

# EMI R&D PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

**Reporting year** 2026

**Project Title:** SEVERE CONVECTIVE WEATHER PHENOMENA AND CLIMATE CHANGE

**Computer Project Account:** SPESVALE

**Principal Investigator(s):** FRANCISCO VALERO

**Affiliation:** FACULTAD DE CIENCIAS FÍSICAS. UNIVERSIDAD COMPLUTENSE DE MADRID

**Name of ECMWF scientist(s) collaborating to the project (if applicable)** Mariano Sastre (UCM), Javier Díaz-Fernández (UVA), Pedro Bolgiani (UCM), Carlos Calvo (UVA), María Luisa Martín (UVA), Daniel Santos (DMI), José Ignacio Farrán (UVA), Juan Jesús González-Alemán (AEMET), Ana Montoro (UVA), Mauricio López-Reyes (UCM)

UCM: Universidad Complutense de Madrid. Spain  
 UVA: Universidad de Valladolid. Spain  
 DMI: Danish Meteorological Institute. Denmark  
 AEMET: Agencia Estatal de Meteorología. Spain

**Start date of the project:** 01/01/2025

**Expected end date:** 31/12/2027

**Computer resources allocated/used for the current year and the previous one**  
 (if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
<b>High Performance Computing Facility</b>	(units)	1200000	1165057	1200000	140000
<b>Data storage capacity</b>	(Gbytes)	10000	10000	10000	10000

### **Summary of project objectives** (10 lines max)

This project leverages ECMWF's HPC resources to analyze the environmental drivers and predictability of catastrophic convective events in Spain through two main lines of research. First, the Pseudo-Global Warming (PGW) approach is applied to investigate how anthropogenic climate change and Mediterranean marine heatwaves modulate high-impact episodes: the August 2022 giant hailstorm, which produced 12 cm hailstones and one fatality, and the devastating October 2024 Valencia flash floods, which caused 228 fatalities. By perturbing historical reanalysis data, we simulate how these severe mesoscale convective systems scale under future thermodynamic conditions. Second, we evaluate the forecasting performance and computational efficiency of the HARMONIE-AROME numerical weather prediction model at sub-kilometer scales during a severe supercell outbreak. This sensitivity analysis compares a high-resolution two-step nested setup (2.5 km to 500 m) against a single-domain 500 m configuration.

### **Summary of problems encountered** (10 lines max)

No problems have been found.

### **Summary of plans for the continuation of the project** (10 lines max)

Future work will expand the sub-kilometre HARMONIE-AROME and WRF numerical modelling frameworks to analyse the specific physical mechanisms connecting ocean-atmosphere forcing to extreme events in more depth. Following on from our recent findings, upcoming simulations will examine how historical marine heatwave anomalies and human-induced thermodynamic trends modify convective parameters, storm-scale kinematics and localised microphysics. This will include conducting focused, high-resolution sensitivity experiments to quantify changes in severe supercell morphology, updraft intensity under varying shear profiles and moisture flux convergence. These numerical experiments will establish robust scaling laws for high-impact phenomena in a context of continued global warming. This will directly improve operational capabilities for early warning and risk assessment of convective-scale phenomena.

### **List of publications/reports from the project with complete references**

- Díaz-Fernández, J., C. Calvo-Sancho, P. Bolgiani, M. Sastre, M. López-Reyes, S. Fernández-González, M.L. Martín (2025). Effect of complex orography on numerical simulations of a downburst event in Spain. *Atmospheric Research*, 314, 107821; <https://doi.org/10.1016/j.atmosres.2024.107821>.
- Calvo-Sancho, C., Díaz-Fernández, J., González-Alemán, J.J., Halifa-Marín, A., Miglietta, M.M., Azorín-Molina, C., Prein, A.F., Montoro-Mendoza, A., Bolgiani, P., Morata, A., & Martín, M.L. (2025). Climate change unleashed: physical-based attribution analysis proves human-induced amplification of Valencia's deadly flooding. <https://doi.org/10.21203/rs.3.rs-6709965/v1>.
- Díaz-Fernández, J., Calvo-Sancho, C., Bolgiani, P., González-Alemán, J.J., Morata, A., Santos-Muñoz, D., & Martín, M.L. (2026). Case study of a supercell outbreak in Spain and cost-benefit analysis of the nesting approach in HARMONIE-AROME. *Atmospheric Research*. *Atmospheric Research* 334, 108774 <https://doi.org/10.1016/j.atmosres.2026.108774>
- Montoro-Mendoza, A., Calvo-Sancho, C., González-Alemán, J.J., Díaz-Fernández, J., Bolgiani, P., & Martín, M.L. (2026). Strengthening of favorable environments for North Atlantic tropical cyclogenesis in midlatitudes in a warmer climate. *npj Clim Atmos Sci* 9, 45. <https://doi.org/10.1038/s41612-025-01317-0>.

