REQUEST FOR A SPECIAL PROJECT 2024–2026

MEMBER STATE: SPAIN

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Project Title: **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***)

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** …………..	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2024	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2024**	**2025**	**2026**
High Performance Computing Facility	[SBU]	15.000,00	15.000,000	15.000,000
Accumulated data storage (total archive volume)[2]	[GB]	250,000	250,000	250,000

EWC resources required for project year:		**2024**	**2025**	**2026**
Number of vCPUs	[#]	10	20	20
Total memory	[GB]	350	350	350
Storage	[GB]	15	25	25
Number of vGPUs[3]	[#]	2	2	2

Continue overleaf.

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[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

Principal Investigator: Jesús Fidel González Rouco

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Extended abstract

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 5,000,000 SBU should be more detailed (3-5 pages).

Summary

Regional climate modelling (RCM) is a key tool for linking the global climate change to expected local impacts and therefore to design efficient pathways in the ecological and energy transition road. The complexity RCMs has increased with the inclusion of a progressively larger number of climate system components and processes with augmented level of realism. However, diverse sources of uncertainty still play a significant role in modulating the simulated regional climate variability. *SmileAtYou* grounds upon the need of augmenting the realism of the state-of-the-art high-resolution RCMs that compromises the reliability of present and future climate variability and change. Specific uncertainty remains in standard model set ups related to the radiative external drivers or to the processes within the land-surface models in RCMs, which preclude realism in simulations when attempting to estimate the occurrence and intensity of extreme climate extremes, having ultimately major implications for future climate assessments. The general objective of *SmileAtYou* is to progress in the understanding of simulated regional and local climate variability and change. Three partial objectives contribute to the above main purpose. On one hand, to investigate the sensitivity of present-day RCMs to the inclusion of a full set of natural and anthropogenic external climatic drivers and to the improvement of the realism of its land-surface component, with a refined representation of internal hydro-thermodynamical processes in historical and future scenario simulations. These goals pursue an additional common objective of achieving as much consistency as possible between the regional model and global parent model avoiding inconsistencies between the global to regional to local scales. On the other hand, we aim at achieving the kilometer-scale spatial resolution allowing the regional model to explicitly solve convective physical processes within a so called "*seamless*" modelling strategy, avoiding spatial scale gaps in the virtual reality of the RCM. *SmileAtYou* will produce a number of high-resolution (9 km) long (30-yr) historical and scenario WRF simulations over the Euro CORDEX domain to undertake the previous research questions. The first challenge will be addressed by including single yearly variations of greenhouse gases, natural and anthropogenic aerosols, solar and land use changes as well as all-forcing simulations during the historical period. The second objective will imply structural improvements of the WRF model land-surface scheme with refined more realistic soil physics in fully forced historical simulations. To this aim we will make use of both global (*MPI-ESM*$_{deep}$) and regional (*WRF*$_{deep}$) own model versions with a deeper soil performed in a consistent fashion between them. The last partial objective of implementing convection permitting RCM (CP-RCM) simulations is planned to start with a calibration of the parametrizations that remain active when the cumulus scheme is muted in shorter and smaller domain simulations to ensure the added value of the CP-RCM approach. Finally we will provide multi-decadal historical and scenario CP-RCM simulations over the EURO-CORDEX domain based on the optimal recalibrated WRF configuration. These endeavors have proven to be able of reducing systematic biases and of constraining uncertainty in regional climate simulations, especially impacting estimates of extreme variability.

PROJECT DESCRIPTION

Regional climate modelling is a key tool for linking the global climate change to expected local impacts and therefore to design efficient pathways in the ecological and energy transition road. Many knowledge areas and applied fields feed from the expert use of regional models such as evaluation and expected changes in extreme events (**García-Bustamante** et al., 2021b) in a climate change adaptation context, renewable energy resources evaluation and change (**Hahmann** et al., 2020), water reservoirs management, climate services, climate-ecosystem interplays, etc.

Regional climate models (RCMs) advance has essentially taken place within two fundamental directions: increased model resolution and greater complexity. Regarding the first and thanks to the enormous computational progress, state-of-the-art RCMs have reached the *convection-permitting* (CP) resolutions, ~1–3 km, at which cumulus convection can be explicitly represented (Giorgi and Prein, 2022) advancing thus in the so called "*seamless*" simulation strategy that allows reducing the uncertainty and biases that arise from the use of parametrizations. Also, RCMs, as Earth System models (ESMs), have evolved to realistically represent many of the processes involved in climate variability and climate change (IPCC 2021). The complexity of ESMs and RCMs has increased with the inclusion of a progressively larger number of climate system components and processes and with an increasing level of realism in representing them. Modelling of radiation, aerosol–cloud interactions, cryosphere, biogeochemical cycles, and other features has been improved or newly included through the most recent phases of the Coordinated Regional climate Downscaling Experiment (CORDEX; Gutowski et al. 2016; Solman et al. 2021) under the auspices of the World Climate Research Program's (WCRP). The scientific community has supported and fostered enormous progress in regional climate modelling (Drugé et al., 2019). In broad terms, the CORDEX community have fostered coordinated efforts to centralize attention on the added value of regional modelling as well as the associated uncertainties (e.g., Hasson et al., 2019, Solman et al., 2021).

Diverse sources of uncertainty play however a significant role in modulating the simulated climate variability at the regional scale and therefore they may compromise the reliability of future projections of regional climate information. Structural model uncertainty affects past and future representations of the climate system. It refers to aspects or processes within the model design that present deficiencies or are still not well understood. Among them critical fields that need enriched research and understanding are the cloud cover feedback representation that strongly affects the radiative balance (Inoue et al., 2021), the inclusion of own radiative external forcings as are implemented in ESMs (Jerez et al., 2018), the unresolved physical processes with typical spatio-temporal scales that need explicitly resolved convection, which it is well-known to produce a significant impact on the amount of simulated precipitation (e. g. Coppola et al., 2020) or the simplified subsurface hydro-thermodynamic processes by LSMs that, as in the case of the ESMs, has proven to have noteworthy implications in land-air interactions with increasing resolutions (Miralles et al., 2019). Therefore, state-of-the-art RCMs lack of realism claims for community experiments in the search of improving their simulated realism.

Justification and contribution to scientific knowledge: background and state-of-the-art.

