SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2024
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
Principal Investigator(s):	Elena García Bustamante
Affiliation:	CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	J. Fidel González-Rouco (Universidad Complutense de Madrid, UCM; Jorge Navarro Montesinos (CIEMAT), Félix Garcia-Pereira (UCM)
Start date of the project:	01/01/2023
Expected end date:	31/12/2025

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	15.500.000	15.500.000	15.500.000	4.074.024
Data storage capacity	(Gbytes)	350.000	50.000	350.000	10.000

Summary of project objectives (10 lines max)

The general objective of this project is to challenge the realism of climate model responses because of improved soil components (depth, configuration, and physics) an RCM. We aim at exploring how sensitive the RCM (WRF) response is in past and future scenarios to changes in the soil physics paying special attention to critical areas in a consistent fashion as in the parent ESM realm; we will also assess the impact of incorporating external natural and anthropogenic forcings on long-term trends and extreme variability of key atmospheric and soil variables, as well as of solar-wind energy resources over the EURO CORDEX domain. This will be accomplished by performing historical and scenario high-resolution (~9 km) long (30 yr.) simulations (assumable with CPU resources) using the own WRF_{deep} model version, forced by the only CMIP6 model with a deep (~ 1.400 m) soil component to allow the hydro-thermodynamics to develop at all time scales including those relevant to incorporate the climate change signal. To our knowledge historical and scenario ESM-RCM downscaled simulations with consistently improved land model components are scarce.

Summary of problems encountered (10 lines max)

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.

Summary of plans for the continuation of the project (10 lines max)

Our project plan includes finalizing the set of SINGLE-forced WRF simulations over the EURO CORDEX domain followed by an ALL-forced simulation in the historical period, driven by the ERA5 reanalysis to be compared with an additional WRF simulation driven by the Max-Planck_{deep} version of the model (CMIP6) for the historical period, as well as for some future scenarios. This is planned in the attempt of evaluating an increase of the realism of the regional model simulations at 9 km . The former will constitute the basis for a new set of experiments where we will increase the spatial resolution up to ~1km over the complex mountainous central Iberian Peninsula region that will allow us an investigation of the physical processes connected to convective phenomena at the local scale, especially those processes related to the land-air interactions involved, which ultimately are derived from a more consistent soil component at the global scale.

In collaboration with the Special Project ("*SmileAtYou*", Universidad Complutense de Madrid, PI J. Fidel González Rouco, project account: *spesgonz*) some of these very high-resolution simulations are already being tested.

List of publications/reports from the project with complete references

- "Evaluación de la variabilidad de la precipitación en la Sierra de Guadarrama - Evaluation of the precipitation variability over the Sierra de Guadarrama". Master Thesis of Emilio Greciano Zamorano, Universidad Complutense de Madrid, dirigido por J. Fidel González Rouco, Elena García Bustamante y Jorge Navarro Montesinos. Febrero 2023.
- "Análisis del viento superficial en Europa: variabilidad y tendencias - Analysis of surface wind in Europe: variability and trends". Master Thesis of Celia Pérez Souto, Universidad Complutense de Madrid, dirigido por J. Fidel González Rouco, Elena García Bustamante y Jorge Navarro Montesinos. Septiembre 2023.
- Steinert N., F. J. Cuesta-Valero, F. García-Pereira, P. de Vrese, C. Melo Aguilar, E. García-Bustamante, J. Jungclaus and J. F. González-Rouco: "Underestimated land heat uptake alters the global energy distribution in CMIP6 climate models". Geophys. Res. Lett. (in press).
- García-Pereira F., J. F. González-Rouco, C. Melo-Aguilar, N. J. Steinert, E. García-Bustamante, P. de Vrese, J. Jungclaus, S. Lorenz, S. Hagemann, F. J. Cuesta-Valero, A. García-García and H. Beltrami: "First comprehensive assessment of industrial era land heat uptake from multiple sources". Earth System Dyn., **15**, 547-564, DOI: 10.5194/esd-15-547-2024
- García-Pereira F., J. F. González-Rouco, T. Schmid, C. Melo-Aguilar, C. Vegas-Cañas, N. J. Steinert, P. J. Roldán-Gómez, F. J. Cuesta-Valero, A. García-García, H. Beltrami, and P. de Vrese: "Thermodynamic and hydrological drivers of the subsurface thermal regime in Central Spain". Soil, **10**, 1-21, DOI: 10.5194/soil-10-1-2024.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

