differences derived from combined historical and future time series (D. Wilks, 2006). If the actual change falls beyond distribution 95th percentile is considered significant. Moreover, two *t*-test configurations are considered, one considering the standard *p*-value and a second applying a False Discovery Rate (FDR) adjustment (Benjamini & Hockberg, 1995; D. S. Wilks, 2016). This latter is idealized to set limits against overstating statistical significance when testing involves collections of spatially autocorrelated time series (D. Wilks, 2006).

Ensemble changes are considered significant only if 50% or more of the models show statistically significant differences (*p*-value <0.05) and 2/3 agree over the sign of the change (Tebaldi et al., 2011).

3. Results

3.1. Historical Period

During the historical period, CPRCMs are confirmed to introduce a warmer/drying signal compared to the driving RCMs, coherently to (S23). Figure 1 shows two representative metrics, the heatwaves mean Tmax and evaporative deficit (HWTXm and HWLHdef) ensemble median and spread for the two resolutions. CPRCMs are warmer, up to ~2°C, especially over low-lying areas (Figure 1a). Higher heatwave Tmax is combined with substantially drier conditions as shown by HWLH (Figure S2e in Supporting Information S1). However, HWLHdef (expressing how anomalously dry heatwaves are) shows an opposite-sign modulation over the northern and southern sectors of the domain. For instance, over the Po valley, despite drier conditions (Figure S2e in Supporting Information S1) we observe a smaller LH deficit, suggesting systematically drier conditions beyond heatwaves, in contrast, to the northern part of the domain. Concerning the ensemble inter-model variability, the

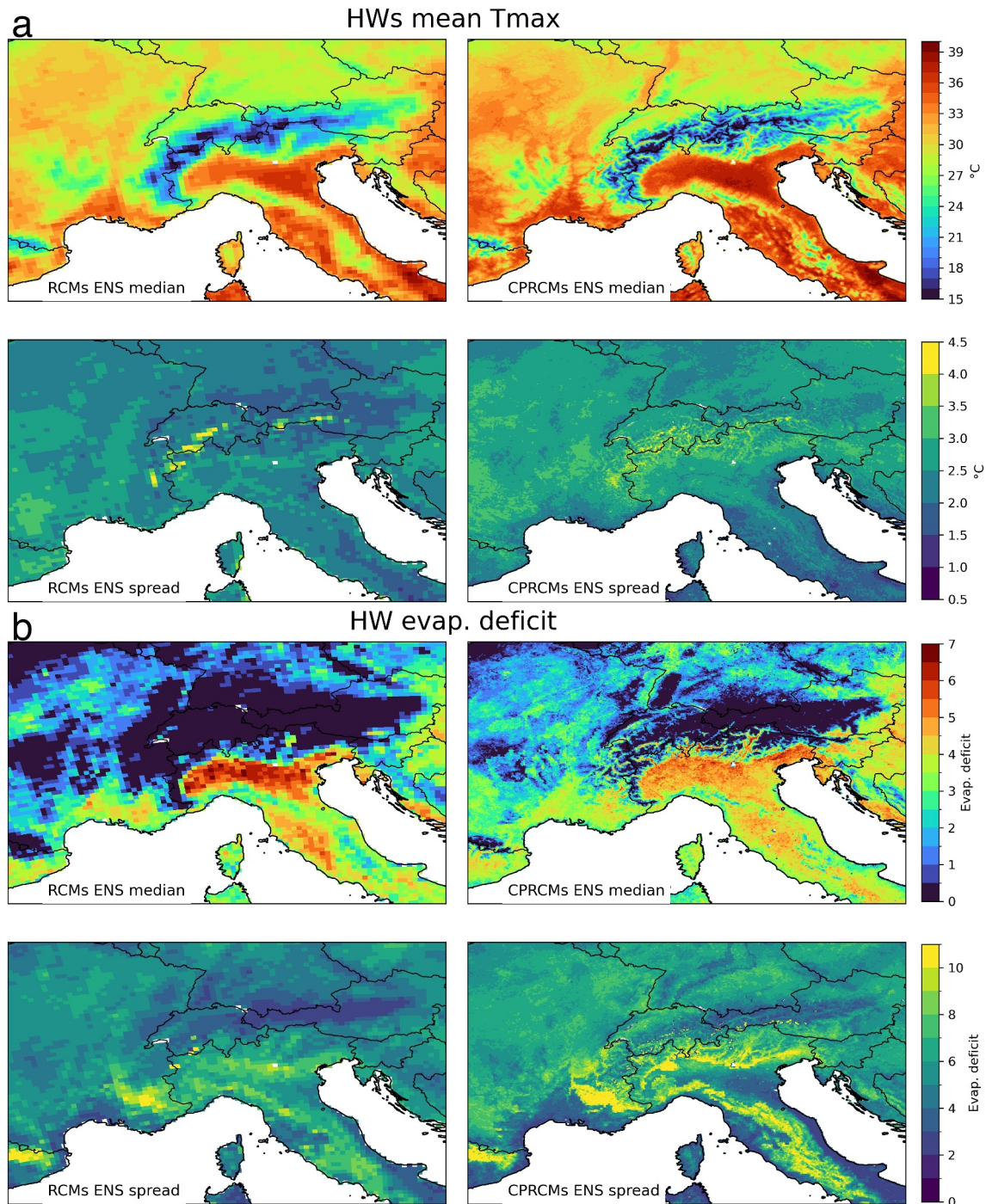


Figure 1. Historical means for HWTxm (a) and HWLHdef (b) metrics. Upper subpanels: RCMs (CPRCMs) ensemble medians on the left (right). Bottom subpanels: ensemble's inter-model spread. HWLHdef unit: dimensionless.

