# 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:** | Re-analysis and Re-forecasting of Extreme Weather Events Using the ICON-LAM Model |
| **Computer Project Account:** | SPITGARB |
| **Principal Investigator(s):** | Valeria Garbero (mcy0), valeria.garbero@arpa.piemonte.it |
| **Affiliation:** | ARPA PIEMONTE |
| **Name of ECMWF scientist(s) collaborating to the project** (if applicable) | Alessio Golzio, alesgolz@arpa.piemonte.it |
| **Start date of the project:** | January 2025 |
| **Expected end date:** | December 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 |
| **High Performance Computing Facility** | (units) | **900.000** | **621.703** | **900.000** | **140.526** |
| **Data storage capacity** | (Gbytes) | 400 | 400 | 800 | 500 |

## Summary of project objectives (10 lines max)

Despite recent advancements in Numerical Weather Prediction (NWP) through improved data assimilation, increased computing power, and a deeper physical understanding, accurately forecasting the spatial and temporal patterns of precipitation and other extreme weather events remains a significant challenge. This project aims to improve future forecasts of severe events—including heavy precipitation, heat waves, and strong winds—by analysing recent extreme weather case studies with advanced numerical modelling. We will use the ICON-LAM model at high resolution (from 2 km down to 500 m). To optimize its performance different model configurations will be tested, varying initial/boundary conditions, physical parameterizations, and urban schemes. For validation, temperature, relative humidity, and wind forecasts will be compared against observations from both meteorological stations and citizen networks. Precipitation forecasts will undergo a rigorous fuzzy verification technique.

## Summary of problems encountered (10 lines max)

None.

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

The project will proceed with an in-depth analysis of extreme weather case studies at very high spatial resolution. We will focus on both heavy precipitation events across Italy that has been poorly captured by operational models and on urban heat waves.
Our primary goal is to identify the optimal model configuration for accurately reproducing these phenomena. To achieve this, we will systematically evaluate different model setups and assess their cability to represent observed events. This work will contribute to improving the reliability of severe weather forecasts at the local scale.

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

R. Negro, *Simulations of convective phenomena with the limited area version of the ICON prediction model and comparison with weather radar observations*. Tutor: D. Tordella, R. Cremonini, V. Poli, **V. Garbero**, A. Golzio. Politecnico di Torino, Corso di laurea magistrale in Ingegneria Aerospaziale, 2025 https://webthesis.biblio.polito.it/36833/

## Summary of results

During the project, three case studies characterized by forecasting challenges were analysed:

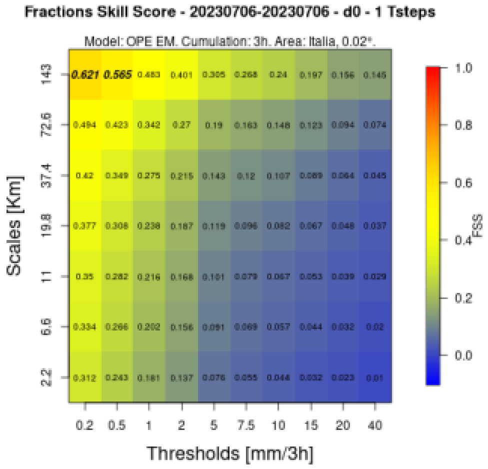
1. the hailstorm event of 6 July 2023, which was not predicted by the operational models
2. the 14 June 2025 event in the Parma area, also missed by the models
3. the 28 August 2025 event, characterized by an overestimation of precipitation over Piedmont and a concurrent underestimation over Emilia-Romagna

