Highlander

High performance computing
to support smart land services

# D4.1 Datasets of downscaled ERA5 reanalysis over Italy

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# Index

# 1 Executive Summary

This document describes the experiment and the preliminary results of the first climate simulation performed by CMCC on CINECA supercomputer cluster Galileo, in the framework of Highlander project, and concerning the dynamical downscaling over Italy of the ERA5 reanalysis from their native resolution (≈31 km) to a resolution of about 2 km.

# 2 Reanalysis

## 2.1 What is a reanalysis

A reanalysis "delivers a complete and consistent picture of the past weather" (https://youtu.be/FAGobvUGl24) through the data assimilation of historical observations provided by different sources (satellite, in situ, multiple variables) but not homogeneously distributed around the globe, within a single consistent numerical weather prediction model.

## 2.2 ERA5 Reanalysis

ERA5 represents the latest climate reanalysis produced by the European Centre for Medium Range Weather Forecast (ECMWF), providing hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty (Hersbach et al. 2020). ERA5 data are available on the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) on a regular latitude-longitude grid at 0.25° x 0.25° resolution, with atmospheric parameters on 37 pressure levels. Currently, ERA5 cover the period from 1950 to the present. It continues to be extended forward in time, with daily updates being available 5 days behind real time. Initial release data, i.e., data no more than three months behind real time, is called ERA5T.

ERA5 data are being used by a wide range of applications such as monitoring climate change, research, education, policymaking and business, in sectors such as renewable energy and agriculture (Buontempo et al., 2020). It forms the basis for monthly C3S climate bulletins, and it is used in the World Meteorological Organization's (WMO) annual assessment of the State of the Climate presented at the Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC).

## 2.3 Potential improvements

Despite the noticeable ERA5 step forward, its coarse resolution (0.25°, ~ 31 km) and some assumptions made in sub-grid parameterisations could not match the requirements for applications, e.g., related to extreme precipitation or local impacts over specific areas of interest. In this perspective, the ongoing developments of convection-permitting regional climate models (CP-RCMs, resolution < 4 km) are providing a possible solution to partly cover this gap. CP-RCMs represent a step change in the capability for understanding past climate and future climate change at local scales and for extreme weather events that most impact society (Kendon et al., 2021). This includes, for the first-time, credible data for short-duration precipitation extremes, as CP-RCMs resolution avoids the use of error-prone deep convection parameterization schemes, responsible in some cases of a misinterpretation of precipitation patterns and trends.

Some European initiatives (e.g., H2020 EUCP, CORDEX-FPS convection, Special Project SPHERA), and an increasing number of scientific works (e.g., Ban et al., 2014; Berthou et al., 2018; Coppola et al., 2020; Fumière et al., 2020; Reder et al., 2020; Fosser et al., 2015; Prein et al., 2015; Piazza et al., 2019; Adinolfi et al., 2021; Raffa et al., 2021; Ban et al., 2021) are providing a reference baseline to demonstrate the added value of this specific configuration. Such an improvement can be noted in a more accurate representation of some features, e.g., the diurnal cycles, hourly precipitation intensities, local–regional circulations, seasonal average precipitation, convective downdrafts, and the representation of cold pools (Coppola et al., 2020; Fowler et al., 2021).

All these insights are encouraging the climate community to deeply investigate the potential added values of CP-RCMs including urban parameterizations for a more adequate representation of climate condition over urban areas, especially for the extremes.

# 3 Regional Climate Model with Urban parameterization: COSMO-CLM with TERRA-URB

COSMO-CLM (Rockel et al., 2008) is a non-hydrostatic limited-area model designed for climate simulations at different horizontal resolution, varying from the meso-$\beta$ scale (~ 20-200 km) to the meso-$\gamma$ one (~ 2-20 km). Such a model exploits finite difference methods to solve on a structured grid the fully compressible governing equations of fluid dynamics.

Specifically, vertical advection computations rely on a fifth-order upwind scheme whereas horizontal advection computation relies on an implicit Crank–Nicholson scheme (Baldauf et al., 2011). As for time integration, COSMO-CLM makes use of a split-explicit third order Runge–Kutta discretization scheme (Wicker and Skamarock, 2002). Cloud microphysics are represented with a single moment scheme by using five hydrometeors (cloud water, rain, ice crystals, snow, and graupel) (Reinhardt and Seifert, 2006).

The radiation scheme is based on a d-two-stream approach as described in Ritter and Geleyn (1992). Turbulent fluxes within the planetary boundary layer are parameterized with a 1.5-order turbulent kinetic energy (TKE)-based scheme (Mellor and Yamada, 1982). The standard parameterization of convection used in the model is based on Tiedtke (1989). Tiedtke scheme is a mass-flux closure approach used to parameterize modifications to the vertical structure of the atmosphere due to deep, midlevel, and shallow convection. If the convection is explicitly solved, only the shallow convection part of the scheme is active, while for deeper clouds the scheme is turned off.

