REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE:	SPAIN
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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

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.)	2023	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2023-2025: (To make changes to an existing project please submit an amended version of the original form.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	9,500,000	**15,500,000**	9,500,000
Accumulated data storage (total archive volume)[2]	(GB)	150,000	**350,000**	150,000

Continue overleaf

[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.

Principal Investigator: Elena García Bustamante - CIEMAT

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

Extended abstract

Summary

Regional Circulation Models (RCMs) have undergone constant progress chasing enhanced realism in simulating climate variability and change. Our project proposes a contribution to this endeavour in what relates the simulated land-air interactions at the regional scale. To this aim various aspects are still subject to improvement. First, the structure (depth, bottom boundary condition placement, vertical discretization and initialization of variables) of the soil component in RCMs offer a generous space for refinement. We plan to achieve a deeper soil scheme. This will allow for a more realistic heat and water redistribution at the subsurface. Also, the thermodynamical and hydrological processes in current state-of-the-art land surface models (LMSs) are essential for the realism of simulated heat fluxes at the surface and therefore need to be assessed for their adequate representation in RCMs, especially in those regions with particular soil processes involved, like water phase changes, snow cover or soil moisture deficits, that have already proven very sensitive to the LSM characteristics and depth from previous experiments within the group. We envisage sensitivity experiments testing the impact of the soil physics in our reference RCM (WRF). Additionally, part of the uncertainty in present historical and future climate simulations arises from a lack of realism or complete absence of natural and anthropogenic radiative forcings. Our aim is to include in our RCM historical and future simulations all sources of climate system external drivers (GHGs, natural and anthropogenic aerosols, land use changes, solar variations and volcanic aerosols) and to implement them following the CMIP6 protocols and in a consistent fashion as in the global feeding model, the MPI-ESM, run by the UCM core team. This project attempts thus a sensitivity analysis by confronting results from the inclusion of single forcings one by one to the case embracing all natural a human induced climatic drivers. This experimental set up aims at evidencing how relevant are all the above mentioned factors, still shallowly matured as a whole within RCMs, in land-atmosphere simulated interplays in CMIP6 downscaling experiments of past and future long (30 years) high resolution (9 km) continued (no reinitialized) simulations over the EURO CORDEX domain, with special emphasis on hot spot regions prone to arid or typically frozen soils that are potentially more vulnerable under altered climate states. We will pay particular attention to recent and future long-term climatic trends of atmospheric an soil variables as well as to simulated heat fluxes, which have a great potential of affecting the availability of renewable (specially wind and solar) energy resources. This project outcomes are therefore designed to constrain the uncertainty and improving our knowledge about physical processes in land-air interactions and new developments of climate models, with potential influences for impact studies and adaptation and mitigation of climate change.

PROJECT DESCRIPTION

BACKGROUND AND RATIONALE

The research interest of the project we propose grounds upon the need of assessing the impacts of increased realism in the representation of land surface components and land-atmosphere interactions in preindustrial, historical and scenario global (ESM, from Earth System Model) and RCMs. Thus, the project aims at improving the hydro-thermal representation of the subsurface by considering the effect of a deeper soil module, latent heat exchange and water transport, as well as more realistic surface land-air interactions through the snow scheme or involving changes in external forcings.

Recent work within the group in the context of a previous project of the group, the GReatModelS (see details below), allowed for analyzing land-air coupling considering thermal and hydrological aspects, and their relevance both at regional and global scales (García-García et al., 2019; Melo et al., 2018). Also, the impacts of improved soil hydrology within a state-of-the-art LSM (JSBACH model) have been analyzed in historical and scenario simulations by using a modified version of JSBACH with respect to that used in CMIP6 (Steinert et al 2021b). The hydrological implications of the previous model changes have also been analyzed and are in development in Perez-Perez et al. (2022), indicating that changes in the model configuration produce different trends during the 21st century as well as different hydrological states. The analysis has been completed by an assessment of hydroclimate variability at global scales and its relationship to internal variability and to external forcing factors during the last millennium (Roldán-Gómez et al., 2020; 2021). Coupled ESM simulations have been performed with a deeper version JSBACH-DEEP (González-Rouco et al. 2021).