Among the challenges defined by the regional model community CORDEX has recently defined a Science Plan, the inclusion of external radiative drivers is not yet an extended practice despite significant efforts in the community (Lawrence et al., 2019). How RCMs deal with the external, natural or anthropogenic forcings is indeed a considerable source of uncertainty of great relevance for the reliability of regional climate projections. The absence of complete sets of anthropogenic and natural external forcings at the regional scale implies an inconsistency with respect to the driving ESMs that can induce biases in regional long-term trends and extreme variability.

The inclusion of GHGs (CO_2, CH_4 and N_2O) is nowadays reasonably extended and the latest versions of WRF (Skamarock et al., 2019) already include transient changes of GHGs. Within our former project, *GReatModelS*, the WRF model set up already allowed incorporated varying CO_2 instead of the classical constant values or climatologies in the past, which is particularly important the larger the size of the RCM domains considered.

The Land Use and Climate Across Scales (LUCAS) initiative, is a Flagship Pilot Study endorsed by the CORDEX community devoted to improving the integration of LULC changes in RCMs so that the biogeophysical impacts of transient LULC can be evaluated and quantified at the local-to-regional-scale (Davin et al., 2020). One of the prominent contributions of this community is to translate the satellite-based products used by CMIP6 models (Hurtt et al., 2020) into land categories read by RCMs, and then perform comparative simulations with multiple RCMs to better understand the effects of varying LULC on the simulated regional climate variability. The *GreatModelS* team has actively participated and contributed with test WRF simulations that include these LULC varying maps. First results suggest a large inter-model spread due to LULC transient changes over Europe for the historical period indicating that uncertainties must be addressed prior the attribution of the role of LULC on regional climates (Davin et al., 2020).

The inclusion of aerosols as an external climatic driver in historical and future RCM simulations, either natural (mineral dust, and sea salt, tropospheric volcanic aerosols) or anthropogenic, is important to simulate multiple radiative interactions in the atmosphere. They are included in ESMs but are rarely accommodated in RCM simulations. Nevertheless, there are special modules that can be coupled to RCMs and that dynamically account for the role of these particles (Drugé et al., 2019). These modules are computationally very expensive. We have designed an intermediate complexity approach in the context of the expired *GReatModelS* project, based on the use of the Max Planck Institute Aerosol Climatology (MACv2, Kinne, 2019) monthly global maps for aerosol properties applied in an offline radiative transfer model to generate aerosol radiative effects that can be used in RCM models. We have explored how the aerosol properties can be inserted in the AOP parametrization (Ruiz-Arias et al., 2014) that runs coupled to the Rapid Radiative Transfer Model for climate models (RRTMG) short-wave radiation scheme in WRF. Such methodology permits realistic interplays of aerosol optical depth in the atmosphere with surface direct and diffuse irradiances saving lots of computational resources for long high-resolution model setups. One of the main burdens when it comes to include external forcings in RCMS is that their choice and implementation should be as coherent as possible to those in the driving global models (Ludwig et al., 2019). Regarding the volcanic and solar variations, that remain a challenge for the RCMs communities, the reckoning of total solar irradiances in regional simulations has been slightly explored in the literature, however the community calls for constraining the uncertainty in the observations and the model set up to implement the solar variations (Kushnir et al., 2019). The implementation of stratospheric volcanic aerosols is yet little extended within the regional modelling community.

The *SmileAtYou* team has already accomplished single forcing experiments, SINGLE-for hereafter (GHGs and LULC changes and explored the implementation of anthropogenic and natural tropospheric aerosols) in historical long simulations at 9 km over the Euro-Med domain driven by ERA5 Reanalysis fields (Herbasch et al., 2020). From that point on, the *SmileAtYou* team will continue with the implementation of solar (SOL) and volcanic (AER + VOL) forcings in SINGLE-for and all forcings (ALL-for) ERA5 and CMIP6 historical and scenario experiments with a consortium-developed MPI-ESM version (deeper land model, *MPI-ESMdeep*). The number of simulations available for the *SmileAtYou* analyses (se Section 3.1) would certainly endow an assessment of sensitivity of individual forcings and how the contribution of a complete set of external drivers impacts on long-term climatic trends, including extremes. At this respect, the team has already produced a high-resolution WRF simulation over the arid land of Northwestern Sahara dedicated to evaluating the ability of the unforced reanalysis driven model to reproduce the expected occurrence and intensity of extreme wind episodes (**García-Bustamante et al., 2021b**).

On the other hand, despite of their complexity, one example of how the representation of mechanisms and interactions involves diverse levels of simplification is modelling of subsurface physics in land surface models (LSMs) within climate models (both ESMs and RCMs). LSMs have experienced significant progress in the last generations of ESMs, including new and more realistic biogeophysical and biogeochemical processes (Bonan and Doney, 2018). LSM components contribute to ESMs and RCMs with the representation of the subsurface thermal and hydrological state that is important for a realistic land–climate interaction (Koster et al. 2006). The interaction between the land and the rest of the Earth’s climate system is characterized by surface and subsurface properties and processes. Since all these processes that shape a multidisciplinary context, are influenced by water, energy and momentum fluxes at the land surface, the realism in the simulation of subsurface thermo- and hydrodynamical processes is important in LSMs.

The SmileAtYou team have already evidenced the influence of including a deeper version of the LSM in the MPI-ESM (*MPI-ESMdeep,* **González-Rouco et al, 2021**) and more developed hydro-thermodynamical schemes in soil compared to the reference version included in CMIP6. Therefore, since substantial changes in the response to improvements in the LSM are noticeable at the regional scale (**Steinert et al 2021**), it seems pertinent to analyze the influence of improved hydro-thermodynamic processes in LSMs and land-air interactions at higher resolutions with the use of RCMs. *SmileAtYou* will focus on analyzing the influences of more realistic hydro-thermodynamical processes in LSMs and assessing their impacts on the simulated regional climate variability and change. The *SmileAtYou* team in collaboration with the running *SMILEME* project group has already successfully coupled *MPI-ESMdeep* to WRF*.*

The land surface component plays a fundamental role to shape the occurrence and intensity of climatic extremes (Berckmans et al., 2019) such as drought and heatwaves, a field where the *SmileAtYou* team has already demonstrated experience (**Jiménez et al., 2011**). A misrepresentation of the soil moisture-surface-temperature coupling may lead to considerable biases in air temperature and precipitation (Jacob et al., 2020). These processes are of special relevance if global/regional hot spots are considered such as semiarid or agricultural areas. **García-Bustamante et al., (2021a)** show how vulnerable are non-wood harvests to soil conditions and to changes in the hydrological cycle. The role of soil moisture is also relevant in mesoscale circulations (Hsu et al., 2017), which eventually affects the variability of wind and solar energy resources. Some studies suggest a considerable effect on the hub-height wind speed over dry soil and highlight the need of refined LSM physics to represent the land surface energy budget in RCMS (Xia et al., 2021).

