SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Sensitivity of regional climate models to improved soil thermo-hydrodynamics and land-air interactions: impacts on future climate and renewable energy resources over the EURO CORDEX domain
Computer Project Account:	spesgarc
Start Year - End Year :	2023 - 2025
Principal Investigator(s)	Elena García Bustamante
Affiliation/Address:	CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas)
Other Researchers (Name/Affiliation):	J. Fidel González Rouco, Jorge Navarro Montesinos (CIEMAT), Elena García Bustamante (CIEMAT), Félix García-Pereira (IGEO), Cristina Vegas-Cañas (IGEO), Nagore Meabe (IGEO), Sara Madera Sánchez (CIEMAT), Luana Cardoso (University of Lisbon)

Summary of project objectives

The project main objective is to perform regional simulations at very high spatial resolution with a regional climate model (RCM, WRF) and it is a combined effort together with another special project (*spesgonz*) from CIEMAT. Together with them, the objective is to achieve a refined version of the regional simulations over the EURO CORDEX domain by incorporating the external climatic forcings to the regional model and by increasing the realism of the soil component in high resolution simulations. The latter implies, among other expected benefits, augmented consistency of the RCM simulations with respect to the driving ESM model (Max-Planck). We will provide multi-decadal historical and scenario CP-RCM simulations over the EURO-CORDEX domain based on the optimal recalibrated WRF configuration. A smaller region of complex terrain (Central System) within the Iberian Peninsula is selected due to its availability of observational data, to generate convection permitting RCM (CP-RCM) simulations with the aim of testing the ability of the model to resolve the atmospheric physics at convective scales making use of convection permitting schemes. Therefore, the main objectives within the present project imply a pool of sensitivity experiments of those parametrizations that remain active when the cumulus scheme is muted (convection permitting scheme) in shorter and smaller domain within the Iberian Peninsula.

Summary of problems encountered

We have performed multiple modifications of the raw code of the WRF model version we are using, such us the inclusion of 4D files for the aerosol depth to include the stratospheric and tropospheric aerosol forcings in our simulations. Our group is the first within the community introducing such changes and we have faced different difficulties at this regard.

Additionally, we have found inconsistencies between our lake mask and the land-sea lake mask that is being used by some members of the LUCAS CORDEX community so we have detected anomalous temperature surface temperature signals that forced the community teams to rerun some of our model simulations. Differences can be found in Figure 1 of this report.

During this year we have faced several difficulties mostly related to 1) the amount of storage needed for the heavy outputs from the RCM simulations considering their length the very high spatial resolution and the resulting amount of fields and variables simulated, which ultimately points to a need of longer/larger storing capacity for the outputs of our simulations, 2) the subsequent download of the simulated fields to our institutional servers and 3) difficulties related to the technical part that seeks improving the RCM code standards to allow for an innovative approach, mainly connected to the management of databases that feed our running system. Nonetheless, it is worth mentioning that our simulations have been running mainly on a twin account connected with this project, due to a mislabelling in our scripts. However, by the end of the year, the full amount of allocated space for this project is planned to be used with the progress of the simulations planned.

Experience with the Special Project framework

Everything has been smooth, doubts solved almost instantly, help available when needed, solutions of potential problems found without delay. Overall, the administrative part has been a real pleasure.

Summary of results

This special project is part of a common effort among several institutions sharing research targets in regional simulations. Therefore, the use of the accounts is designed through the year jointly and the usage of the special project accounts in shared. Here we reflect the final report of the project assigned to this account, which is common to the special project *spesgonz* that runs for another year. Our plan is to continue with that project for which we will need the maximum allowed capacity to

perform the simulations scheduled. The report is essentially common to the two special project accounts (*spesgonz* and *spesgarc*).

We have launched experiments related to a sensitivity analysis to the inclusion of individual forcings in regional simulations for the historical period. The experiments with individual forcings driven by reanalysis data. They incorporate annual variations of Greenhouse Gases (GHGs), Land ... Land Cover chan... ... stratospheric aerosols (AER + ... Total Solar Irr... ...en completed and are currently ...a...sis.