In addition to these developments at the global scale, substantial changes in the response to improvements in the LSM representation are noticeable at the regional scale. Therefore, 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 regional climate models (RCMs).

The scientific community has supported and fostered enormous progress in regional climate modelling (Drugé et al., 2019; CORDEX community and references therein) and it has been granted increasing emphasis on the assessment and quantification of the added value and the associated uncertainties (e.g. Hasson et al., 2019). Diverse sources of uncertainty still 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 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). At this respect, the need of increasing the realism in processes and improving the overall RCMs performance steered the study of land-air synergies. 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 this project team has already demonstrated experience (Jiménez et al., 2011). The coupling between the subsurface water and energy cycles, and the evolution of the surface fluxes has a strong impact on RCM simulated planetary boundary layer or cloud development (Santanello et al., 2018). 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 (e.g. Hsu et al. 2017), which eventually have affected 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).

Therefore, the processes resolved by the LSM component of RCMs become of relevance. First, the selection of an LSM within the options available in an RCM has a non-negligible influence on the simulated mean and especially extreme climate variability. Our team has experience in exploring the impact of the choice of different LSM parameterizations on historical and climate change projections over different regions (Jerez et al., 2012; García-García et al., 2020, 2021; García-Bustamante et al. 2021a). The group has also investigated the sensitivity of the simulated wind field by the WRF model (Skamarock et al., 2019) to LSMs within the frame of the New European Wind Atlas (NEWA) project (Hahmann et al, 2020; Dörenkämper et al., 2020). In the context of the foreproject *GReatModels* the impact of the LSM choice has been investigated in a set of continued long high-resolutions WRF simulations over the European-Mediterranean domain using the standard Noah LSM (Mitchell, 2005), the CLM4 (Oleson et al., 2010), the Noah-MP (Niu et al., 2011) and RUC (Smirnova et al., 2016) LSMs. The differences were manifest at the local to regional scales depending on the LSM selected especially in coastal and complex terrain areas, river basins and arid-and semi-arid domains.

Besides, the depth of the RCM subsurface component has proven pivotal for a correct storage of water and energy in the soil. The cconductive diffusion is the dominant process that lags and dampens the surface temperature signal that propagates with depth. As in global models, 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 (Forrester and Maxwell, 2020). Usually, the depth of the LSMs included in RCMs is ~2m, and although recent efforts of the land modelling community have evolved towards and augmented realism in the depth of the CLM5 LSM (Lawrence et al., 2019), 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). We have developed a new version of the WRF4.2 model that admits a 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 (Herbasch et al., 2020) fields (this version will be denoted as WRFdeep hereafter). Nonetheless, in the context of CMIP6 downscaling experiments, at the time of writing this proposal we have already produced a coupled simulation between the shallow standard WRF4.2.2 model version (WRFshallow) coupled to the MPI-ESMdeep version created by the UCM core team. Fig. 1 represents the annual soil moisture from this simulation which constitutes the first CMIP6 downscaling exercise driven by fields from a coupled simulation of a global model with a much deeper than usual soil component. We plan a sequence of 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.

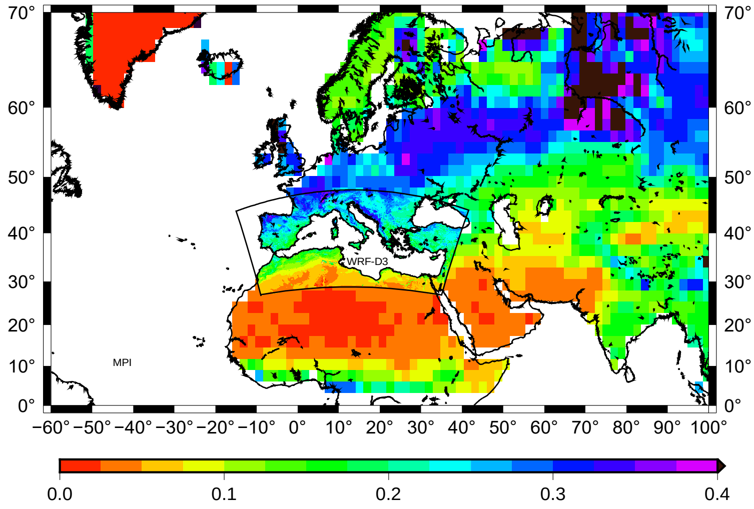

Fig. 1. Annual mean soil moisture (m^3/m^3) for a 1990-2000 WRF simulation coupled to our own MPI-ESMdeep version at the corresponding first soil layer (5 cm for WRF and 6 cm for the MPI-ESMdeep model).