CPRCMs ensemble shows a generally smaller inter-model agreement (i.e., larger ensemble standard deviation), except for coastal areas. These results are true for all the metrics, especially those LH-related and the DSL.

According to a gridded reference product (EMO-5), the CPRCMs warmer signal translates into a reduction of the RCMs cold bias and at the same time, an increase of the warm bias (Figure 2a). Over the other metrics (magnitude, persistence, and frequency), the two resolutions are affected by similar biases (Figure S3 in Supporting Information S1). CPRCMs tend to get too dry over coastal areas and the western part of the domain

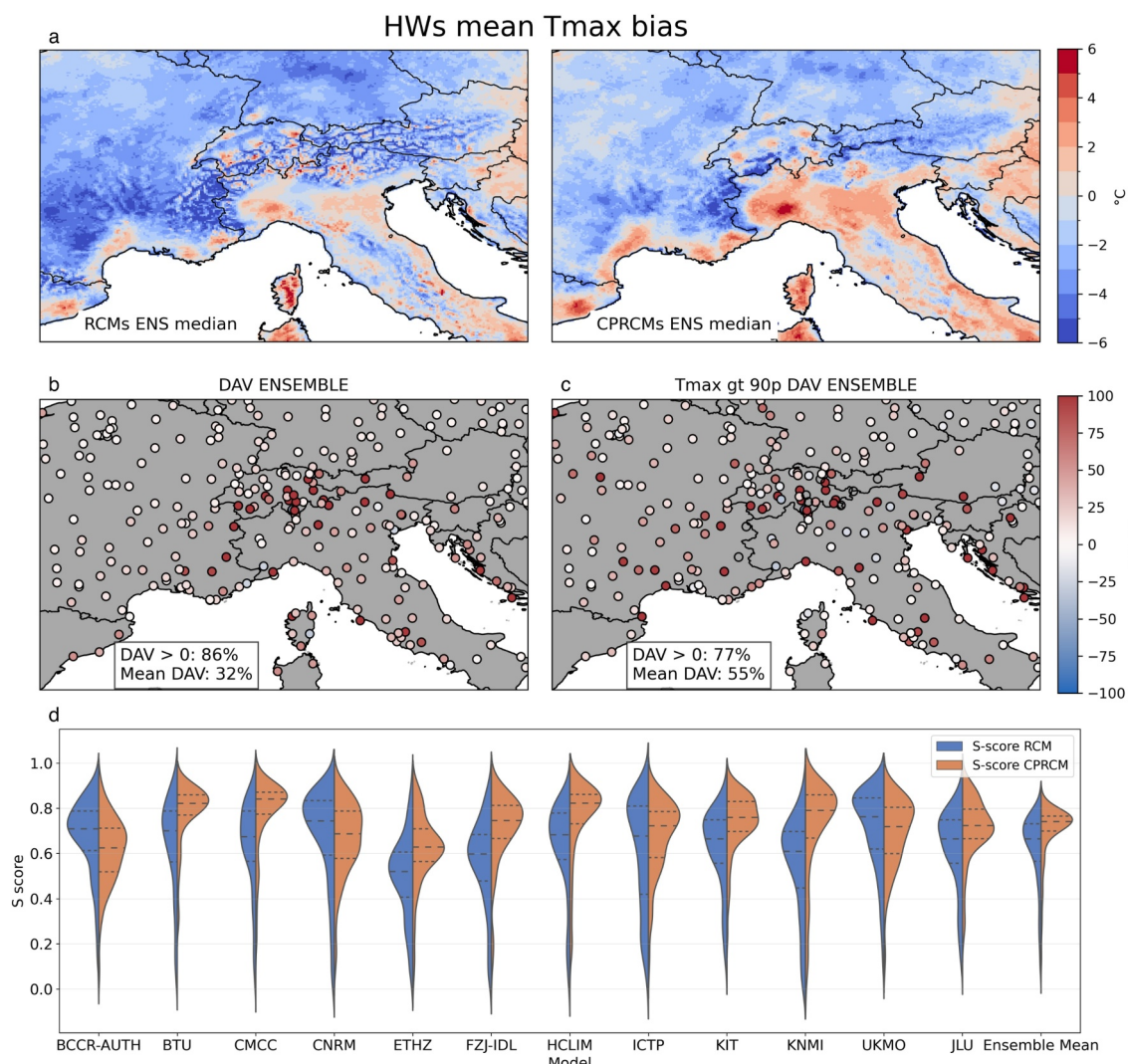


Figure 2. Historical HWTXm bias for the RCM and CPRCM ensemble medians with EMO-5 as reference (a). % DAV built on the entire summer Tmax statistical distribution. Text box shows the percentage of sites with DAV > 0 and the mean DAV (b). DAV built on Tmax > 90th percentile (c). Violin plots identify distributions built on the S score from all sites. Horizontal lines represent 25th, 50th, and 75th percentiles (d).

showing positive DSL biases according to different reference products (Figures S4a and S4b in Supporting Information S1).

