REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Italy

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Project Title: Numerical modeling of precipitation climatology and its sensitivity to climate change effects on the Apennines Mountains

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.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	5.000.000	5.000.000	5.000.000
Accumulated data storage (total archive volume)[2]	[GB]	10 TB	10 TB	10 TB

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

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

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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 10,000,000 SBU should be more detailed (3-5 pages).

Summary

Recent analyses of satellite and surface observations have reported a negative annual precipitation trend in central Italy. The complex orography of the Apennines and the strong influence of climate change in the Mediterranean basin complicate the explanation of such trends and their spatial variability. As a first step towards understanding such climate trends, previous work by Silvestri et al. (2022) described the link between circulation weather types, orography and precipitation patterns observed in central Italy.Using ERA5 reanalysis data from 1951 to 2019, four weather types were identified as most responsible for the spatial variability of rainfall in central Italy. They are associated with cyclonic circulations characterised by high water vapour transport from the west, south-west, south-east and north-east. The analysis of the wind speed and precipitation climatology for the period 1951-2019, derived from both surface observations and reanalysis, confirms a strong influence of humid southwesterly fluxes over the whole area, while the effect of northeasterly fluxes remains limited to the Apennines and the Adriatic coast.

However, ERA5 overestimates annual precipitation in most parts of the region, except in the north-central Apennines, where the underestimation reaches average values of 300 mm. The analysis of the circulation weather types and their associated precipitation variability shows that this deficit can be attributed to a misrepresentation of the orographic precipitation component, as seen by ERA5 in the correspondence of cyclonic northeasterly and westerly flows impinging on the north-central Apennines. In fact, the precipitation associated with northeasterly and westerly flows showed the strongest modulation by orography.

Based on the above analysis, we cannot rely only on the global ERA5 reanalysis to understand the physical mechanisms underlying the climatological spatial distribution of precipitation in the complex terrain of the Apennines. Therefore, in this project we will use previous work by Silvestri et al. (2022) to derive from ERA5 a set of idealised initial conditions representative of each circulation weather type responsible for rainfall in central Italy. We will then try to reproduce the observed precipitation climatology by forcing a cloud-resolving model with such idealised conditions, with a finer horizontal grid resolution, in order to better resolve the orographic component of precipitation. The final objectives of this project are

1. Understand and explain the observed precipitation climatology over central Italy.
2. Understand and explain the recent climate trends observed in the precipitation climatology especially over the Apennines.
3. Generalise and build theoretical models for the effects of climate change on orographic convection and precipitation.

Motivation

Significant negative annual rainfall trends (see Figure 1) have been observed in Central Italy from recent analyses conducted both on satellite products [NASA's Tropical Rainfall Measurement Mission TRMM, Kalimeris and Kolios, 2019] and surface raingauge observations [Pavan et al., 2019, Caporali et al., 2021].