During the first year, the team has been able of successfully install the WRF code at the ECMFWF and we have performed several tests to ensure that results accommodate well with what we would expect if simulations would be run at our own facilities.

We have additionally designed the experiments that include external radiative forcings (greenhouse gases, natural and anthropogenic plus natural aerosols as well as solar variability) and they have successfully run in some of the experiments or the simulation is about to finish in the rest. We show in Figure 1 the comparison of our WRF model simulations of the last 30 years forced with Land Use/Land Cover (LULC) annual changes in comparison with the simulations by similar simulations by our Flagship Pilot Study LUCAS CORDEX colleagues.

We have produced a WRF model version driven by an Earth System Model (ESM) with a deeper soil component (1.400 m and improved hydro-thermodynamics) and we are ready to run historical and future scenario simulations. The coupled historical WRF-Max-Planck$_{deep}$ model simulation is illustrated in Figure 2.

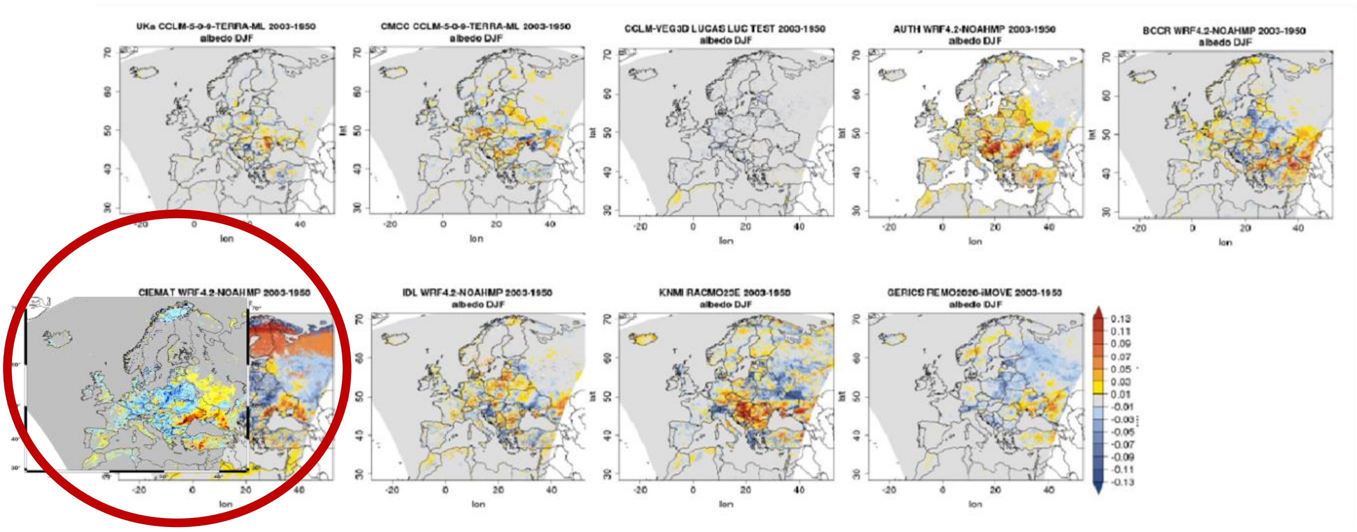

Figure 1. Average winter albedo for the period (2009-2020) simulated by the different regional models performed by the members of the LUCAS COREDX Flagship Pilot Study that incorporate LULC annual changes. The red circle shows our WRF simulation.