Moving to station-scale, distribution-based evaluation metric the DAV shows a clear added value from CPRCMs in reproducing station-scale temperature extremes. When the whole summer Tmax statistical spectrum is considered, the CPRCMs ensemble provides a positive DAV over 86% of reference sites (Figure 2b). When the distributions are built only considering values larger than the 90th percentile (Figure 2c), we obtain fewer sites with positive DAV, but a higher mean improvement (55% vs. 32%). Generally, the largest improvement can be observed over complex orography and along the coastlines. S23 has shown that applying lapse-rate correction derived from simulation-observation elevation differences does not substantially affect DAV results. Figure 2d shows a model-specific comparison of the S score considering the entire summer Tmax distribution.

3.2. Future Changes

In this section, we compare mean values of the future and historical periods for the two-resolution ensemble median. Two exemplary metrics, HWTXm and HWLHdef, are presented (Figures 3a and 3b respectively). Future changes for the other metrics are displayed in Figure S5 in Supporting Information S1. For the HWTXm,

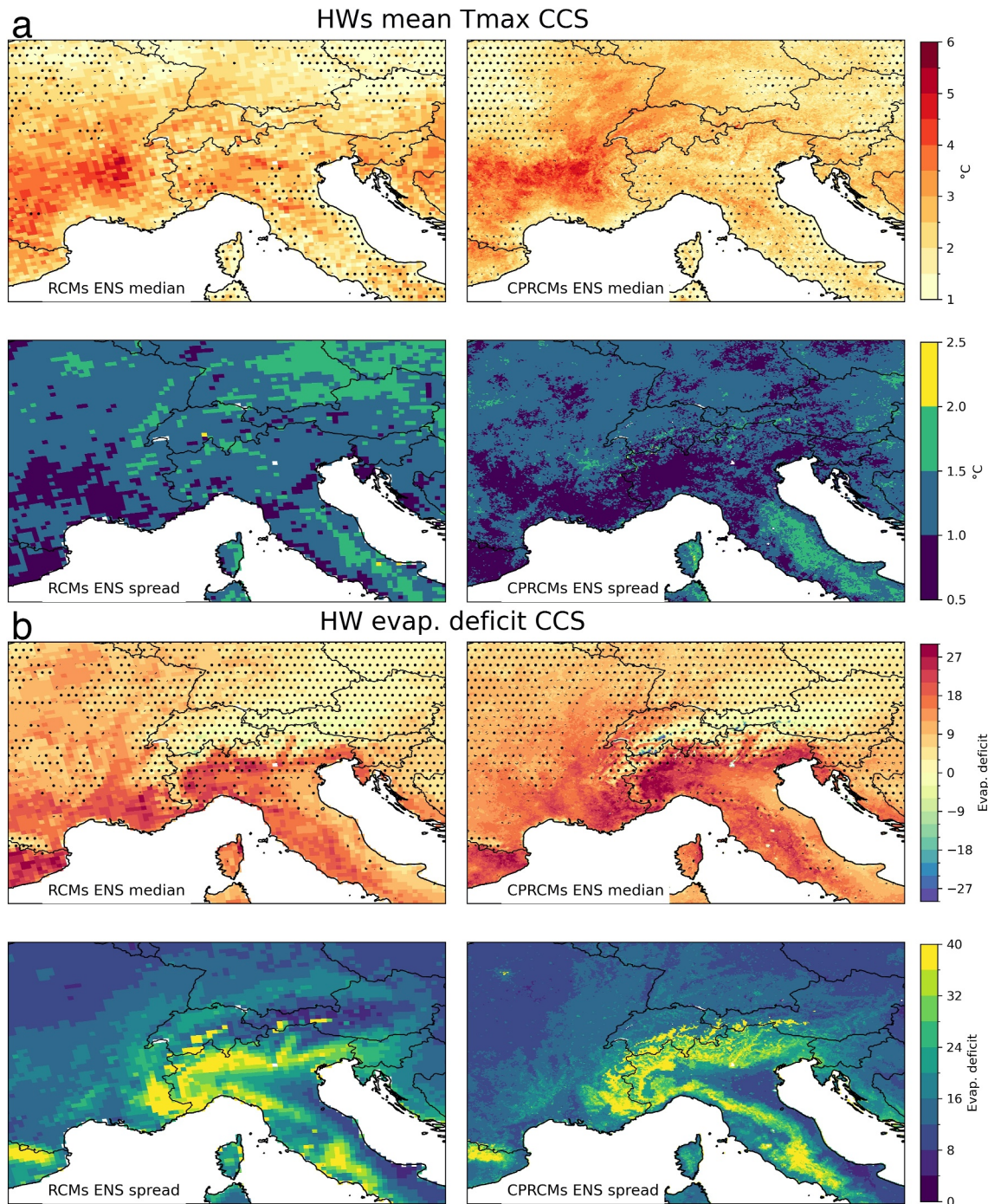


Figure 3. HWTxm (a) and HWLHdef (b) future changes. Upper sub-panels: ensemble median changes. No stippling represents grid points with at least 2/3 of the model agreeing on both signs and significant changes. Bottom sub-panels: ensemble spread. HWLHdef unit: dimensionless.