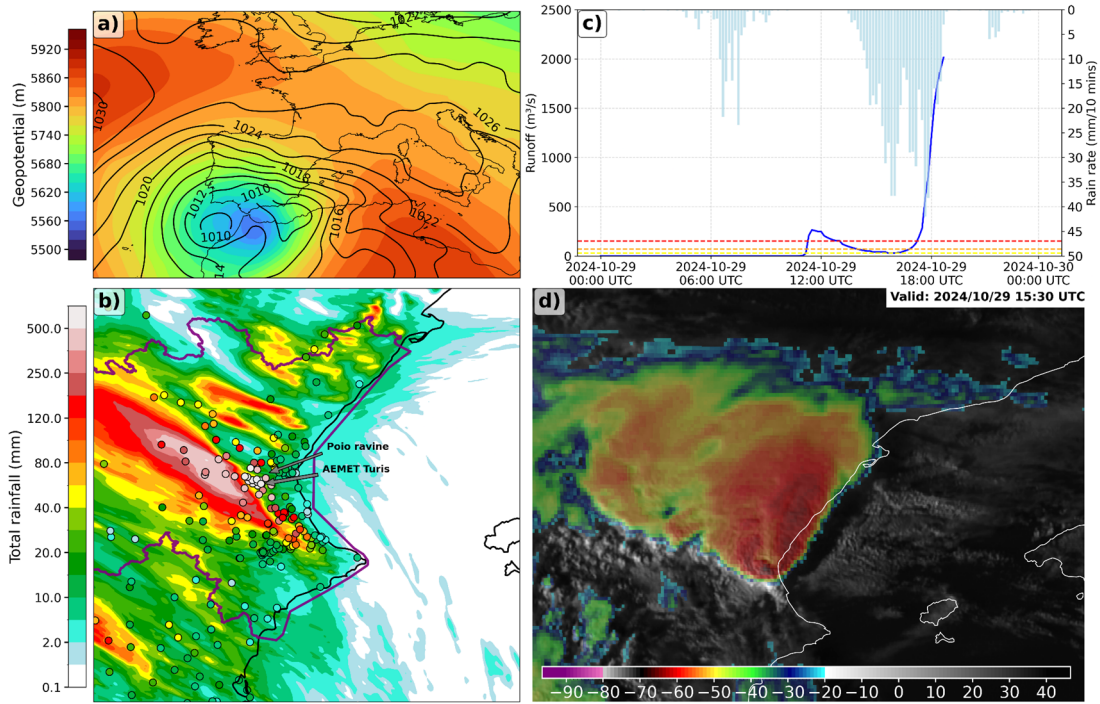
- López-Reyes, M., Martín, M.L., Calvo-Sancho, C. & González-Alemán, J.J. (2026). Dynamic forcing behind Hurricane Lidia's rapid intensification. *Weather and Climate Dynamics*. <https://doi.org/10.5194/wcd-7-523-2026>.
- García-Miguel, A., Díaz-Fernández, J., Calvo-Sancho, C., López-Reyes, M., Bolgiani, P., & Martín, M.L. (2026). Projected changes in wind speed and power over Iberia and surrounding maritime areas using CMIP6 models. *Wind energy*. In review.
- Calvo-Sancho, C., Rotunno, R., Montoro-Mendoza, A., González-Alemán, J.J., Bolgiani, P., & Martín, M.L. (2026). The role of moist convection and mesoscale processes in achieving the final stage of a tropical transition: Hurricane Ophelia. In review.
- López-Reyes, M., Calvo-Sancho, C., León-Cruz, J. F., Meulenert, Á., Galvez, J. M., Díaz-Fernández, J., González-Alemán, J. J., & Martín, M. L. (2026). A multivariable approach to the regional calibration of the Gálvez–Davison Index across Mexico's climate regimes. *Earth Systems and Environment*. In review.
- Gómez-Plasencia, P., González-Alemán, J. J., Calvo-Sancho, C., Rodríguez-Acosta, E. J., Bolgiani, P., Díaz-Fernández, J., Montoro-Mendoza, A., Martín, M. L., & Gómara, I. (2026). Convective activity within a tropical cyclone undergoing extratropical transition over a warmer ocean: Tropical Storm Delta (2005). *Weather and Climate Dynamics*. In review.
- Rodríguez-Acosta, E. J., Gómez-Plasencia, P., Calvo-Sancho, C., González-Alemán, J. J., Bolgiani, P., Gómara, I., & Martín, M. L. (2026). Synoptic-scale environment of African Easterly Waves with anomalous northward trajectories. *Weather and Climate Dynamics*. In preparation.

## Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

On October 29th 2024, the eastern Spanish region of Valencia experienced one of the most devastating flash flood events in recent history, with record-breaking rainfall rates (Figures 1b, c) and cumulative values exceeding annual averages within few hours. The hydrological response was devastating (Figures 1c), triggering extensive flash floods in the south of Valencia metropolitan area. In addition to the heavy rainfall associated with the convective system, 11 tornadoes and large hail were observed (AEMET, 2024). The event resulted in at least 229 fatalities, extensive damage to infrastructure, and economic losses estimated in several billions of euros (Llasat, 2024).

The event was driven by a cut-off low over the Iberian Peninsula (Figure 1a), creating a baroclinic environment where cold air aloft contrasted with warm, moist low-level air advected from the subtropical Atlantic. This strong contrast favored convective instability and the development of quasi-stationary convective systems (Figure 1d). The cut-off low enhanced convection by inducing upper-level divergence, thereby facilitating intense horizontal moisture advection—like atmospheric rivers—from the Mediterranean Sea and northwestern Africa (Huang et al. 2025). This transport increased the supply of humid air and raised the potential for severe storms. This pattern often plays a key role in torrential rainfall events in the eastern Iberian Peninsula (Insua-Costa et al., 2019; Pereira et al. 2020; Lorente-Plazas et al., 2020; González-Hidalgo et al. 2025; Beguería et al. 2025).



**Figure 1:** Valencia's deadly floods are the highest impactful climate event in recent Spanish history. (a) Geopotential height at 500 hPa (shaded) and sea level pressure (contour) on October 29th, 2024, 12:00 UTC from ERA5. (b) Total rainfall accumulation (24h) in the Valencia region in the factual simulation (shaded) and observational weather network (scatter). The purple line represents the river Júcar basin. Station locations are indicated. (c) Evolution of 10 min rainfall rate in Turís (light-blue bars) and 5 min runoff (blue line) in Poio ravine. At 19:00 UTC the flash-flood in the Poio ravine destroyed the stream gauging station. The yellow, orange and red lines shows the runoff warnings in the Poio ravine. (d) View of the storm from Meteosat Second Generation taken at 15:30 UTC in the IR10.8  $\mu\text{m}$  channel ( $^{\circ}\text{C}$ ).

This catastrophe highlights the vulnerability of Mediterranean regions to extreme precipitation events, which seems to be exacerbated in recent years by ACC (González-Alemán et al., 2023; Martin et al., 2024). The anomalously high SST in the western Mediterranean, which keep increasing and reached record levels during summer 2024 (Cheng et al. 2024), likely intensified the event through thermodynamic forcing, increasing atmospheric moisture content and enhancing convective instability (Fischer & Knutti, 2016).

We present a physical-based attribution study using the WRF model sourced with CMIP6 models to assess the ACC contribution to rainfall intensity, moisture content, and storm dynamics (i.e., diabatic heating, vertical motions, microphysical processes). Table 1 shows the CMIP6 models finally selected in the DANA of Valencia case study.

**Table 1:** CMIP6 models selected for this study case. Further details for each model are available in the references listed in this table.