We have performed a first assessment of temperature variability at interannual and decadal timescales in Sierra de Guadarrama, a high mountain protected area of the Central System in the Iberian Peninsula based on 1 km (spatial resolution) WRF simulations. We have found that the regional simulation, as well as the ERA5 reanalysis, tend to underestimate the observational mean temperatures and anomalies at high-altitude stations. The results show that WRF provides a better performance than the reanalysis, as it shows smaller biases with respect to observational temperature anomalies. Finally, the study of temperature trends over the Sierra de Guadarrama and its surroundings for the period 2000–2018 shows a warming in the area, significantly pronounced in autumn. This is represented in Figure 3 of this report.

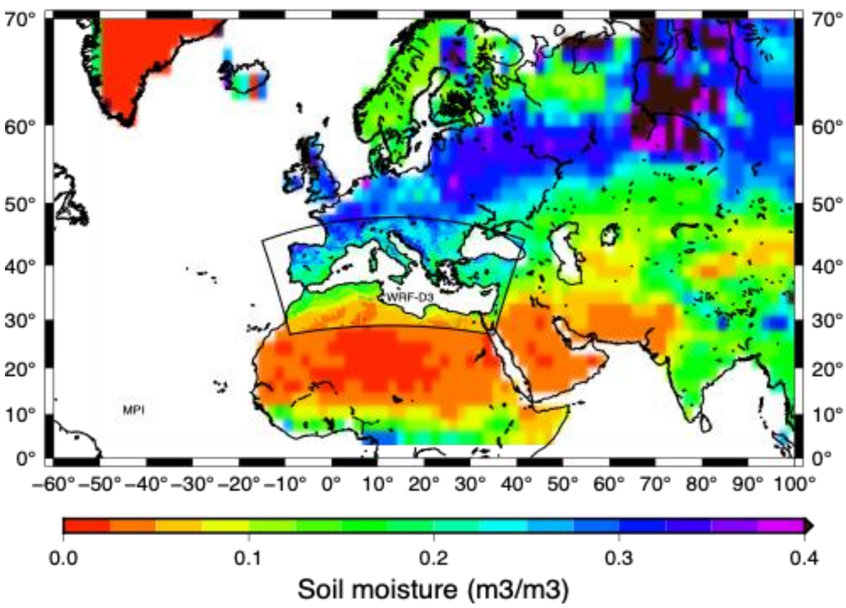

Figure 2. Average soil moisture for the period (2000-2010) for the EURO-CORDEX domain simulated by the coupled system Max-Planck$_{deep}$ – WRF.

We have also explored the variability of the precipitation over the Sierra de Guadarrama from our WRF - km scale simulation during the period 1990-2020. This study has been afforded in collaboration with J. Fidel Gonzalez Rouco (project account *spesgonz*). The comparison with observations and the ERA5 fields revealed the added value of the increasing resolution of WRF simulation in reproducing the observations. Results show that the increase in WRF resolution from 9 to 3 km produces a better representation of precipitation. The 1 km resolution represents better the distribution of precipitation, but overestimates total accumulations. Also, an altitudinal gradient of precipitation is observed and best simulated by the most accurate resolutions. This is represented in Figure 4 of the present report.

The latter calls for an exploration of the added value of very high spatial resolution simulations and we performed km-scale sensitivity simulations over the Sierra de Guadarrama to explore the adequacy of the microphysics and cumulus/convection parametrizations that better serve for the purpose of selecting the most suitable model set up to be run at very high resolution (1 km) within a smaller domain. The sensitivity experiments are described in Table 1, where we show the reference configuration and the combinations of microphysics and cumulus in the tested cases.