**6 July 2023**

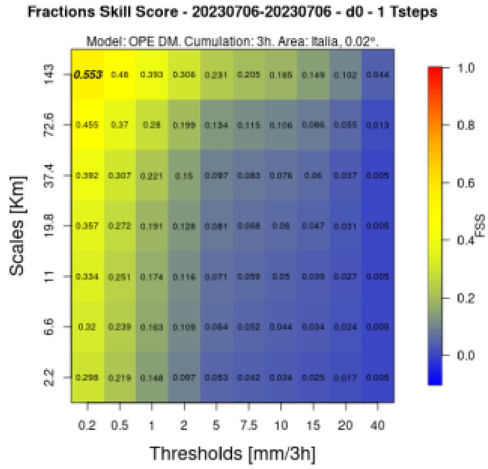
The supercell thunderstorm that occurred over central Piedmont on 6 July 2023 was poorly predicted by the operational models. Four re-forecasts of this event were conducted using ICON at 2 km resolution, each differing in the combination of microphysical parameterisation scheme and data assimilation technique used. ICON was compiled with the *--enable-emvorado* configuration, in order to produce radar reflectivity fields to be compared with those used for assimilation (based on Mie scattering).The first experiments reproduces the operational setup of ICON-2I, operational model run by ARPAE, employing a bulk-moment microphysics scheme without data assimilation (OPE EM); the second one adopts a double-moment microphysics scheme, also without assimilation (OPE DM). The third and fourth experiments implement a 24-hour LHN data assimilation cycle, using respectively bulk and double-moment schemes (OPE LHN and OPE DMLHN).

| Configuration | Initial Conditions | Boundary Conditions | Microphysics | Assimilation |
|---|---|---|---|---|
| OPE EM/IC1M | ICON-EU analysis | ICON-EU forecasts | Bulk-moment scheme | No |
| OPE DM/IC2M | ICON-EU analysis | ICON-EU forecasts | Double-moment scheme | No |
| OPE LHN/ IC1M-LHN | ICON-EU analysis | ICON-EU forecasts | Bulk-moment scheme | LHN |
| OPE DMLHN/ IC2M-LHN | ICON-EU analysis | ICON-EU forecasts | Double-moment scheme | LHN |

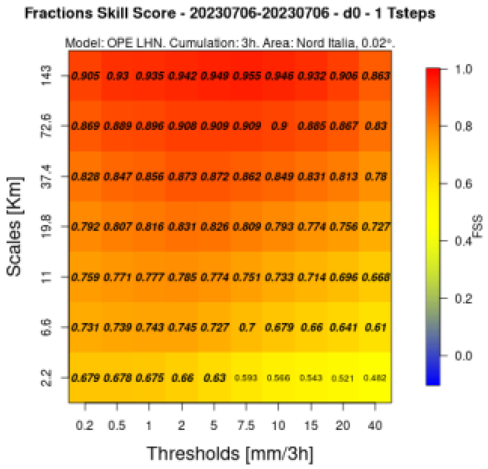
The performance of the different configurations in simulating severe convective storms was evaluated through comparison with radar observations, complemented by radio soundings and surface weather stations. A detailed analysis of the event and a discussion of the results are provided in the Master's thesis by R. Negro. The FSS verification process was adopted to evaluate the accuracy of the model's precipitation forecasts. Initially, a 2D fuzzy verification is performed by directly comparing the model's 3-hourly precipitation fields with observations. While the non-assimilated runs only exhibit their first useful spatial scale at 143 km, the assimilated runs prove skillful predictions even at the model's nominal resolution of 2.2 km for low to medium precipitation thresholds ($\leq 5mm/3h$). Accurately simulating convective events remains a particular challenge, primarily due to the inherent difficulty of triggering convection at small scales without data assimilation. A minor difference emerges between IC1M and IC2M with regard to the maximum precipitation threshold at which a useful scale is achieved. This threshold is found to be 0.5 mm/3h for the single-moment scheme and at 1.2 mm/3h for the double-moment scheme. However, this marginal improvement does not substantially alter the overall assessment of poor model performances. For higher accumulated precipitation thresholds (e.g., 40 mm/3h), the non-assimilated runs fail to produce useful skill scale. In contrast, the LHN runs show significant improvement: IC1M-LHN successfully captures intense rainfall events, those with a 40 mm/3h threshold, within a spatial range of 6.6 km from the observed locations, for instance. IC2M-LHN, instead, doesn't produce any useful scale at this threshold. When the threshold is lowered to 20 mm/3h, the first useful spatial scale for IC2MLHN is encountered at 37.4 km. These good results further demonstrate the temporal accuracy of the LHN when applied to the single-moment scheme.