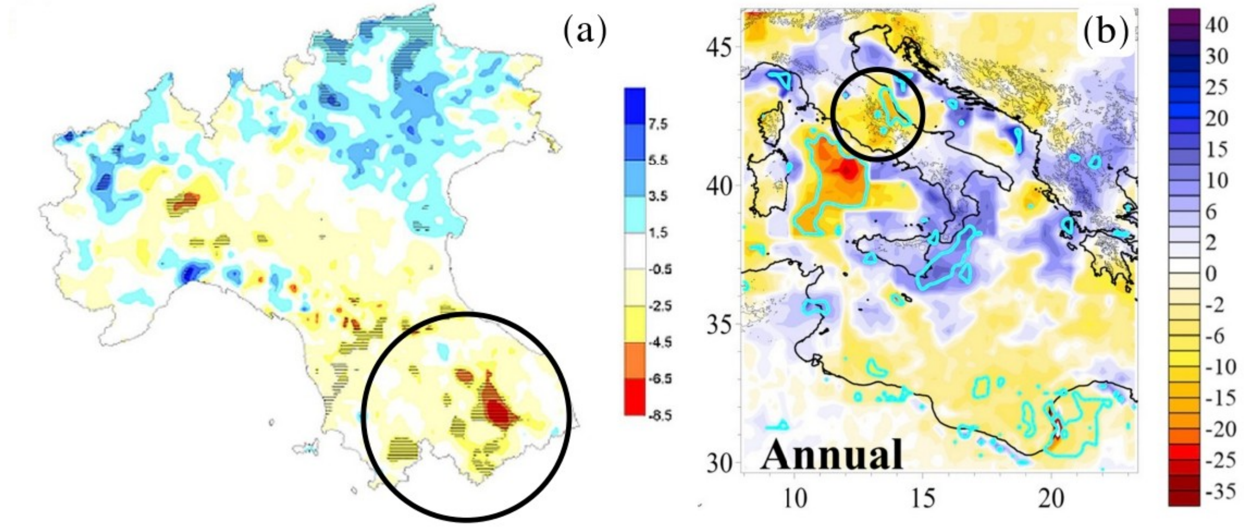

Figure 1: Annual rainfall trends in mm/year as observed in Italy from: a) raingauge observations [adapted from Pavan et al., 2019]; TRMM satellite observations [adapted from Kalimeris and Kolios, 2019]

Some studies revealed a pronounced significant negative trend on Apennines mountains [Appiotti et al., 2014, Pavan et al., 2019, Scorzini and Leopardi, 2019, Gentilucci et al., 2019, Curci et al., 2021]. Sometimes this is also accompanied by a pronounced warming over mountainous regions [Scorzini and Leopardi, 2019].

These trends have been usually studied in literature by correlating them with:

- changes in large-scale circulation patterns such as NAO [López-Moreno et al., 2011];
- changes in Circulation Weather Types (CWT) frequencies [Trigo and DaCamara, 2000].

However such correlations are complicated by the complex orography of Central Italy, together with its central position on the Mediterranean basin where precipitation occurs as a result of different meteorological processes [Millán et al., 2005, Vallorani et al., 2018, Miró et al., 2020].

To demonstrate that, we studied the CWT affecting precipitation climatology in Central Italy [Silvestri et al., 2022], and no significant correlations have been found between changes in large-scale circulations and observed precipitation trends.

A further difficulty arises from global warming which can be the driver of dynamical and thermodynamical changes of physical processes leading to precipitation. In particular, the orographic component of precipitation, which is evident from high-resolution climatologies of Italy [Crespi et al., 2018, Pavan et al., 2019], will be affected by non-trivial feedbacks in climate change scenarios [Teixeira et al., 2016] and the way it will respond to climate change depends on many different factors [Siler and Roe, 2014]. As an example, the drying ratio (DR) is expected to decrease with increasing surface temperature [Kirshbaum and Smith, 2008]. This effect could be even enhanced by the observed amplification of warming with elevation which is connected to different types of climate feedbacks [Pepin et al., 2015]. Other than enhancing precipitation, mountains can also suppress it by, for example, blocking moist impinging flow or inducing vertical mixing with dry air aloft [Kirshbaum et al., 2018]. All these phenomena are strictly connected to air stability and surface temperature.

Methodology

In order to tackle this problem we need a numerical approach that allows us to understand and explain the observed precipitation climatology. A similar approach can be found in Hughes et al. [2009] for studying the orographic precipitation in Southern California.

The experiment strategy can be summarized in the following points:

1. Run a regional climate simulation (with an high resolution model) for a long period (of the order of months) over Central Italy starting from *idealized initial conditions derived from ERA5 climatology*. *Such initial conditions should represent the most common atmospheric conditions bringing rainfall in Central Italy*.
2. Validate the regional simulation against raingauges and satellite observations. Try to motivate differences. If the modeled and observed climatology are comparable, then you can proceed with the next step.
3. Perform sensitivity experiments to simulate climate change effects, by perturbing initial and boundary conditions.
4. Generalize findings and try to extract theories for explaining observed precipitation changes and correlation between climate change and orographic rainfall.