More than the structure, the configuration and depth of the soil layers, 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). Modelling the endless number of biogeophysical and biogeochemical processes that take place underground demands a large body of experiments and test cases (Santanello et al., 2018) and becomes particularly arduous in a context with very limited observations to stablish a robust comparative frame (Niu et al, 2011) as is the case of soil physics community. Forrester and Maxwell (2020) performed a sensitivity analysis using the WRF model to explore the impact of ground water as well as the subsurface lower boundary conditions to investigate the low atmosphere evolution and found a direct influence on the wind currents over complex terrain and in the precipitation via a weaking of the land-air coupling. Gómez et al. (2021) investigated the effects of vegetation options within the Noah and Noah-MP coupled to WRF regional simulation over a semi-arid region in Spain to show the fundamental role of the ground water and heat flux in modulating the land-surface flux exchanges emphasizing the sensitivity of WRF simulated fields to the physics emulated by the LSMs.

The Noah-MP LSM (Niu et al., 2011) is a development of the Noah scheme (Chen and Dudhia, 2001) that improves processes related to the energy balance of the vegetation cover, a model for the snow layers, a conceptual representation of frozen soil and infiltration phenomena, an interaction between soil moisture and groundwater and the derived runoff effect as well as a modellization of the vegetation phenology. The analyses show that 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, consistently with what was found as a result of the *GReatModelS* experiments at the global scale (Steinert et al., 2021b). 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 performing a pool of WRF downscaling experiments that will enable enhanced realism on the physical processes with an already deeper soil component using the Noah-MP available alternatives.

On the other hand, an additional source of uncertainty in regional modelling that is of great relevance for the reliability of the regional climate projections is how RCMs deal with the external, natural or anthropogenic, forcings. The inclusion of these external drivers is not yet an extended practice despite significant efforts in the community towards providing more realistic regional simulations compatible with the forced ESM simulations that drive regional climate projections (Lawrence et al., 2019). While coordinated efforts exist within the GCMs/ESMs community (PMIP4/CMIP6; Eyring et al 2016), the regional model community still lacks a coordinated assessment framework (Jerez et al., 2020). However, the uncertainty arising from the forced variability can acutely reshape the land-atmosphere interactions simulated by RCMs, with potentially severe impacts on the realism of the simulations. In particular, 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. An example of the later is the omission of suitable LULC changes in regional simulations that may hamper the simulation of the observed *wind stilling* anomaly (Azorín et al., 2017).

The inclusion of GHGs (CO_2, CH_4 and N_2O) is nowadays reasonably extended and the latest versions of WRF already include transient changes of GHGs. This is relevant for climate attribution purposes with RCMs, which would benefit from implementing additional forcings consistently with ESMs (Zhai et al., 2018). Our simulations within the *GReatModelS* RCM set up already incorporate varying CO_2 instead of the classical constant values or climatologies in the past, all these issues gaining importance 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 reginal climate variability. First results of this associated effort will probably see the light in the close future since the LULC annual varying maps that RCMs used to run historical and scenario simulations and the first test experiments are under discussion at the moment of writing this proposal. This project team is actively participating and contributing 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 so that it can be said that our results also show that uncertainties have to 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 granting physical consistency to the atmospheric simulated processes affected by direct scattering and absorption or indirect thermodynamic effects on clouds (Drugé et al., 2019). These modules are computationally very expensive, and an intermediate complexity approach has been designed, 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. In our WRF simulations, the aerosol properties were inserted in the AOP parametrization (Ruiz-Arias et al., 2014) that runs coupled to the Rapid Radiative Transfer Model for climate and weather 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. Additionally, this approach grants consistency with the corresponding forcing as implemented in the *MPI-ESMdeep* that drives the regional model experiments. In fact, 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). A historical run has been produced in the context of our single forcings experiments including this methodological variant and the impacts of the cloud formation as well as in the surface radiative fluxes and is being analyzed.