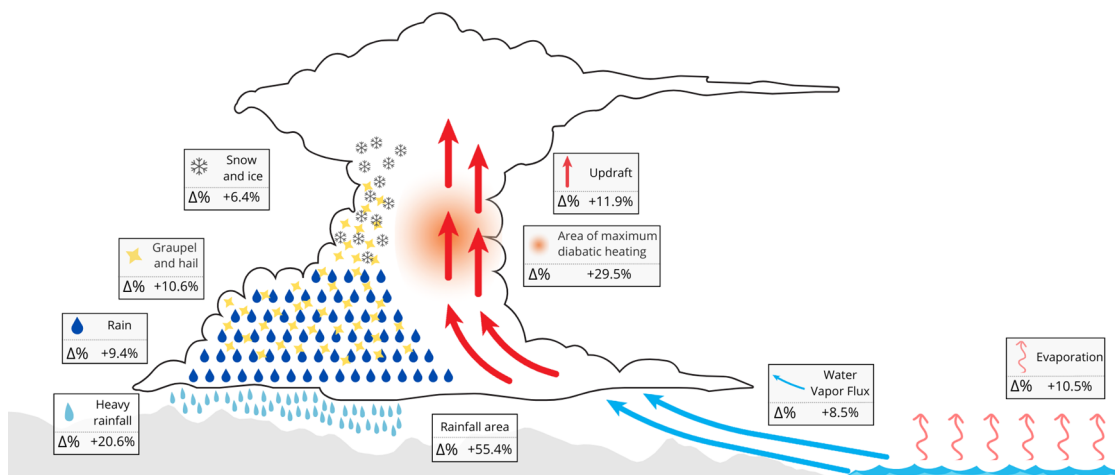
GCM	Institute ID	Resolution (lat. x lon.)	Reference
AWI-CM-1-1-MR	AWI (Germany)	0.937° x 0.937°	Semmler et al. (2018)
CESM2-WACCM	NCAR (USA)	1.3° x 0.9°	Danabasoglu (2019)
EC-Earth3	EC-Earth-Consortium (Europe)	0.7° x 0.7°	EC-Earth (2019)
FGOALS-g3	CAS (China)	2° x 2°	Li et al. (2020)
GISS-E2-1-G	NASA (USA)	2° x 2.5°	Kelley et al. (2020)
GISS-E2-1-H	NASA (USA)	2° x 2.5°	Kelley et al. (2020)
INM-CM4-8	INM (Russia)	1.5° x 2°	Volodin et al. (2018)
INM-CM5-0	INM (Russia)	1.5° x 2°	Volodin et al. (2018)

IPSL-CM6A-LR	IPSL (France)	1.3 x 2.5°	Boucher et al. (2018)
MCM-UA-1-0	UA (USA)	2.25° x 3.75°	Stouffer (2019)
MIROC-ES2L	MIROC (Japan)	2.8° x 2.8°	Tachiiri et al. (2019)
MIROC6	MIROC (Japan)	1.4° x 1.4°	Tatebe et al. (2019)
MRI-ESM2-0	MRI (Japan)	1.121° x 1.125°	Yukimoto et al. (2019)
NorESM2-LM	NCC (Norway)	1.9° x 2.5°	Seland et al. (2020)
NorESM2-MM	NCC (Norway)	0.94° x 1.25°	Seland et al. (2020)

In this study, a convection-allowing model with 1-km horizontal grid spacing to simulate the event in the present-day (factual, 2009-2038) and pre-industrial-like climate (counterfactual, 1850-1879) is utilized, using the physical-based attribution approach. This methodology enables for a thorough evaluation of how ACC has intensified the extraordinary Valencia floods of October 2024 by examining changes in rainfall intensity and spatial coverage, changes in moisture content, and shifts in the underlying physical mechanisms governing this extreme rainfall event.

ACC notably increases both the intensity and the spatial extent of the extreme rainfall Valencia event. Under present-day climate conditions, 6-hr rainfall rates and extreme rainfall thresholds (P90, P95, AEMET red warning for heavy rainfalls in the Valencia region and P99) show a significant spatial expansion. Figure 2 outlines conceptually the main changes found in this study, showing increments in the analyzed factors with respect to the counterfactual climate conditions. The enhanced moisture content, in combination with largely unchanged wind fields, leads to more efficient moisture transport and reduced the entrainment. Together, these factors lead to the intensification of this rainfall event, as highlighted by the changes in PW and WVMXR in comparison to the pre-industrial era conditions. These results are in line with the Clausius-Clapeyron relationship (O’Gorman & Muller, 2010; Schneider et al. 2010; Donat et al. 2016; Da Silva and Haerter, 2025). Moreover, the strengthened horizontal WVFlux (+8.5%) underscores that moisture transport enhancement is one of the primary drivers of intensified rainfall, rather than changes in wind dynamics. The increased CAPE illustrates larger atmospheric instability under current climate conditions, promoting more vigorous vertical transport of humidity, convection and stronger latent heat release. All these non-linear processes collectively contribute to intensified rates exceeding the Clausius-Clapeyron scaling (see Limitation Statement in the Methods section). The increase in atmospheric content of water vapor significantly promotes changes in the storm dynamics, including latent heat release (+29.5%), vertical velocities (+11.9%) and cloud microphysics (~ +9%). In addition, the simulated increase in the warmer cloud layer height enhances the warm rain processes. These changes result in increased precipitation efficiency and larger areas (+55.4%) experiencing intense rainfall rates (+20.6%), resulting in flash-flood risks.