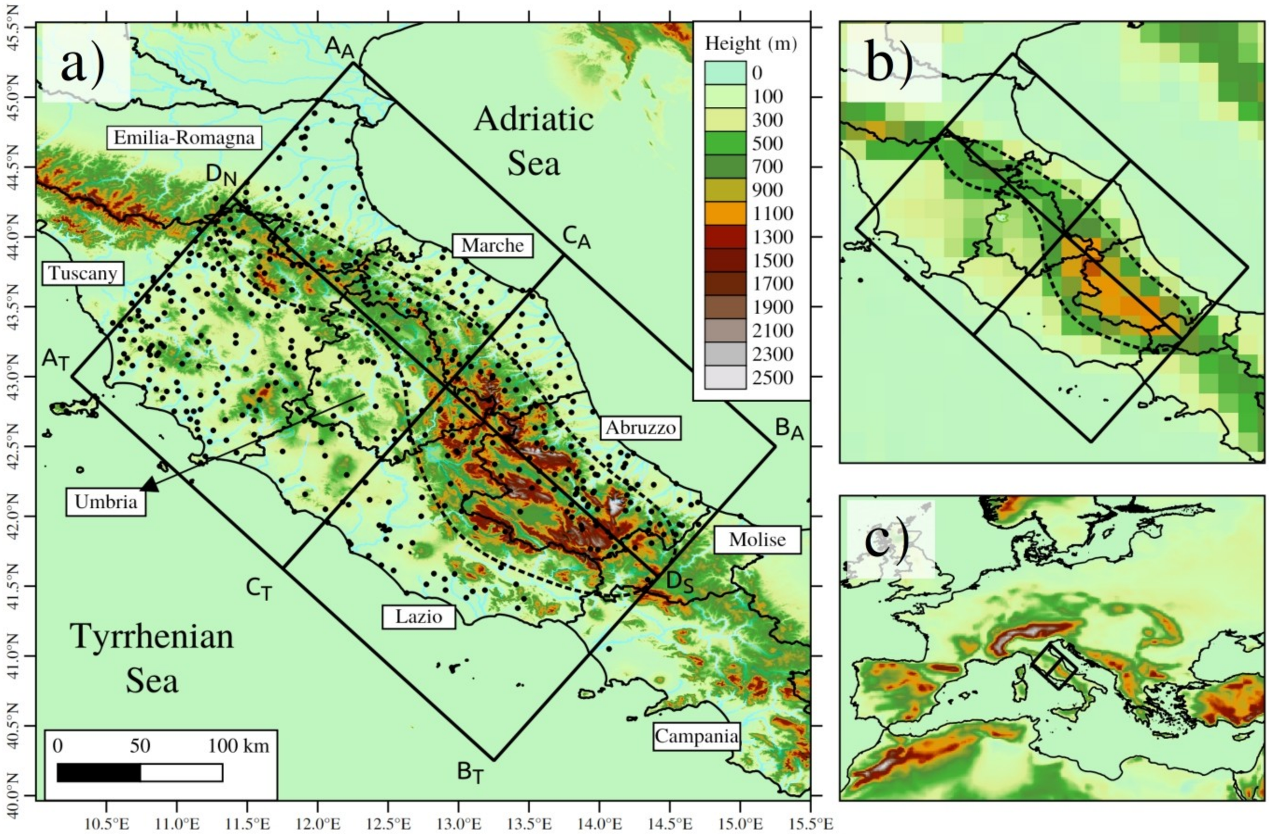

Figure 2: Study domain and orography: a) high resolution topography from a DEM and reference lines, and areas used throughout the work. The dashed black line circumscribes the Central Apennines area, while black dots represent surface stations. b) ERA5 topography on the study domain. c) overview of the study domain with respect to the Mediterranean region and ERA5 orography.