CPRCMs amplify the change signal over the northwestern Alpine sector and generally across the northern portion of the domain. Conversely, a damping is observed over the Po Valley. This modulation is consistent for HWTXx (Figure S5a in Supporting Information S1), showing a much higher change signal than HWTxm. CPRCMs also amplify the mean heatwave persistence and the related magnitude change signals over the western Italian peninsula, northwestern Po Valley, and western Alps, exacerbating a southwest-northeast heatwaves change gradient, as observed by Lin et al. (2022). Similarly, an amplification is observed for the LH-related heatwave

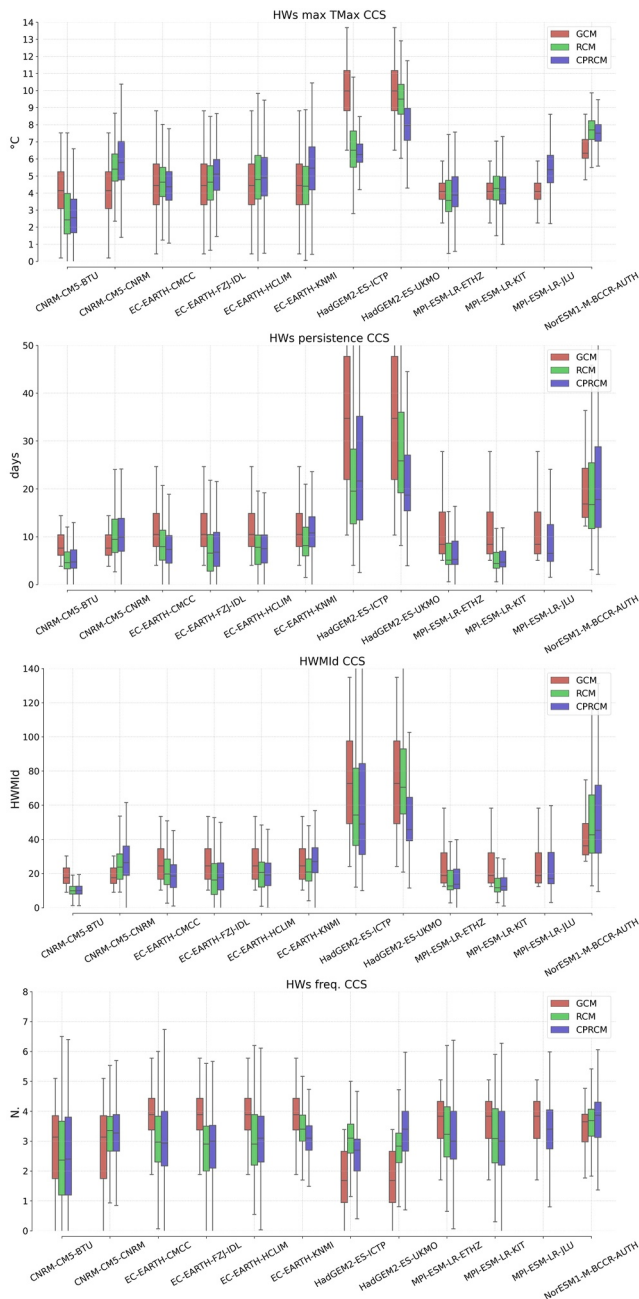


Figure 4. Boxplots represent distributions of four representative heatwave metrics change signals built on all grid points. x-axis ticks report the entire modeling chain (GCM-RCM-CPRCM).

DSL (~ 1 – ~ 3), which CPRCMs augment by up to ~ 3 to ~ 7 over Po Valley and the western sector of the GAR. Here, we recall that CPRCMs are characterized by higher inter-model spread (Figure S5f in Supporting Information S1).

4. Discussion and Conclusion

A recent study highlights CPRCMs introducing warmer/drier conditions during heatwaves and in general during the summer season (S23). Here, we explore if this signal modifies also heatwave future changes. During the historical period, CPRCMs signature translates to a reduction (increase) of cold (warm) biases affecting RCMs ensemble during heatwaves considering high-resolution gridded observations. This is combined with an

metrics. The largest modification introduced by CPRCMs involves DSL changes, where a doubling of the signal is observed over a vast portion of the domain, including the Italian peninsula coastal areas, Po Valley, and the western sector. Interestingly and contrary to the historical period, the CPRCMs ensemble reduces the inter-model spread compared to the RCMs ensemble for all metrics, excluding DSL, where CPRCMs project a more pronounced DSL extension combined with a larger inter-model spread. A comparison of future changes' significance resulting from original and FDR-adjusted *t*-test p-values is shown in Figure S6 in Supporting Information S1. It can be observed that FDR-adjusted and bootstrapping produce similar significance patterns, preserving differences between the two resolutions.