...h... objective is to ... ... illustrate the par... ...c aerosol regional simulations, ... a moderate im... ...anic eruptions (e.g., Pinatubo, ...se individual 1... ...ponse in specific periods and ...s, we are conc... ...al and regional-scale impacts. ...time is required to ...comprehensively estimate the individual and combined influence of these forcings. Nevertheless, preliminary results already suggest distinct global *vs.* regional features of these impacts over the study domain.

ol 1991-abr nwl:0 Extinction aerosol 199 abr nwl:9
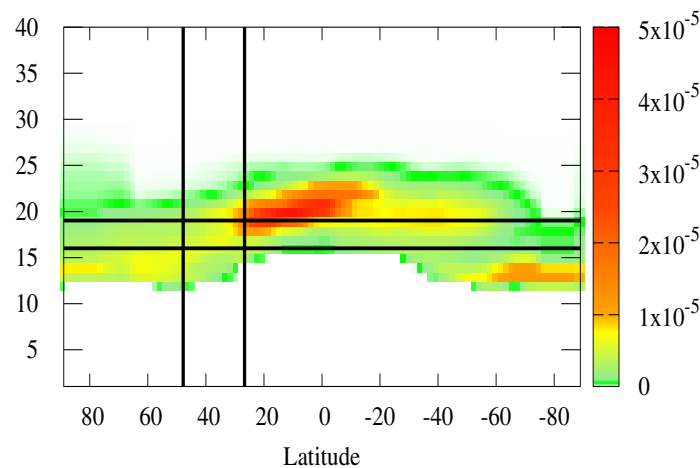
ol 1991-oct nwl:0

Fig. 1. Shortwave extinction coefficient as a function of latitude and altitude for October 1991 in the simulation including stratospheric aerosols within the visible spectral band.

lat:47.5
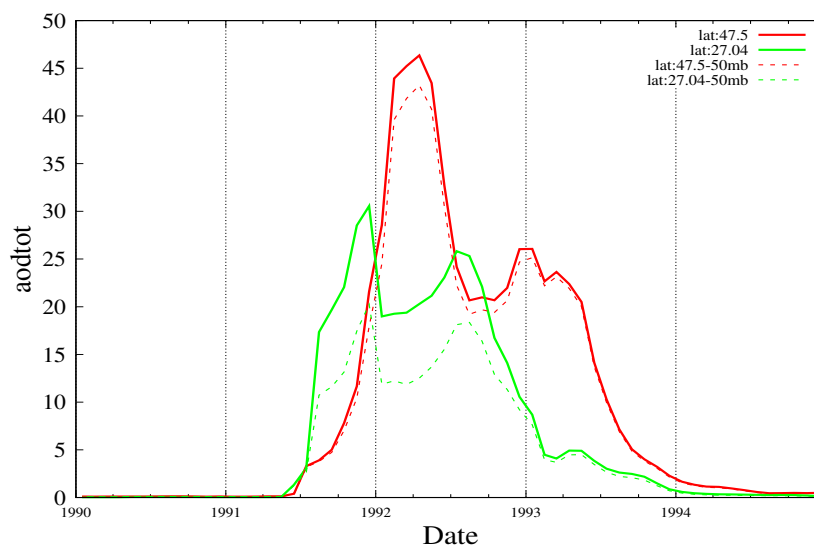lat:27.04
lat:47.5-50mb
lat:27.04-50mb

Fig. 2. Temporal evolution of Aerosol Optical Depth (AOD) integrated over all altitudes and spectral bands of the model. Values are shown in red for latitude 47.5ºN (upper boundary of the WRF simulation domain) and in green for latitude 27.0º