Model configuration

The WRF-ARW model will be used for this work. The domain configuration can be of two types and it will depend on the available power resources:

- A single domain (approximately 600 km x 600 km) over Central Italy (see Figure 2a) with an horizontal resolution of 1 km;
- A nested domain configuration starting from 3 km domain all over Italy and focusing with a smaller 1 km domain resolution over Central Italy.

The model will be initialized by four different idealized conditions (pressure and sea surface temperature, vertical profiles of wind, temperature and relative humidity) as derived from the four cyclonic circulation weather types which are responsible for the 75 % of rainfall in Central Italy [Silvestri et al., 2021]:

1. Type 1: a low pressure center is positioned over the Adriatic Sea, north-easterly fluxes develops and the Tyrrhenian coast receives very low amount of rainfall compared to the eastern side of the Apennines and the Adriatic coast;
2. Type 2: a low pressure center is positioned over the Ligurian Sea, strong south-westerly winds cause strong precipitation intensities concentrated over the Tyrrhenian coast and the inner part of Central Italy. Orographic enhancement is evident on the western side of the Apennines, especially in the Lazio region where high mountains are located in

proximities of the sea. The Adriatic coast, especially in the southern part where Apennines reaches high altitudes, receive a low amount of rainfall due to the blocking exerted by mountains;

3. Type 5: a low pressure center is positioned over northern Italy, moderate westerly winds develop and precipitation is distributed homogeneously over the territory, with a strong orographic enhancement over the entire Apennines;
4. Type 7: a low pressure center is positioned over Southern Italy, moderate south easterly fluxes develop over the Adriatic bringing more rainfall over the Southern Apennines and the southern Adriatic coast.

Average winds, pressure, water vapour transport and observed mean daily rainfall climatology for each type can be seen in Figure 3.

Periodic lateral boundary conditions will be set and no seasonality effects will be investigated in these first experiments. Instead the initial conditions will be extracted from ERA5 as average values over all days exhibiting those circulation weather types from 1951 to 2019. The model will be run for a long time period (at least one month).