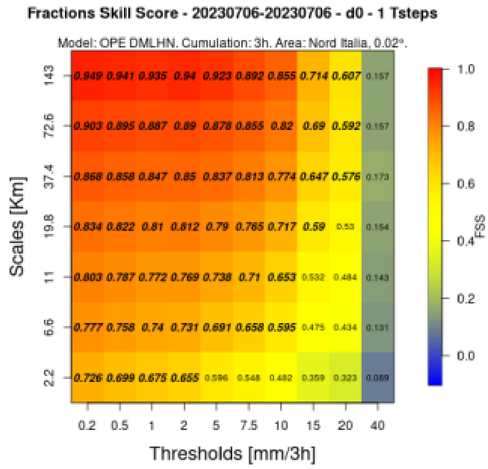

**(a)** IC1M




**(b)** IC2M

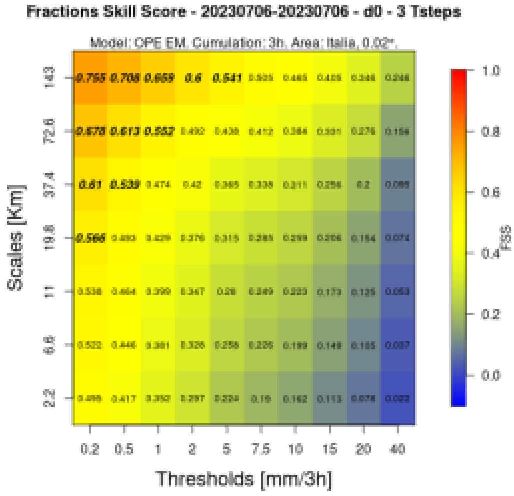



**(c)** IC1M-LHN

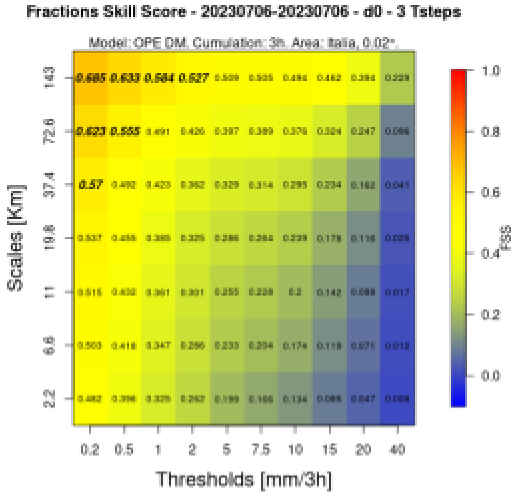



**(d)** IC2M-LHN

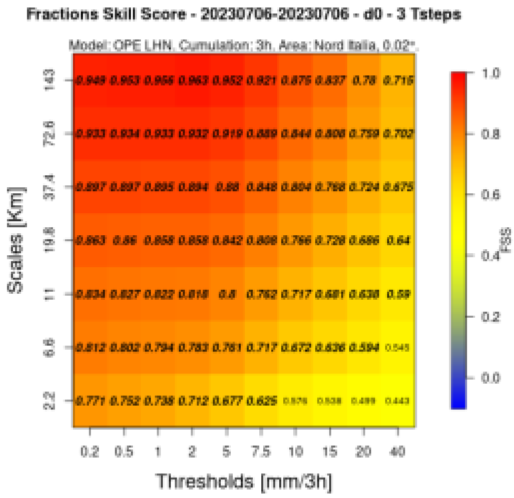
To account for potential temporal displacements of the model's precipitation structures, the analysis is then expanded into a <u>3D fuzzy verification</u>, which incorporates the preceding and subsequent 3-hourly simulated fields. Notably, fuzzy verification revealed that 24-hour Latent Heat Nudging (LHN) assimilation significantly improves the model's performance in these simulations.
The effect of increasing the temporal integration window differs significantly between simulations with and without assimilation. For runs without assimilation, this extended timeframe is particularly beneficial at low precipitation thresholds. The useful scale for IC1M increases substantially, decreasing from 143 km to 37.4 km at the 0.5 mm/3h threshold. Meanwhile, IC2M shows a similar improvement at the 0.2 mm/3h precipitation threshold. These results suggest that, despite exhibiting errors in the timing of convective initiation, the model maintains reasonable skill in representing the thermodynamic environment conducive to light-to moderate precipitation events. In contrast, LHN runs exhibit a twofold behaviour in FSS scores at high thresholds when longer averaging periods are used. For the single-moment scheme, the LHN technique appears to provide excellent temporal and spatial localization of extreme precipitation events. Consequently, expanding the analysis window introduces noise by potentially combining precipitation patterns that occurred before or after the actual event. This effect is clearly demonstrated by the increase of the useful scale at the highest threshold (40 mm/3h) from 6.6 km to 11 km when transitioning from 2D to 3D fuzzy. In contrast, the FSS values of the double-moment scheme for the 3D fuzzy are characterized by a slight improvement, particularly at the 20 mm/3h threshold, where the useful scale decreases from 37.4 km to 19.8 km. A substantial improvement is also evident in the useful precipitation threshold at the model resolving scale of 2.2 km, which increases from 2 mm/3h to 7.5 mm/3h.