In Figure 3 we show the three nested model domains of the WRF model with horizontal resolutions of 9 km, 3 km, and 1 km used in a 30-year experiment focusing on the eastern sector of the Iberian Peninsula Climate System. In this area, an initial compilation of precipitation data was carried out for both mountainous locations and, for comparison, lowland sites (symbols shown in Figure 9). The model configuration followed the reference setup described in Table B1. The analysis compared the occurrence and magnitude of simulated precipitation—both annually and seasonally—with observations, selecting the grid point closest to each observational station (Greciano-Zamorano, 2023).
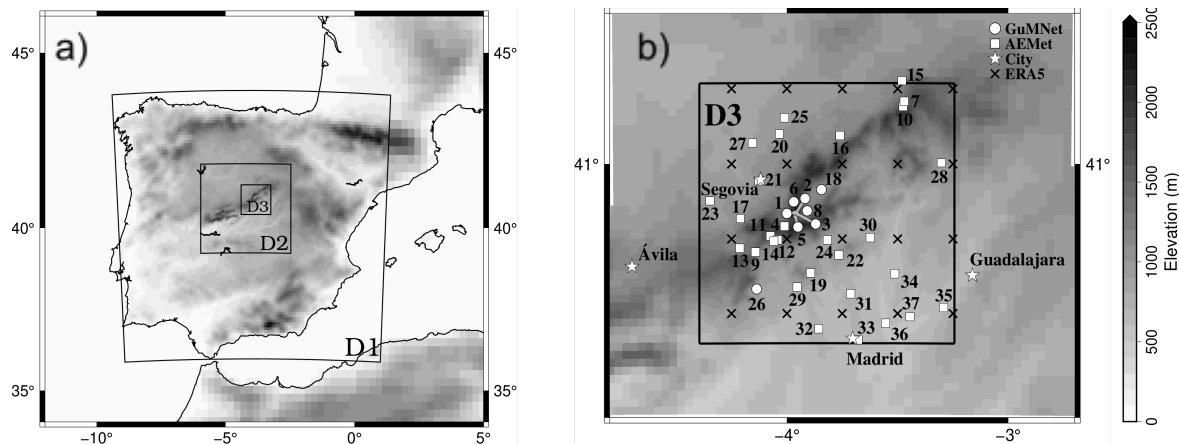

Figure 3. Configuration of the three WRF domains and distribution of the available observational stations used in the study by Greciano-Zamorano (2023a,b). a) WRF simulation domains D1 to D3. **b)** Zoom into domain D3, showing the locations of GuMNet stations (circles) and AEMET stations (squares), ERA5 grid points within domain D3 (crosses), and reference cities (stars). Grey shading represents terrain orography at ERA5 resolution outside the WRF domains, which increases in detail across the nested domains as they focus on the Sierra de Guadarrama region.

The analyses in this part indicated that, in general, all simulations overestimate the probability of precipitation occurrence. The latter can be appreciated in Figure 4. We have observed that model outputs were comparable to observations when only days with appreciable observed precipitation were considered; however, the model frequently produced wet days that were recorded as dry in the observational data. The number of simulated wet days tended to increase with horizontal resolution. In addition, WRF simulations exhibited a positive bias in total precipitation that also increased with resolution. In this configuration, convection was not explicitly resolved but was instead parameterized.
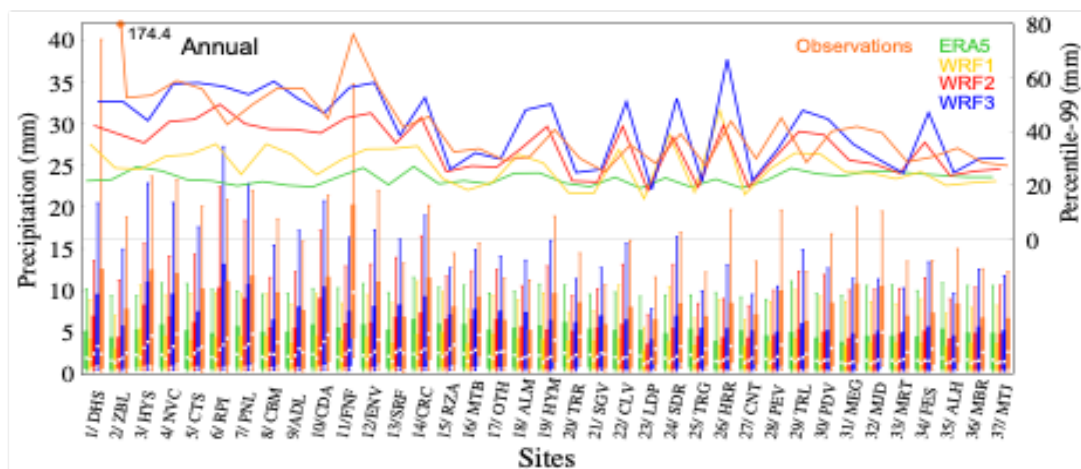

Figure 4. Top: box plots of the daily appreciable (> 0.2 mm) precipitation of the three resolutions of WRF, ERA5 and the observations at each station. WRF and ERA5 data has been co-located for each observational site, as well as temporally masked to data existence. On each box plot: the bottom whisker represents the percentile-10; the lowest part of the box shows the first quartile; the highest part of the box shows the third quartile; the top whisker shows 90-percentile and the lines above show the 99-percentile (note the different axis). Median is represented with a white dot

inside the box. Bottom: analogous representation for the seasonal assessment, focusing on WRF2, WRF3 and observations.

