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1. Technical references

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PP = Restricted to other programme participants (including the Commission Services)

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2. ABSTRACT

This deliverable describes the setup of a numerical modelling chain, allowing the downscaling of global climate projections up to local scales, meant for the production of high-resolution climate information for climate change impacts assessment with a focus on small scales and extreme events. We briefly describe the state of the art of climate modelling, highlighting both the importance of reaching very high resolutions and the difficulties posed by such a challenge.

We define and illustrate the protocol of the simulation (domain, scenarios) and the models chain adopted in the framework of DS8 of the RETURN project to meet the requirements posed by climate impact modellers: a double nesting of a regional climate model (RCM) nested within a General Circulation Model (GCM) to generate fine-resolution climate information which is also adequate to give the boundary conditions to convection-permitting models that could be run in limited areas following the needs of the impact researchers.

Some preliminary results of the simulations performed so far are shown in the last sections of this document.

The whole activity of task 4.1 will last till the end of the project, this document has to be intended as first interim report of Deliverable 8.4.1. Regular updates will be given.

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4. Proof of concept for the description of cloud dynamics in convection permitting models: first interim report

4.1 State of the art of high resolution climate modeling

4.1.1 From Global to Regional and Convection Permitting Models

Reliable climate information at regional scale is of primary importance for users and decision makers. The production of such kind of information undergoes a series of strict passages.

Global Models are the unavoidable tool for understanding how climate may change in the future under specific hypothesis of the increasing rate of greenhouse gases (scenarios), as they include all the relevant large scale forcings and simulate the large-scale circulation dynamics. Global Models include General Circulation Models (GCMs), both atmospheric-only (AGCMs) and coupled atmosphere-ocean models (AOGCMs), and Earth System Models (ESMs). The latter aiming to simulate the entire Earth System including chemical and biological processes and not only the atmospheric and ocean physics. State of the art global models have typical nominal horizontal resolution of 100-200 km, while the effective resolution is about 3 to 5 times larger (Klaver et al., 2020). To compare the results of the projections coming from different models, since 1995 the World Climate research programme (WCRP) launched the Coupled model Intercomparison Project (CMIP) which is now in its sixth phase (CMIP6). CMIPs define the standards for the simulations, and the multi-model approach allows to estimate errors and uncertainties in the model simulations due to the internal variability of the climate system and of climate models (Olonscheck and Notz, 2017). Recently, coordinated experiments using very high-resolution global models HighResMIP (at least 50 km) have addressed the point of enhanced horizontal resolution in global models (Haarsma et al., 2016). The main advantage of such simulations will be not only to better capture local processes with respect to standard GMs, but also the impact of teleconnections among distant regions and the possibility to provide directly the boundary conditions to high resolution Regional Climate Models. However, such efforts are highly computer demanding and the management of huge data volumes is challenging.

Although global models provide the first source of climate information also for the regional scale, particularly as to the attribution of the forced changes and to the quantification of the role of the internal variability, the dynamical downscaling by means of Regional Climate Models (RCMs) allows to represent at higher resolutions the complex phenomena that emerge over regions of complex orography or with heterogeneous surface characteristics (Doblas-Reyes et al. 2021), such as the Mediterranean basin and our national territory. As a matter of fact, the last Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR) acknowledged that regional climate information for impacts and risk assessment is increasingly robust and mature to feed climate services and impact studies with the higher resolution they need (Ranasinghe et al. 2021). RCMs are dynamical models like GCMs, as to the complexity of the physics processes resolved and/or parameterized, but they are defined on a limited area with a horizontal resolution much higher than GCMs and are implemented as a boundary condition problem, with boundary information provided by the GCMs, that act as drivers of the regional models. RCMs can both provide sub-continental climate information and improve process understanding. As well as for GCM, an initiative for the realization of coordinated experiments with RCMs has been realized. The COordinated Regional climate Downscaling Experiment (CORDEX) (Giorgi et al., 2009; Giorgi and Gutowski, 2015) provides multi-model ensemble of historical and future projections for various regions in the world. Typical resolutions for the CORDEX experiment range from 50 to 10 km. The CORDEX experiments include 14 different regions of the world, and among them the European region (EURO-CORDEX) and the Mediterranean region (MED-CORDEX, Ruti et al., 2016). EURO-CORDEX simulations are conceived as dynamical downscaling experiments from CMIP models performed with atmospheric RCMs at two different resolutions, a coarse one (0.44°) and a finer one (0.11°/12 km). While the The EURO-CORDEX experiment is more focused on the continental part of the domain, the MED-

CORDEX one is centered on the Mediterranean Sea and its originality consists in the use of regional coupled models, including at least the atmosphere, ocean and land components, or even more complex Regional Earth System Models, that include a representation of the biogeochemical processes of the Mediterranean Sea. The presence of the sea, and the air-sea interaction do affect the climate of our regions, being our territory particularly vulnerable to both hydrogeological risks (heavy rainfall, landslides, flooding) and coastal risks (regional sea level rise, marine heat waves) with effects on the health and economies of communities.