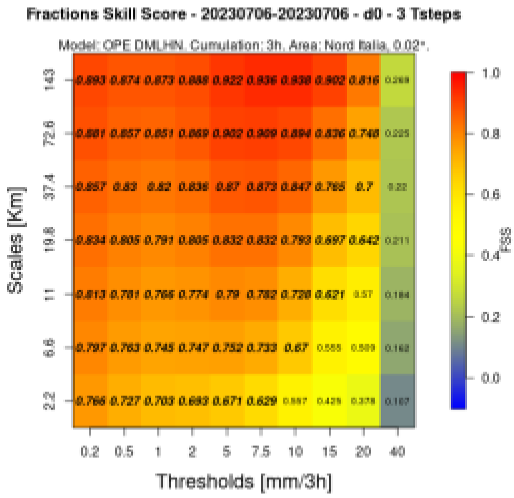

(a) IC1M




(b) IC2M



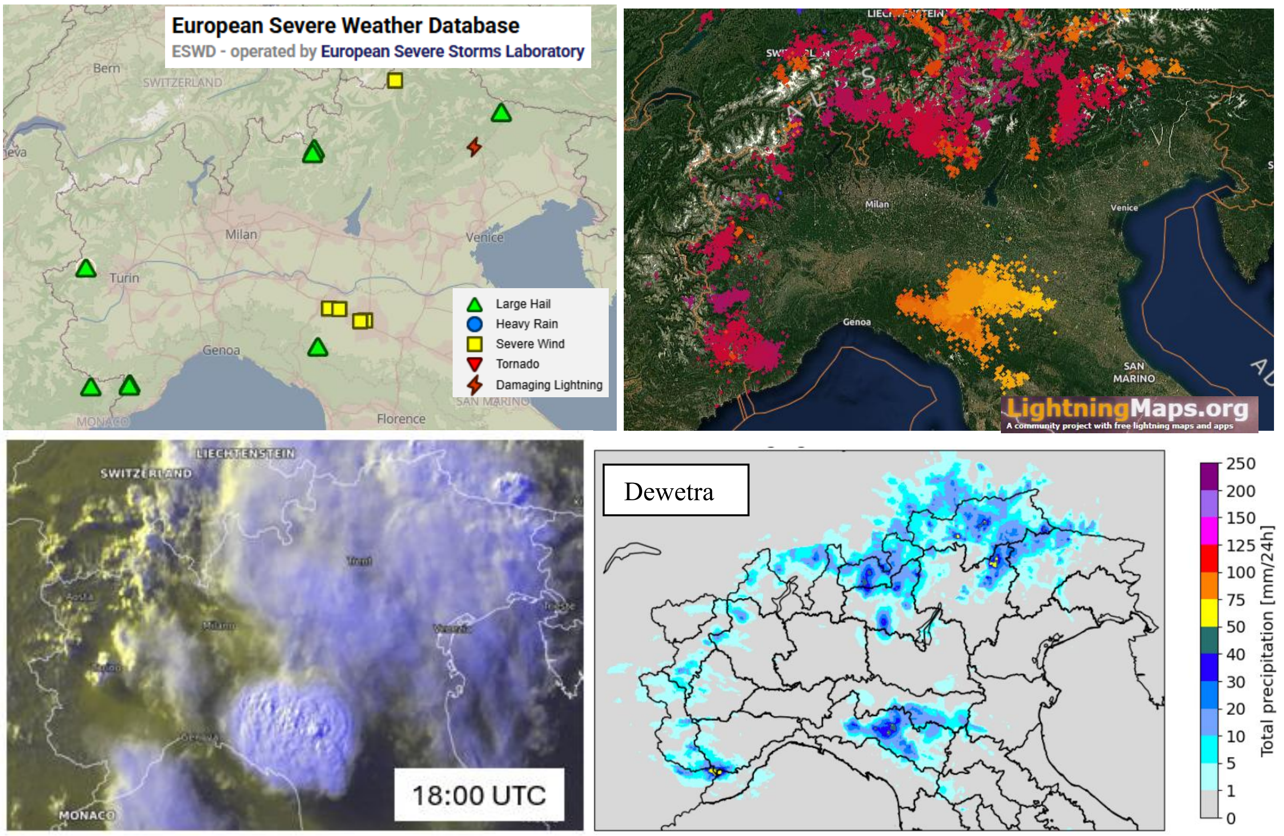

(c) IC1M-LHN




(d) IC2M-LHN

**14 June 2024**

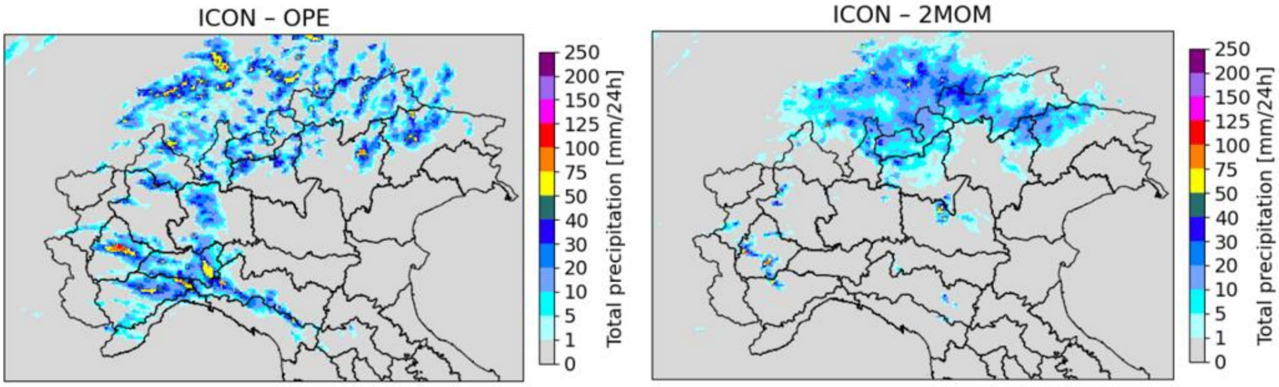
On 14 June 2025, the European synoptic-scale circulation was dominated by a strong African anticyclonic ridge extending from Algeria to the Scandinavian Peninsula, while an Atlantic trough with its associated low-pressure centre over the British Isles, was slowly advancing eastward. Northwestern Italy, located along the western edge of the anticyclone, was affected by the intrusion of cooler south-westerly upper-level flows combined with the high thermodynamic instability of the western Po Valley, where very warm and humid conditions prevailed in the lower troposphere. These conditions favoured the development of prefrontal convection over the Alpine regions and the Apennines.Thunderstorms were initially triggered by orographic lifting and were accompanied by hail and intense lightning activity, as documented by reports collected in the European Severe Weather Database and by the lightning map covering the previous 24 hours provided by LightningMaps.org. During the afternoon, convective cells that formed over the Emilian Apennines organized into a mesoscale convective system because of low-level convergence lines and strong vertical wind shear. The system affected the areas between Parma, Reggio Emilia, and Modena, producing intense electrical activity and downbursts with wind gusts exceeding 100 km/h. The associated precipitation resulted in daily accumulation of 40–60 mm, as indicated by the 24-hour precipitation field derived from radar estimates corrected using rain-gauge observations (Dewetra). Peak rainfall intensities reached 30–40 mm h$^{-1}$. Despite the favourable large-scale environment for convective development, operational numerical weather prediction models struggled to accurately reproduce the spatial distribution and intensity of the observed precipitation, as is often the case in weakly forced convective situations. This highlights the inherent challenges in forecasting localized, rapidly evolving convective systems, whose evolution is strongly controlled by mesoscale and local-scale processes.