...ct, a ar, sensitivity experiments were conducted by modifying the reference configuration to explicitly resolve convection using a convection-permitting scheme (CPS), along with changes in the model's microphysics and cumulus parameterizations. The aim was to assess whether employing a CPS configuration at 1 km resolution (Figure 3; WRF3) could yield a more realistic simulation of precipitation. A comparative analysis was carried out between a reference simulation using the standard configuration previously adopted in earlier project and six additional simulations that implemented different combinations of cumulus and microphysics parameterizations (Table 1).

	PARAMETERIZATION					
	WRF1		**WRF2**		**WRF3**	
	Microphysics	Cumulus	Microphysics	Cumulus	Microphysics	Cumulus
Reference (Ref)	Thompson (Thompson et al., 2008)	New Tiedke (Zhang et al., 2017)	Thompson (Thompson et al., 2008)	New Tiedke (Zhang et al., 2017)	Thompson (Thompson et al., 2008)	New Tiedke (Zhang et al., 2017)
Simulation 1 (S1)	NSSL2 (Mansell et al., 2010)	New Tiedke (Zhang et al., 2017)	NSSL2 (Mansell et al., 2010)	New Tiedke (Zhang et al., 2017)	NSSL2 (Mansell et al., 2010)	New Tiedke (Zhang et al., 2017)
Simulation 2 (S2)	Thompson (Thompson et al., 2008)	Kain-Fritsch (Kain, 2004)	Thompson (Thompson et al., 2008)	Kain-Fritsch (Kain, 2004)	Thompson (Thompson et al., 2008)	Kain-Fritsch (Kain, 2004)
Simulation 3 (S3)	Thompson (Thompson et al., 2008)	Grell-Freitas (Grell et al., 2014)	Thompson (Thompson et al., 2008)	Grell-Freitas (Grell et al., 2014)	Thompson (Thompson et al., 2008)	Grell-Freitas (Grell et al., 2014)
Simulation 4 (S4)	Thompson (Thompson et al., 2008)	New Tiedke (Zhang et al., 2017)	Thompson (Thompson et al., 2008)	New Tiedke (Zhang et al., 2017)	Thompson (Thompson et al., 2008)	-
Simulation 5 (S5)	Thompson (Thompson et al., 2008)	Kain-Fritsch (Kain, 2004)	Thompson (Thompson et al., 2008)	Kain-Fritsch (Kain, 2004)	Thompson (Thompson et al., 2008)	-
Simulation 6 (S6)	Thompson (Thompson et al., 2008)	Grell-Freitas (Grell et al., 2014)	Thompson (Thompson et al., 2008)	Grell-Freitas (Grell et al., 2014)	Thompson (Thompson et al., 2008)	-