The physics processes that cannot be explicitly resolved at the resolution scale of the model's grid, either global or regional ones, are treated by means of parameterizations. A relatively recent thread in regional climate modelling consists in pushing model resolution to scales where deep convection can be solved explicitly rather than parameterized. At few kilometers of horizontal resolution (< 4 km) convection parameterization can be switched off. The interest in studying and simulating convection is mostly related to its high relevance in driving extreme events such as heavy precipitation, windstorms and floods. An extended review on regional convection-permitting climate modelling can be found in Prein et al., 2015 that highlights advantages and drawbacks of the method. Most of the efforts in this field are focused on the simulation of the climate over the European region. In Wahl et al., 2017, results from the first regional reanalysis on the convection permitting scale covering the central Europe domain at 2 km of horizontal resolution are presented. This work was based on an NWP version of the COSMO model and made use of data assimilation. The system was run for seven years between 2007 and 2013 and the precipitation field was analyzed, against both coarser reanalysis and in-situ observations. The results indicate that a grid spacing of 6 km is already sufficient to reproduce precipitation accumulations comparable to point observations, at least for accumulation times of 1 hour and more. On the other hand, the very high-resolution reanalysis performs better in the point-to-point evaluation of local precipitation events, which is due to the combination of data assimilation techniques, higher resolution and convection permitting model formulation.

In a more climate study perspective, the CORDEX initiative dedicated a Flagship Pilot Study whose major findings are described in Coppola et al., 2020, Ban et al.,2021 and Pichelli et al. 2021. Besides a first study of specific extreme events characterized by heavy precipitation phenomena (Coppola et al. 2020), the CORDEX-FPS produced a multi-model ensemble of simulations on a domain centered over the Alps, known as Great Alpine Region, extending latitudinally from 40°N to 49°N, and longitudinally from 1°E to 16°E, for several time slices covering a decade: 2000-2009 for ERA-interim reanalysis driven experiment (ensemble of 23 members, Ban et al.,2021), and 1996-2005, 2041-2050, 2090-2099 for RCP8.5 scenario simulations (12 members ensemble, Pichelli et al. 2021). The high-resolution CPM simulations in the hindcast period show better performance in reproducing high precipitation events and the diurnal cycle of precipitation. However large ensemble means appear more reliable than single model realizations, due to the wide ensemble spread. On the other hand, the kilometer-scale climate projections show important differences from the coarser resolution simulations. Although further study is needed to prove the robustness of the results, they seem encouraging towards the use of convection-permitting model ensembles to produce assessments of the local impacts of future climate change.

4.2 Model setup

4.2.1 Dynamical downscaling from CMIP6 drivers with nested RCMs

We use a double-nested domain to downscale the coarse global CMIP6 forcing data from a regional domain, covering the whole Europe, to a fine spatial scale domain centered over Italy. The first domain (D01) is projected on a Lambert conformal with a horizontal spatial resolution of 15 km, while the nested domain (D02) has a resolution of 5 km. The output from the nested domain D02 could be used for further downscaling at resolutions of the order of 1-2km using Convection-Permitting Models.