In Figure 4, we further examine the inter-model variability of future changes. Here, we integrate change signals from driving GCMs, offering insight into the dependency of downscaled simulations' future changes on those generated by the driving GCM. While the modulation introduced by CPRCMs compared to RCMs is primarily linked to local scale forcing, the large-scale forcing signal introduced by the GCM can still significantly influence the magnitude of changes in the nested simulations. This can be noticed in HadGEM-driven simulations, where the signal of the downscaled simulations mirrors the GCM showing outstanding changes. In this context, we also observe how this signal is differently modulated by the two nested RCMs, UKMO and ICTP, with the former unveiling a higher dependency on the GCM signal and the second bringing the value closer to the RCMs ensemble variability. In this context, UKMO produces the largest modification of the signal between RCM and CPRCM. KNMI CPRCM amplifies the change signal across all the metrics, except for the heatwave frequency. For the remaining models, we find no change signal systematic modulation moving from RCM to CPRCM.

Figure 5 summarizes the modulation of heatwave metrics change signals across four subdomains representing the northern, western, Po Valley, and Alpine sectors of the GAR. Diverse future changes in Tmax-based metrics are observed, with amplifications occurring over the Alps and the northern sector by up to 0.5°C . Conversely, smaller but opposite-sign modulation is evident in the other sectors. CPRCMs augment the change signal of heatwave persistence by approximately 2 days on average over the Alps and Po Valley. Similar modulation is observed for the related heatwave magnitude. Notably, LH-related metrics exhibit a more substantial modulation. The CPRCMs ensemble amplifies the reduction in mean heatwave days' LH (HWLH) by about 20% over the northern GAR compared to the RCMs ensemble. Regarding evaporative deficit (HWLHdef), CPRCMs indicate a drier signal than the RCMs ensemble, particularly over the Alps (approximately 1/3 drier). As mentioned, the largest modulation is observed for the DSL change signal. Unlike other metrics, CPRCMs show a roughly symmetric modulation across different sectors. RCMs project a slight increase in mean

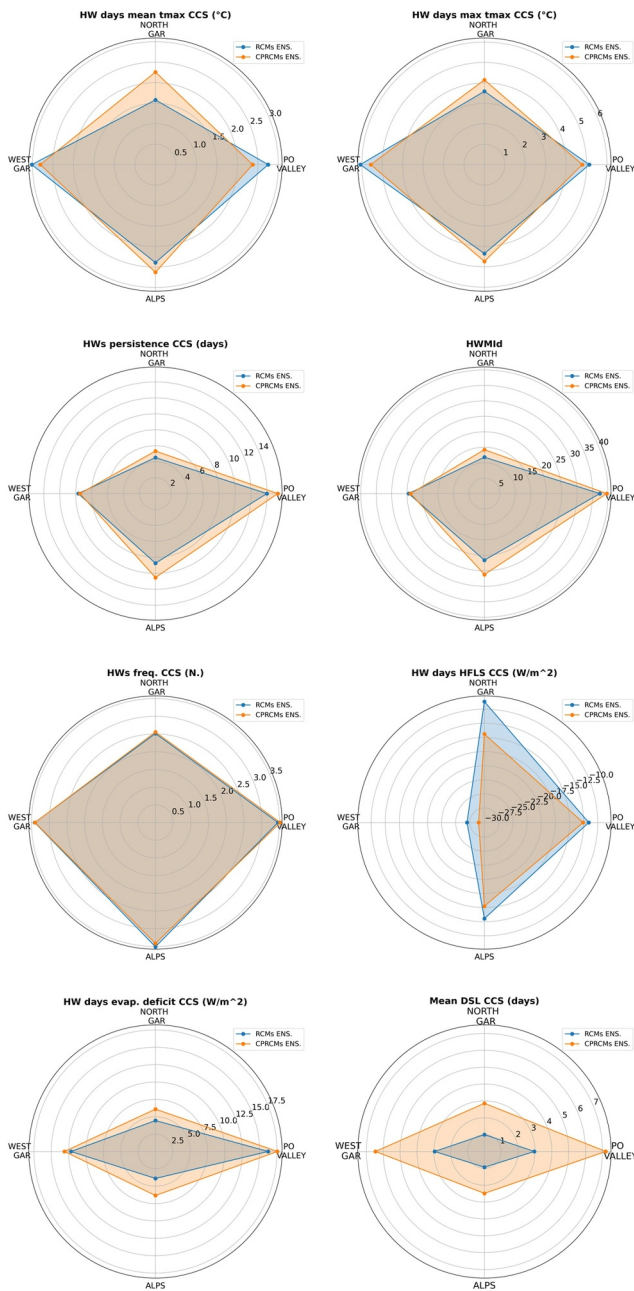


Figure 5. Radar plots summarize the eight metrics ensemble median change signals for different subdomains.

robustness to these first results. In 10-year time segments, climate variability cannot be properly represented, hampering findings robustness.