Table 1. Microphysics and cumulus parameterization configurations for domains D1 (WRF1), D2 (WRF2), and D3 (WRF3) (see Figure 9) in the reference simulation and the six sensitivity experiment simulations for the year 2009. Experiment S1 modifies the microphysics parameterization across all domains. Experiments S2 and S3 introduce changes in the cumulus parameterizations. Experiments S4 to S6 disable cumulus parameterization in the innermost domain (D3), allowing convection to develop explicitly.
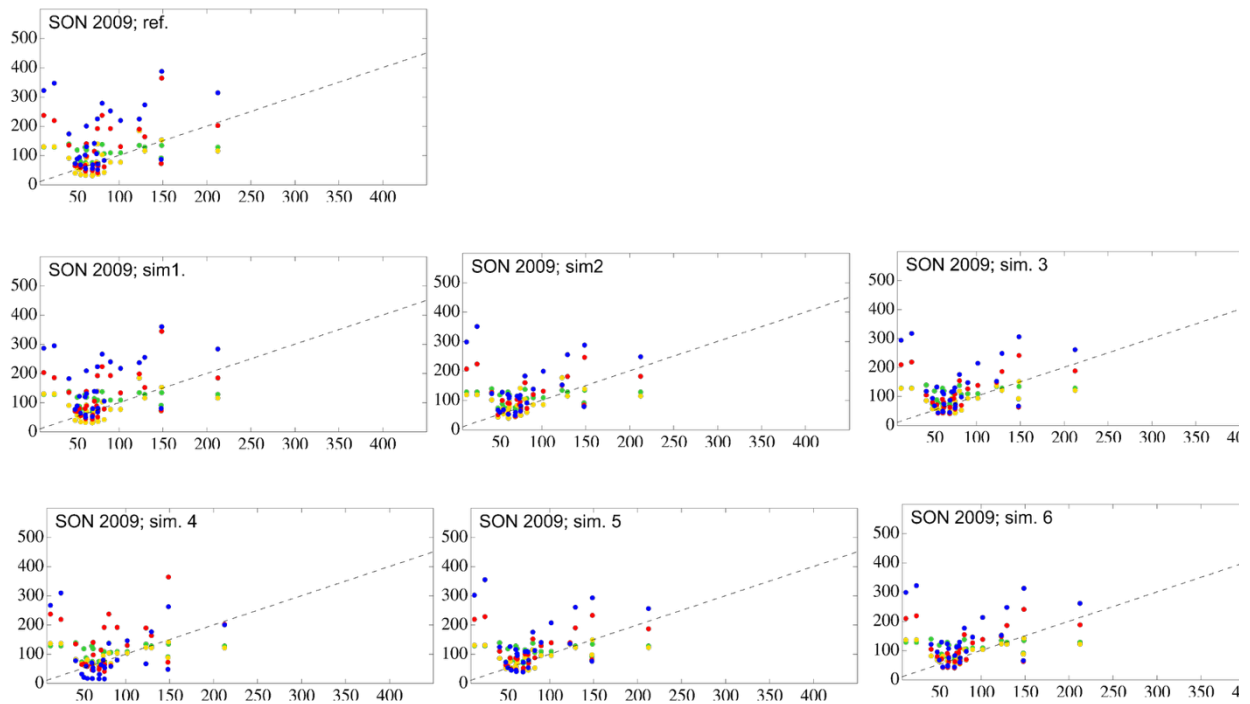
Figure 5. Comparison between observed and simulated mean of seasonal accumulated precipitations by WRF and ERA5 within the D3 domain. Big coloured circles represent appreciable precipitation during the time of data availability for each site (unmasked data). The numbers labeled in the top panel correspond to stations in Table 1.

These simulations focused on repeatedly modelling the year 2009 in order to isolate the sensitivity of precipitation output to the selected parameterizations. The modifications described in Table 1 were applied across the three spatial resolutions (9 km, 3 km, and 1 km) and domains previously used in related studies (Greciano-Zamorano, 2023). For this analysis, only the area enclosed by domain D3 in Figure 3 (Sierra de Guadarrama) was considered, along with the observational stations available within this subregion (Figure 3b).

This study analyzes precipitation data from 37 meteorological stations located in the Sierra de Guadarrama and the adjacent lowlands in central Spain, encompassing an altitudinal range from approximately 600 to 2200 meters above sea level (masl). These observational datasets are compared with the ERA5 reanalysis and with outputs from the Weather Research and Forecasting (WRF) regional climate model at three horizontal resolutions—9 km, 3 km, and 1 km—for the period 1990–2019. The comparison aims to characterize the spatial distribution of precipitation in the region, evaluate the performance of ERA5, and assess the added value associated with increasing the horizontal resolution of WRF simulations in capturing observed precipitation patterns.

The sensitivity analysis results indicate that increasing WRF resolution from 9 km to 3 km improves the model's ability to reproduce observed precipitation. The 1 km resolution further enhances the spatial representation of precipitation distribution, particularly in complex terrain, although it tends to overestimate total precipitation amounts. An altitudinal gradient in precipitation is clearly detected, and it is most accurately simulated by the highest-resolution WRF configurations.

As before, precipitation occurrence exhibits the highest model–observation agreement when the analysis is restricted to observed wet days, indicating that the model successfully reproduces the days on which precipitation occurs in reality. Conversely, all model configurations tend to overestimate the number of wet days, independent of horizontal resolution and parametrization. These additional wet days are typically associated with low-intensity rainfall, yet they contribute to an overall overestimation of total precipitation, both on annual and seasonal timescales.