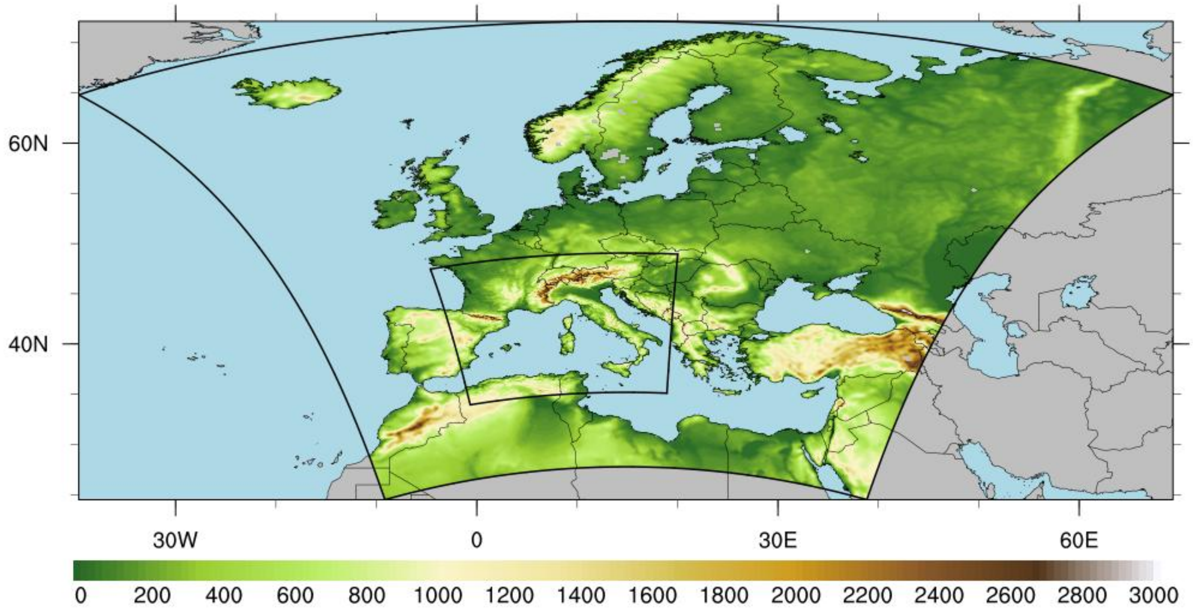

Figure 1: Model domains used for the downscaling with WRF regional model: European domain (D01-15km), national domain (D02- 5 km).

4.2.2 Simulation protocol

We produce a coherent set of high-resolution multi-scenario climate simulations based on the Weather Research and Forecasting model (WRF version 4.2.2, Skamarock et al. 2008) that employs hybrid vertical levels instead of sigma-p vertical coordinates. Moreover, we have implemented the microphysics and cumulus parameterization proposed by Morrison et al. (2009) and Janjić et al. (1994), respectively.

To validate the system a hindcast simulation initialized and forced through ERA5 (Hersbach et al. 2020) has been produced to reproduce present climate over the Euro-Mediterranean region for period 1980-2014 for domains D01 and D02.

For future impact assessment, a historical and three CMIP6 global scenario simulations (SSP1-2.6, SSP2-4.5, SSP5-8.5, Eyring et al. 2016; O'Neill et al. 2016) will be downscaled; in particular we have selected the CMIP6 MPI-ESM1-2-HR (Gutjahr et al. 2019) as driving model that uses the spatial grid T127 (0.93° or ~ 103 km). Among all the available CMIP6 models, in addition to the relatively high spatial resolution, we selected the MPI-ESM1.2-HR as it has a well-balanced radiation budget and its climate sensitivity is explicitly tuned to 3 K (Müller et al. 2018), making this model well suited for prediction and impact studies.

Both the present-climate experiments cover the period 1st August 1980-31st December 2014, while future climate simulations span the period 2015-2100.

Historical and scenario simulations on D01 have been started and are currently running.

4.3 Preliminary results

According to the simulation protocol described in the previous session, two hindcast simulations, on both the D01 and D02 domains, have been performed and completed using the ERA5 dataset as boundary condition. The simulations covered the period 1980-2014.

The aim of these kind of simulations is to test the performance of the model configuration in reproducing the current climate and allows the validation of the model against observational dataset and/or other reanalysis product. In the following we show some preliminary results showing the seasonal mean over the entire period of the near surface temperature (T2m) and of total precipitation. These variables belong to the category of Essential Climate Variables (ECVs). The Global Climate Observing System (GCOS - https://gcos.wmo.int/en/home) developed the concept of essential climate variables (ECVs), namely relevant parameters for the characterization of Earth's climate. ECVs can be either physical, chemical or biological, single or grouped (due to their joint concurrence in determining critical processes). They provide reliable, traceable, observation-based evidence that enables the accurate modelling and prediction that support policy development and adaptation planning, by helping scientists understand the drivers of past, current, and future climate variability (GCOS 2016). ECVs also provide a benchmark for climate model validation and guidance as to the essential variables that should constitute the standard output of any numerical experiment. Among ECVs, temperature and precipitation are known to affect a wide variety of processes and systems, with important consequences for natural ecosystems and human society.

4.3.1 Results from the hindcast run on D01

Figure 2 shows the seasonal mean of the near surface temperature, computed from the hindcast simulation performed on domain D01 at the coarse resolution of 15km over the European domain.