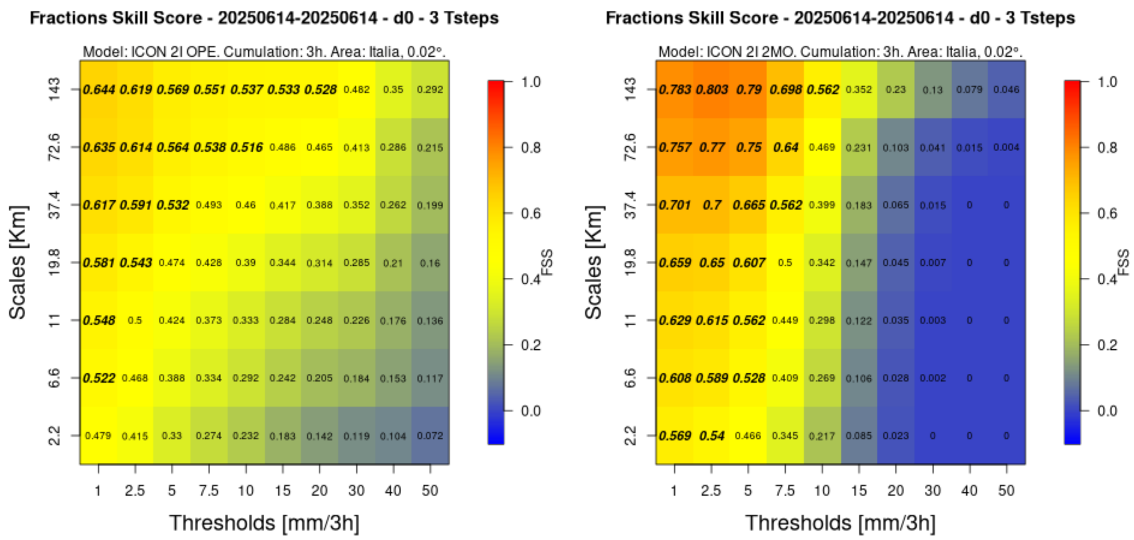

Two reforecasts of the event were therefore performed using the ICON model to assess whether modifications to specific physical parameterizations could improve the forecasts. In particular, the new two-moment microphysics scheme, recently implemented in ICON (via the *TWOMOM_MCRPH_NML* namelist), was tested. Initial conditions were provided by the ICON-EU analysis, without applying any data assimilation, while boundary conditions were taken from ICON-EU forecasts. Simulations were carried out at 2 km resolution over the entire Italian domain, adopting the operational ICON-2I setup provided by ARPAE and comparing the one-moment microphysics scheme (*inwp = 2*) with the two-moment microphysics scheme (*inwp = 4*).

| **Configuration** | **Initial Conditions** | **Boundary Conditions** | **Microphysics** |
|---|---|---|---|
| OPE | ICON-EU analysis | ICON-EU forecasts | inwp=2 |
| 2-MOM | ICON-EU analysis | ICON-EU forecasts | inwp=4 |

The new simulations still fail to reproduce the thunderstorms over the Parma area. The OPE configuration predicts widespread precipitation over Piedmont and the northern Apennines, which was not observed, while the 2-MOM configuration shows a partial improvement in representing instability over the Lombard and Trentino Alps.