The atmosphere is coupled with the underlying surface through a stability and roughness-length dependent surface flux model, acknowledged as TERRA_ML (Doms et al., 2011). Such a model computes surface fluxes by simultaneously solving a separate set of equations describing thermal and hydrological processes within the soil. With respect to the original formulations, a new scheme for water runoff (Schlemmer et al., 2018), dependent on orography, is considered.

To properly parameterize urban physics in COSMO-CLM, a bulk scheme acknowledged as TERRA-URB (Wouters et al., 2016) can be introduced. Such a scheme makes use of a tile approach to discern for each grid cell between urban canopy and natural land cover and compute adjusted soil and water fluxes considering urban environment features. Synthetically, TERRA-URB parameterization relies on:

(i) the application of the Semi-empirical URban canopY (SURY) scheme; it translates urban-canopy parameters containing the three-dimensional urban-canopy information into bulk parameters (De Ridder et al., 2012; Demuzere et al., 2008) by assuming appropriate parameters for albedo, emissivity, heat capacity and heat conductivity and aerodynamic roughness length;

(ii) the representation of buildings and pavements on top of the natural soil; it allows a comprehensive representation of the heterogeneous urban environment consisting of impervious surfaces, bare soil, vegetation, water puddles and snow cover;

(iii) the introduction of a new bare-soil evaporation resistance formulation and vegetation skin-temperature parameterization (Schulz et al., 2016).

# 4 Downscaling activity of ERA5 with COSMO-CLM Regional Climate Model over Italy

## 4.1 Experimental Setup and Nesting Strategy

ERA5 is dynamically downscaled at the convection permitting scale (0.02°, ~ 2.2 km) over Italy (Lon = 5°W-20°E; Lat = 36°N-48°N) for the period 01/1989 – 10/2020, assuming 1988 as spin up[1].

The downscaling is performed with the regional climate model COSMO-CLM (Rockel et al., 2008) switching on the module TERRA-URB (Wouters et al., 2016) for accounting the urban parameterizations.

*Figure 1 displays the computational domains used for the downscaling activity while*

Table 1 reports the main features of the experiment configuration.

[1] Climate simulation required to add an additional 1 year of simulation for soil moisture initialisation (permitting to the soil model to reach the steady state). This additional year is not considered in the post-processing phase.

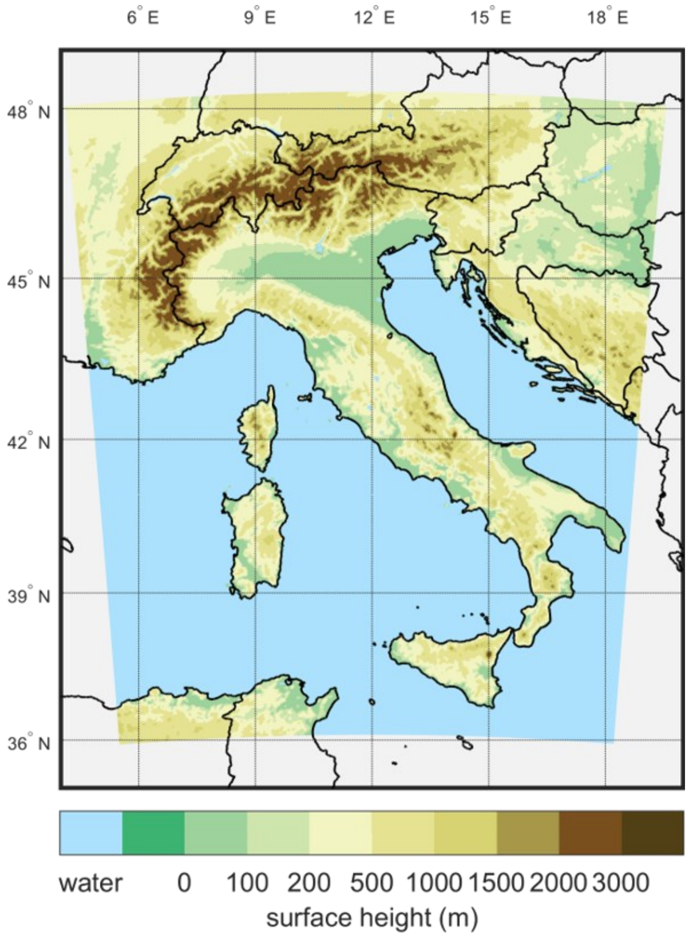



*Figure 1: Computational domain*

*Table 1: Experiment configurations (Raffa et al., 2021)*

| **Model** | **VHR-REA_IT** |
|---|---|
| Boundary forcing | ERA5-Reanalysis |
| Horizontal resolution | 0.02° (~2.2 km) |
| Time step | 20 s |
| N° grid points | 585 x 730 |
| N° vertical levels | 50 |
| Output frequency | 1 h |
| Sponge zone | 25 grid points |
| Radiation scheme | Ritter and Geleyn (1992) |
| Convection scheme | Shallow convection based on Tiedtke (1989) |
| Microphysics scheme | Doms et al. (2011); Baldauf and Schulz (2004) |
| Land surface scheme | TERRA-ML (Doms et al., 2011) with TERRA-URB (Wouters et al., 2016) parametrization |

| | |
|---|---|
| Land use | GLC2000 (Bartholomé and Belward, 2005) |
| Planetary boundary layer scheme | Mellor and Yamada (1974) |
| Lateral Boundary Condition (LBC) update frequency | 3 h |
| Soil initializations | Temperature and moisture obtained by interpolation from ERA5-Reanalysis |