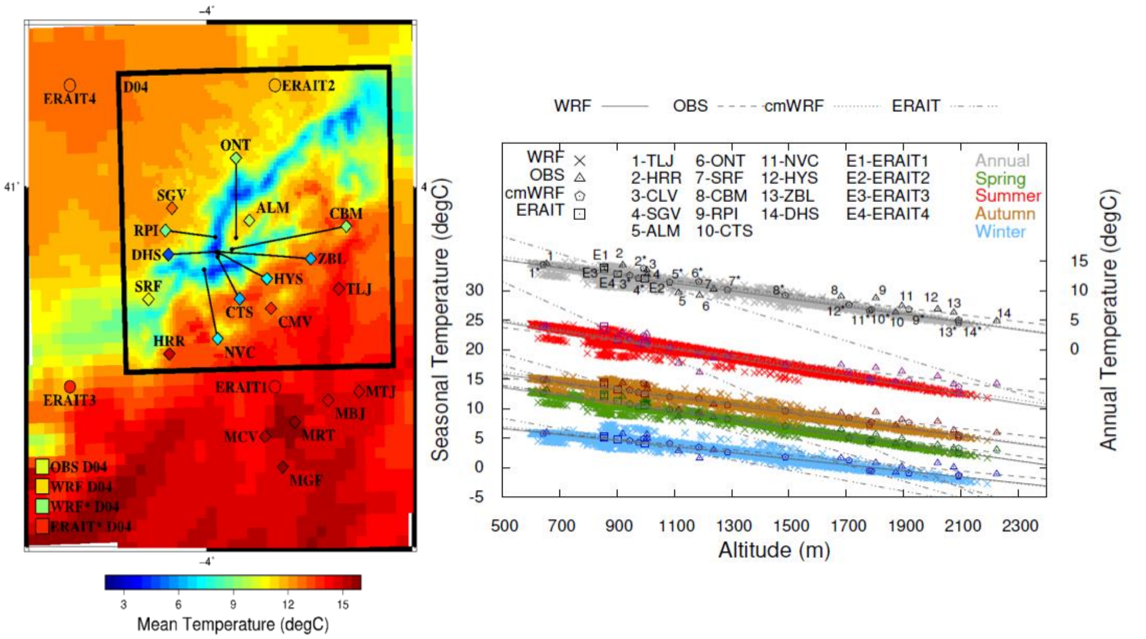

Figure 3. Left: Summer mean temperature in the period 2000–2018 for spring (a), summer (b), year (c), autumn (d), and winter (e) for the simulated and observed data: The shading represents the WFR simulated field, the diamonds indicate the observational stations, and the circles the ERA5 ones. The squares at the bottom left represent the regional averages for the OBS (observational stations), the WRF inside domain D4, the ERA5 inside domain D4, and the complete WRF domain D4 field. Right: Distribution of vertical temperature gradients of OBS, WRF, cmWRF (masked with obs), and ERAIT, represented by triangles, crosses, pentagons, and squares, respectively for the annual (black/grey), spring (green), summer (red), autumn (brown), and winter (blue) cases. A linear fit is shown for every dataset in a dashed line for the OBS, a continuous line for WRF, a dotted line for WRF, and a dot-dashed line for ERA5. All the fits show a significant relationship of temperature with altitude.