How the RCM discretizes the soil layers and where the bottom layer is placed is essential for a realistic representation of the soil thermal and hydrodynamical processes. So far, the land components in RCMs are too shallow to allow an adequate propagation of the surface temperature changes or to permit a more suitable evolution of the hydrological subsurface processes or a correct storage of water and energy in the soil (Forrester and Maxwell, 2020). Usually, the depth of the LSMs included in RCMs is ~2m and the impact of the redistribution of water and heat through a deeper ground in the context of regional simulations remains marginally investigated (Flanagan et al., 2019). The *SmileAtYou* team has developeda new version of the WRF4 model that admits a much deeper than the standard ~2m Noah-MP module, consistent with the depth of the deeper soil component of the MPI-ESM (JSBACH), and that also runs also driven by ERA5 reanalysis fields (this version will be denoted as WRF_{deep} hereafter). The *SmileAtYou* team plans some experiments that pursues exploring how important the soil depth, vertical discretization and initial conditions of the soil parameters are in the simulations of regional land-atmosphere interactions (see Sections 3.1 and 3.2). Additional to the previous, how the LSM deals with the multiple processes that take place in the ground related to the surface water and the ground heat flux remains a challenge for the community, especially in those regions where the climate change signal indicates land vulnerabilities like the Mediterranean (Yves et al, 2020).

The soil hydrology coupled to the subsurface thermodynamics have a strong impact at the regional scale, producing its largest expression over areas subject to water phase changes or sensible areas like the Mediterranean (**Steinert et al., 2021**). This proposal will focus on evaluating the role of the thermodynamical and hydrological mechanisms particularly those connected to water phase changes in the soil by enabling enhanced realism on the physical processes with an already deeper soil component (WRF_{deep}) using the Noah-MP scheme.

Finally, the regional modelling community CORDEX encourages the research groups to progressively explore simulations at increasing higher resolutions (~1- 4km) following strategies known by *Convection Permitting Schemes* (CPS). Some years ago, CPS modelling approaches arose as a desirable and computationally cost-effective strategy for very high resolution in long climate simulations explicitly resolving deep convection instead of making use of the cumulus well-known parametrizations that tend to introduce considerable uncertainty as well as biases (Lucas-Picher et al., 2021). This approach is denoted as a "s*eamless*" strategy since it releases the modeling frame from the expenses of parametrizing by resolving important physical processes related to convective phenomena in a physically consistent and without a scale gaps scheme.

Convective processes imply a number of relevant impacts and how they are reproduced by models is of enormous interest for regional modelers and climate impact scientists, since the increased realism in modelling approaches is of a large added value to properly estimate hazardous extreme events as for example heavy precipitation and derived floods, windstorms, etc. (Stucki et al. 2015). Additionally, the importance of understanding and representing these processes correctly within models is also related to the fact that convection dominates the precipitation regimes in many regions of the globe as in the tropics and strongly influences the large-scale circulation via cloud-circulation and tropospheric mixing interactions (Bony et al. 2015). Besides, climate change can alter the character of convection, making extreme precipitation more extreme, and potentially modify large-scale conditions (atmospheric circulation and stratification) that favor convection, inducing changes in return periods of extremes or in the spatio-temporal distribution of events. Understanding convective mechanisms and their evolution under climate change conditions is therefore of relevance (Coppola et al., 2020).

The main difficulty in simulating this type of physical processes is that they require finer resolutions than usually achieved RCMs and therefore they need to be parametrized introducing so significant biases (Dirmeyer et al. 2012) and presumably contributes to add uncertainty in how the circulation will respond to the increased GHGs concentration (Webb et al. 2015). The fact that several other parametrizations within a regional model have an interplay with the convection mechanisms adds further uncertainty to climate simulations (Stevens and Bony 2013). Therefore, there is a quite urgent demand for experiments aligned with the reduction of model-errors related to convection representation (Solman et al., 2021).

Even in convection permitting RCM (CP-RCM) simulations, shallow convection is still not explicitly resolved (Soares et al. 2004). However, convective systems in summer over land are to a great extent controlled by the transition from shallow to deep convection (Wu 2009) and besides, shallow convection is connected to deep convection at the tropics. CP-RCM modeling is also markedly dependent on the specific model. To address this uncertainty associated with model dependency one usual approach is to perform several simulations with different models to account for the inter-model variability. Despite the computational cost and the need of coordination within the community, an ensemble of several integrations where the set up and forcing conditions have been previously agreed among the participants can contribute to mitigate the uncertainty and help in evaluating the added value of such strategies. Recently a Flagship Pilot Study project within the CORDEX umbrella (CORDEX-FPS[2]) has been launched, aimed at creating for the first time an ensemble of climate simulations with CP-RCM models to analyze present and future convection-affected processes and associated climate extremes over the European and the Mediterranean region (Coppola et al., 2020, Pichelli et al., 2021).

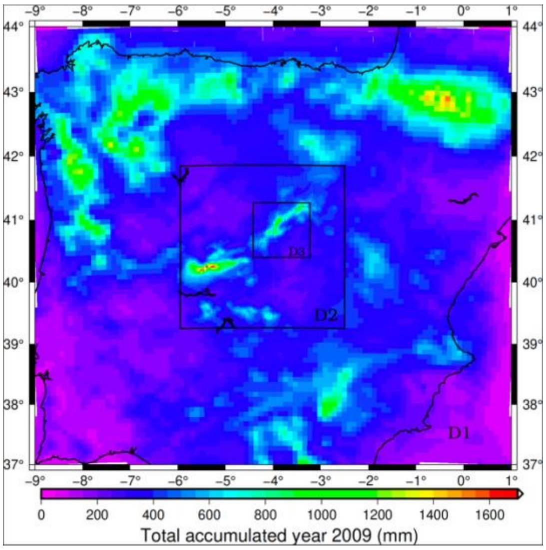

Figure 1. Annual mean precipitation over the Iberian Peninsula for a 1-yr simulation (2009) with a CP-WRF scheme. 3 domains with 9 km – 3 km and 1 km are shown.