**Anthropogenic Climate Change differences with pre-industrial conditions for deep-moist convection**

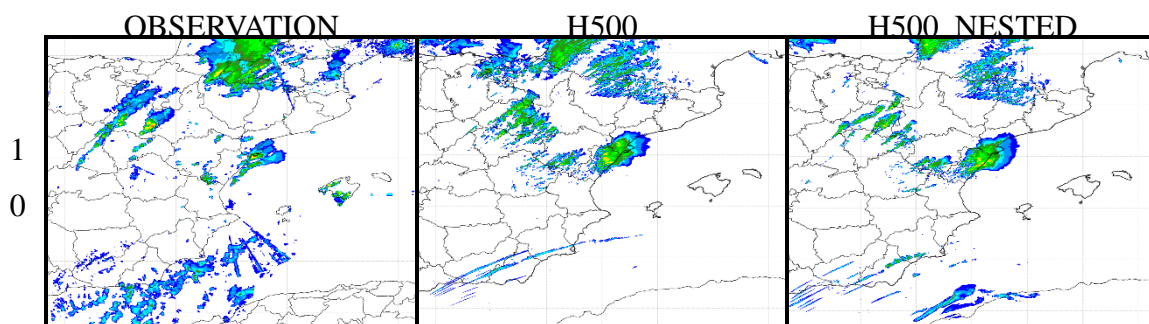


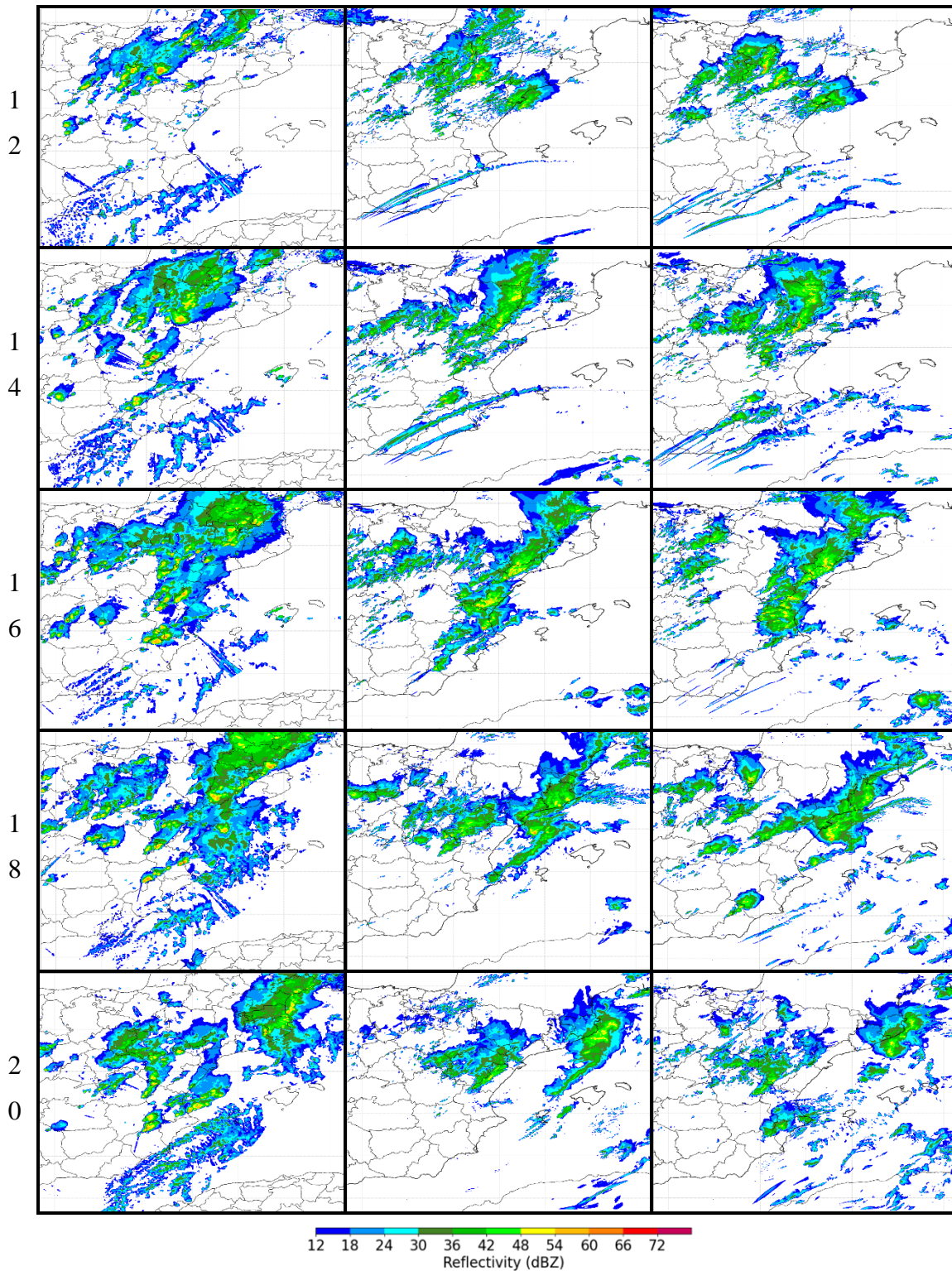
**Figure 2:** Extreme heavy rainfall events intensify with human-induced climate change in the Valencia case study. Heavy rainfall events intensify due to enhanced moisture content, which increases the latent heat release, and causes stronger positive vertical motions. These changes promote more intense microphysics processes, stronger heavy rainfall (6 h) and increases in the total rainfall area.