Regarding the remaining external forcings, volcanic and solar variations still remain a challenge for the RCMs communities (Doblas-Reyes et al., 2021). 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). In addition, the implementation of stratospheric volcanic aerosols is yet little extended within the regional modelling community.

We have already accomplished single forcing experiments, SINGLE-for hereafter (GHGs, anthropogenic and natural aerosol and LULC changes) in historical long simulations at 9 km over the Euro-Med domain driven by ERA5 Reanalysis fields. The question assessed is whether for large RCM domains there is an impact in considering a more realistic forcing representation within the domain and not only feed the RCM with the effects of externally forced changes via the boundary conditions.

Our project team plans to have completed the historical SINGLE-for (GHGs, aerosols and LULC changes) simulations as a part of CMIP6 downscaling exercises (*MPI-ESMdeep* to *WRFdeep*) by the end of the year 2022. From that point on, we will continue with the implementation of solar (SOL) and volcanic (VOL) forcings in SINGLE- and also ALL-for ERA5 and CMIP6 historical and scenario experiments. The latter would potentially allow sensitivity analyses that ultimately would well serve for the purpose of a robust identification of individual forcings on land-air interactions at the regional scale. Despite this attribution exercises are not necessarily within the scope of this proposal, the experimental set up conceived for *SMILEME* would eventually be of great value for the regional model's community. Thus, although separating forced climate signals from internally induced variability at the regional scale requires very specific techniques applied as well over preferably large ensemble of multi-model and multi-physics simulations (Lavin-Gullon et al., 2021), nevertheless the amount of simulations planned 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 associated to the variability of the land-air interactions. At this respect, our 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).

In summary, recent developments by the applicants have focused on including realistic anthropogenic forcings in WRF and on creating a WRF version with a deeper soil component. Thus, we aim at evaluating the impact of correcting the traditional shallow land modules within WRF in CMIP6 downscaling exercises driven by the MPI-ESMdeep run by the UCM core team and considering consistently HTC hydro-thermodynamic processes and land air interactions. We will pay attention to those regions with particular soil conditions, where the global model has already shown to considerably change its response, like areas with soil freezing/thawing processes or regions where aridity dominates. The lack of realism that this proposal addresses, which has proven to induce ill-represented land-atmosphere interactions at the regional to local spatial scales, interacts with an incomplete representation of the anthropogenic radiative forcings in historical regional simulations. We claim that the effects of allowing for more space for energy and water storage and an improved physics representation over the EURO CORDEX domain at ~9 km resolution will have meaningful impacts. Together with a complete set of SINGLE-for and ALL-for (including solar and volcanic) we attempt to characterize at least part of the uncertainty in the models response at the regional scale for the historical period and the future climate in continued 30-yr simulations, with a particular focus on regional climate trends and extreme variability.

PARTICIPANTS AND IMPACT

This proposal involves two institutions with a long record of collaborations and joint efforts). In fact, both institutions are currently collaborating in the project *GReatModelS* (*Global and Regional Impacts of using more realistic land Modelling on Historical and climate change scenario Simulations*; extended until September 2022, RTI2018-102305-B-C21 and RTI2018-102305-A-C22, from Ministerio de Ciencia e Innovación). Additional project proposals have been submitted with scientific objectives aligned with the topics described herein as a natural continuation of the research lines of the UCM-CIEMAT group ("*SMILEME* - Sensitivity of global climate Models to Improved soil thermo-hydrodynamics and Land-air interactions: impacts on future climate and renewable energy resources over the European-MEditerranean domain" – UCM and "*NIWA - New Iberian Wind Atlas: from* wind resource assessment at the European scale to the Iberian Peninsula in present and future conditions" – UCM-CIEMAT consortium, both calls from the Ministerio de Ciencia e Innovación).

The UCM team is focused in exploring similar questions as in the regional case but with the GCM/ESM model (MPI-ESM) that provides initial and boundary conditions to the RCM, while CIEMAT is focused on the regional scale (WRF). The CIEMAT objectives and tasks feed from the planned test experiments and model design in the UCM, and *vice versa*. The coordination between CIEMAT (P.I. Elena García Bustamante) and UCM (Universidad Complutense de Madrid, J.P.I. J. Fidel González-Rouco) will grant consistency in the analyses, thereby targeting the assessment of similar processes in both model frames and a desirable consistency between both model configurations.