The *SmileAtYou* team is collaborating with different simulations in the frame of CORDEX experiments. We have already performed kilometer-scale simulations over the Iberian Peninsula to evaluate the impacts in precipitation over mountainous areas of achieving the convective scales required, allowing the convective processes to be explicitly resolved. Fig. 1 shows the annual mean precipitation in a 1-yr simulation achieving 1 km resolution over the Iberian Central System. Within *SmileAtYou* context we aim at producing several kilometer-scale simulations over the Iberian Peninsula, in a wide enough domain to allow the large-scale convective cells to mature and fully develop but reducing the EURO CORDEX domain used by the *GReatModelS* and *SMileAtYou* so that different integrations may be feasible. Also, the proposed simulations will be of sufficient length so that systematic biases can be identified. The experiment proposed herein will include a sensitivity analysis to investigate the role of the interactions of the remaining parametrizations (such as Mycrophysics or PBL) with the explicit convection resolved by the regional model WRF, and ultimately, to assess how reliable are the kilometer-scale simulations in reproducing heavy precipitation and wind extreme events. These simulations will be performed following the CORDEX-FPS convention and will be evaluated against observations over the area to allow for a more in depth understanding of the model performance and the uncertainty. A decadal-long historical and future scenario simulation that will also serve the purpose of the recent CORDEX CPS regional model ensemble project will be produced as a final project product. The latter constitute an added value that can reach decision making contexts.

CP-RCMs have additionally proven their added value in the estimation of solar and wind energy resources since it is expected to improve the cloud-aerosol-radiation feedback and also the clear sky estimates, important for the solar irradiance parameters as well as it corrects biases in

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[2] https://cordex.org/experiment-guidelines/flagship-pilot-studies/

wind speed variability estimates, as the *SmileAtYou* team has shown in previous works (**Jiménez et al., 2011, 2012, 2013**).

OBJETIVES, METHODOLOGY AND WORK PLAN

3.1. General and specific objetives.

The general objective of *SmileAtYou* is to progress in the understanding of simulated regional and local climate variability and change. We aim at the following specific objectives:

O1. To evaluate the sensitivity of the RCM climate response in high resolution historical and scenario simulations using SINGLE-for specifications and with a complete set of forcings (ALL-for), driven by reanalysis and also and ESM, consistently as implemented therein over the EURO CORDEX domain. This will allow for an evaluation of the impact of incorporating external natural and anthropogenic forcings on long-term trends and extreme variability of key climate variables, as well as of those parameters that are central for the availability of solar-wind energy resources over the European-Mediterranean region.

O2. To investigate the impact of improved LSM characteristics (based on the Noah-MP scheme): boundary bottom condition placement (BBCP), vertical discretization, the initial and boundary data for soil parameters and the land surface physical options that allow for a more realistic description of hydro-thermodynamic and water redistribution processes within the soil, with special emphasis in regions with snow cover, permafrost or soil moisture deficits (drought-prone) in a consistent approach as in the parent ESM model in multidecadal high-resolution historical and scenario simulations.

O3. To explore the added-value of kilometer-scale long simulations making use of convectio-permitting strategies within a "*seamless*" approach to permit convective processes to fully develop and explicitly be resolved by the RCM in specific subdomains and selected multiyear periods in the attempt of understanding the model abilities and limitations to reproduce convective-driven processes that are to a great extent related to extreme precipitation extremes and windstorms. A sensitivity analysis will be performed to evaluate the impact of eliminating the convection parametrization produces on other parametrization that usually present synergies with the previous in RCMs.

These objectives project onto the workplan of activities based on the following tasks. The tasks are defined to configure a realistic objectives-tasks scheme within the length and the members involved in this project.

Tasks-1 (T1): 'Coherent SINGLE- and ALL-for historical downscaling sensitivity analysis' (correspond to O1)

T1.1. 'SINGLE-Forcing (*SINGLE-for*) reanalysis driven experiments'

In this part of the project the focus is placed on providing individual external forcings to the WRF simulations during the historical period. The *SmileAtYou* team has solved partly technical issues regarding the inclusion of GHGs, LULC and tropospheric aerosols (AER) and already produced a reference no-forced (REF) for comparison. Thus, SINGLE-for simulations with the individual forcings will be produced including those with volcanic year-to-year changes of stratospheric natural aerosols (AER + VOL) and total solar irradiance (SOL) variations. These set of individually forced WRF experiments are driven by the ERA5 reanalysis, and we will use what we will denote as the $WRF_{shallow}$ version (the WRF_{deep} version, will arise in Tasks -2).

T1.2. 'ALL-Forcing (*ALL-for*) 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*-$\mathrm{ESM}_{\mathrm{deep}}$ driving fields. This implies a data flush from our collaborators from the *SMILEME* project at the UCM. 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 (Tasks-2). The viability of running $MPI\text{-}ESM_{deep}$ output downscaled with WRF has already been ensured during the predecessor *GReatModelS* project.

T1.3. 'Sensitivity analysis of single and full forced WRF historical simulations (subtasks T1.1 + T1.2)'

This subtask attempts at analysing the six simulations performed in the two previous subtasks and carrying out a sensitivity analysis of the impact of each individual SINGLE-for and the joint ALL-for WRF of the land-atmospheric relevant fields, thereby identifying the role of forced variations at the regional scale. The question to what extent the sum of all contributions departs from the linear superposition of single forcings seems pertinent at this stage for the regional scale. These analyses may be of importance for posterior studies (out of the scope of *SmileAtYou*) attempting to distinguish forced versus internal variability at the regional scale over the broad EURO CORDEX domain.

Tasks-2 (T2): 'Structural improvements of the land surface scheme. Refined and more realistic soil physics in fully forced historical WRF$_{deep}$ simulations' (Corr. to O2).

We will modify the WRF LSM configuration so that properties mirror those from the land surface module in the new *GReatModelS MPI-ESM$_{deep}$* attending its structure and hydro-thermodynamical processes.