Another extreme event is additionally studied (Díaz-Fernández et al., 2026). The six supercell events that formed in the complex orography of eastern Iberian Peninsula on July 31, 2015, are simulated using two HARMONIE-AROME nesting strategies to evaluate their performance. The first, H500\_NESTED, employs a two-step nesting approach, while the second, H500, uses a single-domain setup, with both final spatial resolutions of 500 m. The ability of both nesting approaches is evaluated by comparing maximum reflectivity observations from OPERA radar and precipitation and temperature from weather stations. The pre-convective conditions are validated using the Murcia radiosonde.

The modeled maximum reflectivity is compared with radar data from the OPERA network. Although differences between H500 and H500\_NESTED are minor, both exhibit some discrepancies against observations (Figure 3). H500 shows delayed and weaker supercell storm development, whereas H500\_NESTED better captures the supercell evolution, particularly at later stages, with improved representation of high-reflectivity cores. Analyzing the time series reveals substantial differences in the two models' ability to reproduce the observed supercells in Murcia (south of the Iberian Peninsula). At 16:00 UTC, the H500\_NESTED simulation fails to reproduce the intensity and position of SP-5 (north of Murcia), whereas the H500 simulation accurately captures both its strength and location. However, between 18:00 and 20:00 UTC, the roles are reversed: H500\_NESTED better captures the growth and development of SP-6. Despite this, H500\_NESTED produces a spatial displacement and overestimates the supercell's intensity, while H500 fails to adequately simulate the structure and evolution of SP-6 during this period.

As expected, both simulations produce more diffuse supercell structures, lacking the fine-scale organization seen in the observation. Reflectivity is systematically underestimated, with biases of -5.85 dBZ for H500 and -5.78 dBZ for H500\_NESTED. Despite their similar RMSE values (5.45 dBZ for H500 and 5.48 dBZ for H500\_NESTED) and identical correlation coefficient (0.41), H500\_NESTED captures slightly higher reflectivity values and better-defined convective cores, in line with its reduced bias. Additionally, the Mann–Whitney U test yields a p-value of 0.27, indicating no statistically significant differences in reflectivity distributions between the two simulations. Although the nested approach improves spatial detail and intensity representation, the overall statistical performance of H500\_NESTED and H500 remains similar. The nesting strategy enhances the depiction of convective structures but does not significantly improve RMSE or correlation. These findings contrast from those of Pilguy et al. (2019), who used the high-resolution WRF model to simulate an isolated tornadic supercell in Poland and reported an overestimation of maximum reflectivity in their results, using double-moment microphysics.