Nonetheless, the computational needs only arise from the regional model code, WRF since the ESM is already being run in the Max-Planck Hamburg/DKRZ German facilities.

The coherence of physical parametrizations and inclusion of external climatic drivers across-scales implies a hunted achievement within the CMIP6-downscaling community. Our project aims a step forward in the assessment of impacts due to improved Land Surface Model (LSM) processes on coupled climate simulations at global and regional scales, with emphasis on particularly sensitive regions like the Arctic or the Euro-Mediterranean domain. We postulate that the processes addressed within our planned experiments will imply a sizeable impact on the simulated climates and a relevant contribution to CMIP/PMIP frames. Moreover, the downscaling community will largely benefit from efforts seeking physical coherence between the parent ESM set up and the RCM simulations. In this sense *this project* will well serve as an agent of the CMIP6 diagnostic community.

In summary, the experimental set up and understanding generated within this project will contribute to model assessment and development with the potential of being influential for the climate impacts and adaptation/mitigation communities. Additionally, *we* will contribute with products, in terms of global and regional-EURO CORDEX simulations of relevance for other scientific and climate service-oriented communities.

SCIENTIFIC PLAN

The general objective of this project is to challenge the realism of climate model responses as a result of improved soil components (depth, configuration and physics) a RCM. We aim at exploring how sensitive the RCM 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 WRFdeep model version. To our knowledge historical and scenario ESM-RCM downscaled simulations with consistently improved land model components are scarce. The specific objectives to achieve can be segregated as follows:

O1. To explore the sensitivity to the increased realism in the design of the LSM structure (based on the Noah-MP scheme): boundary bottom condition placement (BBCP), vertical discretization and not less important, the initial and boundary data for soil parameters. All the previous in meaningful consistency with the forcing global model (MPI-ESMdeep, own version within the UCM-CIEMAT group)

O2. To explore the sensitivity of the RCM climate response in simulations using a SINGLE-forcing specification and simulations using a complete set of forcings (ALL-forcing) consistently as implemented in the global model for a sound CMIP6 downscaling exercise.
O3. To determine 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 in a consistent approach as in the parent ESM model.
O4. To understand how the integration of all the above improvements impacts past and future climate variability, specially in what regards long-term trends and extreme variability of temperature and hydroclimate variables as well as wind and solar energy related variables over the EURO CORDEX domain.

The workplan to achieve the described objectives is based on the following tasks:
(All simulations are performed over the EURO CORDEX domain at 9 km of horizontal resolution. *CMIP6* refers to driving initial and boundary fields from our *MPI-ESMdeep* & HTC model versions from the UCM team and ERA5 refers to reanalysis driven WRF simulations. Unless otherwise specified all simulations are 30-yr long, either 1990-2010 for the historical period or 2070-2100 for scenario projections).

T1: 'Structural improvements of Land Surface Component Modelling' (Corr. to O1)

T1.1 'Sensitivity of WRF simulations to soil initial and boundary'
Two different soil parameter datasets will be used accounting for root and bedrock depths, in order to understand how sensible the soil moisture and temperature simulated by WRF is to the specific soil parameters that serve to initialize the LSM processes.
T1.2 'Mimic the depth, BBCP and vertical discretization of JSBACH in the Noah-MP LSM within WRF'
This task is designed to upgrade the configuration of the Noah-MP LSM used so that the BBCP in WRF and in MPI-ESM are consistent. Correspondingly, the specific vertical discretization within a deeper soil to be used from here on in the rest of the experiments will be adapted. Independently of the soil depth already fixed, two different vertical discretization will be explored with different soil layers, one with more density at the surface.
T1.3 'Analysis of sensitivity of *WRFdeep* to the soil layers structure and soil initialization parameters
This subtask provides a sensitivity analysis by comparing results from the simulations of the simulation exercises in the two previous subtasks and presenting in the community a comprehensive explanatory case of how to refine the land module in WRF for further users.