T2.1 'Emulating *MPI-ESM$_{deep}$* LSM configuration in WRF: creating *WRF$_{deep}$*'

We will mimic the depth, BBCP and vertical levels discretization of the *MPI-ESM$_{deep}$* LSM (JSBACH) in the Noah-MP LSM within WRF, giving rise to the *WRF$_{deep}$ SmileAtYou* version reaching a depth of ~ 200 m so that the energy and water budgets can be adequately distributed in depth in climate change experiments. Also, for the sake of consistency between the parent global model we will make use of the same soil parameters that serve to initialize the LSM processes in *MPI-ESM$_{deep}$* in WRF following **Steinert et al. (2021)**, accounting for root and bedrock depths. With this FULL-for *WRF$_{deep}$* configuration will finally generate a 9 km 30-yr HIS simulation.

T2.2 'Scoring an improved thermo-hydrodinamical core in the *WRF$_{deep}$* soil component: towards the *FULL-phys WRF$_{deep}$* version'

In this task we aim at including a i) *refined frozen water description*, ii) improved *runoff and groundwater free drainage processes, iii) an implicit snow/soil temperature time-scheme* and iv) setting a *zero heat flux from bottom as the lower boundary condition of soil temperature.* Finally, 30-yr 9 km historical and scenario simulations including all the increased realism in the soil physics (FULL-phys) options will be generated.

T2.3 'Analysis of the sensitivity of a deeper soil component (*WRFdeep*) and improved soil physics (FULL-phys *WRFdeep)* in multi-decadal historical and scenario CMIP6 simulations (subtasks T2.1 + T2.2)'

This subtask provides a sensitivity analysis by comparing results from the simulations exercises in the two previous subtasks, illustrating the effect of improved space in the soil for water and heat allocation first and to improved hydro-thermal processes after within the LSMs in RCMs. Both will be compared as well to their corresponding reference simulation (Sim1.6 with the *WRF$_{shallow.}$* version). We expect regional to local sensible impacts as a result from these analyses. We will finally analyze the climate change signal from a 30-yr SSP scenario simulation from this last refined *WRF$_{deep}$* version including all external forcings and augmented realism in the subsurface structure and processes.

Tasks-3 (T3): '*Convection Permitting simulations: towards a "seamless" regional modelling approach'* (Corr. to O3)

The former refined version of the WRF model with a more consistent and realistic LSM set up as in the parent model and a fully-forced scheme will be used in the final step in which we will increase the spatial resolution so that we can deactivate the convection parametrization. First, we will explore how this interacts with the remaining parametrizations in an adapted sensitivity analysis

T3.1. 'Calibrating the interplays between the inactive cumulus and active microphysics, PBL and LSM parametrizations options'

This task will be devoted to evaluating what are the optimal values for some parameters within the remaining parametrizations since many studies underlined the synergies between the resolved convection and those processes that still need to be parametrized and have a role in the distribution of the radiative and turbulent fluxes. They will be driven by ERA5 reanalysis fields as they need to be compared to observational evidence to assess the added value. As these simulations are very high computationally demanding we will perform shorter (2-3 yr) periods and over a smaller domain over the Iberian Peninsula.

T3.2. 'Evaluation of the added value of CP simulations with respect to observed values'

The assessment of an added value should be based on proper comparison with available observations focusing as much as possible in extreme events, their occurrence and intensity, so that the increased realism of the convection as explicitly resolved by within the virtual reality of the regional model can be evaluated comparatively with the real climate system. We will implement this analysis using the wind data base EusWio (Rojas et al., 2022), that count on surface and tower data observations as well as the available standard data of temperature and precipitation from AEMET.

T3.3. ‘Generating long m*ulti-decadal historical and scenario CP-RCM simulations over the EURO-CORDEX domain*‘

Based on the results from T3.1 and T3.2 we will decide the optimal configuration to perform a long simulation over the whole EURO-CORDEX domain, *WRF$_{deep}$, ALL-for* and with improved land-air interactions as result of efforts from tasks T1 and T2. The first *HIS* simulation will be reanalysis driven and compared to Sim1.5 as reference of a coarser resolution experiment and then we will produce the final *HIS* CMIP6 (*MPI-ESM$_{deep}$,* using as reference Sim1.6) and ideally if time allows, one SCE (SSP2) 30-yr simulation.

T3.4 ‘Historical and future projection analysis of trends and extreme variability based on CMIP6 downscaling experiments using our final *SmileAtYou* revised and CP WRF model version’

This task will imply to explore how the integration of all the above improvements impacts the past (and ideally future) regional climare variability, specially in what regards long-term trends and extreme variability of hydrological variables as well as wind and solar irradiances variables over the Euro-MED CORDEX domain.

Fig. 2 summarizes the pool of RCM simulations proposed within the Workplan and mentioned so far in the Tasks and Milestones described.

3.2. Description of the methodology.

The Weather Research and Forecasting (WRFv4.4.2) model (Skamarock et al., 2019) is a freeware code provided by the National Center for Atmospheric Research (NCAR). As a representation of a very complex system, the use and modification of the code in practice demands reasonable experience and profound knowledge on the model specifications and the physics involved. The *SmileAtYou* team have long proven expertise in using the model and introducing code modifications (**Jiménez et al., 2011, 2012, 2013, Vegas-Cañas et al., 2020, Hahmann et al 2020**) and extremes (**García-Bustamante et al., 2021**).

Some participants of the *SmileAtYou* team have contributed to the development of a new parametrization (e.g., Jiménez et al., and helped in code modifications[3]).

The starting point for the sensitivity study is based on an RCM reference configuration from our previous analyses in *GReatModelS*. The simulations are produced following a continued running strategy (instead of resetting initial conditions every week as in the NEWA simulations).

Already at the first stages of the project we will need inputs from the *MPI-ESM$_{deep}$*. The *SMILEME* team from the UCM will provide 6-hourly global coupled climate simulations from their own improved version with suitable modifications of the LSM component (JSBACH). They will provide historical and climate change scenario simulations (at least SPS126 and SPS585). 2012) and helped in code modifications[4].

The starting point for the sensitivity study is based on an RCM reference configuration from our previous analyses in *GReatModelS*. The simulations are produced following a continued running strategy (instead of resetting initial conditions every week as in the NEWA simulations).