Data Availability Statement

Climate simulations analyzed are available from an open repository: Sangelantoni et al. (2024). Moreover, the whole CORDEX-FPS Convection ensemble archiving is underway at the DKRZ node of the ESGF data portal (https://esgf-metagrid.cloud.dkrz.de/search/cordex-dkrz/?project=CORDEX-FPSCONV&data_node=esgf1.dkrz.de). Codes for generating heatwaves and analyses are available from Zenodo (Sangelantoni, 2024).

exacerbation of dry conditions especially over coastal areas and western GAR. Moving to a point-scale evaluation (DAV), the CPRCMs ensemble turns out to substantially improve summer season Tmax distribution representation. This is considering both the entire distribution and only the distribution right tail. The CPRCM added value is especially evident over complex orography (Alps) and coastal areas. Combining the evaluation experiment in S23 with the current results based on an independent and extended data set of station-scale observations supports CPRCMs' drier/warmer signature pointing to an improved representation of temperature extremes. However, the local tendency to drift toward too prolonged dry spells, even over areas with improved Tmax, is still an open issue. One path of future research is paved by recent evidence indicating a still too-crude/missing representation of land surface/subsurface processes and human water use (e.g., irrigation) in the current CPRCMs, getting even more crucial when approaching km-scale resolutions, and underlying development and amplification of heat extremes (Graf et al., 2021; Polcher et al., 2022; Warrach-Sagi et al., 2022). An example is the tendency toward exaggerated evaporation until the soil water is depleted and triggering excessive heat (Folwell et al., 2022). At the same time, adding extra surface physics (e.g., ground-water) could not solve atmospheric problems in origin (Ha et al., 2022).

CPRCMs show a diversified modification of heatwave future changes. Tmax-based metrics signal is mostly modulated over the GAR northern sector where CPRCMs introduce an amplification up to 0.5°C for the HWTXm. For the same metrics, an opposite sign, though smaller, modulation occurs over Po Valley. This could be motivated by a stronger drying between the historical and future periods in the RCMs since CPRCMs were already dry in the historical period. This determines a larger increase of the sensible heat component in the RCMs. Conversely, in the northern sector, the historical period availability of surface moisture sustains the stronger atmospheric water demand in CPRCMs leading to a larger future drying (Figure S5e in Supporting Information S1) which in turn drives the larger Tmax increase. CPRCMs project substantially drier summer conditions, even though according to different spatial patterns as physical LH or its deficit is considered. Nevertheless, the most pronounced modulation introduced by the CPRCMs is the amplification of DSL change signal. This can be interpreted as the inextricably entangled effect of stronger land-atmosphere interactions and convection inhibition (Ha et al., 2022), postulating similar mesoscale circulation between the resolutions as found in S23. Another finding is that excluding the DSL, the CPRCMs ensemble shows a reduced inter-model spread of future changes, resembling results by Fossier et al. (2024) for precipitation extremes. This supports the plausibility of CPRCMs signature also under a warmer climate. Nevertheless, being the first-of-its-kind assessment further process-based studies are necessary to confirm these hypotheses. At the same time, longer simulations are crucial for attributing statistical