Among the tested configurations, WRF3 (1 km resolution) shows the largest positive bias in precipitation amounts at most sites. Nevertheless, both WRF3 and WRF2 (3 km resolution) demonstrate added value compared to lower-resolution configurations, particularly at high-altitude locations, where ERA5 and WRF1 (9 km resolution) tend to underestimate precipitation. This improvement is attributed to the enhanced representation of topography in higher-resolution simulations, which allows a better characterization of the orographic influence on precipitation. Consequently, WRF3 yields the most accurate spatial distribution of precipitation at high elevations, although it slightly overstates precipitation totals in these regions. This overestimation is likely related to the representation of convection within the WRF model, which is consistent across the three configurations used in this study. A more detailed investigation into the sensitivity of simulated precipitation to variations in cumulus parameterization schemes (e.g., Zhang and Wang, 2017) and convection-permitting configurations (e.g., Belušić et al., 2020) could provide further insight into the causes of this positive bias, particularly in high-altitude areas. The results related to the snow cover (WRF simulated snow cover for the different domains and resolutions represented in Figure 6) do not significantly change from those found for the case of precipitation.
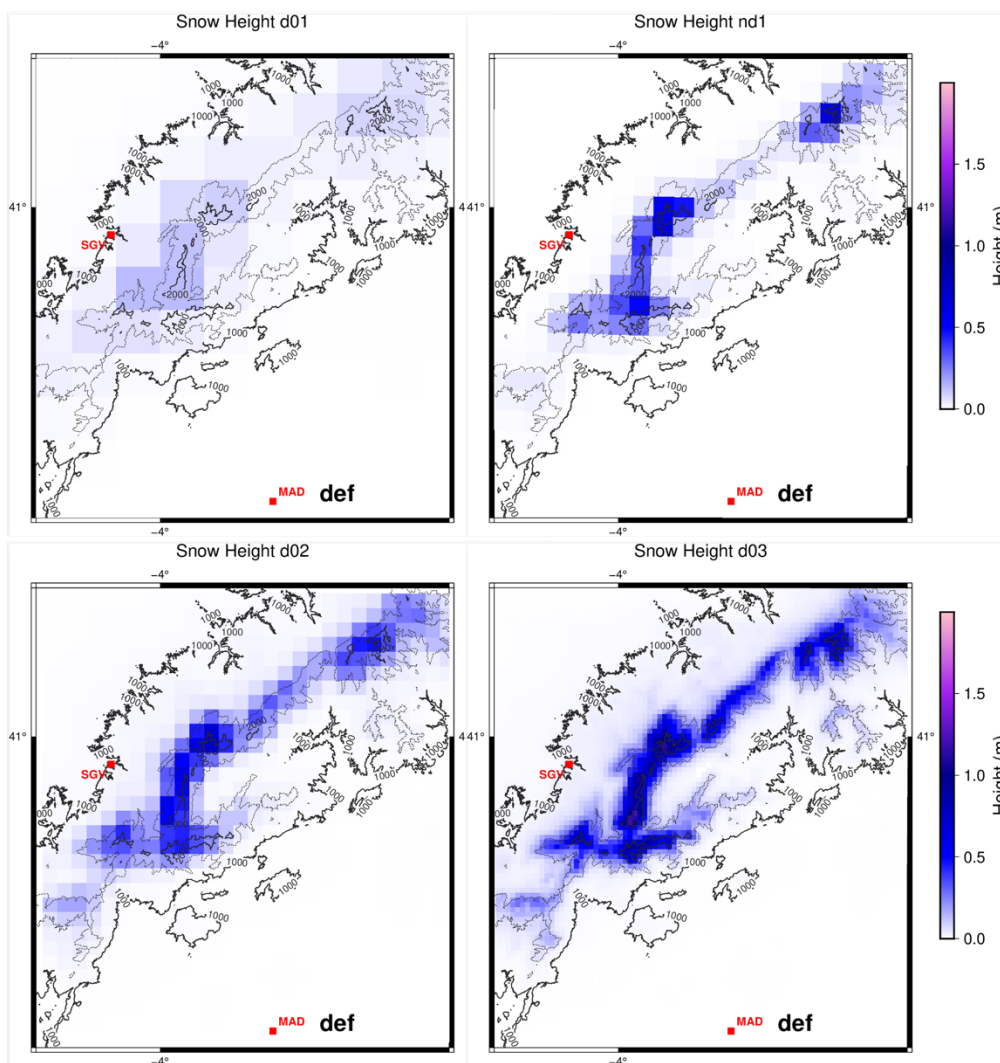

Figure 6. Snow cover at the different spatial resolutions as simulated by the WRF model in the smaller area of the Iberian Central System (Sierra de Guadarrama)