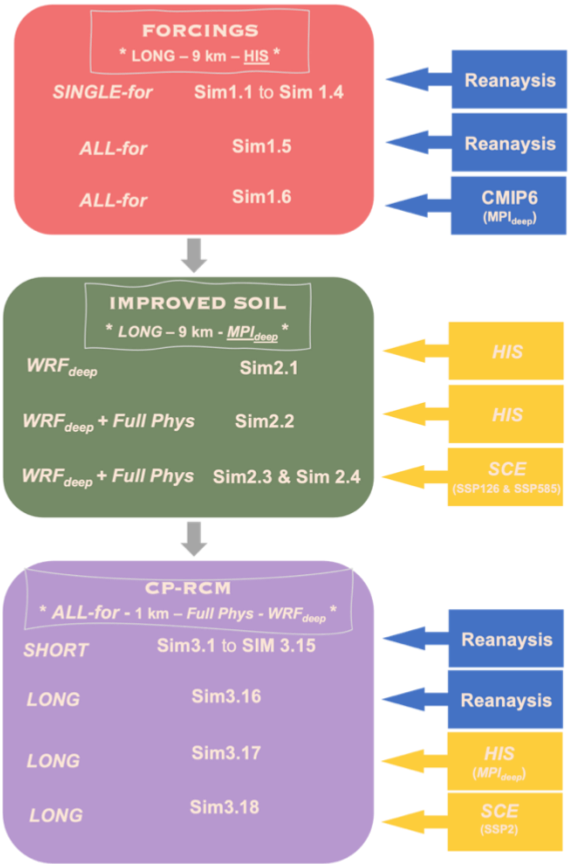

Figure 2. Schematic chart showing the three main blocks of simulations: 1) the external forcing drives, 2) the refine soil module and 3) the kilometer scale convection permitting calibrations and historical and scenario simulations.

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[3] https://github.com/wrf-model/WRF/releases/tag/v4.0.3

[4] https://github.com/wrf-model/WRF/releases/tag/v4.0.3

By the time *SMileAtYou* starts we estimate that GHGs and LULC SINGLE-for simulations will be already running and possibly finished. Also, the technical issues related to incorporating the natural and anthropogenic aerosols (see Section 2.1) and solar variations in the WRF configuration (AER+VOL and SOL) will possibly be partly or totally solved and the respective simulations ready to be launched. The databases required for these individually forced experiments will be included in the WRF radiation schemes by allowing year-to-year variations, identically as implemented in the CMIP6 community and with the same databases: Arfeullie et al., (2014) and the updated Thomason et al., (2018) as well as Kinne et al., (2019) for stratospheric aerosols and volcanic eruptions (VOL) and Matthes et al., (2017) in the case of the solar radiance (SOL) variations.

Regarding the refinement of the land surface component in Tasks-2 we selected the Noah-MP scheme for several reasons. First, because the pace at which the CLM4 simulations run made it unaffordable in case studies with numerous long simulations at very high-resolution; second, Noah-MP was selected to mimic the experimental approach within the CORDEX LUCAS community and at the NCAR institution and third, because Noah-MP offers the possibility of generating a deeper land module in Noah-MP (in spite of CLM4 offering somewhat deeper versions currently) and the asset of counting on a substantial amount of physical choices that can be specifically used to implement hydro-thermodynamical modifications, such as water movement and land-air related changes. Thus, aspects related to the *frozen non-linear soil permeability* and the *supercooled liquid water (or ice fraction)* will be included and the impact of these processes in regions where soil freezing can affect the moisture distribution will be analyzed. Also, a full *implicit snow/soil temperature time scheme* will be implemented. This is expected to have a sensible impact in the simulated exchange of heat and water fluxes by WRF (Li et al., 2021). Connected with addressing the permeability of the soil, the *vertical transport of soil water* and particularly the *runoff groundwater at the bottom of the soil column* are represented in a very rudimentary fashion in classic standard LSMs. However, it can result in large biases at the surface and soil temperatures, especially over regions where the subsurface tends to largely dry out (e.g., Mediterranean summer). Therefore, a physically consistent representation of vertical water flux usually lacks in soil modelling. Additionally, the subsurface heat flux is frequently estimated by solving the equation of heat diffusion with a prescribed boundary soil temperature at the bottom of the solution domain. However, a more realistic/deeper BBCP changes the vertical temperature distribution so that non negligible effects are expected from this structural modification within this physical option of the LSM. Thus, we will force the soil module to set a *zero heat flux from bottom as the lower boundary condition of soil temperature.*

The convection permitting modelling with regional models requires deactivation of the cumulus option. Despite this approach is aimed at adding consistency on the simulated physical processes, as several other sub-grid processes still need to be parametrized (e.g., microphysics, turbulence, or shallow convection), these schemes need to be revised and re-calibrated. The redistribution of the turbulent or the heat fluxes generated by the newly resolved deep convection within the CP-RCM simulations may affect for instance the precipitation regimes simulated by the model (Matsui et al., 2020). We propose thus a set of SHORT 2-yr CP-RCM experiments exploring the optimal calibration parameters related with convection permitting exercises as stated by Bellprat et al., (2016). This includes: 1) with respect to the PBL, parametrization (MYNN, Njuki et al, 2022), we will explore several values of the *scalar resistance for the latent and sensible heat fluxes*, 2) as for the microphysics (Thompson, Mekawy et al., 2023), we will explore the sensitivity of the simulated fields to the 2.a) *cloud ice* and the 2.b) *subgrid cloud formation*; 3) additionally, it is important to adjust the *shallow convection entrainment rate* from the cloud parametrization since the kilometer-scale resolution can only partly resolve convective clouds (Chow et al., 2019); 4) regarding the role of the surface module in simulating land-air interactions and therefore, their impacts on the simulated extremes (**Garcia-Garcia et al., 2020**), we will see the impact of varying the *root depth field* and 5) it has been show that adapting the time step could have as well a positive impact (Barret et al., 2019). If time frame allows, we will revise the *turbulence closure scheme* so that we can go from the present 2.5 closure to a 3D parametrization in case it demonstrates further added-value in the CP-RCM simulations.

3.3. Work plan and schedule.

Table 1. Workflow chart indicating the distributions of tasks and milestones according to the objectives and tasks defined in Section 3.1. Colors correspond to simulation blocks in Fig. 2.

