

We are grateful to the reviewer for the assessment of our manuscript and for providing insightful suggestions. The comments provided are very constructive and have helped us significantly improve the quality of our work. Below, we provide a point-by-point response to each comment and detail the changes made to the revised text.

Please note that all line numbers correspond to the new revised manuscript, and all updated text is quoted in full below.

Major:

1) The discussion employing the classical Froude Number (Fr) to describe airflow dynamics over the Apennines is methodologically flawed. The standard criterion ($Fr < 1$ for flow splitting/blocking) is derived for isolated, three-dimensional topographic obstacles. For an extended, continuous 2D mountain barrier like the Central Apennines, lateral deflection is heavily constrained by the broad scale of the ridge. Consequently, stable air can frequently be forced over the barrier, rather than simple horizontal splitting. I recommend either removing the classical Froude number argument or revising the text to reflect the specific dynamics of elongated 2D ridges (referencing relevant literature on 2D mountain flow regimes).

R1) Following your recommendation, we have entirely removed the classical Froude number argument from the manuscript, considering that interpretation in terms of Fr is not straightforward. The corresponding text (lines 258–269 in the marked-up version) and related discussions have been deleted to avoid misleading interpretations and to ensure the description of airflow dynamics remains physically accurate.

2) While the authors acknowledge the underestimation of the peak rainfall (180 mm simulated vs 419 mm observed at Cantiano), the manuscript would benefit from a deeper physical discussion on why the simulated storm decays prematurely after 17:00 UTC. Is this decay driven by excessive cold-pool propagation, insufficient surface latent heat fluxes, or microphysical parameterization limits? Expanding slightly on these potential physical mechanisms would provide greater insight into why NWP models systematically fail to reproduce the extreme tail (>400 mm) of such localized convective events.

R2) We completely agree that a deeper physical discussion regarding the premature decay of the simulated storm may add significant value to the manuscript.

Regarding the hypothesis of excessive cold-pool propagation, our analysis of the observational data did not reveal a distinct cold-pool signature during the event. Conversely, rather than a

dynamic misrepresentation of a cold pool, we found that the premature decay of rainfall in the model is primarily driven by a marked near-surface thermodynamic bias. To investigate this, we expanded our analysis of the thermodynamic fields after 17:00 UTC. As now detailed in the revised Section 4.3 and shown in the new Figure 8, the simulation exhibits a significantly warmer near-surface environment, with temperatures remaining even 5-6°C higher than observations during the decay phase. This warm thermal structure directly affects the saturation state over time: considering that the specific humidity is well represented, the higher temperatures increase the saturation vapor pressure, causing the low troposphere to drop from a saturated state to well below 100%, shifting the modeled environment to a sub-saturated state that can no longer sustain condensation and heavy precipitation. This comprehensive physical discussion, together with the corresponding spatial maps and temporal profiles, has been integrated into Section 4.3 (lines 209-226) of the revised manuscript and now reads as follows:

“To investigate the physical mechanisms driving this premature convective decay, an analysis of the near-surface thermodynamic fields was conducted. For the 2 m temperature (T_{2m}) and 2 m relative humidity (RH_{2m}) analysis, data from 104 stations within domain d02 (which covers the entire Marche region) and 54 stations within domain d03 (covering only the portion of the region directly affected by the rainfall) were utilized. The validated station observations used for this comparison were retrieved from the official platform of the Civil Protection Department of the Marche Region (<http://app.protezionecivile.marche.it/>) and basic quality control procedures were applied to ensure data consistency and filter out anomalies. Figure 8 compares the observed and simulated T_{2m} and RH_{2m} spatial maps at 18:00 UTC (panels a and b), alongside their temporal evolution (panels c and d) for selected stations (Arcevia, Cantiano, and Colle).

The analysis reveals that the rapid decay of precipitation is related to near-surface thermodynamic biases. The simulation exhibits a significantly warmer environment, with temperatures remaining up to 5-6°C higher than observations during the decay phase.

This warm bias directly affects the near-surface relative humidity over time (Fig. 8d). Due to the higher simulated temperatures, the saturation vapor pressure increases, which in turn reduces the relative humidity (considering that the bias in specific humidity is small). Consequently, the simulated environment fails to maintain saturation. The drop in RH_{2m} represents a physical transition from a saturated state (necessary to sustain condensation and precipitation) to a sub-saturated environment that inhibits rainfall generation. This underestimation is further illustrated by comparing the 24 h maximum cumulative rainfall in the control simulation (REF) — evaluated both at the station point (REF_point) and using a 10 km neighborhood maximum (REF_10km) — with rain gauge observations (Table 3).”