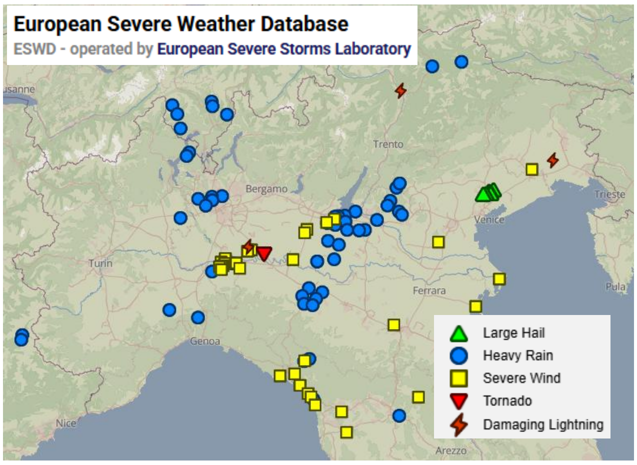

Quantitative verification using 3D fuzzy techniques indicates that the OPE configuration performs better at high thresholds, with a useful scale of about 140 km for the 20 mm/3h threshold and 72 km for 10 mm/3h. The 2-MOM configuration, on the other hand, shows improved skill for low and intermediate thresholds, reaching a useful scale of about 2 km for the 2.5 mm/3h threshold and 6 km for the 5 mm/3h threshold.
Overall, the new microphysics scheme appears to provide benefits mainly in representing light to moderate precipitation, but it still fails to correctly simulate the most intense convective phenomena over the Parma area.

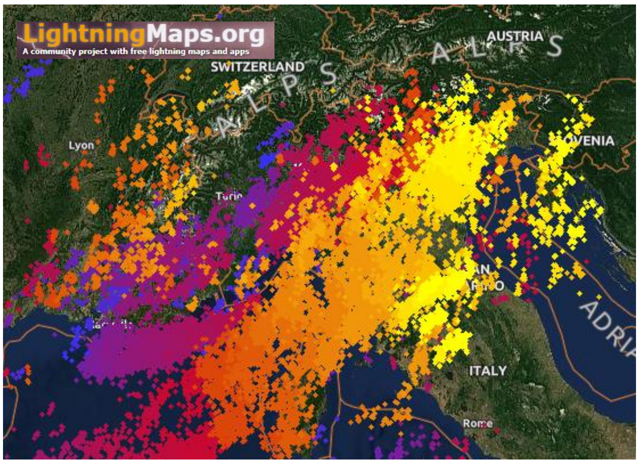



## 28 August 2024

On 28 August, the European synoptic pattern was characterized by the southward extension of a trough, with its low-pressure centre over the British Isles, reaching as far as the Spanish coasts, while the central Mediterranean was influenced by an African-origin anticyclonic ridge. The strong contrast between warm and moist southerly air masses affecting northern Italy and the influx of colder air aloft associated with the trough resulted in widespread heavy, and in some areas very heavy, precipitation over northern Italy.
Daily accumulated rainfall on 28 August reached values close to 200 mm/24 h over northern Piedmont and up to 130 mm/24 h between the provinces of Parma and Piacenza. In addition to the intense rainfall, frequent lightning activity, strong wind gusts, and localized hail were reported, as documented by reports from the European Severe Weather Database and by the 24-hour lightning map provided by LightningMaps.org.
The operational model runs issued on 27 August at 00 UTC showed, for 28 August (D1), widespread precipitation over the northern Alpine sectors, with 24-hour accumulations exceeding 150 mm predicted by all models over the Piedmont–Lombardy region, and reaching as much as 400 mm/24 h

in the ICON-2I simulations. The ICON model significantly overestimated precipitation between Piedmont and Lombardy and failed to capture the precipitation that propagated from the Apennines into the Po Valley.