	2024				2025				2026		
Tasks-1	T1.1	T1.2	T1.2	T1.3	T1.3						
Tasks-2	T2.1	T2.1	T2.2	T2.2	T2.2	T2.2	T2.3	T2.3			
Tasks-3	T3.1	T3.1	T3.1	T3.1	T3.2	T3.3	T3.3	T3.3	T3.3	T3.4	T3.5

This proposal applies for a 3-year project. Tasks-1 are planned to cover from Jan 2024 until the end of 2024. The corresponding evaluation and analyses might well be extended until the first months of 2025. By Jan 2024 we count with Sim1.2 and Sim1.2 finished and to have solved technical requirements for Sim1.3 and Sim1.4. The coupling to the *MPI-ESM*$_{deep}$ is already implemented as commented before. We allocate about 6 months to complete each 30-yr simulation, 3 months for the subsequent analyses and another 3 months until a publication is submitted. Tasks-2 can start at the beginning of 2024 but launching the simulations will have to wait at least until Sim1.6 is running since the ALL-for serves as reference for block 2 simulations (see Fig. 3). The same time allocation for completing the simulations and analyses as in Tasks-1 can be observed distributed throughout 2025. Tasks-3 begin as well in 2024. Sensitivity simulations from T3.1 are much shorter although with higher resolution. The three long simulations will require presumably more than another year of computation to be in the safe side. Analyses and writing are thought to cover the last year 2026. Kick-off, mid- and final project meetings as well as dissemination activities are programmed at the middle and final stages of the project duration.

7. REFERENCES (research and work team members are indicated in **bold**)

Arfeuille, F., et al., 2014: “Volcanic forcing for climate modelling: ...”. *Clim. Past*, *10*(1), 359-375.

Ban, N., et al., 2021: “The first multi-model ensemble of regional climate...” *Clim. Dyn.*, 57, 275-302.

Barrett, A.I., et al., 2019: “One step at a time: How…” *J. Adv. Model. Earth Syst.*, 11(3), 641-658.

Bellprat, O., et al., 2012: “Objective calibration of…” *J. of Clim. 29, 819–838.* .

Berckmans, J., et al., 2019: “Bridging the Gap...”. *J. Geophys Res.: Atmospheres*, 124(12), 5934-5950.

Bonan, G. B., and S. C. Doney, 2018: "Climate, ecosystems, and...". *Science*, 359, eaam8328.

Bony, S., et al., 2015: “Clouds, circulation and climate sensitivity” *Nat. Geosci.* 8(4), 261–268.

Chen, F. and J. Dudhia, 2001: “Coupling an advanced land...”. Mon. Weather *Rev.*, 129(4), 569-585.

Christensen, J.H.,et al., 2013: “Climate phenomena and their relevance for futurel…”: Working group I contribution to the fifth assessment report…, Cambridge University Press, 1217-1308.

Chow, et al., 2019: “Crossing multiple gray zones…”. *Atmosphere*, 10(5), 274.

Coppola, E., et al., 2020: “A first-of-its-kind multi-model convection permitting…” *Clim. Dyn.*, 55, 3-34.

Davin, E. L., et al., 2020: “Biogeophysical impacts of forestation ...”. *Earth Syst. Dyn.*, 11(1), 183-200.

Dirmeyer, P.A., et al., 2012: “Simulating the diurnal cycle of rainfall….” *Clim. Dyn.*, 39(1–2), 399–418.

Dörenkämper, M., B. T. Olsen, B. Witha, **A. N. Hahmann**, N. N. Davis, J. Barcons, Y. Ezber, **E. García-Bustamante**, J. F. González-Rouco, **J. Navarro,** et al., 2020: “The making of the New European ...”. *Geosci. Model Dev.*, *13*(10), 5079-5102.

Drugé T., et al., 2019: “Model simulation of ammonium and ...”. *Atmos. Chem. Phys.,* 19, 37073731. Special Issue: Chemistry… (ChArMEx) (ACP/AMT inter-journal SI).

Ekici, A., et al., 2014: "Simulating the high-latitude permafrost...". *Geosci. Model Dev.*, 7, 631–647.

Eyring, V., et al., 2016: "Overview of the coupled model ...". *Geosci. Model Dev.*, 9, 1937–1958.

Flanagan, J., et al., 2019: “Towards a definitive historical high-resolution ...”. *Adv. Sci. Res.*, 15, 263.

Forrester, M. M. and R. M. Maxwell, 2020: “Impact of lateral groundwater flow ...”. J. Hydrometeorol., 21(6), 1133-1160.

García-Bustamante, E., J. F. Fidel González-Rouco, E. García- Lozano, F. Martinez- Peña, and **J. Navarro**, 2021a: “Impact of local and regional climate ...”. *Int. J. Climatol*, 41, 5625-5643.

García-Bustamante, E., J. F. González Rouco, J. Navarro, **E. E. Lucio Eceiza**, and C. Rojas Labanda, 2021b: “Expected Recurrence of Extreme Winds in ...”. *Energies*, 14(21), 6913.

García-García, A., F. J. Cuesta-Valero, H. Beltrami, J. F. González-Rouco, **E. García-Bustamante**, and J. Finnis, 2020: “Land surface model influence on ...”. *Geosci. Model Dev.*, 13(11), 53.

García-García, A., F. J. Cuesta-Valero, H. Beltrami, J. F. González-Rouco, **and E. García-Bustamante**, 2021: "WRF v. 3.9 sensitivity to land ...". *Geosci. Model Dev. Discuss.*, 1-32.

Giorgi F., Prein A.F., 2022: “Populated regional climate models…” PLOS Clim., 1(7): e0000042.

González-Rouco J. F., N. J. Steinert, **E. García-Bustamante**, S. Hagemann, P. de Vresse, J. J. Jungclaus, S. J. Lorenz, C. Melo-Aguilar, F. García-Pereira, and **J. Navarro**, 2021: "Increasing the depth of a Land Surface Model. Part I: ...". *J. Hydrometeorol.*, 22, 3211-3230.

Gutowski Jr., W. J., et al., 2016: "WCRP Coordinated Regional...". *Geosci. Model Dev.*, 9, 4087–4095.

Hagemann, S., and T. Stacke, 2015: "Impact of the soil hydrology ...". Climate Dyn., 44, 1731–1750.

Hahmann, A.N., T. Sīle, B. Witha, N. N. Davis, M. Dörenkämper, Y. Ezber, **E. García-Bustamante,** J. F. González-Rouco, **J. Navarro**, et al., 2020: “The making...". *Geosci. Model Dev.*, 13(10), 5053-5078.

Hasson, S., et al., 2019: “Low fidelity of CORDEX and ...”. *Clim. Dyn.*, 52: 777–798.

Hersbach, H., et al., 2020: “The ERA5 global reanalysis”. *Q. J. R. Meteorol. Soc.*, 146(730), 1999.