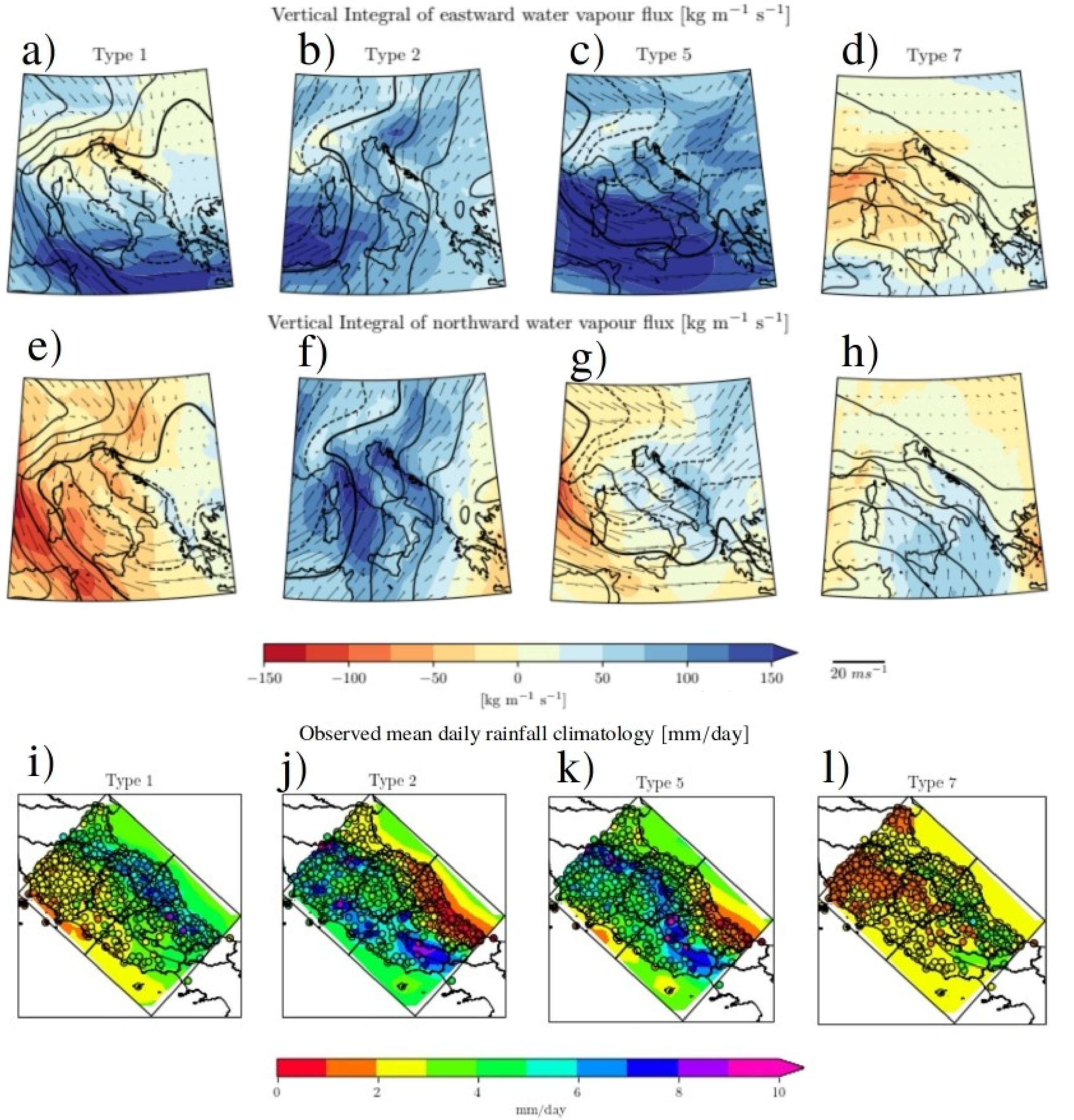

Figure 3: Vertical Integral of eastward (Figures a, b, c and d), northward (Figures e, f, g, h) water vapour flux and mean daily rainfall climatology (i, j, k, l) for the 4 cyclonic types. Positive fluxes are from west to east and from south to north. Shading is indicating the magnitude of each component of IVT. Arrows shows 850 hPa wind vectors. Thick black line is the 1013 hPa reference line. Solid lines denotes values above the reference line, while dashed lines denotes values below the reference line

Model validation

Daily mean precipitation obtained from the model will be compared with that obtained from quality-checked raingauge observations over the Central Italy. This comparison will be made by interpolating raingauge observations to the model grid by using geostatistical methods. Another method would be the comparison of areal averages or the use of satellite products climatology.

Model perturbation

Once the model is validated we will run sensitivity experiments on initial conditions and see how the precipitation climatology would change. Some perturbation examples are provided in the following:

- increasing average surface temperature over land (Pseudo-Global-Warming technique);
- increasing sea surface temperature on Adriatic or Tyrrhenian Sea (Pseudo-Global-Warming technique);
- varying orography (experiments with and without the orography)
- exhamining different subgrid-scale parametrizations (turbulence, microphysics, radiation)

Justification of the Computer Resources and preliminary results

In order to estimate the computing resources needed for the project, we ran a test over the WRF domain shown in Figure 4a for the Type 5 initial conditions. The run was performed on the ATOS HPC facility and we used about 800.000 SBU for a 60-day run with a horizontal grid resolution of 1 km and a domain extension of about 600 x 600 km. These simulations generated 1.7 TB of data. Preliminary results of the mean precipitation rate are shown in Figure 4b, while the corresponding observed climatology is shown in Figure 4c. Such a preliminary test shows similar values of daily precipitation intensity, but with a wrong spatial distribution over the domain. Therefore, we also need additional computational resources (about 450.000 SBU) to investigate the effect of different initial conditions (instead of taking the average of the reanalysis field), or different sub-grid scale models. In the following we summarise the computational resources and the scientific plan as estimated from this preliminary test. We also need to consider a spin-up time of 10-15 days before the average precipitation rate becomes statistically stable (see Figure 5).