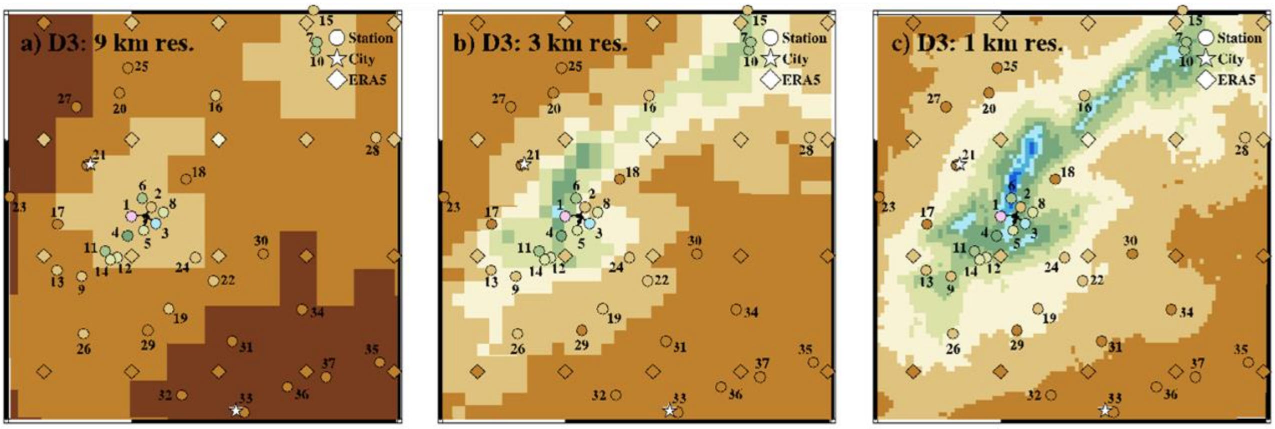

Figure 4. Annual mean of daily accumulated precipitation for the three resolutions of WRF (9 km, 3 km and 1 km), observations (circles) and ERA5 data (diamonds), over the D3 domain.

PARAMETERIZATIONS						
	WRF1		**WRF2**		**WRF3**	
	Microphysics	Cumulus	Microphysics	Cumulus	Microphysics	Cumulus
Reference	Thompson	New Tiedtke	Thompson	New Tiedtke	Thompson	New Tiedtke
Simulation 1	NSSL2	New Tiedtke	NSSL2	New Tiedtke	NSSL2	New Tiedtke
Simulation 2	Thompson	Kain-Fritsch	Thompson	Kain-Fritsch	Thompson	Kain-Fritsch
Simulation 3	Thompson	Grell-Freitas	Thompson	Grell-Freitas	Thompson	Grell-Freitas
Simulation 4	Thompson	New Tiedtke	Thompson	New Tiedtke	Thompson	-
Simulation 5	Thompson	Kain-Fritsch	Thompson	Kain-Fritsch	Thompson	-
Simulation 6	Thompson	Grell-Freitas	Thompson	Grell-Freitas	Thompson	-

Table 1. Sensitivity experiments designed to test the ability of different cumulus and microphysics parametrizations in the three nested domains reaching 1 km of horizontal resolution.

Results evidence that no combination of physics scheme outperforms and a tendency of the simulation precipitation to overestimate the number of wet days from observations has been detected, although to some extent Kain-Fritsch and Grell-Freitas parametrizations tend to overestimate in a less degree compared to New Tiedke cumulus parametrization. The latter is shown in Figures 5 and 6 where the percentage of wet days from the reference simulations and the variants explored and the total accumulated precipitation from observations and simulations are represented, respectively.