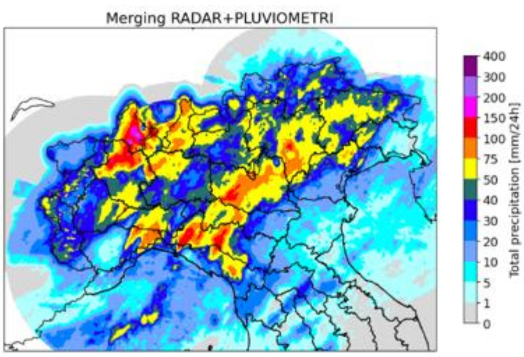


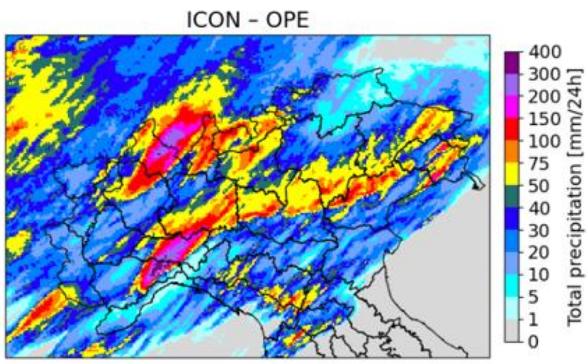



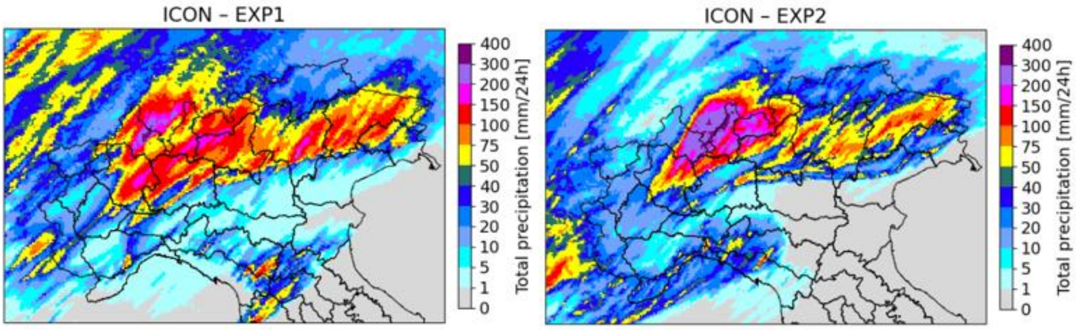

To address the issue of precipitation overestimation in ICON, a targeted approach was developed in collaboration with ARPAE to assess the impact of domain size and initial and boundary conditions (IC/BC). Case studies characterized by south-westerly flow— a synoptic configuration frequently associated with overestimation events, including the present case—were selected, and a sensitivity analysis was performed focusing on the operational domain and the adopted IC/BC.
To this end, three reforecasts of the event were conducted using ICON-EU analyses as initial conditions, without applying any data assimilation, and ICON-EU forecasts as boundary conditions, and compared with simulations conducted by ARPAE using IFS as initial and boundary conditions. The simulations were carried out at 2 km resolution over three domains: operational, reduced, and extended.

| Configuration | Initial Conditions | Boundary Conditions | Domain |
|---|---|---|---|
| ICON-2I t24 | IFS analysis | IFS forecasts | Operational |
| ICON-2I t25 | IFS analysis | IFS forecasts | Reduced |
| ICON-2I t26 | IFS analysis | IFS forecasts | Extended |
| OPE | ICON-EU analysis | ICON-EU forecasts | Operational |
| EXP1 | ICON-EU analysis | ICON-EU forecasts | Reduced |
| EXP2 | ICON-EU analysis | ICON-EU forecasts | Extended |

The resulting precipitation patterns are more consistent with observations, including rainfall over the Po Valley. However, both EXP1 and EXP2 still overestimate peak precipitation between Lombardy and Piedmont.






The fuzzy verification results indicate that the new experiments outperform the ICON-2I simulations run by ARPAE, which include data assimilation and are forced by IFS, for intermediate to high precipitation thresholds. A useful scale of 6 km is achieved for thresholds of 5 mm/3h, while a scale of 70 km is reached for thresholds of 20 mm/3h. No significant differences in performance are observed when varying the domain; however, the impact on the structure of the precipitation pattern is striking and warrants further in-depth investigation.