Activity	**2025**	**2026**	**2027**
Set up (and spin-up) control simulations: initial and boundary conditions	450.000 SBU x 4 (All Weather Types)		
Long run of test cases	800.000 SBU x 4 2.5 TB X 4 (All Weather Types)		
Perturbation run on initial conditions (surface temperature, etc..)		1.250.000 SBU x 4 2.5 TB X 4 (All Weather Types)	
Perturbation run on orography, horizontal resolution and sub-grid scale parametrizations			1.250.000 SBU x 4 2.5 TB X 4 (All Weather Types)
Total	5.000.000 SBU 10 TB	5.000.000 SBU 10 TB	5.000.000 SBU 10 TB

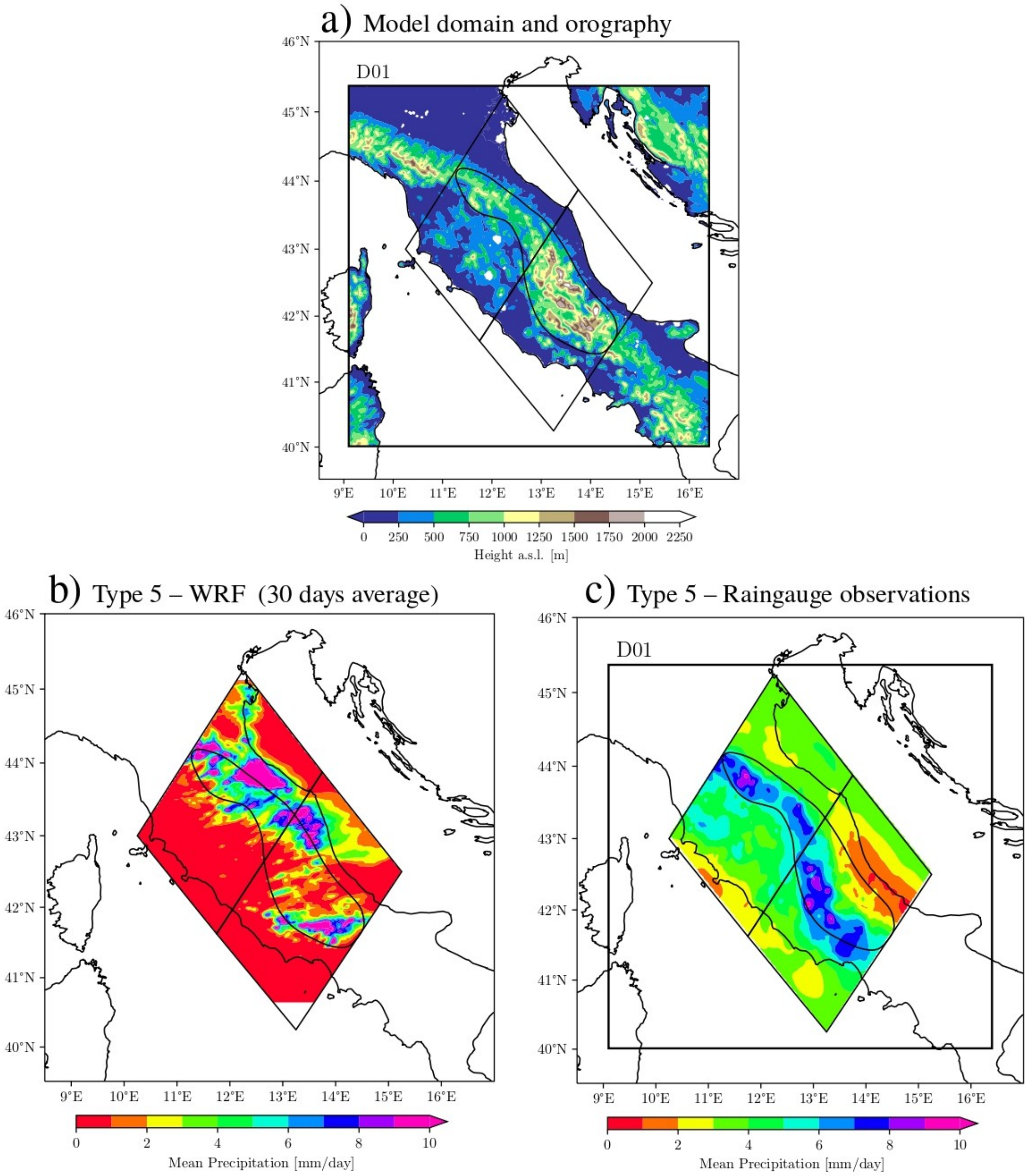

Figure 4: Preliminary results of WRF simulation for Type 5 initial conditions: a) model domain and orography; b) simulated mean daily precipitation averaged over 30 days; c) observed raingauges climatology.

References

F. Appiotti, M. Krželj, A. Russo, M. Ferretti, M. Bastianini, and F. Marincioni. A multidisciplinary study on the effects of climate change in the northern adriatic sea and the marche region (central italy). Regional environmental change, 14(5):2007–2024, 2014.

C. Beck, J. Jacobeit, and P. Jones. Frequency and within-type variations of large-scale circulation types and their effects on low-frequency climate variability in central europe since 1780. International Journal of Climatology: A Journal of the Royal Meteorological Society, 27(4):473–491, 2007.

P. Bongioannini Cerlini, K. A. Emanuel, and E. Todini. Orographic effects on convective precipitation and space-time rainfall variability: preliminary results. Hydrology and Earth System Sciences, 9(4):285–299, 2005.

E. Caporali, M. Lompi, T. Pacetti, V. Chiarello, and S. Fatichi. A review of studies on observed precipitation trends in italy. International Journal of Climatology, 41:E1–E25, 2021.