The configuration relies on the optimized COSMO-DE setup, resulting from the protocol established in the frame of the Coordinated Downscaling Experiment (CORDEX) (Giorgi et al., 2015; Jacob et al., 2014) of the World Climate Research Programme (WCRP) for the Flagship Pilot Study (FPS) on convection (Coppola et al., 2020). Such an FPS focuses on the investigation of convective-scale events in a few key regions of Europe and the Mediterranean basin with convection-permitting regional climate models.

The setup was borrowed from the ERA5 evaluation downscaling experiments performed by Raffa et al. (2021) over part of central Europe, including some cities such as Cologne (Germany) and Paris (France). These experiments were performed to identify the most reliable nesting strategy to be adopted for localizing ERA5 climate signal at convection permitting scale (~ 2.2 km) with COSMO-CLM switching on the module TERRA-URB in the view of derive precipitation characteristics at city scale or at the event scale. Specifically, Raffa et al. (2021) tested and evaluated two nesting strategy: the former, labelled as “CCLM002-Direct”, relying on a one-step nesting strategy in which the simulation at 2.2km is directly “one-way nested” in ERA5 (1:15 resolution jump); the latter, labelled as “CCLM002-Nest”, considering a “two-step nesting strategy” in which the simulation at 2.2 km is one-way nested in a 12 km grid spacing which in turn is one-way nested in ERA5 (1:3:6 resolution jump).

The Authors pointed out that CCLM002-Direct outperforms CCLM002-Nest if it is evaluated at the city scale or at the event scale. Specifically, at the city scale, CCLM002-Direct well-reproduces trends and peaks of monthly precipitation amounts at city scale and well-recognizes timing and intensity of the rainfall events at the event scale. This tendency was ascribed to the fact that CCLM002-Nest is driven at the Lateral Boundary Condition (LBC) by a freely evolving (i.e., not nudged) intermediate simulation allowing internal variability to develop (Coppola et al., 2020). For this reason, events at the meteorological scale and over a very limited area of interest could not be correlated with ERA5. Conversely, such a tendency seems to be attenuated when CCLM002 is directly nested into ERA5. For this reason, for the aim of this activity, the produced dataset (VHR-REA_IT hereafter) is directly “one-way nested” in ERA5 to ensure reliability, coherence, and consistency as for climate statistics as for limited area and periods (e.g., city scale).

Figure 2 shows the operative simulation workflow adopted for this study.

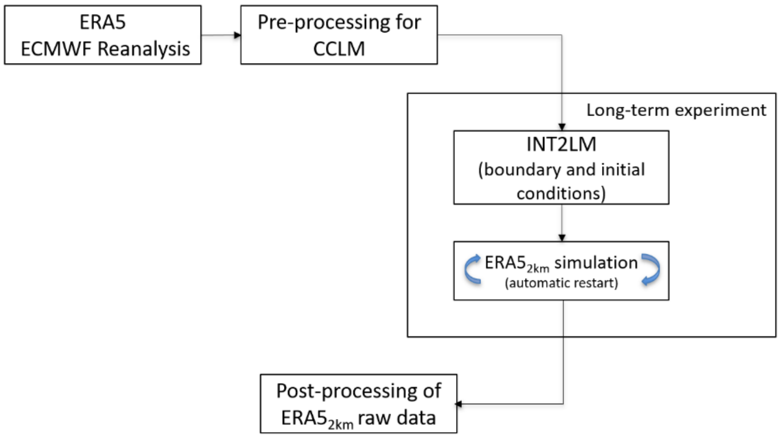



*Figure 2: Simulation workflow*

Specifically, ERA5 data are firstly pre-processed to be adapted for COSMO-CLM simulation within the COSMO-CLM community, with the support of Helmholtz-Zentrum Geesthacht (HZG) and Deutscher Wetterdienst (DWD). The pre-processed data are then used as input for the interpolation pre-processor (INT2LM) to generate the initial and boundary conditions on the VHR-REA_IT grid. Finally, a long-term climate simulation is performed setting-up an automatic restart procedure to avoid potential interruptions of simulation.