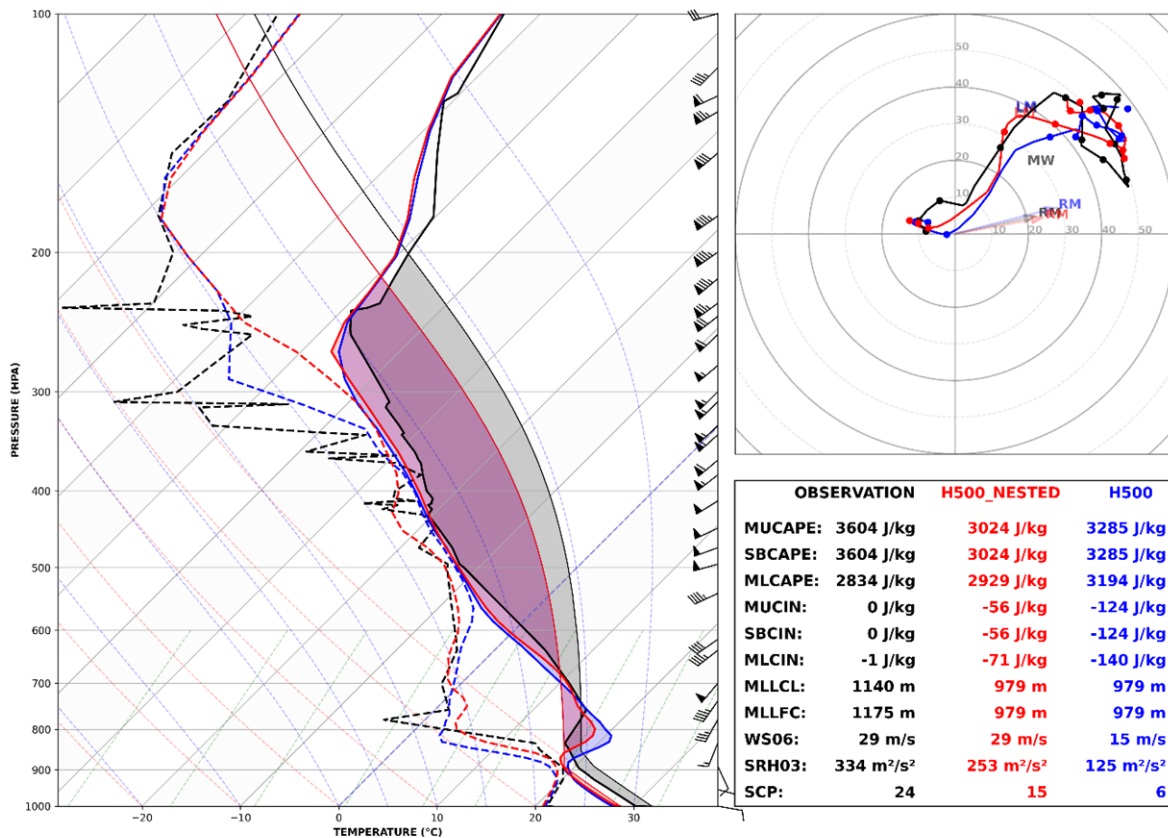
**Figure 3.** Maximum reflectivity observed (OBSERVATION) and simulated (H500 and H500\_NESTED) for the period 10:00 – 20:00 UTC 31 July 2015.

Vertical profiles observed and simulated of H500\_NESTED and H500 of the supercell event at the Murcia-sounding station show a favourable environment for deep convection development (Figure 4). Overall, both simulations capture the general trend of the observed temperature profile and the thermal inversion. However, there are significant differences in the intensity of temperature inversions and the detailed structure of the atmospheric profile. The H500\_NESTED simulation achieves a closer match to the observed temperature in the lower atmospheric levels (900 – 800 hPa) since the inversion is more accurately captured than the H500 simulation. However, both simulations exhibit a tendency to smooth

out the sharp gradients of the observed temperature inversion. In mid-levels, both simulations slightly underestimate the temperature compared to observations. The dew point has a very similar behaviour as the temperature, and the H500\_NESTED has a better approximation to the observed dew point. These findings underscore the importance of incorporating higher-resolution configurations or refined physical parameterizations to better replicate the fine-scale features of atmospheric inversions, which play a critical role in modulating vertical mixing and influencing weather patterns.

Related to convective parameters, the sounding observations reveal higher MUCAPE (3604 J/kg) and SBCAPE (3604 J/kg) than the simulated ones (3024 J/kg for H500\_NESTED and 3285 J/kg for H500), indicating a more unstable atmosphere profile in the observations. The lower CAPE in the simulations can be attributed to lower surface temperatures, which suggests that while the models successfully capture atmospheric instability, they tend to underestimate the potential for severe thunderstorms development. Markowski & Richardson (2010) emphasize that high MUCAPE values ( $> 3000$  J/kg), as seen in both observations and simulations, are strongly associated with enhanced vertical accelerations—a key factor in supercell dynamics. Consequently, an increase in MUCAPE correlates with heightened storm severity, including a greater likelihood of large hail formation (Taszarek et al., 2017; Xie et al., 2010). Therefore, the underestimation of CAPE in the simulations may lead to weaker simulated updrafts, potentially affecting the representation of supercell structure, longevity, and severity, including hail production and mesocyclone intensity. Observational sounding shows no convective inhibition (MUCIN: 0 J/kg, SBCIN: 0 J/kg), whereas the simulations introduce moderate convective inhibition, with values of -56 J/kg for H500\_NESTED and -124 J/kg for H500. This suggests a more stable atmospheric profile in the simulations, which could delay or suppress convective initiation. The discrepancy can be attributed to the lower simulated surface dew point and temperature values, which reduce the buoyancy of air parcels and increase the energy barrier required to initiate deep convection. Consequently, the simulations tend to overestimate atmospheric stability, inhibiting the development of deep convective processes. When compared to the findings of Calvo-Sancho et al. (2022), which analyzed supercell convective environments in Spain using ERA5 reanalysis, the simulated MUCAPE and MUCIN values in this event exceed the 95th percentile of ERA5 supercell hail events in northeastern Spain. This underscores the exceptional instability and inhibition present, and further suggests that even small biases in model thermodynamics can significantly impact the realism of supercell simulations and the reliability of severe weather forecasts.