A. Crespi, M. Brunetti, G. Lentini, and M. Maugeri. 1961–1990 high-resolution monthly precipitation climatologies for italy. International Journal of Climatology, 38(2):878–895, 2018.

G. Curci, J. A. Guijarro, L. Di Antonio, M. Di Bacco, B. Di Lena, and A. R. Scorzini. Building a local climate reference dataset: Application to the abruzzo region (central italy), 1930–2019. International Journal of Climatology, 2021.

M. Gentilucci, M. Barbieri, H. S. Lee, and D. Zardi. Analysis of rainfall trends and extreme precipitation in the middle adriatic side, marche region (central italy). Water, 11(9):1948, 2019.

F. Giorgi. Thirty years of regional climate modeling: where are we and where are we going next? Journal of Geophysical Research: Atmospheres, 124(11):5696–5723, 2019.

F. Giorgi, C. Torma, E. Coppola, N. Ban, C. Schär, and S. Somot. Enhanced summer convective rainfall at alpine high elevations in response to climate warming. Nature Geoscience, 9(8): 584–589, 2016.

M. Hughes, A. Hall, and R. G. Fovell. Blocking in areas of complex topography, and its influence on rainfall distribution. Journal of Atmospheric Sciences, 66(2):508–518, 2009.

M. Hughes, J. D. Lundquist, and B. Henn. Dynamical downscaling improves upon gridded precipitation products in the sierra nevada, california. Climate Dynamics, 55(1):111–129, 2020.

A. Kalimeris and S. Kolios. Trmm-based rainfall variability over the central mediterranean and its relationships with atmospheric and oceanic climatic modes. Atmospheric Research, 230: 104649, 2019.

D. J. Kirshbaum and R. B. Smith. Temperature and moist-stability effects on midlatitude orographic precipitation. Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography, 134(634):1183–1199, 2008.