## 4.2 Data Description

*Table 2: Overview of key characteristics of the Downscaling at very fine resolution of ERA5 reanalysis over Italy by COSMO-CLM for 1989-2020 dataset*

| | |
|---|---|
| **Dataset title** | Downscaling at very fine resolution of ERA5 reanalysis over Italy by COSMO-CLM for 1989-2020 |
| **Dataset acronym** | VHR-REA_IT |
| **Description** | The dataset contains dynamically downscaled ERA5 reanalysis, originally available at ≈31 km x 31 km horizontal resolution, to 2.2 km x 2.2 km. Dynamical downscaling has been conducted directly for the project (foreground) through Regional Climate Model (RCM) COSMO5.0_CLM9 e INT2LM 2.06. The temporal resolution of outputs is hourly (like for ERA5). Runs cover the whole Italian territory (and neighbouring areas according to the necessary computation boundary) so to provide a very detailed (in terms of space-time resolution) and comprehensive (in terms of meteorological fields) dataset of climatological data for at least the last 30 years (01/1989-10/2020).<br>Typical use of similar dataset is (applied) research and downstream services (e.g., for decision support system) |
| **Data type** | Model-generated data (numerical)<br>• Re-analysis downscaling |
| **Dataset archiving and preservation** | Raw dataset (model output) will be stored at CINECA and a copy will be archived at the CMCC supercomputing centre.<br>Data will be stored for the entire project duration and will be available also at the end of the project |
| **Dataset security** | CINECA backup storage architectures |
| **Dataset owner/provider** | Fondazione CMCC |
| **Dataset manager** | Fondazione CMCC |
| **Dataset Reference Person** | Name/Last name: Paola Mercogliano<br>Affiliation: Fondazione CMCC<br>E-mail: paola.mercogliano@cmcc.it |
| **Dataset Author** | Name/Last name: Mario Raffa<br>Affiliation: Fondazione CMCC<br>E-mail: mario.raffa@cmcc.it |
| **Data source** | COSMO-CLM model |
| **Data licence** | The use of the COSMO CLM model is completely free of charge for all research applications.<br>The use of COSMO-CLM generated data within HIGHLANDER is free for partners (acting as intermediate users) for the project’s purposes; the use for other purposes (and by further external end-users) requires an appropriate disclaimer and if additional data post-processing (e.g., fields elaboration or new formats) is required, this can be agreed on after discussing with Dataset Manager/Owner/Provider |

| | |
|---|---|
| **How are data made accessible to end-users** | Data access tools will be provided, and sub-set of data will be made available, as agreed during the project, through the HIGHLANDER WEB portal/Catalogue |
| **Physical characteristics (Main variables)** | See Table 3 |
| **Dimensions** | time, longitude, latitude, single vertical level |
| **Data input format** | NetCDF (Climate and Forecast (CF) Metadata Convention; http://cfconventions.org/) both for input and output format. Exceptions under CF are however compliant with the UNIDATA Common Data Model (CDM) to codify the Coordinate Reference System (https://www.unidata.ucar.edu/software/netcdf-java/v4.6/CDM/index.html) |
| **Data spatial structure** | Rotated grid |
| **Update frequency** | None |
| **Real time availability** | No |
| **Data quality control** | Yes |
| **Increase of dataset size per month (in case of (near) real time)** | The dataset will be provided una-tantum, so no increase of the dataset size is expected (Total size < 13 TB) |
| **Temporal coverage** | 01/01/1989 00:00 to 31/10/2020 23:00 (the 1 year spin up period 1988 is excluded) |
| **Temporal resolution** | 1 h |
| **Spatial extent (Horizontal coverage)** | Latitude range: 36°N-48°N<br>Longitude range: 5°W-20°E |
| **Coordinate System** | WGS84 EPSG 4326 |
| **Spatial resolution (Horizontal resolution)** | ≈2.2 km x 2.2 km (irregular/rotated pole grid) |
| **Vertical coverage** | Surface, 2 or 10 meters from surface, or 1,3,9,27,81,243,729 cm depth depending on the variable |
| **Vertical resolution** | All output variables are on single levels except soil moisture provide for 7 soil levels. |

## 4.3 Variable Description

*Table 3: Overview and description of variables*

| **Variables** | | | |
|---|---|---|---|
| **Long-Name** | **Short-Name** | **Units** | **Description** |
| 2m temperature | T_2M | K | Temperature of air at 2 m above surface |
| 2m dew point temperature | TD_2M | K | Temperature to which the air, at 2 m above surface, would have to be cooled for saturation to occur |
| Total precipitation | TOT_PREC | $kg/m^2$ | Accumulated liquid and frozen water, comprising rain and snow, that falls to the surface |
| U-component of 10m wind | U_10M | m/s | Eastward component of the 10m wind |
| V-component of 10m wind | V_10M | m/s | Northward component of the 10m wind |
| 2m maximum temperature | TMAX_2M | K | Maximum temperature of air at 2 m above surface |
| 2m minimum temperature | TMIN_2M | K | Minimum temperature of air at 2 m above surface |
| mean sea level pressure | PMSL | Pa | The pressure (force per unit area) of the atmosphere at the surface |
| specific humidity | QV_2M | kg/kg | The mass fraction of water vapor in (moist) air |
| total cloud cover | CLCT | 1 | Proportion of a grid box covered by cloud; cloud fractions vary from 0 to 1 |
| Surface Evaporation | AEVAP_S | $kg/m^2$ | Accumulated amount of water that has evaporated from the surface |
| Averaged surface net downward shortwave radiation | ASOB_S | $W/m^2$ | Amount of solar radiation (also known as shortwave radiation) that reaches a horizontal plane at the surface (both direct and diffuse) minus the amount reflected by the surface (which is governed by the albedo) |
| Averaged surface net downward longwave radiation | ATHB_S | $W/m^2$ | Thermal radiation (also known as longwave or terrestrial radiation) refers to radiation emitted by the atmosphere, clouds and the surface. This parameter is the difference between downward and upward thermal radiation at the surface |
| Surface snow amount | W_SNOW | m | Liquid water equivalent thickness of surface snow amount |
| Soil (multi levels) water content | W_SO | m | Liquid water equivalent thickness of moisture content of soil layer |