T2: 'Coherent SINGLE- and ALL-Forcing historical downscaling sensitivity analysis' (Corr. to O2)

T2.1. 'SINGLE-Forcing (*SINGLE-for*) reanalysis driven experiments'
In this part of the project the focus is placed on providing a complete set of natural and anthropogenic forcings to the WRF model simulations during the historical period, including volcanic aerosols and solar variability. These databases will be included in the WRF radiation schemes by allowing variations. Databases will be those used in the CMIP6 community. To be fairly comparable to experiments already performed regarding anthropogenic forcings and these set of single-forced WRF experiments are driven by the ERA5 reanalysis and still with the WRFshallow version, to grant independency in the assessment from other changes.
T2.2. 'ALL-Forcing (*ALL-for*) reanalysis and CMIP6 driven experiments''
Fully-forced WRF simulations (GHGs, AER, LULCC, VOL, SOL) during the historical period will be carried out based both in ERA5 reanalysis and finally with *MPI-ESMdeep* driving fields.
T2.3. 'Sensitivity analysis of single and full forced WRF historical simulations (subtasks T2.1 + T2.2)'
This subtask attempts at analysing the two 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.

T3: 'Refined more realistic soil physic processes in fully forced historical WRF*deep* simulations' (Corr. to O3)
In this part of the project several options of the Noah-MP improved version of the WRF LSM will be tested allowing for a sensitivity study that will help in constraining the uncertainty associated to the multiple hydro-thermodynamics processes in the soil will be paid herein (such as freeze/thawing effects, runoff, etc.).

T3.1. '*Exploring* the role of a refined frozen water description'
This task will be devoted to investigating those processes not included in standard soil model schemes, like the *frozen non-linear soil permeability* and the *supercooled liquid water (or ice fraction)*. Also, a full implicit snow/soil temperature time scheme will be implemented.
T3.2. '*WRFdeep* historical (ERA5-driven) simulation including runoff and groundwater free drainage'
A physically consistent representation of vertical water flux usually lacks in soil modelling. This task will explore these issues in a long simulation where the long-term biases can be assessed.

T3.3. '*WRFdeep* historical (ERA5-driven) simulation where the lower boundary condition of soil temperature is zero heat flux from bottom'

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. This task will pay attention to the sensitivity to introducing a more realistic/deeper BBCP within the physical options of the LSM.

T3.4 '*WRFdeep* historical (ERA5-driven) simulation with all the above physical options (T3.1 + T3.2 +T3.3)

Finally, a simulation including all the increased realism soil physics (FULL-phys) options will be generated. The latter will allow a closing to the sensitivity analyses above and generating a simulation that will serve as the basis for the CMIP6 downscaling experiments in the next step with meaningful historical and future scenario experimental set ups.

T4: 'Historical and future projection analysis of trends and extreme variability based on CMIP6 downscaling experiments using the final revised WRF model version' (Corr. to O4)

This task will generate the historical and time slice scenario projections accounting for changes in climatic long-term trends and extremes occurrences (extreme wind, precipitation and drought events), both experienced in the past and expected under climate change conditions over the EU-MED CORDEX domain. An added value in this part of the project will be to generate maps of availability of wind and irradiances necessary to assess the future evolution of these renewable energy resources.

JUSTIFICATION OF THE RESOURCES REQUESTED

The Weather Research and Forecasting (WRF, Skamarock et al., 2019) model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. It features two dynamical cores, a data assimilation system, and a software architecture supporting parallel computation and system extensibility.

The large spatial (EURO CORDEX at 9 km) and temporal domain (a minimum of 30 years in a continuous way) with which we want to do the simulations, forces us to run the WRF model in an HPC architecture. To meet the computational requirements to achieve the goals of this special project, we have estimated that we will use 4.750.000 System Billing Unit (SBU) per task, as defined in https://confluence.ecmwf.int/display/UDOC/HPC+accounting#HPCaccounting-SystemBillingUnit(SBU), in addition we will need a storage capacity of about 2.5 TB per year of simulation.

Our goal would be performed about two task per year, totalizing the requested 9,500,00 USBs. per year. The storage will be managed to only keep the output of these simulations while temporary and extra output will be removed after the analysis.

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