D. J. Kirshbaum, B. Adler, N. Kalthoff, C. Barthlott, and S. Serafin. Moist orographic convection: Physical mechanisms and links to surface-exchange processes. Atmosphere, 9(3):80, 2018.

J. López-Moreno, S. Vicente-Serrano, E. Morán-Tejeda, J. Lorenzo-Lacruz, A. Kenawy, andM. Beniston. Effects of the north atlantic oscillation (nao) on combined temperature and precipitation winter modes in the mediterranean mountains: Observed relationships and projections for the 21st century. Global and Planetary Change, 77(1-2):62–76, 2011.

J. Lundquist, M. Hughes, E. Gutmann, and S. Kapnick. Our skill in modeling mountain rain and snow is bypassing the skill of our observational networks. Bulletin of the American Meteorological Society, 100(12):2473–2490, 2019.

M. M. Miglietta and S. Davolio. Dynamical forcings in heavy precipitation events over italy: lessons from the hymex sop1 campaign. Hydrology and Earth System Sciences, 26(3):627–646,2022.

M. Millán, M. J. Estrela, and J. Miró. Rainfall components: variability and spatial distribution in a mediterranean area (valencia region). Journal of Climate, 18(14):2682–2705, 2005.

M. M. Millán. Extreme hydrometeorological events and climate change predictions in europe. Journal of Hydrology, 518:206–224, 2014.

J. Miró, N. Pepin, J. Peña, and J. Martin-Vide. Daily atmospheric circulation patterns for catalonia (northeast iberian peninsula) using a modified version of jenkinson and collison method. Atmospheric Research, 231:104674, 2020.

N. Otero, J. Sillmann, and T. Butler. Assessment of an extended version of the jenkinson– collison classification on cmip5 models over europe. Climate dynamics, 50(5):1559–1579, 2018.

V. Pavan, G. Antolini, R. Barbiero, N. Berni, F. Brunier, C. Cacciamani, A. Cagnati, O. Cazzuli, A. Cicogna, C. De Luigi, et al. High resolution climate precipitation analysis for north-central Italy, 1961–2015. Climate Dynamics, 52(5-6):3435–3453, 2019.

N. Pepin, R. S. Bradley, H. Diaz, M. Baraër, E. Caceres, N. Forsythe, H. Fowler, G. Greenwood, M. Hashmi, X. Liu, et al. Elevation-dependent warming in mountain regions of the world. Nature climate change, 5(5):424, 2015.

A. R. Scorzini and M. Leopardi. Precipitation and temperature trends over central italy (abruzzo region): 1951–2012. Theoretical and Applied Climatology, 135(3):959–977, 2019.

N. Siler and G. Roe. How will orographic precipitation respond to surface warming? An idealized thermodynamic perspective. Geophysical Research Letters, 41(7):2606–2613, 2014.

L. Silvestri, M. Saraceni, and P. Bongioannini Cerlini. Links between precipitation, circulation weather types and orography in central italy. *International Journal of Climatology* 42.11: 5807-5825, 2022.

P. Stocchi and S. Davolio. Intense air-sea exchanges and heavy orographic precipitation over italy: The role of adriatic sea surface temperature uncertainty. Atmospheric Research, 196: 62–82, 2017.

M. A. Teixeira, D. J. Kirshbaum, H. Ólafsson, P. F. Sheridan, and I. Stiperski. The atmosphere over mountainous regions. Frontiers in Earth Science, 4:84, 2016.

R. M. Trigo and C. C. DaCamara. Circulation weather types and their influence on the precipitation regime in portugal. International Journal of Climatology: A Journal of the Royal Meteorological Society, 20(13):1559–1581, 2000.

R. Vallorani, G. Bartolini, G. Betti, A. Crisci, B. Gozzini, D. Grifoni, M. Iannuccilli, A. Messeri, G. Messeri, M. Morabito, et al. Circulation type classifications for temperature and precipitation stratification in italy. International Journal of Climatology, 38(2):915–931, 201