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References

- Bakke, S. J., Ionita, M., & Tallaksen, L. M. (2023). Recent European drying and its link to prevailing large-scale atmospheric patterns. *Scientific Reports*, 13(1), 21921. <https://doi.org/10.1038/s41598-023-48861-4>
- Ban, N., Caillaud, C., Coppola, E., Pichelli, E., Sobolowski, S., Adinolfi, M., et al. (2021). The first multi model ensemble of regional climate simulations at kilometer scale resolution, part I: Evaluation of precipitation. *Climate Dynamics*, 57(0123456789), 275–302. <https://doi.org/10.1007/s00382-021-05708-w>
- Barlage, M., Chen, F., Rasmussen, R., Zhang, Z., & Miguez-Macho, G. (2021). The importance of scale-dependent groundwater processes in land-atmosphere interactions over the Central United States. *Geophysical Research Letters*, 48(5), 1–10. <https://doi.org/10.1029/2020GL092171>
- Benjamini, Y., & Hockberg, Y. (1995). Controlling the False Discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society*, 57(1), 289–300.
- Careto, J. A. M., Cardoso, R. M., Soares, P. M. M., & Trigo, R. M. (2018). Land-atmosphere coupling in CORDEX-Africa: Hindcast regional climate simulations. *Journal of Geophysical Research: Atmospheres*, 123(19), 11048–11067. <https://doi.org/10.1029/2018JD028378>
- Coppola, E., Sobolowski, S., Pichelli, E., Raffaele, F., Ahrens, B., Anders, I., et al. (2020). A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. *Climate Dynamics*, 55(1–2), 3–34. <https://doi.org/10.1007/s00382-018-4521-8>
- Dunn, J. H. R., Willett, M. K., Parker, E. D., & Mitchell, L. (2016). Expanding HadISD: Quality-controlled, sub-daily station data from 1931. *Geoscientific Instrumentation, Methods and Data Systems*, 5(2), 473–491. <https://doi.org/10.5194/gi-5-473-2016>
- Folwell, S. S., Taylor, C. M., & Stratton, R. A. (2022). Contrasting contributions of surface hydrological pathways in convection permitting and parameterised climate simulations over Africa and their feedbacks on the atmosphere. *Climate Dynamics*, 59(1), 633–648. <https://doi.org/10.1007/s00382-022-06144-0>
- Fosser, G., Gaetani, M., Kendon, E. J., Adinolfi, M., Ban, N., Belušić, D., et al. (2024). Convection-permitting climate models offer more certain extreme rainfall projections. *Npj Climate and Atmospheric Science*, 7(1), 51. <https://doi.org/10.1038/s41612-024-00600-w>
- Graf, M., Arnault, J., Fersch, B., & Kunstmann, H. (2021). Is the soil moisture precipitation feedback enhanced by heterogeneity and dry soils? A comparative study. *Hydrological Processes*, 35(9). <https://doi.org/10.1002/hyp.14332>
- Ha, M. T., Bastin, S., Drobinski, P., Polcher, L. F. J., Belušić, M. C. D., Bock, O., et al. (2022). Precipitation frequency in med CORDEX and EURO CORDEX ensembles from 0.44° to convection permitting resolution: Impact of model resolution and convection representation. *Climate Dynamics*, 62(6), 4515–4540. <https://doi.org/10.1007/s00382-022-06594-6>
- Hohenegger, C., Brockhaus, P., Bretherton, C. S., & Schär, C. (2009). The soil moisture-precipitation feedback in simulations with explicit and parameterized convection. *Journal of Climate*, 22(19), 5003–5020. <https://doi.org/10.1175/2009JCL12604.1>
- Karypidou, M. C., Sobolowski, S. P., Sangelantoni, L., Nikulin, G., & Katragkou, E. (2023). The impact of lateral boundary forcing in the CORDEX-Africa ensemble over southern Africa. *Geoscientific Model Development*, 16(7), 1887–1908. <https://doi.org/10.5194/gmd-16-1887-2023>
- Lin, C., Kjellström, E., Wilcke, R. A. I., & Chen, D. (2022). Present and future European heat wave magnitudes: Climatologies, trends, and their associated uncertainties in GCM-RCM model chains. *Earth System Dynamics*, 13(3), 1197–1214. <https://doi.org/10.5194/esd-13-1197-2022>
- Molina, M. O., Sánchez, E., & Gutiérrez, C. (2020). Future heat waves over the Mediterranean from an Euro-CORDEX regional climate model ensemble. *Scientific Reports*, 10(1), 1–10. <https://doi.org/10.1038/s41598-020-65663-0>
- Perkins, S. E., Pitman, A. J., Holbrook, N. J., & McAneney, J. (2007). Evaluation of the AR4 climate models’ simulated daily maximum temperature, minimum temperature, and precipitation over Australia using probability density functions. *Journal of Climate*, 20(17), 4356–4376. <https://doi.org/10.1175/JCL14253.1>
- Polcher, J., Schrapf, A., Dupont, E., Rinchuso, L., Zhou, X., Boucher, O., et al. (2022). Hydrological modelling on atmospheric grids; using graphs of sub-grid elements to transport energy and water. 1–34.
- Russo, S., Sillmann, J., & Fischer, E. M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, 10(12), 124003. <https://doi.org/10.1088/1748-9326/10/12/124003>
- Sangelantoni, L. (2024). Codes for “Heatwave future changes from an ensemble of km-scale regional climate simulations within CORDEX-FPS convection. *Zenodo*. [Computational Notebook]. <https://doi.org/10.5281/zenodo.13892459>
- Sangelantoni, L., Sobolowski, S., Lorenz, T., Cardoso, R. M., Soares, P. M. M., Ferretti, R., et al. (2023). Investigating the representation of heatwaves from an ensemble of km-scale regional climate simulations within CORDEX-FPS convection. *Climate Dynamics*, 62(6), 4635–4671. <https://doi.org/10.1007/s00382-023-06769-9>
- Sangelantoni, L., Sobolowski, S. P., Soares, P. M. M., Goergen, K., Cardoso, R. M., Adinolfi, M., et al. (2024). Heatwave future changes from an ensemble of km-scale regional climate simulations within CORDEX-FPS convection, dataset. *Open repository of the Jülich Supercomputing Centre*. [Dataset] https://datapub.fz-juelich.de/slots/cordex_fpsconv_future_heatwaves/index.html
- Santanello, J. A., Peters-Lidard, C. D., & Kumar, S. V. (2011). Diagnosing the sensitivity of local land-atmosphere coupling via the soil moisture-boundary layer interaction. *Journal of Hydrometeorology*, 12(5), 766–786. <https://doi.org/10.1175/JHM-D-10-05014.1>
- Schumacher, D. L., Seneviratne, S. I., Singh, J., Hauser, M., Fischer, E. M., & Wild, M. (2024). Exacerbated summer European warming not captured by climate models neglecting long-term aerosol changes. *Communications Earth & Environment*, 5(1), 182. <https://doi.org/10.1038/s43247-024-01332-8>
- Seneviratne, S. I., & Koster, R. D. (2012). A revised framework for analyzing soil moisture memory in climate data: Derivation and interpretation. *Journal of Hydrometeorology*, 13(1), 404–412. <https://doi.org/10.1175/JHM-D-11-044.1>
- Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., et al. (2021). Weather and climate extreme events in a changing climate. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working group I to the Sixth assessment report of the Intergovernmental panel on climate change* (pp. 1513–1766). Cambridge University Press. <https://doi.org/10.1017/9781009157896.013>
- Soares, P. M. M., & Cardoso, R. M. (2018). A simple method to assess the added value using high-resolution climate distributions: Application to the EURO-CORDEX daily precipitation. *International Journal of Climatology*, 38(3), 1484–1498. <https://doi.org/10.1002/joc.5261>
- Soares, P. M. M., Cardoso, R. M., Miranda, P. M. A., de Medeiros, J., Belo-Pereira, M., & Espírito-Santo, F. (2012). WRF high resolution dynamical downscaling of ERA-Interim for Portugal. *Climate Dynamics*, 39(9–10), 2497–2522. <https://doi.org/10.1007/s00382-012-1315-2>
- Soares, P. M. M., Careto, J. A. M., Cardoso, R. M., Goergen, K., Katragkou, E., Sobolowski, S., et al. (2022). The added value of km-scale simulations to describe temperature over complex orography: The CORDEX FPS-convection multi-model ensemble runs over the Alps. *Climate Dynamics*, 62(0123456789), 4491–4514. <https://doi.org/10.1007/s00382-022-06593-7>