The observed sounding shows a WS06 of 29 m/s, which is accurately captured by H500\_NESTED. In contrast, H500 underestimates this parameter (WS06 = 15 m/s). Similarly, the observed SRH03 ( $334 \text{ m}^2/\text{s}^2$ ) indicates an environment highly favorable to storm rotation and organized convection, exceeding the simulated SRH03 ( $253 \text{ m}^2/\text{s}^2$ ) for H500\_NESTED and the H500 one ( $125 \text{ m}^2/\text{s}^2$ ). These differences in WS06 and SRH03 are attributed to small discrepancies in the simulated wind speed and direction at low atmospheric levels compared to the observed profile (not shown), which directly impact the calculation of these parameters. The observed WS06 and SRH03 highlight a strongly favorable environment for organized convection and mesocyclone formation (Markowski & Richardson, 2010). While both simulations successfully capture the robust deep-layer shear required for supercell development, the underestimation of SRH03 in both models may result in weaker low-level rotation and an underrepresentation of tornadic potential (Thompson et al., 2003). Moreover, the observed WS06 and SRH03 values align with the higher percentiles reported in Calvo-Sancho et al. (2022), reinforcing the exceptional convective potential in the observed environment.



**Figure 4.** Skew-T log-P diagram comparing vertical profiles of temperature and dew point (in °C) and convective parameters. Observational data from the Murcia radiosonde (black) are compared with model soundings from H500\_NESTED (red) and H500 (blue) at 12:00 UTC on 31 July 2015.

Main conclusions can be summarized as follow:

**Computational efficiency:** On the ECMWF’s HPCF, H500\_NESTED require approximately 30% more computational resources than H500 because it involves two sequential simulations (parent and nested domains), whereas H500 uses a single-domain configuration. Given that this study is conducted exclusively within the ECMWF HPCF, the recommendation should be interpreted with caution.

**Model performance:** Both H500\_NESTED and H500 reproduce the overall structure of the supercell outbreak. H500\_NESTED provides slightly better representation of convective core structure, high reflectivity values, and a closer approximation to observed temperature and wind profiles. However, precipitation results show a mixed performance: while H500\_NESTED slightly reduces bias for moderate rainfall, it introduces larger errors in the most extreme range, where overestimation in the nested experiment is significantly greater than in H500. Both configurations systematically underestimate light precipitation and overestimate moderate to heavy amounts, but the nested approach does not consistently improve accuracy and, in some cases, worsens performance for extreme rainfall. Although these findings indicate that the benefits of nesting are limited and less consistent for precipitation than for temperature (where improvements are more evident), the gain is minimal when considered in relation to the increased computational cost.

**Environmental conditions:** Both simulations capture the general atmospheric profile but tend to underestimate instability and helicity, which may affect the accurate prediction of storm intensity and rotation. Convective parameters such as CIN, WS06, SRH03, and SCP in H500\_NESTED are closer to those observed in the Murcia sounding, while CAPE values in H500 match observations more closely. These results confirm that the environment is highly favorable for deep convection, as indicate by CAPE (3604 J/kg), SRH03 (334 m<sup>2</sup>/s<sup>2</sup>), and WS06 (29 m/s).

**Implications and limitations:** This study is motivated by the need to improve the understanding and prediction of severe convective storms in complex terrain, and the scarce bibliography available on

nesting results with HARMONIE-AROME simulations. The results highlight both the benefits and limitations of high-resolution nested configurations for representing mesoscale and convective-scale processes. While nesting improves temperature representation and slightly reduces bias for moderate precipitation, its overall impact on precipitation skill scores is inconsistent and, in the most extreme ranges, may even worsen performance. Although this analysis is based on a single, well-documented event, it serves as a proof of concept and provides a framework for future multi-event and seasonal assessments to validate the robustness and cost-effectiveness of the nesting strategy.

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