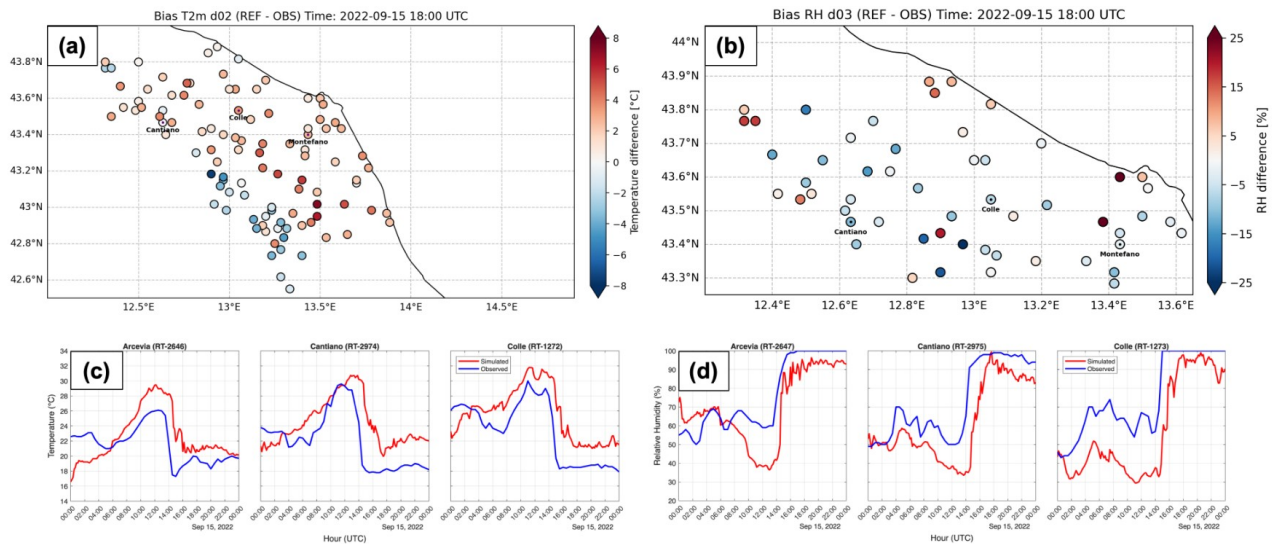


Figure 8. Comparison of observed and simulated (REF) near-surface (a) T_{2m} over a portion of the d02 domain and (b) RH_{2m} over the d03 domain at 18:00 UTC. Temporal evolution of (c) T_{2m} and (d) RH_{2m} comparing observations and model outputs (REF) for the selected stations of Arcevia, Cantiano, and Colle.

Minor:

3) To enhance readability and provide a clear overview for the reader, please include a summary table listing the maximum predicted 24-h precipitation across the different sensitivity experiments (NCEP GDAS, HRES ECMWF, NCEP GFS, ERA5) alongside the observed rain gauge maxima (e.g., Cantiano, Frontone).

R3) We have added a new table (Table 3 in the revised manuscript) comparing the 24 h maximum cumulative rainfall observed by the rain gauge network against the control simulation (REF), evaluated both at the exact station locations and within a 10-km neighborhood box. We have also added the 24 h maximum cumulative rainfall predicted by each sensitivity experiment improving the existing Table 4.

Table 3. Comparison of 24 h maximum cumulative rainfall and corresponding percentage errors between the control simulation evaluated at the nearest grid point ($\text{REF}_{\text{point}}$), the maximum value within the 10 km neighborhood ($\text{REF}_{10\text{km}}$), and weather station observations (OBS) for selected locations.

Station	$\text{REF}_{\text{point}}$	$\text{REF}_{10\text{km}}$	OBS	Error ($\text{REF}_{\text{point}}$)	Error ($\text{REF}_{10\text{km}}$)
	[mm]	[mm]	[mm]	$\frac{\text{OBS} - \text{REF}_{\text{point}}}{\text{OBS}} \cdot 100$ [%]	$\frac{\text{OBS} - \text{REF}_{10\text{km}}}{\text{OBS}} \cdot 100$ [%]
Arcevia	35.2	109.7	129.8	72.9	15.5
Cantiano	164.2	180.1	420.6	61.0	57.2
Colle	72.4	89.9	204.0	64.5	55.9
Jesi	34.4	78.8	126.0	72.7	37.5
Frontone–Monte Acuto	172.4	180.6	387.2	55.5	53.4
Montefano	99.8	122.5	150.8	33.8	18.7

Table 4. Summary of the WRF sensitivity experiments. All simulations share the same domains and grid spacing (10 km, 2 km, 0.66 km). Δt_{BC} indicates the update frequency of the lateral boundary conditions. All simulations share the same physical parameterizations, except for the “Modified physics” experiment (panel d). This specific run employs the Thompson microphysics scheme (Thompson et al., 2008), the Kain-Fritsch cumulus parameterization (Kain, 2004), the Dudhia shortwave and RRTM longwave radiation schemes (Dudhia, 1989; Mlawer et al., 1997), and the Unified Noah Land Surface Model (Tewari et al., 2004).

Panel	Sensitivity	Forcing Dataset	Start Time (UTC)	Δt_{BC} [h]	24 h Max. Rain [mm]	Remarks
a	REF	NCEP GDAS/FNL (0.25°)	15/09/2022 00:00	3	180.6	Control simulation
b	I.C.	NCEP GDAS/FNL (0.25°)	15/09/2022 06:00	3	98.9	Delayed initialization
c	B.C.	NCEP GDAS/FNL (0.25°)	15/09/2022 00:00	6	197.1	Lower boundary update frequency
d	Physics	NCEP GDAS/FNL (0.25°)	15/09/2022 00:00	3	74.2	Modified physics (see caption)
e	I.C. / B.C.	NCEP GFS (0.25°)	15/09/2022 00:00	3	129.5	Historical forecast archive
f	B.C.	I.C. GDAS / B.C. GFS	15/09/2022 00:00	3	156.1	Mixed forcing datasets
g	I.C. / B.C.	HRES ECMWF (0.1°)	15/09/2022 00:00	3	49.3	High-resolution operational analysis
h	I.C. / B.C.	ERA5 (0.25°)	15/09/2022 00:00	1	108.5	Hourly reanalysis