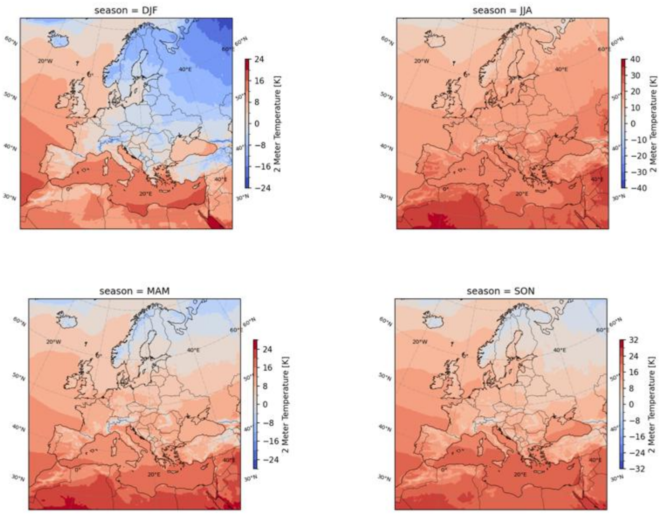

Figure 2: T2m (°C) on European domain (D01- 15km), seasonal means over 1980-2014

The seasonal means produced at the intermediate resolution correctly reproduce the latitudinal gradient of temperature. A different scale of the temperature has been used for the different seasons, to better represent the spatial patterns of the temperature.

Figure 3 shows the temporal evolution of the near surface temperature averaged over different subdomains covering the simulation domain. Such subdomains are known as Prudence domains and are used as standard regions for the evaluation of Euro-CORDEX climate simulations (see for example Kotlarski et al. 2014): BI-British Islands, IP-Iberian Peninsula, FR-France, ME-Middle Europe, SC- Scandinavia, AL-Alps, MD-Mediterranean, EA-Eastern Europe. Figure 3 shows that the hindcast simulation closely follows the interannual variability of the driver for all the subdomains. Some slight biases, within 0.5°C can be seen in the IP, MD and SC domains, and they are within the standard deviation of the interannual variability of the period.

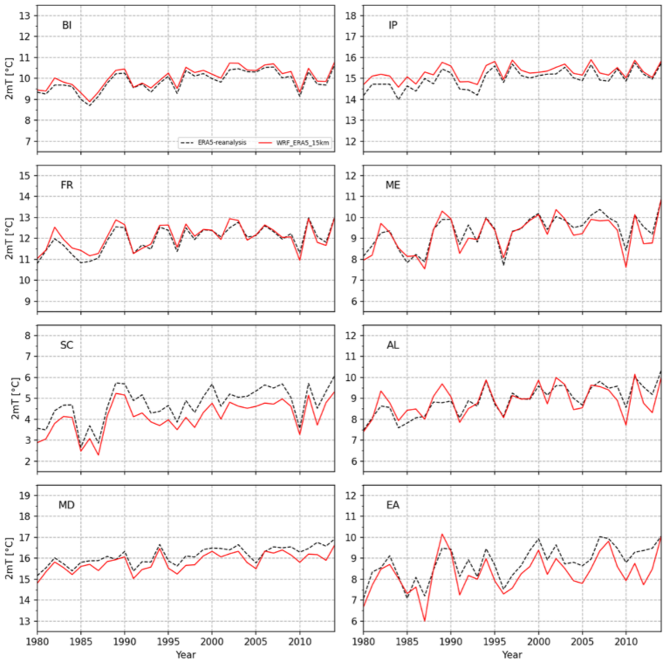

Figure 3: Interannual variability of the T2m(°C) on the Prudence subdomains: black dashed line: ERA5 reanalyses, red line: hindcast simulation D01-15Km.

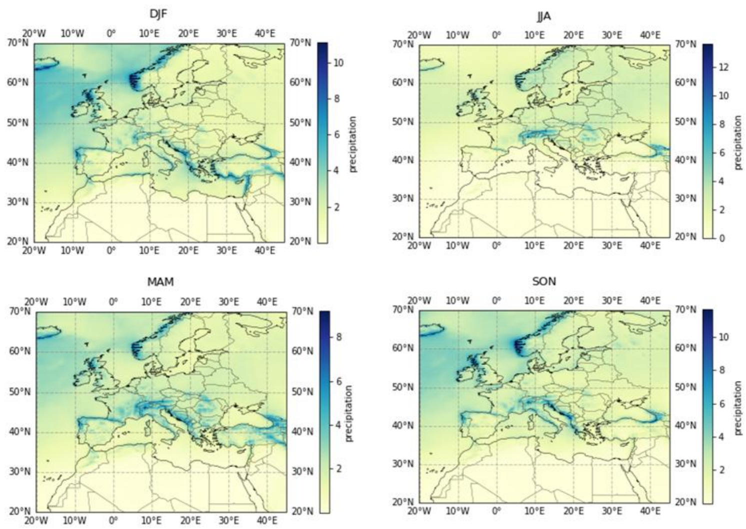

Figure 4: Precipitation on European domain (D01- 15km), seasonal means over 1980-2014

Figure 4 shows the seasonal mean of the precipitation, computed from the hindcast simulation performed on domain D01. The seasonal means correctly reproduce the known spatial distribution of precipitation over the European domain, characterized by the orography.