# 5 Evaluation

This section shows the results of a preliminary evaluation activity performed for VHR-REA_IT data in terms of temperature (i.e., 2m temperature) and precipitation (i.e., Total precipitation). Specifically, these variables are assessed by assuming as reference daily precipitation and daily temperature included into gridded observational dataset E-OBS v. 23.1 (Cornes et al., 2018; Haylock et al., 2008); such an assessment is also performed with respect to ERA5 to detect the potential added value of VHR-REA_IT against its parent reanalysis.

E-OBS represents a daily gridded land-only observational dataset over Europe at a horizontal resolution of 0.1° (~11 km) for the period 1950-2020[2], containing data for precipitation amount, mean/maximum/minimum temperature, sea level pressure, and surface shortwave downwelling radiation. E-OBS relies on the "blended" time series from the station network of the European Climate Assessment & Dataset (ECA&D) project. It is calculated following a two-stage process to derive the daily field and the uncertainty in these daily estimates.

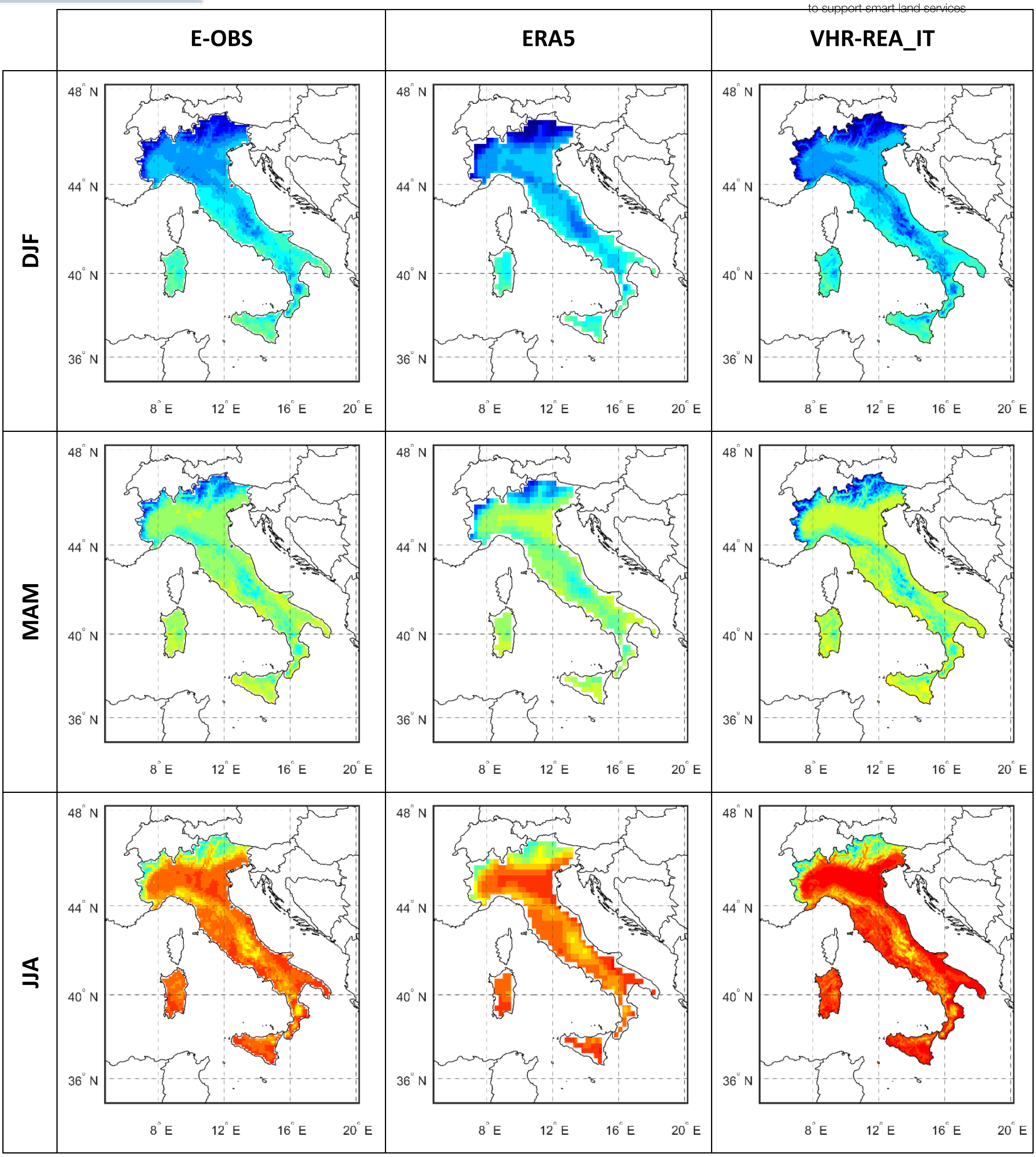
While E-OBS represents a valuable resource for climate research in Europe, some limitations in the dataset exists and taking it as reference does not mean it represents the reality but rather a useful independent product for comparison purposes (e.g., Prein and Gobet, 2017).