- Soares, P. M. M., Careto, J. A. M., Cardoso, R. M., Goergen, K., & Trigo, R. M. (2019). Land-atmosphere coupling Regimes in a future climate in Africa: From model evaluation to projections based on CORDEX-Africa. *Journal of Geophysical Research: Atmospheres*, 124(21), 11118–11142. <https://doi.org/10.1029/2018JD029473>
- Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. M., & Santos, J. A. (2018). European temperature responses to blocking and ridge regional patterns. *Climate Dynamics*, 50(1–2), 457–477. <https://doi.org/10.1007/s00382-017-3620-2>
- Taylor, C. M., De Jeu, R. A. M., Guichard, F., Harris, P. P., & Dorigo, W. A. (2012). Afternoon rain more likely over drier soils. *Nature*, 489(7416), 423–426. <https://doi.org/10.1038/nature11377>
- Taylor, C. M., Parker, D. J., & Harris, P. P. (2007). An observational case study of mesoscale atmospheric circulations induced by soil moisture. *Geophysical Research Letters*, 34(15), 2–7. <https://doi.org/10.1029/2007GL030572>
- Tebaldi, C., Arblaster, J. M., & Knutti, R. (2011). Mapping model agreement on future climate projections. *Geophysical Research Letters*, 38(November), 1–5. <https://doi.org/10.1029/2011GL049863>
- Thiemig, V., Gomes, G. N., Sköien, J. O., Ziese, M., Rauthe-Schöch, A., Rustemeier, E., et al. (2022). EMO-5: A high-resolution multi-variable gridded meteorological dataset for Europe. *Earth System Science Data*, 14(7), 3249–3272. <https://doi.org/10.5194/essd-14-3249-2022>
- Van Oldenborgh, G. J., Wehner, M. F., Vautard, R., Otto, F. E. L., Seneviratne, S. I., Stott, P. A., et al. (2022). Attributing and projecting heatwaves is hard: We can do better. *Earth's future*. John Wiley and Sons Inc. <https://doi.org/10.1029/2021EF002271>
- Vautard, R., Cattiaux, J., Hap  , T., Singh, J., Bonnet, R., Cassou, C., et al. (2023). Heat extremes in western Europe are increasing faster than simulated due to missed atmospheric circulation trends to cite this version: HAL id: Hal-03937057 heat extremes in western Europe are increasing faster than simulated due to missed atmospheric c.
- Vautard, R., Kadyrov, N., Iles, C., Boberg, F., Buonomo, E., B  low, K., et al. (2021). Evaluation of the large EURO-CORDEX regional climate model ensemble. *Journal of Geophysical Research: Atmospheres*, 126(17). <https://doi.org/10.1029/2019JD032344>
- Warrach-Sagi, K., Ingwersen, J., Schwitalla, T., Troost, C., Aurbacher, J., Jach, L., et al. (2022). Noah-MP with the generic crop growth model gecros in the WRF model: Effects of dynamic crop growth on land-atmosphere interaction. *Journal of Geophysical Research: Atmospheres*, 127(14). <https://doi.org/10.1029/2022JD036518>
- Wilks, D. S. (2006). In R. Dmowska, D. Hartmann, & T. Rossby (Eds.), *Statistical methods in the atmospheric sciences* (2nd ed.). Elsevier.
- Wilks, D. S. (2016). “The stippling shows statistically significant grid points”: How research results are routinely overstated and overinterpreted, and what to do about it. *Bulletin of the American Meteorological Society*, 97, 2263–2273. <https://doi.org/10.1175/BAMS-D-15-00267.1>

References From the Supporting Information

- Fantini, A. (2019). Climate change impact on flood hazard over Italy.
- Isotta, F. A., Frei, C., Weigluni, V., Per  c Tadi  , M., Lass  gues, P., Rudolf, B., et al. (2014). The climate of daily precipitation in the Alps: Development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. *International Journal of Climatology*, 34(5), 1657–1675. <https://doi.org/10.1002/joc.3794>
- Quintana-Segui, P., Turco, M., Herrera, S., & Miguez-Macho, G. (2017). Validation of a new SAFRAN-based gridded precipitation product for Spain and comparisons to Spain02 and ERA-Interim. *Hydrology and Earth System Sciences*, 21(4), 2187–2201. <https://doi.org/10.5194/hess-21-2187-2017>
- Rauthe, M., Steiner, H., Riediger, U., Mazurkiewicz, A., & Gratzki, A. (2013). A Central European precipitation climatology - Part I: Generation and validation of a high-resolution gridded daily data set (HYRAS). *Meteorologische Zeitschrift*, 22(3), 235–256. <https://doi.org/10.1127/0941-2948/2013/0436>