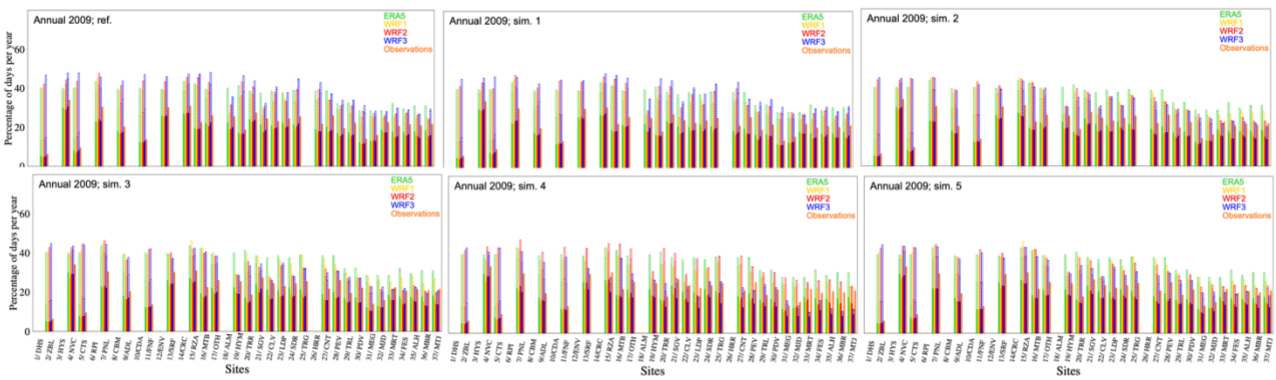

Figure 5. Percentage of wet days from the reference simulation and the set of sensitivity experiments with alternative microphysics and cumulus schemes calculated at three nested domains (9km for WRF1, 3 km for WRF2 and 1 km of horizontal resolution for WRF3) together with the same for the observational data set and the reanalysis ERA5 for comparison).

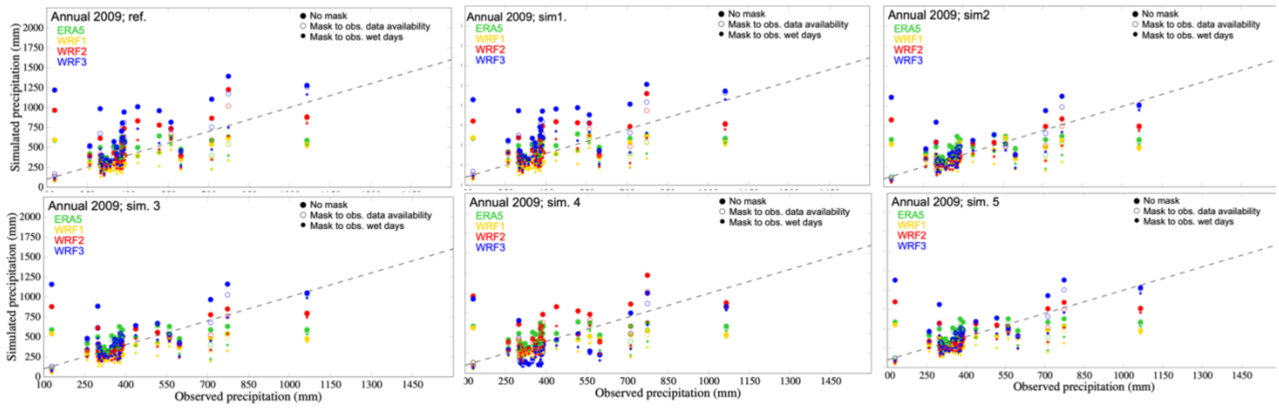

Figure 6. Dispersion diagram showing the precipitation amounts from the observations compared to that from the reference simulation and the set of sensitivity experiments with alternative microphysics and cumulus schemes calculated at three nested domains (9 km for WRF1, 3 km for WRF2 and 1 km of horizontal resolution for WRF3) together with the same for the observational data set and the reanalysis ERA5 for comparison).

We have significantly enlarged our knowledge about the configuration of the model (parametrizations set up) and the technical requirements that allow us to produce a more realistic WRF model version, including radiative forcings at the regional scale a deeper land module, allowing for a better distribution of soil temperature and moisture at the subsurface. The historical and production runs will be launched after summer.

As a result of our collaboration with the CORDEX community during these years it has been evidenced that our approach to increase the realism of the model is of interest to test the ability of the simulation to reproduce the observations in a context of very high resolution (~1km). Also, we have gained knowledge about how to reach the km scale information from our WRF model version, in collaboration with the *spesgonz* project, and we are exploring the added value of several convection permitting schemes with our refined model version. This part of the results and experiment is provided within the project progress report with totle “**S**ensitivity of regional **M**odels to **I**mproved **L**and-air interactions and **E**xternal forcings setup: **A**pproaching a "*seamless*" s**T**rategy to reduce s**Y**stematic biases in very high-res**O**lution climate sim**U**lations (***SmileAtYou***)“.

Our expectation within this is to produce a number of runs at very high spatial resolution that will increase the computational demand sharply during the next few months and the subsequent year.