4.3.2 Results from the hindcast run on D02

Figures 5 and 6 respectively show the seasonal mean of the near surface temperature and of precipitation, computed from the hindcast simulation performed on domain D02 at the finest resolution of 5km.

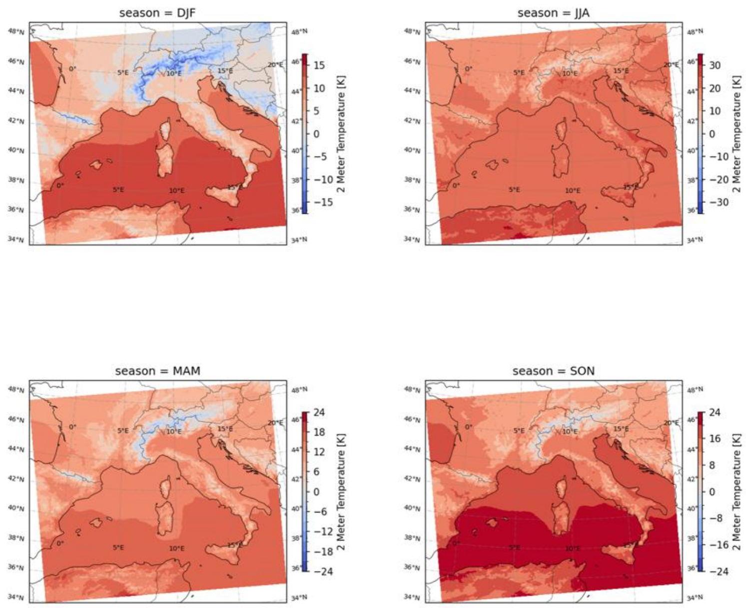

Figure 5: T2m on the inner domain (D02-5km)

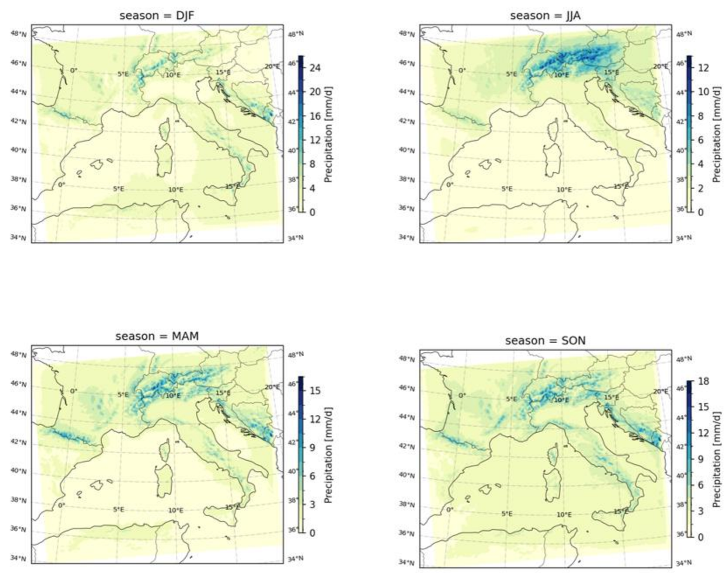

Figure 6: Precipitation on the inner domain (D02-5km)

This simulation used the results of the simulation at D01 as boundary condition, so it includes both the effects of the first dynamical downscaling and the effects of the high-resolution on D02, which are particularly evident in the alpine zone where the details of orography can be captured.

5. Conclusions

A numerical modelling chain to produce multi-scenario simulations at different resolution has been realized.
A protocol simulation has been defined and its effectiveness has been proven using the ERA5 dataset as global driver. The realization of the hindcast run is of primary importance as it allows to test the ability of the numerical instrument to reproduce the current climate and to validate the system against the reanalysis and observational datasets.
Preliminary results of the hindcast simulation have been shown, further analyses will be done and presented in the subsequent releases of the deliverable, together with results of future scenario simulations.

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