Holtzman, N. M., et al., 2020. “Tailoring WRF...”. *J. Adv. Model. Earth Syst.*, 12(3), e2019MS001832.

Hsu, H., et al., 2017: "Relation between...". *J. Geophys. Res.: Atmospheres*, 122(12), 6319-6328.

Hurtt, G.C., et al., 2020: “Harmonization of global land use...”. *Geosci. Model Dev.*, 13(11), 5425-5464.

Inoue, J., et al., 2021: “Clouds and radiation...”. *J. Geophys. Res.: Atmospheres*, 126(1), e2020JD033904.

IPCC, 2021: Summary for Policymakers. In: "Climate Change 2021:…". Contribution of Working Group I to the Sixth Assessment… " [Masson-Delmotte, V., et al. (eds.)]. *Cambridge University Press*.

Jacob, D., et al., 2020: “Regional climate downscaling over ...”. *Reg. Environ. Change*, 20(2), 1-20.

Jerez, et al., 2018: “Impact of evolving greenhouse gas forcing…” *Nat. Commun*., 9(1), 1-7.

Jiménez, P. A., J.F. González-Rouco, J. Montávez, **J. Navarro, E. García-Bustamante**, and J. Dudhia, 2013: "Analysis of the long-term surface ...". Clim. Dyn., 40, 1643-1656.

Jiménez, P.A., J. Dudhia, J. F. González-Rouco, **J. Navarro**, J. P. Montávez., and **E. García-Bustamante**, 2012: “A revised scheme for the WRF ...”. Mon. Weather Rev., 140(3), 898-918.

Jiménez, P. A., J. Vila-Guerau de Arellano, J. F. González-Rouco, **J. Navarro**, J. P. Montávez, **E. García-Bustamante,** and J. Dudhia, 2011: "The effect of heatwaves...". *J. Clim.*, 24, 5416-5422.

Kinne, S., 2019: “The MACv2 aerosol climatology”. *Tellus B: Chem. Phys. Meteorol.*, 71(1), 1-21.

Koster, R. D., et al., 2006: "GLACE: The Global Land–Atmosphere…” *J. Hydrometeorol.*, 7, 590–610.

Kushnir, Y., et al., 2019: “Towards operational predictions of the ...”. *Nat. Clim. Change*, 9(2), 94-101.

Lawrence, P. J., et al., 2019: "The community land model ...". J. Adv. Model. Earth Syst., 11, 4245.

Li, X., Wu, et al., 2021: “Assessing the Simulated Soil Thermal ...". *Geosci. Model Dev.,* 14, 1753.

López-Padilla, S., 2021: “*Regional climate simulations over the Euro-Mediterranean ...*”. Master Thesis for the Master in Computational Biology program. Universidad Politécnica de Madrid. Supervisors: Raul García Castro (UPM) and J. F. Fidel González Rouco. Collaborators: **E. García Bustamante**, **J. Navarro Montesinos**, E. de la Rubiera Narganes. 10 de Septiembre de 2021.

Lucas-Picher, P., et al., 2021: “Convection-permitting modeling…” WIREs Clim. Change, 12:e731.

Ludwig, P., et al., 2019: “Perspectives of regional paleoclimate…”. *Ann. N. Y. Acad. Sci.*, 1436(1), 54.

Matsui, T., et al., 2020: “Impact of radiation frequency, precipitation…”. Clim. Dyn., 55, 193–213.

Matthes, K., et al., 2017: “Solar forcing for CMIP6 (v3.2)”. *Geosci. Model Dev.*, 10(6), 2247-2302.

Mekawy, M., et al., 2023: “Evaluation of WRF Microphysics Schemes…” *Climate*, 11, 8.

Miralles, D.G., et al., 2019: “Land–atmospheric feedbacks during...". *Ann. N. Y. Acad. Sci.*, 1436(1), 19.

Niu, G. Y., et al., 2011: “The community Noah land ...”. *J. Geophys. Res.: Atmospheres*, 116(D12).

Njuki, S.M., et al., 2022: “Influence of Planetary Boundary Layer (PBL)…” *Atmosphere*, 13, 169.

Pichelli, E., et al., 2021: “The first multi-model ensemble of regional…” Clim. Dyn., 56, 3581–3602.

Rojas-Labanda C., J. F. González-Rouco, **E. García-Bustamante, J. Navarro, E. E. Lucio-Eceiza**, et al., 2022: “Surface wind over Europe…” Int. J. Climatol. 43(1), 134-156.

Ruiz-Arias, J. A., et al., 2014: “A simple parameterization of...”. *Geosci Model Dev.*, 7(3), 1159-1174.

Skamarock, W. C., et al., 2019: “A description of the advanced… “. *NCAR: Boulder, CO, USA*, 145.

Soares, P.M.M., et al., 2004: “An eddy diffusivity/mass-flux…” *Q. J. R. Meteorol. Soc.*, 130, 3365–3384.

Solman, S., et al., 2021: "The future scientific challenges for CORDEX". White paper.

Steinert, N. J., J. F. González-Rouco, P. de Vresse, **E. García-Bustamante**, et al., 2021: "Increasing the depth...". J. Hydrometeorol., 22, 3231-3253.

Stevens, B. and Bony, S., 2013: “What are climate models missing?” Science, 340(6136), 1053-1054.

Stucki, P., et al., 2015: “Dynamical downscaling and…” *Bull. Am. Meteorol. Soc.,* 96(8), 1233–1241.

Thomason, L. W., et al., 2018: “A global space-based ...”. *Earth Syst. Sci. Data*, 10(1), 469-492.

Vegas-Cañas, C., J. F. González-Rouco, **J. Navarro-Montesinos, E. García-Bustamante, E. E. Lucio-Eceiza,** et al., 2020: “An assessment of observed and ...”. *Atmosphere*, 11(9), 985.

Webb, M.J., et al., 2015: “The impact of parametrized…” *Philos. Trans. R. Soc. A.*, 373: 20140414.

Wu, L., 2009: “Comparison of atmospheric infrared…” *J. Geophys. Res.*, 114(D19205).

Xia, G., et al., 2021: “Quantifying the Impacts of Land ...”. *Mon. Weather Rev.*, 149(9), 3101-3118.

Yves, T., et al., 2020: “Challenges for drought assessment in ...”. *Earth Sci. Rev.*, 103348.