## 5.1 Temperature

Figure 3 shows the seasonal spatial distribution of temperature computed for the period 1989-2020 with E-OBS, ERA5, and VHR-REA_IT, respectively.

Table 4 reports the average temperature over Italy provided by three datasets; moreover, for each dataset, it is also reported the standard deviation and bias (model – observation).

[2] The evaluation analysis is performed over the period starting from January 1989 up to October 2020 (as reported in the table) then only 10 months are covered in 2020 because November and December are not simulated.


E-OBS
ERA5
VHR-REA_IT
DJF
MAM
JJA
48° N
44° N
40° N
36° N
8° E
12° E
16° E
20° E

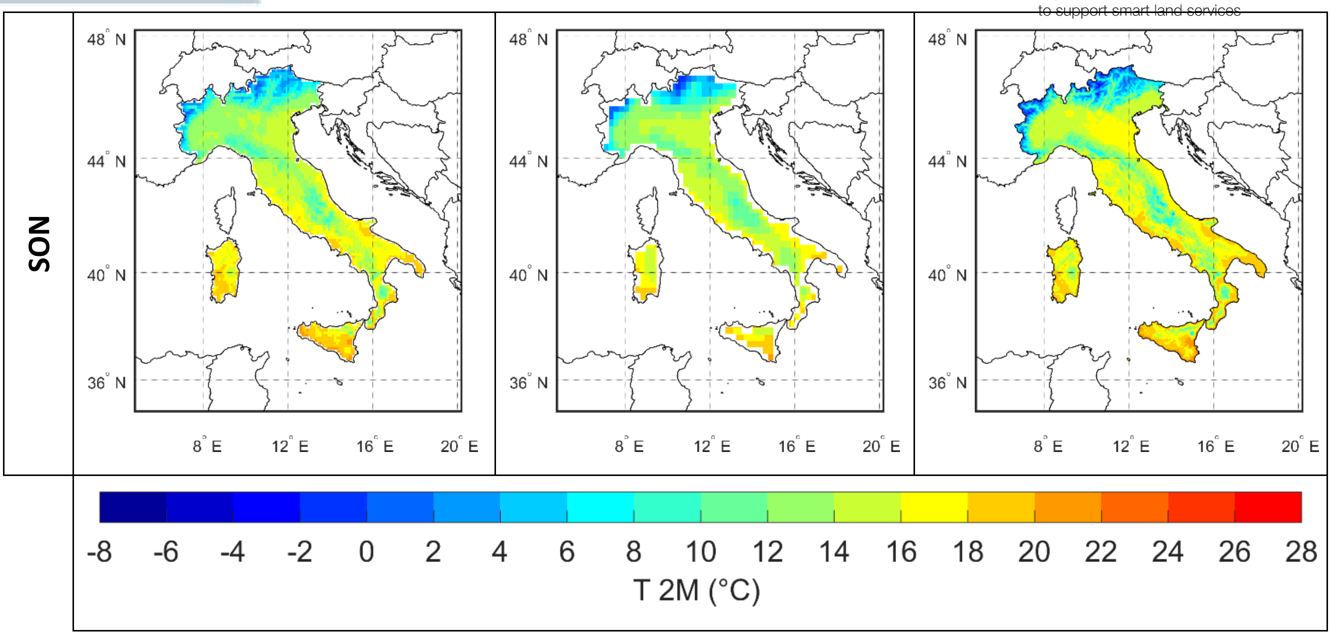



*Figure 3: Seasonal (in row) spatial distribution of temperature for the period 1989-2020 provided by E-OBS, ERA5, and VHR-REA_IT (in column).*