We have as well performed a 4 km simulation that will serve as the forthcoming 1 km simulation over the Central System in the Iberian Peninsula with an optimized configuration after the experiments we have commented about above. In this region an extended data base shown in Figure 6 together with the WRF domain is shown.
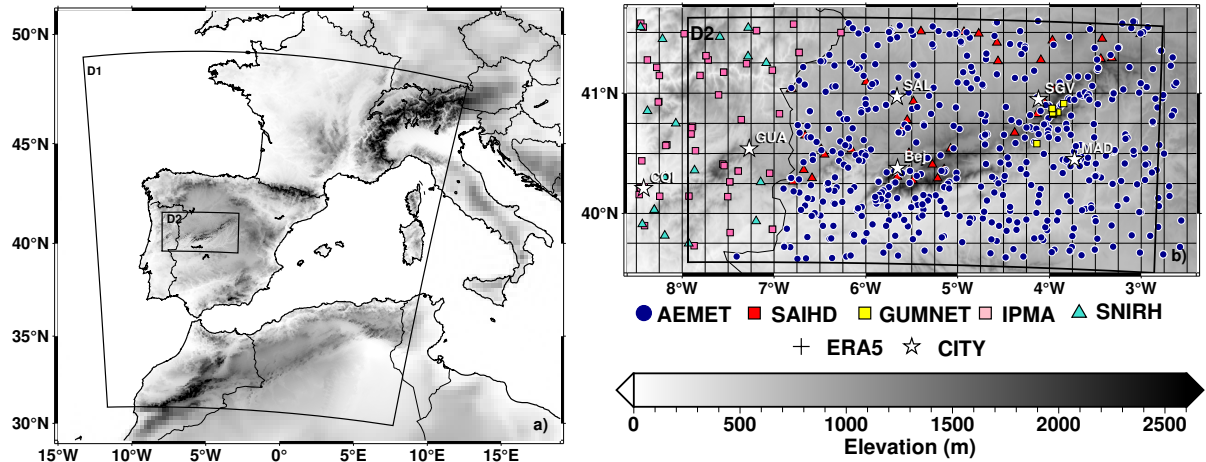

Figure 7. Configuration of the two Weather Research and Forecasting (WRF) domains of WRF´s simulation. Spatial distribution of observational sites within the smallest ND1 WRF domain including AEMET (red points), DUERO (blue triangles), GumNet (green squares), IPMA (black crosses) and ULisboa (yellow diamonds) observational sites. The white stars represent the nearest relevant cities which are Segovia (SGV), Madrid (MAD) and Salamanca (SAL) in Spain and Guarda (GUA) and Coimbra (COI) in Portugal. Grey shading depicts the orographic altitude.

It can be said that the simulated temperature as shown in Figure 7 evidences a climatological pattern spatial and altitude dependent.
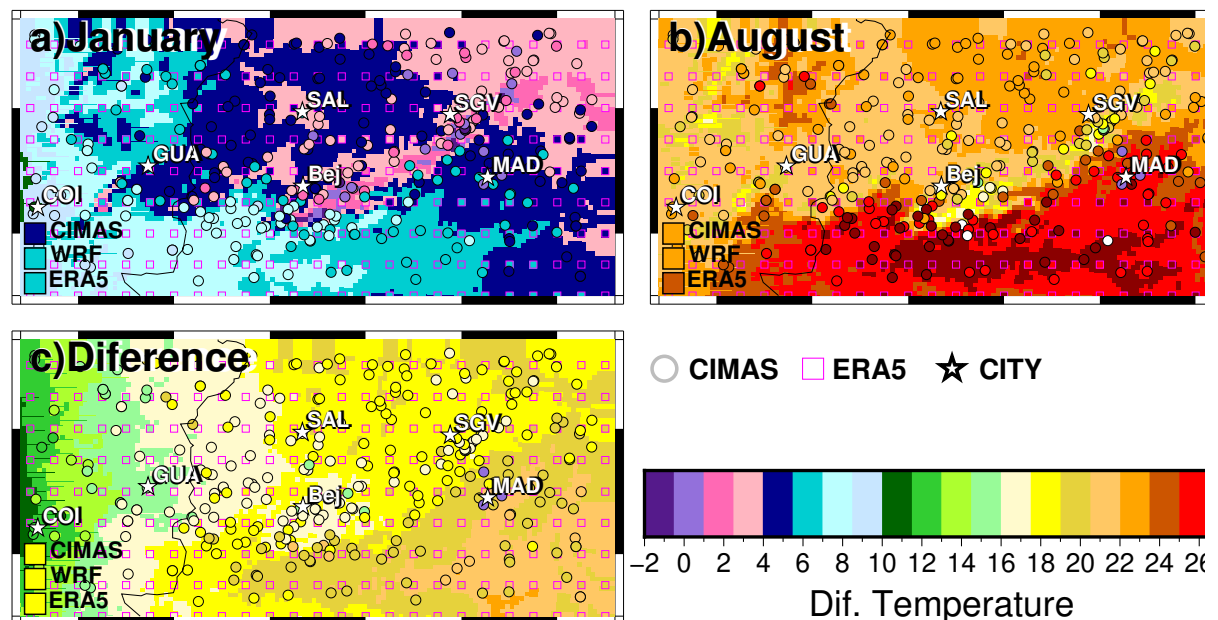