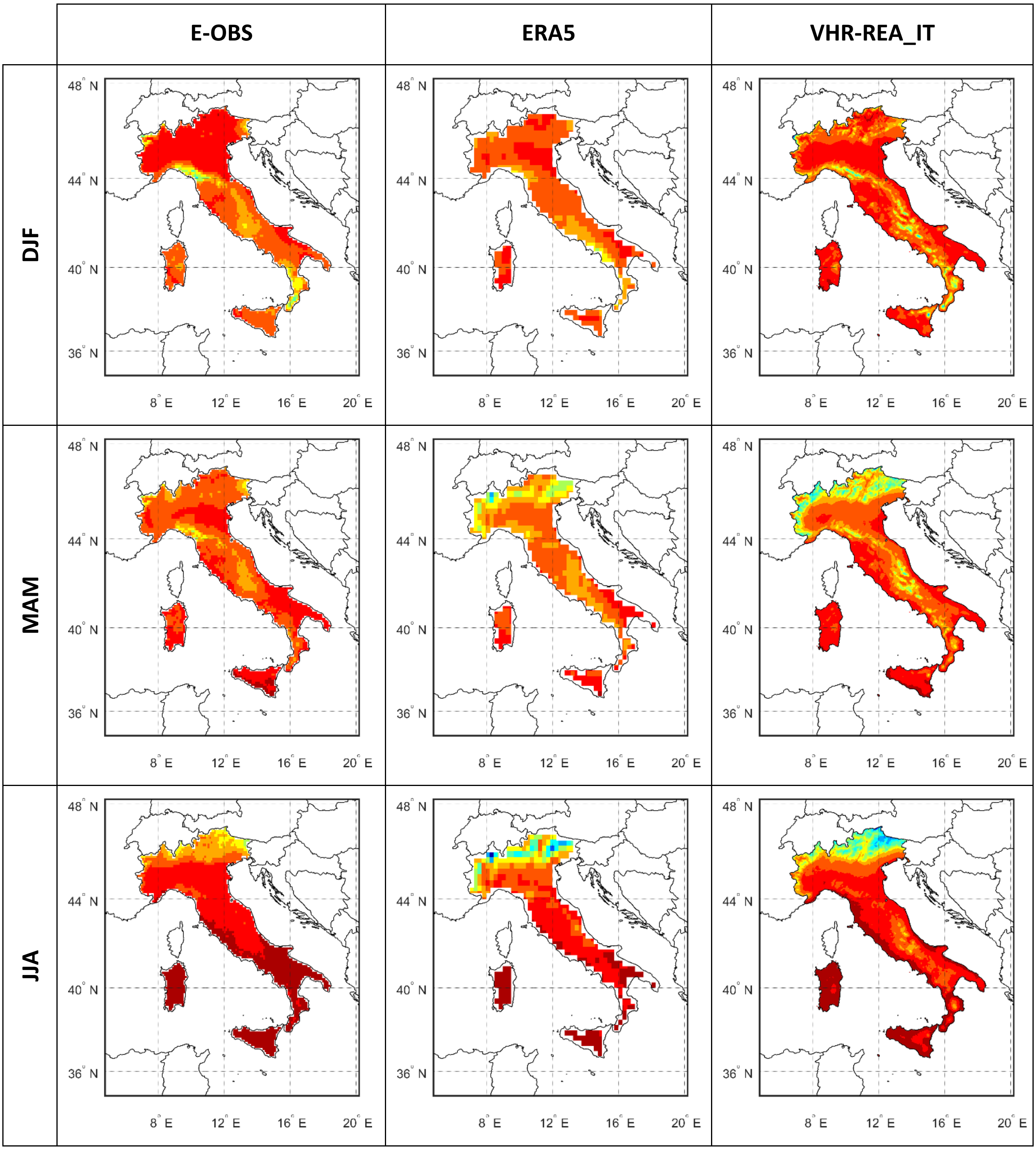
*Table 4: Average temperature (°C) for Italy over 1989-2020 provided by E-OBS, ERA5 and VHR-REA_IT. For each dataset, it is reported standard deviation and bias.*

| | | E-OBS | ERA5 | VHR-REA_IT |
|---|---|---|---|---|
| **DJF** | *Mean (°C)* | 5.3 | 4.8 | 4.6 |
| | *Dev. St. (°C)* | 4.1 | 4.7 | 4.1 |
| | *Bias (°C)* | - | -0.5 | -0.7 |
| **MAM** | *Mean (°C)* | 11.7 | 11.7 | 12.3 |
| | *Dev. St. (°C)* | 3.6 | 3.6 | 4.2 |
| | *Bias (°C)* | - | -0.1 | 0.6 |
| **JJA** | *Mean (°C)* | 21.4 | 21.5 | 23.3 |
| | *Dev. St. (°C)* | 3.8 | 3.7 | 4.5 |
| | *Bias (°C)* | - | 0.1 | 1.9 |
| **SON** | *Mean (°C)* | 13.9 | 13.8 | 14.4 |
| | *Dev. St. (°C)* | 4.1 | 4.1 | 4.4 |
| | *Bias (°C)* | - | -0.2 | 0.5 |

## 5.2 Precipitation

Figure 4 shows the seasonal spatial distribution of daily precipitation for the period 1989-2020 provided by E-OBS, ERA5, and VHR-REA_IT, respectively.

Table 5 reports the average daily precipitation over Italy provided by three datasets; moreover, for each dataset, it is also reported the standard deviation and bias (model – observation).