Figure 8. Mean temperature in the period 2010-2022 for (a) January, (b) August and (c) their difference over the Central System of the Iberian Peninsula. The circles represent the observational stations, the squares show ERA5 reanalysis and the shading depict WRF4 simulated temperature. The squares at the left bottom stand for the regional mean temperature of the observational data (OBS) and the WRF data (WRF) inside the study domain.

Collaborations with other research groups directly linked to the project

The *SmileAtYou* project maintains regular collaboration with the IGEO-CSIC group led by J.F. González Rouco, with whom coordinated regional modeling efforts have been conducted historically. Stable collaborations are ongoing with the University of Lisbon (Instituto Dom Luiz, Rita Cardoso and Luana Santos Cardoso), the regional WRF modeling department at NCAR (USA, J. Dudhia), and the CORDEX community, particularly within the Flagship Pilot Study LUCAS (Dr. Rechid et al.).

These collaborations are instrumental in the technical implementation of code modifications to WRF, as many of the changes applied in our simulations are novel to the scientific community. The joint analysis of the impacts, enriched by the collective expertise of these institutions—many of whose members are part of this project—takes place in nearly weekly discussions.

Collaborations with companies or socio-economic sectors directly linked to the project

AEMET (Climate Evaluation and Modeling Area) collaborates within the CIMAs project (Climate Research Initiative for Iberian Mountain Areas), focusing on high-resolution climate simulations in complex orographic regions. This collaboration enables in-depth analysis of land surface components and addresses challenges in high-resolution convection-permitting simulations.

In parallel, collaboration with CSIC's PTI Clima in a Climate Services initiative alongside AEMET fosters idea exchange in a regional high-resolution context. These interactions are particularly valuable, given that future developments under *SmileAtYou* could feasibly support the provision of climate services for the Iberian Peninsula based on the very high-resolution simulations produced, which would be a highly desirable objective for the project's continuation.

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Future plans

Connected with the special project *spesgonz*, we plan to launch ALL-Forcing reanalysis and CMIP6 driven experiments. Fully forced WRF simulations (GHGs, AER+VOL, LULCC, SOL) during the historical period (1990-2020) will be carried out using first in ERA5 reanalysis and finally with *MPI*-ESM$_{deep}$ driving fields, our own refine version of the parent Earth System Model providing initial and boundary conditions to the RCM simulations. This implies a data flush to our collaborators from the *spesgarc* project at the CIEMAT. The first of the two runs will be the reference fully forced

simulation driven by closer-to-reality fields (reanalysis) and the second constitutes the first CMIP6 downscaling experiment with a deeper soil module and will be the basis for the future scenario projections and for the following analysis about the soil physics options. The viability of running *MPI-ESM$_{deep}$* outputs downscaled with WRF has already been ensured during previous experiments and projects.

One main objective next year is to launch the refined 1km CP-RCM simulation, probably reaching the 200 m spatial resolution region for some specific regions within the smaller domain over the Iberian Peninsula located over the Central System (see results below) to explore the added value of the convection permitting schemes over the mountainous area mentioned. A parent 4km has already been performed in collaboration with the special project *spesgonz*. Previously, the group has applied effort in experimenting with increasing resolution and sensitivity to specific boundary layer physics and microphysics parametrizations over a smaller subdomain over the eastern bound of the Central System in Iberia (Sierra de Guadarrama) is to allow for an insight in the potential of the model to capture the mean and climate and variability at different timescales. Some results are shown below.

Finally, we plan to perform a series of regional simulations testing structural improvements to the land surface scheme that might lead to a more realistic sub-surface physics and the corresponding land-air interactions in WRF simulations with full forcing over the historical period.