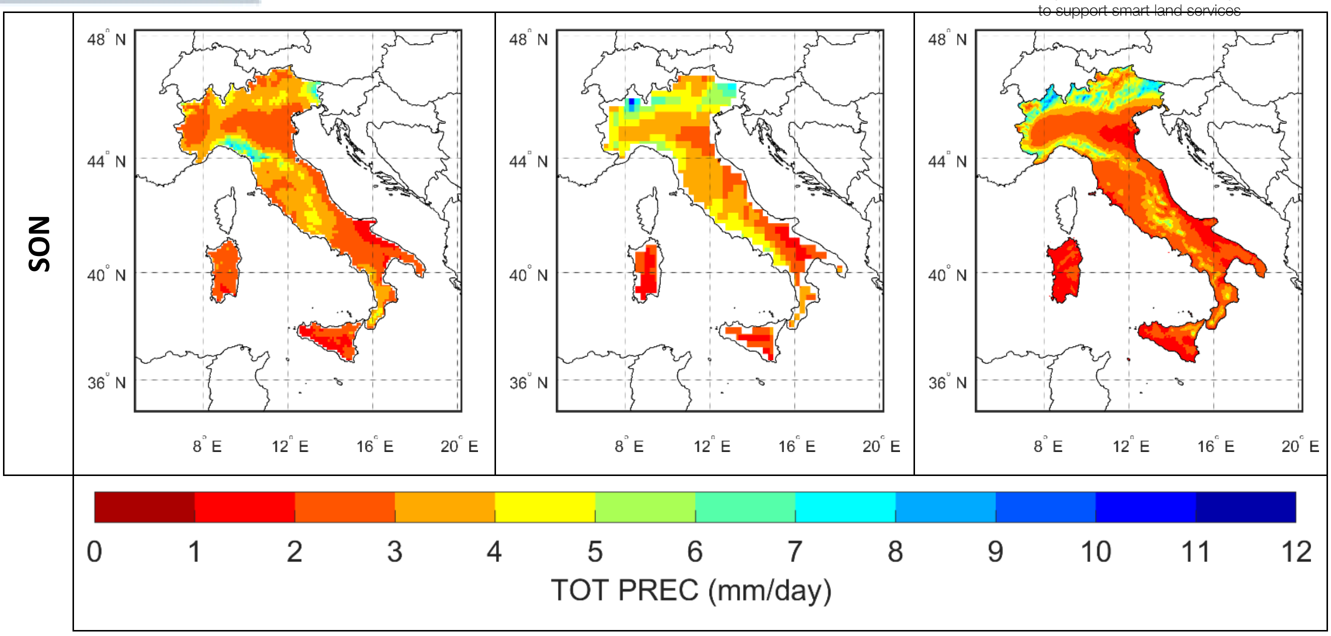



*Figure 4: Seasonal (in row) spatial distribution of daily precipitation for the period 1989-2020 provided by E-OBS, ERA5, and VHR-REA_IT (in column).*

*Table 5: Average daily precipitation (mm/day) for Italy over 1989-2020 provided by E-OBS, ERA5 and VHR-REA_IT. For each dataset, it is reported standard deviation and bias.*

| | | E-OBS | ERA5 | VHR-REA_IT |
|---|---|---|---|---|
| **DJF** | *Mean (mm/day)* | 2.27 | 2.54 | 2.27 |
| | *Dev. St. (mm/day)* | 0.88 | 0.63 | 0.94 |
| | *Bias (mm/day)* | - | 0.27 | 0.00 |
| **MAM** | *Mean (mm/day)* | 2.15 | 2.86 | 2.67 |
| | *Dev. St. (mm/day)* | 0.70 | 1.02 | 1.34 |
| | *Bias (mm/day)* | - | 0.71 | 0.53 |
| **JJA** | *Mean (mm/day)* | 1.44 | 2.16 | 2.05 |
| | *Dev. St. (mm/day)* | 1.09 | 1.81 | 1.69 |
| | *Bias (mm/day)* | - | 0.72 | 0.62 |
| **SON** | *Mean (mm/day)* | 3.02 | 3.52 | 2.97 |
| | *Dev. St. (mm/day)* | 0.97 | 1.25 | 1.36 |
| | *Bias (mm/day)* | - | 0.50 | -0.05 |

# 6 Conclusions

The document reports a general description of the first dataset of climate simulation running on the CINECA supercomputer in the framework of the Highlander project. More specifically the simulation concerns a climate dataset covering the period 1989-2020 (2020 year is covered only up to October). The simulation is obtained by the dynamical downscaling over Italy of the ERA5 reanalysis at a resolution of about 2 km. The model output, established in agreement with HIGHLANDER project partners, are now available for DApOS analysis.

In the next months, additional simulations are planned in order to provide over the same area also climate projection permitting the assessment and evolution of the climate-related impact considered in the project.

Moreover, preliminary analysis, to be completed in the next months, attests the reliability of the output by comparing them with other state of art dataset available over Italy (E-OBS and ERA5). Specifically, the results will be validated by comparing output with different independent high resolution observational datasets, available at high resolution at regional level and also evaluating the performance of the dataset on specific regional context for specific properties characterizing temperature and precipitation patterns (e.g., frequency and magnitude of more extreme events).

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